Eucalypts in Asia

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Preface

As the global population grows and areas of native forest decrease, particularly in developing countries, tree plantations and agroforestry have become an increasingly important source of timber, fuelwood and raw materials for pulp and paper. In these new forests, species of the genus *Eucalyptus* are now being widely used throughout the world to provide wood products in regions of scarcity of wood and other tree products. Eucalypts are highly productive and well adapted to dry, infertile sites, and are a productive land use of degraded land no longer suitable for agriculture. They can also contribute to the protection of land and water systems. Nowhere is the utility of eucalypts more evident than in Asia where these plantations have become a significant feature of the natural resource base in a number of countries, particularly India, China, Vietnam and Thailand, where they support major industries and contribute to alleviation of rural poverty.

The introduction of new species and the development of new rural industries have brought new research needs and challenges, which have been addressed by a number of research institutions in Asia over the past decades. The 'International Conference on Eucalypts in Asia' was conceived by the China Eucalypt Research Centre of the Chinese Academy of Forestry. It provides a timely examination of the role of these species in Asia and reports on the state of the science in this region. The proceedings deal with socioeconomic, genetics, nutrition, pests and diseases, environmental impacts and utilisation issues. The increase in the area of eucalypt plantations in Asia has not been without contention, and some of the issues, particularly water, are well-addressed in these proceedings. This conference is the first to consider such a wide range of issues about eucalypts in the Asian region, and is a valuable contribution to our knowledge and ability to manage these species for maximum benefit and sustainability.

The Australian Centre for International Agricultural Research (ACIAR) was pleased to provide support for this conference. Australia is, after all, home to most species of eucalypts, and Australian involvement in the conference reflects the long-term research collaboration between several Australian research institutions and counterparts in Asia. This collaboration is reflected by the number of reports based on ACIAR-supported projects The conference also demonstrates the increasing level of skills in scientific forestry in Asia, from which these countries can only benefit.

Finally, ACIAR wishes to thank the Directors, Yang Minsheng and Xie Yaojian, and staff of the China Eucalypt Research Centre in Zhanjiang for hosting the workshop and organising the field tour. The efforts of Chen Shaoxiong as Secretary of the Chinese Organising Committee are especially appreciated. Thanks are also due to staff of CSIRO Forestry and Forest Products, Canberra, and the Forest Science Centre, Heidelberg,

Victoria who worked closely with the Chinese organisers to develop the workshop program. The workshop would not have been possible without the generous support and sponsorship of the Zhanjiang Municipal People's Government, Chinese Academy of Forestry, Guangdong Science and Technology Department, UPM–Kymmene Group, Metso Paper, Leizhou Forestry Bureau, Zhanjiang Forestry Bureau, Zhanjiang Science and Technology Bureau, the Crawford Fund and organisations that enabled the attendance of individual participants.

John Fryer
Research Program Manager, Forestry
ACIAR

Present Situation and Prospects for Eucalypt Plantations in China

Yang Minsheng[1]

Abstract

The area of eucalypt plantations, mainly *Corymbia citriodora* (*Eucalyptus citriodora*) and *E. exserta*, increased rapidly in China from the late 1960s to the early 1980s. In the 1980s, more eucalypts were introduced, and provenances of species such as *E. urophylla*, *E. grandis*, *E. camaldulensis* were tested. More recently, research has also been conducted to select species and develop production systems for cold-tolerant eucalypts for use in cool regions of southern China. From a breeding base of over 2000 species, provenances/families, and clones, selected material has been deployed on a large scale to establish fast-growing, high-quality, eucalypt plantations. There are now over 1.54 million ha of eucalypt plantations in China. Since 1990, most plantations have been managed for the production of pulpwood and some for sawn timber production. Eucalypt plantations in China should have good prospects. The Chinese Government has implemented preferential policies, including reducing taxes and increasing investment, to encourage development of short-rotation, industrial timber, eucalypt plantations. Also, larger markets are stimulating local and foreign capital enterprises to actively invest in Chinese eucalypt plantations. For a long period, pulpwood has been the main product, but utilisation for sawn wood and solid timber products is now an important trend. Further research is necessary to select and breed new species, to improve wood quality and cultivation technologies, and to achieve sustainable development of eucalypt plantations in China.

Eucalypts were first planted in China in 1890. From 1890 to 1950, many eucalypt species were introduced from foreign countries but, as the process was fragmented and not centrally coordinated, progress was slow. The main species planted were *Eucalyptus camaldulensis, E. globulus, Corymbia citriodora* (*E. citriodora*), *E. tereticornis* and *E. exserta* (Wang Huoran 1999).

From the 1950s to the 1970s, eucalypts were planted on a large scale. In 1954, the first eucalypt forest farm, Yuexi Forest Farm (formerly Leizhou Forest Bureau), was established in Guangdong province. In 1963, Guanan Eucalypt Forest Farm (Guanan Forest Bureau) was established in Guangxi province, and by the end of 1960 there were over 10 eucalypt

forest farms in this province. In 1972, a cooperative group for eucalypt research was established (Qi Shuxiong 2002). Overall, in the 1950s to 1970s, techniques eucalypts breeding and management developed slowly, and plantations with low-intensity management expanded. Nevertheless, it was a good beginning to eucalypt plantation development in China. In this period, *C. citriodora* and *E. exserta* were the main species planted on a large scale. Also, a local natural hybrid, *E.* Leizhou No. 1, was planted widely. However, for many technical and other reasons, by the 1990s these species had largely disappeared (Hu Tianyu 2002).

The 1980s saw further rapid expansion of plantations, and initiation of research programs on eucalypts. Two key projects were initiated during the 1980s. The first was the China–Australia Afforestation Project at Dongmen State Forest Farm, Guangxi

[1] China Eucalypt Research Centre, Zhanjiang, Guandong, China

province, which introduced 110 species/350 provenances/1100 families. The other was the ACIAR/Chinese Academy of Forestry project: 'Introduction and Cultivation Experiments for Australian Broad-leaved Tree Species'. In 8 years, this project contributed to 1400 ha of eucalypt research plantations, introduced over 100 species/200 provenances, and established 40 ha of seed orchards of *E. urophylla*, *E. tereticornis, E. camaldulensis* and *E. grandis* etc. to form the largest eucalypt gene base in China (Qi Shuxiong 2002). This basic material was introduced scientifically and breeding groups were established. Some superior provenances and families were selected and bred, and used widely to greatly increase the productivity of Chinese eucalypt plantations. In the 1980s, over 20 species were planted on a large scale. Some of the most successful introductions in this period were *E. urophylla*, and hybrids such as *E. grandis × E. urophylla* (Zhang Ronggui 2002). They formed a good base for the development of eucalypts in the 1990s, and had a major influence on the eucalypts now planted in China.

In the 1990s, there was vigorous research and development of eucalypt plantations. The China Eucalypt Research Centre (CERC) was established. The China Eucalypt Association (CEA), which currently has 500 members in 18 provinces, was founded. The CEA fosters initiation of much new research on eucalypts. The main task of CERC is collaboration with research groups and undertaking key projects of national eucalypt research. It organises the promotion and application of research achievements, provides technical assistance in tree breeding and propagation, and technical services and training.

In the past 10 years, extensive research has been carried out on utilisation of eucalypts for pulp production and solid wood products, and on the cold-tolerant eucalypts, through national key projects, superior technology introduction projects and international cooperation projects. About 2000 families of *E. urophylla*, *E. grandis*, *E. globulus, E. wetarensis*, *E. pellita*, *E. dunnii, E. smithii* and *E. tereticornis* have been tested for their adaptability in southern provinces, especially in Fujian, Guangdong, Guangxi, Hunan, Sichuan and Yunnan. Selection and hybrid breeding has provided numerous superior provenances/families and clones, many of these have been deployed for plantation develop-

ment (Xu Jianmin, pers. comm. 2003). Availability of eucalypt species/varieties well adapted for degraded hill country and cooler regions of south-central China is increasing rapidly, and there is greater focus on developing sustainable management techniques to ensure long-term high productivity of plantations.

There are now about 1.54 million ha of eucalypt plantations in China (Qi Shuxiong 2002), and the area is still expanding. Eucalypts grow fastest in southern China, producing economic and ecological benefits that are welcomed widely by the government and local people.

Status of Eucalypt Research

Since the 1990s, there has been a focus on new species for pulp production. The aims have been to improve productivity by better silvicultural techniques, to shorten coppice rotations, and to increase social, economic and ecological benefits. These studies have been carried out in international key projects ('Eight-five', 'Nine-five' and 'Ten-Five'), local government and departmental key projects, international cooperation projects, national projects to introduce superior technology, and cooperation between forest research and wood product departments. These studies have achieved high returns.

Breeding new species for pulpwood has been important and the following have been among the main species involved: *E. grandis* (14 provenances), *E. urophylla* (97 provenances), *E. tereticornis* (59 provenances)*, E. camaldulensis* (136 provenances), *E. wetarensis* (8 provenances)*, E. pellita* (15 provenances), *E. dunnii* (15 provenances)*, E. globulus, E. smithii, E. cloeziana, E. maidenii, E. saligna* and *E. benthamii*. Provenance trials and selection, plus tree selection and progeny testing, have been carried out in eight provinces. Breeding has been undertaken to obtain superior hybrids, e.g. *E. urophylla × E. grandis, E. grandis × E. urophylla, E. urophylla × E. tereticornis, E. urophylla × E. camaldulensis,* and *E. saligna × E. exserta*. Selection of clones has resulted in increased productivity, with some superior clones giving up to 40–50 $m^3\,ha^{-1}\,yr^{-1}$. More than 200 superior clones have been planted from the breeding programs of CERC, Dongmen Farm (Guangxi) and Zhanjiang Forestry Bureau.

Plantation Management Technologies

We have aimed to improve plantation management technologies. Studies have been made to determine the optimal rotation length for pulpwood productivity for different eucalypt species. There have also been studies on technologies to enhance productivity, e.g. initial plant density, quantity and timing of fertiliser application, cultivation strategies, and the relationship of these factors with wind tolerance and afforestation on hilly land.

Cultivating Large-Diameter Eucalypts

Cultivating large-diameter eucalypts is a new trend in China and elsewhere. Generally, the value of large diameter eucalypts is 5–10 times the value of eucalypts used for pulpwood. CERC is the manager of two key projects: 'The cultivation technology of large diameter eucalypts' and 'Introduction of high value eucalypt species'. It has established provenance/family trials and 400 ha of plus-selection and progeny testing of more than 10 species/500 families. The main species being tested are *E. benthamii, E. camaldulensis*, *E. cloeziana, E. globulus, E. grandis*, *E. pellita, E. saligna* and *Corymbia torelliana,* in Fujian, Guangdong, Guangxi, Hainan, Hunan and Yunnan. Concurrently, there are studies of management technology and wood properties. Some interim conclusions indicate good prospects for cultivating large-diameter eucalypts.

Selection of Cold-Tolerant Eucalypts

Cold-tolerant eucalypts are important for improving living standards of the poor in mountainous areas. Lack of cold tolerance is the key factor restricting eucalypt planting in northern China, and research is in progress to find species suitable for planting in cooler regions of south-central China (Hunan) and in the southwest (Sichuan and Yunnan). In Australia, many eucalypts occur in areas with cold winters, and some species have been introduced successfully (Luo Jianzhong 2002). A key international cooperation project, 'Development of germplasm and production systems for cold-tolerant *Eucalyptus* for use in cool regions of southern China (ACIAR FST/96/125)', has been in progress since 1999. Through provenance/family trials, plus-selection and progeny testing, superior material has been developed and is now being planted on a large scale in, for example, Guangxi, Yunnan, Hunan and Fujian provinces. The main cold-tolerant species are *E. dunnii, E. grandis, E. globulus, E. camaldulensis, E. saligna* and *E. smithii.*

Wood Properties, Processing and Utilisation

Research into wood properties, processing and utilisation is a new area of activity. Before the 1980s, the aim of eucalypt introduction and silviculture was production of fuelwood, poles and mining timbers. Today, the focus is on production of fibre, e.g. export woodchips, medium density fibreboard (MDF) and particleboard. About 3 million m^3 of eucalypt wood is used by more than 20 MDF and particleboard factories in southern China. No large-scale pulp mill exists yet in southern China, so most eucalypt wood is exported to Japan, Korea and other regions of the world. Exports of woodchips amount to 1.1 to 1.5 million oven-dry tonnes. Planning is in progress to build a few large-scale eucalypt pulp and paper mills.

China is the largest producer of eucalypt leaf oils in the world, with 1000 t exported annually. They are produced from *E. globulus* and *C. citriodora* in Yunnan, Guangdong, Guangxi, Sichuan, Chongqin, Hainan and Fujian provinces. Solid eucalypt timber is used on a small scale for construction and furniture. Products include finger-jointed timber, laminated veneer lumber board and veneer from small diameter (< 25 cm) logs (Peng Yan 2001). Overall, there is very little utilisation of eucalypts for higher value end products.

Two key factors limiting higher value use of young eucalypts as saw logs are high growth stress and difficulties of wood drying (Yang Junli, pers. comm. 2003). The Chinese Academy of Forestry (CAF), CERC and others are implementing an International Tropical Timber Organization funded project 'Improved and diversified use of tropical plantation timbers in China to supplement diminishing supplies from natural forests'. The theme of this project is silviculture and processing of eucalypts for higher-value products.

Effect of Eucalypt Plantations on the Environment

It has been suggested that high growth rates and short rotations are associated with excessive water use and

depletion of soil nutrient reserves. Removal of organic matter and exposure of the soil surface by litter collection and whole-tree harvesting are common. To address this problem, CERC cooperated with the Guangdong Science and Technology journal in 1998 to invite research and production specialists to discuss eucalypt–ecosystem interactions (Yang Minsheng 2002). In 1999, the Research Institute of Tropical Forestry initiated a collaborative ACIAR project 'Eucalypts and groundwater: management of plantations to avoid resource depletion and environmental degradation in China and Australia with the Centre for Forest Tree Technology (Australia). Other partners in the project include the South China Institute of Botany, China Eucalypt Research Centre, CSIRO Land and Water and the University of Melbourne (China–Australia Collaborative Project 2000).

At the same time, many local research and production departments have carried out extensive trials to find optimal management protocols to minimise any negative effects of eucalypts on the environment. These have included mixed plantings of *Eucalyptus* and *Acacia* species to increase productivity while permitting sustainable management (Huang Jincheng 2000). Scientific management of plantations, improved silvicultural techniques, site–species–variety matching etc. can benefit the environment in many ways. Establishing plantations on degraded sites can renew vegetation, increase biological diversity, improve soil structure and the soil flora and fauna, and improve the microclimate and environment of forested land (Xie Yaojian, pers comm. 2003). Recent research indicates that good plantation management will not deplete groundwater, cause severe erosion of deep red soils, or lead to a decline in fertility of plantation soils (Bai Jiayu and Gan Siming 1996).

The suitability of eucalypt plantation wood for use in the built environment has been studied systematically. The chemical and acoustic properties, wood colour and light resistance of five eucalypts, including *E. urophylla, E. urophylla × E. grandis* and *E. cloeziana*, were tested by Professor Jiang Zehui and Zhao Rongjun. The aim was to provide reliable technological parameters to support the use of eucalypt timber in architecture and building (Zhao Rongjun 2002).

New Technologies

At present, standard breeding and selection are the main means of eucalypt improvement in China, but new technologies such as gene transfer and molecular markers have good prospects. CERC has collaborated with the Chinese Academy of Agriculture in research on *Pseudomonas solanacearum* tolerance, by applying gene transfer and molecular markers, and have produced some disease-resistant material for field testing. Using RAPD technology, Dr Mu Xiaoyong has researched genetic linkage maps of *E. wetarensis.* Dr Gan Siming of the Research Institute of Tropical Forestry (Zhu, C., pers. comm. 2003) has constructed two, middle-density genetic linkage maps and determined the location of 4QTLs controlling seedling height in *E. urophylla* and *E. tereticornis.*

Development of Eucalypt Industry Policies Affecting Forestry Development and Research

Economic reform in China has led to dramatic and continuous economic growth in the country. The purchasing power of various groups and individuals has greatly increased in relative terms. China has been recognised as a huge market for numerous products, including wood as both raw material and finished products. The country's enthusiasm for economic development, greater purchasing power of the increasing population, and insufficient domestic production of roundwood and wood-based products have, in combination, accelerated the demand for wood. Being aware of the deficiency in forest resources, the Chinese Government has set up a strategic goal to increase forest cover to 17% by early this century (Zhou Shengxian 2002). However, despite a significant reforestation effort, China's domestic wood supply will not be able to keep up with its demand. Limited availability of land and water will also put a strain on the scale of reforestation. As a result, the gap between demand and supply is expected to remain over the next few decades. In the last few years, utilisation of wood-based panel products has gained tremendous momentum, and the imports of logs and various other wood products have also considerably increased. The State Forest Administration plans to establish 2.6 million ha of high-yield pulpwood plantations in the next 10 years. As a

result, larger pulp and paper factories (>500,000 t/yr) using eucalypt chips will be established in southern China to meet the strong domestic demand for paper (Wang Kai 1999).

China therefore urgently needs to establish more plantations and to improve efficiency in utilising its available forest resources. The national and local governments have instituted a series of policies to increase investment in forestry development and research. They include reduction of forestry taxes and other fees, relaxation of harvesting restrictions, and provision of loan funds at subsidised rates. Taxes and fees for eucalypt plantations have been reduced by 20% or more (Zhang Zuofeng 2000). Preferential policies are currently promoting widespread investment in eucalypt cultivation management and research.

The Chinese Government has also made a large investment to establish an improved seed and seedling program. Since 1998, China's Planning and Development Commission (SDPC) and the State Forestry Administration (SAF) have approved 2111 forestry seed and seedling programs to provide superior and standard seedlings. This has entailed a total investment of up to 436 million RMB (Anon. 2003). An example is the Southern State Tree Seed and Seedling Base at Zhanjiang. This facility concentrates on production, management, research and development, and science promotion. It is focusing on tree improvement, economy of scale, modernisation and commercialisation. It has an annual capacity of 58.6 million plants, including 40 million cutting/seedlings.

Larger Scale Intensive Management, and Integrated Processing and Utilisation

China is a net importer of wood pulp and forest products. The chronic shortage has been exacerbated by the logging ban on large areas of native forests, entry to the World Trade Organization and increasing awareness of environmental problems. Wood pulp and wood-based panel products have become more important with Chinese national economic development. There is a need to increase local production but this is seriously constrained because of the shortage of wood resources. China urgently needs to establish more plantations and to improve efficiency in utilising its available forest resources. Currently, the enormous market opportunity is stimulating many

investments in processing facilities and new plantations. Pulp mills will be rapidly developed in southern China, e.g. a eucalypt pulp mill in Zhanjiang with an annual output of 700,000 t is planned (Academy of Forest Inventory, pers. comm. 2002).

Improvement of Wood Quality and Economic Returns — Developments for Sawn Timber and Solid Wood Products

In the last few years, the utilisation of wood-based panel products has gained tremendous momentum, and imports of logs and various other wood products have also increased greatly. China has a chronic shortage of large-diameter, high-quality logs. It has been recognised that eucalypts can offer more than just pulp and paper, charcoal, fuelwood, poles and mining timbers. More importantly, it is recognised that value-adding to eucalypts is a future economic necessity.

Eucalypt plantations can be managed to produce both pulpwood and sawn timbers/solid wood products. Growing eucalypts for both pulp and sawn timber requires optimal silvicultural practices; earlier thinnings can be used for pulp, and more mature trees for solid wood products. Research is under way to select and breed trees for solid wood products, define optimal silviculture practices, and determine wood properties.

Increase Growth Rates and Expand the Plantation Estate

Few of the more than 300 eucalypt species introduced into China have been studied systematically and used successfully in production forestry. For further improvement, it is necessary to establish and improve some permanent breeding bases. Average mean annual increment of large-scale production eucalypt plantations is very low, frequently less than $10 \ m^3 \ ha^{-1} \ yr^{-1}$ (Xu Daping et al. 2000), less than half the average productivity ($20 \ m^3 \ ha^{-1} \ yr^{-1}$) of eucalypt plantations in other parts of the world (Brown et al. 1997). Moreover, productivity of Chinese eucalypt plantations is very variable, from 2–$70 \ m^3 \ ha^{-1} \ yr^{-1}$. This indicates great potential for improving productivity of eucalypt plantations in southern China. So, ongoing breeding of new fast-

growing species, accelerating breeding for cold tolerance, increasing production of improved planting material, and expanding areas of higher quality plantations is a positive trend.

Sustainable Management of Eucalypt Plantations

The main target of sustainable management of eucalypt plantations is maintaining long-term productivity of the land. As the eucalypt plantation area expands, rotation lengths shorten, and inappropriate plantation establishment and management techniques are applied. Diseases and insect pests are increasing, there is severe erosion of deep red soils, and soil fertility is declining. This situation is becoming a key factor limiting production of industrial wood (Sun Xiaomei and Zhang Shougong 2002). To prevent the productivity decline, reasonable management strategies must be employed. Planting monocultures with a narrow genetic base is a major reason for the increases in diseases and insect pests in eucalypt plantations. There is potential danger in establishing large areas of one species, especially of a single clone. Stability of eucalypt plantations can be improved by adopting many species and various clones, and mixing different plantations in the landscape, controlling genetic resources, and scientific management (Jiang Youxu 2001).

New Technology

There are prospects for applying genetic engineering to breed new species in eucalypts. Insertion of cold-tolerance gene(s) and genes for disease resistance would be an outstanding achievement. Moreover, the use of genetic engineering to control fibre quality and reduce lignin, so as to increase the productivity of pulp and reduce the cost of making pulp and paper, is feasible. These technologies have been applied in poplar and other species, and are being researched for eucalypts.

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Clonal *Eucalyptus* Plantations in India

P. Lal[1]

Abstract

Shortage of industrial roundwood has hampered modernisation, growth and expansion of wood-based industries in India, resulting in increasing imports of timber, paper and wood-based products. Wood-based industries cannot raise captive plantations for meeting their future raw material requirements, because of statutory ceilings on agricultural land-holdings. Some progressive industrial units have promoted farm forestry plantations through supply of planting stock, technical extension services and buy-back arrangements, with varying degrees of success. Large-scale *Eucalyptus* plantations have been raised on forest and farm lands, community lands and road/rail/canal strips. Most plantations have low productivity and large genetic variation because of the unimproved seed used. However, productivity and profitability of plantations has been revolutionised with the development of genetically improved, fast-growing and high-yielding clonal planting stock of poplars and eucalypts. Since 1989, significant improvements in quality of produce and reductions in per unit production costs have been possible using true to type, uniform and genetically improved clonal planting stock of eucalypts in Andhra Pradesh state. Average productivity of commercial clones is about 20–25 m^3 ha^{-1} yr^{-1}, and many farmers have achieved 50 m^3 ha^{-1} yr^{-1}, making farm forestry an economically attractive option. Clonal eucalypt plantations benefited nearly 2000 farmers who planted 5.6 million clonal saplings on 3217 ha in 1992–1999. In addition, 1.6 million improved clones were supplied to state forest departments /forest development corporations. More than 10 million clonal eucalypts were supplied in 2000–2002, and the target for 2003 is 6 million clonal plants. A large number of new clones are now under field evaluation in Andhra Pradesh and Punjab. Additional facilities will be set up to meet the growing demand for improved clonal material by farmers in Punjab, Haryana and adjoining states in north India. Key factors leading to success of clonal eucalypt plantations have been: (1) improved profitability due to high productivity and better quality of wood; and (2) a series of demonstration plots, high-quality technical extension services, and buy-back arrangements.

Forest cover in India is only 15.7%, compared with the world average of 26.6%, and per capita forest is only 0.06 ha while the world average is 0.64 ha. This is far short of the 33.3% forest cover envisaged in the national forest policy (Anon. 1999). Forests have very low growing stock, (65 m^3 ha^{-1}) and a mean annual increment less than 1 m^3 ha^{-1}. Substantial improvement in productivity of forest resources, and promotion of large-scale farm forestry plantations are essential to meet national needs for fuelwood, timber and wood products on a sustainable basis, and to ensure environmental amelioration and conservation of the biodiversity in natural forests.

Nearly 50% of forest areas have suffered severe degradation because of mounting biotic pressures and poor budgetary support for sustainable development of government-owned forest resources over many decades. Poor increments, extremely low yields and increasing demand led to a growing shortage of timber and fuelwood in India. Fuelwood needs have been met from agricultural residues and largely through unregulated, illicit and unsustainable

[1] Pragati Biotechnologies, 666 Urban Estate, Phase II, Jallandhar City 144022.
   Email: <piarelal@hotmail.com>..

removals from forests. However, modernisation, growth and expansion of wood-based industries have suffered for want of sustained supplies of industrial roundwood at reasonable prices, and this has increased imports of newsprint/paper and wood products.

Wood-based industries cannot raise captive plantations to meet their future raw material requirements because of statutory ceilings on agricultural landholdings in India. National Forest Policy (1988) enjoins wood-based industrial units to meet their future raw material requirements through developing partnerships with farmers. Unfortunately, this policy has not addressed the legitimate and genuine concerns of the forest-based industries, including their demand for partnership with state governments for time-bound reforestation of degraded forest lands. Moreover, major disincentives, such as mandatory requirements for felling permission and transit permits, continue to hamper development of farm forestry in many states (Lal 2000)

Poplar Plantations

The safety match industry in northern India imported huge quantities of veneer quality logs of semal (*Bombax ceiba*) and gutel (*Trewia nudiflora*) from Nepal for nearly a decade from mid 1970s onwards, for manufacture of match splints. Simultaneously, based on limited successful trials by the Uttar Pradesh Forest Department, they decided to promote poplar (*Populus deltoides*) plantations on private farms to meet their future matchwood requirements. Commercial-scale plantations of poplars under agroforestry have been expanding since the Wimco-sponsored farm forestry project was launched in 1984 with refinance assistance from the National Bank for Agriculture and Rural Development (Jones and Lal 1989).

Suitable poplar clones grown with assured and ample irrigation by farmers have already changed the landscape in many districts of Punjab, northwestern Uttar Pradesh, Uttranchal and parts of Haryana. Poplars can produce high-quality veneer logs on short rotations of 6–8 years, and achieving high productivity of 20 m^3 ha^{-1} yr^{-1}. Winter crops can be grown along with poplars throughout the rotation period, because poplars are deciduous. Fast-growing poplar clones, supported with an improved package of practices, excellent technical extension services, long-term bank finance and growing market demand

for poplar wood, have made poplar plantations on private farms a unique success story (Lal 1991). Currently, about 15 million poplar plants are raised in agroforestry plantations in these states every year, covering about 30,000 ha. A similar area is harvested annually yielding about 360,000 m^3 of wood for the match industry and for hundreds of veneer and plywood units.

Eucalypt Plantations

With no other option open to wood-based industries, some progressive industrial units have promoted farm forestry plantations through supply of planting stock, technical extension services and buy-back arrangements, with varying degrees of success. This is despite major constraints and logistical problems, such as the need for motivating very large numbers of farmers and huge costs on collection and transport of wood from scattered smallholdings.

Because of market uncertainties and the need for early returns, farmers prefer short-rotation, fast-growing species, and the paper industry has promoted mainly *Eucalyptus* spp. and, to some extent, *Acacia* spp., *Casuarina equisetifolia* and subabul (*Leucaena leucocephala*) plantations (Saigal and Kashyap 2002). Large-scale eucalypt plantations have been raised on forest and farm lands, community lands and road/rail/canal strips. These plantations have created a very useful resource for timber, poles and fuelwood, but have had low productivity (6–10 m^3 ha^{-1} yr^{-1}), large genetic variation and poor returns, as most seed used was from unimproved seed sources (Lal 1993).

Development of *Eucalyptus* Clones

Productivity and profitability of eucalypt plantations have been revolutionised with the development of genetically improved, fast-growing and high-yielding clonal planting stock. Visionary management of one of the leading integrated pulp and paper mills launched a well-planned research and development program in Andhra Pradesh in 1989 to develop genetically improved, clonal planting stock of eucalypts. Sixty-four candidate plus trees (CPTs), selected on desirable phenotypic characters, were cloned in the first year and 21 clones were tested in September 1989. Five, genetically superior, fast-growing and disease-resistant clones were short-

listed after 2 years and two demonstration plantations were set up in August 1991. The objective was to move from seed-based plantations to clonal plantations in the shortest possible time, so as to improve the productivity and profitability of farm plantations. Meanwhile, evaluation of clones continued, and clonal planting stock of the five most promising clones was released to farmers on a selective basis for large-scale field trials from 1992 onwards. Care was taken to ensure that clonal plantations raised by selected farmers also developed into excellent demonstration plots.

Even though 2 years is not sufficient for final selection of superior clones, this management decision was taken based on the premise that a start must be made with the best available clones while the search for better clones continued. The major research goal was to achieve high productivity of short-rotation clonal eucalypt plantations to produce pulpwood and poles. This decision has been vindicated, as comparatively disease-resistant clones with outstanding performance in the first 2 years have mostly maintained their superiority in subsequent years. Valuable time was thus saved, paving the way for early adoption of clones and expansion of clonal plantations in farm forestry.

More than 800 CPTs have been cloned and tested in field trials to evaluate their comparative genetic superiority and adaptability to different soil types. This ensured a wide and diverse genetic base of clones. Fifty commercial clones now form the basis of large-scale farm forestry plantations. The best 15 of these clones constitute the bulk of clonal planting stock supplied to farmers. Twenty-three high-yielding clones adapted to high pH, alkaline soils have been identified and have transformed the productivity of such refractory sites.

The average productivity of commercial clones is around 20–25 m^3 ha^{-1} yr^{-1} under rain-fed conditions. However, many farmers have achieved growth rates of 50 m^3 ha^{-1} yr^{-1}, making farm forestry economically attractive with better net returns than traditional crops. Significant improvements in quality of produce and reductions in per unit production costs have also been possible with the use of true-to-type, uniform and genetically improved clonal planting stock (Lal 2001).

Development of Hybrid Clones

The clonal option exploits existing natural variation for fast and immediate genetic gains, taking full advantage of superior genetic qualities of field-tested clones. Highest productivity potential of each clone can be achieved through careful matching of clones most adaptable to each category of soils within the climatic regions suitable for the species. Of course, an improved package of practices, integrated management of pests and diseases, management of soil fertility and nutrient deficiencies, protection, and optimum irrigation will contribute immensely to overall productivity improvement.

Each clone will reach its maximum productivity if all conditions are optimal. A two-pronged strategy was adopted to break such a barrier to replace the best available clones with even better clones. Further introductions, evaluation and selection of new clones from CPTs selected with more stringent stipulations is continuing. However, major attention was focused on development of control-pollinated hybrids, followed by cloning of outstanding individual hybrids showing good heterosis. Intraspecific hybrids were developed through reciprocal crosses between promising clones of *E. tereticornis*. Interspecific hybrids were developed through controlled pollination between selected clones of *E. tereticornis* and candidate plus trees of other eucalypt species (Lal 2001). A large number of hybrid clones, developed from hybrid trees with good heterosis, is under field evaluation in Andhra Pradesh and Punjab. Growth at 1 to 3 years of age indicates that many of these hybrid clones will redefine productivity standards by achieving unprecedented high yields.

Farmers' Preferences

Farmers all over India appreciate the many benefits of trees and for decades they have maintained sporadic naturally grown trees on their farms. Many farmers planted a few trees along farm boundaries or roads as shelterbelts and for production of small timber/fuelwood. Such trees have provided a good hedge against risks of crop failures and generated lump-sum incomes in times of need. However, as land-holdings are very small and farmers are generally very poor, they prefer to grow short-rotation seasonal or annual crops for their livelihood and for regular income to meet family needs. Even absentee land owners mostly prefer to lease their lands on

annual terms instead of growing trees, because of uncertainties of market demand and the inconvenience of statutory regulations that, in many states, make government permission mandatory for felling of farm-grown trees and the transport of timber to markets.

Yet, farmers have amply demonstrated with poplar and clonal eucalypt plantations that many of them are keen to have farm forestry plantations if there are major benefits and substantially higher returns from this option. They are willing to pay reasonably higher prices for genetically improved planting stock. Important considerations for farmers to take up the agroforestry option include:

- demonstrated major benefits and substantially higher returns from agroforestry plantations compared with alternative land use options

- Long-term sustainable market demand, regulated timber markets or, preferably, buy-back arrangements for farm-grown timber

- availability of genetically improved, high-yielding and fast-growing planting stock.

- knowledge of improved practices for tree crops and timely availability of professional technical extension services

- freedom to harvest, transport and market their farm-grown wood at fair and competitive prices in a transparent manner without restrictive requirements of felling permits and transport/transit permits and exploitation by middlemen

- visits to successful demonstration plots, and positive exposure through print and electronic media

- professional competence, demonstrated leadership and credibility of promoters

- nearness to markets and wood-processing units and, preferably, integrated development of farm forestry and wood-based industries.

- positive influence of village opinion leaders and influence of peer, pioneering farmers who have adopted agroforestry as a remunerative and more profitable land-use option.

Ready availability of long-term bank loans with reasonable interest rates, a flow of benefits to farmers treating their farm forestry plantations as carbon sinks, and integrated development of farm forestry and wood-based industries can give a further big boost to the growth of this sector.

Adoption of *Eucalyptus* Clones by Farmers

The pulp and paper mill, which pioneered research and development of these versatile eucalypt clones, simultaneously promoted large-scale, clonal eucalypt plantations on private farmlands in Andhra Pradesh. Lessons learnt from poplar plantations under farm forestry in north India, and most of the factors listed above within the control of the company, were considered when devising and implementing strategies for rapid expansion of clonal eucalypt plantations. From the beginning, the company adopted a policy to establish long-lasting, durable and mutually rewarding relationships with the farmers. Successful clonal demonstration plots convinced the farmers of the unique qualities of the clonal planting stock, e.g. uniformity, excellent bole form, very fast growth rates and unprecedented high yields with better quality wood. The company entered into buy-back agreements with farmers who wanted such commitments and yet provided great flexibility to the farmers permitting them to sell their farm-grown eucalypts to other parties if they preferred. Many high-yielding clones extremely well-adapted for problematic alkaline soils were also identified through replicated trials, which transformed the productivity of such sites. Improved packages of practices and silvicultural management techniques were explained and demonstrated to the farmers. These positive and innovative features, supported by efficient technical extension services, sincerity, credibility and commitment of plantation managers of the company, helped in better awareness, acceptance and adoption of clonal plantations.

Assured long-term market demand, and prospects of substantially better returns from plantations compared with returns from traditional agricultural crops on similar sites, played the most important role in farmers' decision-making for large-scale adoption of eucalypt clones. Most of the clonal plantations in Andhra Pradesh are on rain-fed lands. High risks of failure of agricultural crops because of erratic monsoon rains and insect pests, and wide fluctuations in prices of commercial agricultural crops, have also been very important considerations in favour of planting trees on farm lands.

Clonal eucalypt plantations benefited 1914 farmers who planted 5.6 million clonal saplings covering 3217 ha in 1992–1999. Also, 1.6 million saplings of improved clones were supplied to state forest

departments /forest development corporations. They now form the basis of clonal eucalypt plantations in those states. More than 10 million clonal eucalypt plants were supplied in 2000–2002, and the target for 2003 is 6 million. Thus, nearly 2000 farmers are now planting nearly 3500 ha marginal lands with eucalypt clones every year in Andhra Pradesh.

There are three wood-based pulp and paper mills in Andhra Pradesh and one rayon grade pulpmill. Mills from adjoining states also buy part of their pulpwood requirements from Andhra Pradesh. There is good demand for eucalypt poles for scaffolding, shuttering support and mining pit props. It is not surprising that Ongole city in the Parkasam district of Andhra Pradesh has emerged as the largest market for pulpwood and poles in southern India. Similarly, Yamuna Nagar is the biggest market for farm-grown poplars and eucalypts in Haryana state in northern India. When there is oversupply of wood because of local imbalance in demand and supply, farmers reconsider their options and planting of trees on farms is reduced. Farmers reduced planting of poplars this year in northern India because of a steep decline in poplar log prices, and large nursery stocks remained unsold leading to serious losses for many nursery growers (Singh and Dhaliwal 2003).

Clonal Plantations in Other States

Many state forest departments and forest development corporations have adopted high-yielding clones of eucalypts for their reforestation programs and to supply improved clonal planting stock to the farmers. Many states in which World Bank-aided forestry development projects have been implemented, introduced and adopted *Eucalyptus* clones developed by the ITC group in Andhra Pradesh. More than 7000 ha of degraded forest lands in Andhra Pradesh have been planted with high-yielding, fast-growing and disease-resistant eucalypt clones. West Bengal, Madhya Pradesh, and Maharashtra adopted these clones on a small scale for reforestation of degraded forest lands. Some paper mills in Orissa and Karnataka are also promoting clonal plantations on a limited scale.

A new, clonal-technology research centre, greenhouses and modern clonal nurseries have been set up by a private entrepreneur in Punjab state for supply of clonal plants of eucalypts to farmers in northern India, and to continue the research and development of better clones. Many new eucalypt clones including

those of intra- and interspecific hybrids are under field evaluation in Andhra Pradesh and Punjab. Many farmers quickly adopted eucalypt clones in Punjab and Haryana states because of availability of high-yielding clonal planting stock, professional guidance and extension inputs, and successful demonstration plots. These were complemented by the urgent need for diversification of agriculture, decline in prices of poplar logs, and demand for eucalypt logs for rural housing and plywood mills. These clonal plantations may exceed productivity records set in Andhra Pradesh, because of the more fertile deep alluvial soils and availability of irrigation facilities (Lal 2003). Present annual capacity of the 525 m^2 greenhouses commissioned during June 2002 in Punjab is 750,000 clonal eucalypt saplings. Additional greenhouses will be set up to meet the growing demand for clonal stock by farmers of Punjab, Haryana and adjoining states. The current price of clonal planting stock of eucalypts is in the range Indian Rupees 800–1000 (ca US$17–21) per 100 plants delivered at the farmers' fields.

Conclusions

Forests in India cannot meet national demand for firewood, timber and wood-based products on a sustainable basis, because of low growing stock, poor increments, inadequate financial and technological inputs, severe biotic pressures and serious degradation of forest resources. Rising shortages of industrial round-wood have hampered modernisation and growth of wood-based industries. Genetically improved, high-yielding clones of poplars and eucalypts, and large domestic demand for timber, have made farm forestry plantations an economically attractive land-use option. Most of the veneer/plywood mills, safety match industry and wood-based pulp/paper mills currently meet the bulk of their raw material requirements from farm-grown, fast-growing trees. India has tremendous potential to expand the growth of farm forestry plantations and wood-based industries because of its comparative advantage of a huge domestic market, a large land mass, good rainfall and water resources, a tropical climate and ample sunshine for rapid growth of trees, sufficient labour and world-class scientists.

However, it is critically important that all concerned governments plan for integrated development of farm forestry plantations and wood-based industries for expanding sustained market demand for

farm-grown timber. Present restrictive regimes hampering growth of farm forestry in many states, e.g. permits for felling and transport/transit of timber, need to be replaced with positive, innovative policies with incentive mechanisms. This will assist modernisation and growth of wood-based industries, safeguard against violent fluctuations in prices of timber, and create vast opportunities for local value-addition and employment. Technology-based clonal plantations can help India become self-sufficient in timber, newsprint and wood-based products on a sustainable basis and reduce the huge outflows of foreign exchange. Moreover, such plantations can provide a sustainable and renewable resource for meeting the huge firewood requirements, benefit the environment and indirectly conserve biodiversity in natural forests. Moreover, they are efficient carbon sinks.

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Social Dimensions of Silviculture, Especially with Regard to Forest Plantations

Masatoshi Endo[1]

Abstract

Silviculture traditionally focuses on various aspects of tree plantings such as tree selection, genetic improvement, site selection, regeneration methods, site preparation, tree density management, seedling preparation, fertilisation, pest management, thinning, pruning and so on. However, social dimensions of silviculture are rarely discussed. This paper argues that how trees are planted and managed and how a forest plantation project is organised have a long-term effect on people. However, as forest plantations become more widely established, the impacts of forestry programs on people become substantial and need attention. While carrying out silvicultural prescriptions, training and/or treatment, workers may affect both the quality of plantations and the quality of life of workers. In the long-term, this is a factor forest plantation managers cannot ignore. This paper does not discuss results of sophisticated scientific studies, but rather includes sketches and thoughts regarding interaction between forestry and the people, arising from the author's experiences in forest plantations in the North America, South America and China. Suggestions for future research are given. An important goal of research may be, 'how to make a forestry project more people-friendly while maintaining or improving the project's competitiveness'.

Silviculture is typically concerned with various aspects of tree planting, such as tree selection, genetic improvement, site selection, regeneration methods, site preparation, tree density management, seedling preparation, fertilisation, pest management, thinning and pruning. Silviculture was formerly concerned primarily with wood production. In fact, Daniel et al. (1979), writing about the 1950s, argued that the role of silviculture at that time was to manage forests scientifically for continuous production of goods and services while meeting biological and economic requirements.

In the past, the role of silviculture was to implement defined objectives (e.g. timber production) through forest management (O'Hara et al. 1994).

However, 'new paradigms' emphasising ecological values such as the biological diversity of forests have evolved recently. Suddenly, clear-cutting, a mainstream forestry practice, was resented by the public. The public argued that silviculture had to adapt to rapidly changing social values and continuously revise objectives rather than simply implement objectives. Managing forests to meet social aspirations and ecological requirements is now in the realm of silviculture.

The role of plantation forestry must be examined. The global area of plantations in 2000 was 187 million ha, a significant increase over the 124 million ha in 1995 (FAO 2001). About half of forest plantation output is used for industrial purposes. These plantation forests accounted for less than 5% of global forest cover, and for less than 22% of global roundwood supplies to industry. There are contrasting views on whether plantation forestry has a

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[1] Guangxi Oji Plantation Forest Co. Ltd, President, 21 Floor Wukuang Building, 32 Yuanhu Road, Nanning, Guangxi, China 530022.
Email: <forester@nn.gx.cninfo.net>.

role in development. Dudley et al. (1995) criticised traditional forestry management for focusing solely on wood production. They argued that typical forest management often has negative impacts on local communities due to reduced biodiversity, disruption in agricultural systems, and loss of traditional values and customs. An authority in this field, Westoby (1962, 1978), argued that industrial forestry has a role in development if applied correctly. Gow (1992) contended that forestry is uniquely positioned to make a major contribution to address problems of environmental degradation and rural poverty if done properly. Gow's discussion focuses mainly on so-called social forestry and agroforestry, but his argument that sustainable development can be achieved only with increased equity and empowerment for local people may be valid in all the circumstances, including plantation forestry projects. However, it appears not easy to realise increased equity and empowerment for locals. Fortmann (1988) stated that many social forestry projects that were supposed to assist and benefit the poor, often ended up benefiting the rich, thus further increasing the disparity between rich and poor. Of course, the author does not intend to argue that plantation forestry has a primary responsibility to correct social injustice, but those working in projects should understand social issues and care for local people. Gow noted that social analysis may be useful to understand social issues, but just conducting an analysis will change nothing. He argued that recommendations (to assist locals) must be taken seriously and acted upon.

Observations

The purpose of this section is to demonstrate the complexity and depth of social issues. based on the author's experiences and thoughts regarding social dimensions of forestry in different parts of the world.

Methods of observations

The following section introduces some useful tools to analyse the social issues in forestry.

Rapid rural analysis or rapid rural appraisal (RRA) is a technique often used in development study (Chambers 1992). It is relatively informal, as researcher(s) observe the subject and issues in a participatory manner. Gow (1992) called it 'investigative journalism' that uses commonsense observation. He suggested that in rapid rural analysis one has to visit the area, participate in the community, and listen and learn from the locals.

Grounded theory is a qualitative research tool for finding theory. The aim of this approach is to discover, by means of open-ended interviews with subjects, social relationships that shape human behaviour. An emphasis is placed on freeing the mind from pre-conceived expectations about the results. To follow this mode of inquiry, the researcher must concentrate on data with an open mind. Data are compared continuously with other data (constant comparison method) to detect emerging categories and themes, and to direct the data-collection process (Glaser and Strauss 1967).

Symbolic interactionism rests on the belief that objects and events have no intrinsic meaning separate from the meanings people assign to them in the course of everyday social interaction. Three fundamental premises in symbolic interactionism are:

(i) human beings act toward things on the basis of the meanings the things have for them

(ii) the meaning of such things derives from the social interaction

(iii) these meanings are handled in, and modified through, an interpretive process.

In other words, this perspective emphasises that object and idea have meanings only because people attach meanings to them (Blumer 1969). For example, 'multinational companies' to some people may mean 'social and environmental exploitation', but 'advanced technologies and development' to others. Such differentiation occurs through one's interactions with others.

Corporate social performance is an abstract measure of the effects of business behaviour on society. While operational measures of corporate social performance are not well defined, for large companies, *Fortune* magazine's social rating and Kinder, Lydenberg, and Domini's (KLD) social database provide quasi indicators of the corporate social performance. While no single measures are complete in representing the social performance of an entity, these indicators can be a starting point.

Cases in Colombia

Eucalypts on dry lands: hatred for multinational companies

During the author's work period (1989–1993) and his rapid rural appraisal trip (1994) in Colombia, many people protested that eucalypts desiccate and/

or sterilise lands. However, in many instances, decreased water flow may be caused by deforestation of natural forests rather than planting of eucalypts. It was quite difficult to determine the real cause of reduced water levels. During RRA, the author encountered a locally well known 'vocal environmental activist'. During the interview, the activist responded. 'The real issue is not *Eucalyptus*. We have to fight against multinational companies because multinational companies exploit national wealth…'. It appears that extremely skewed land and wealth distribution in Colombia tend to foster hatred against multinational companies.

In contrast, in a so-called social forestry program of Cooperation Regional de Valle de Cauca, locals were asked, 'What kind of trees do you want to plant?' A few people responded, *'Eucalyptus'*, because eucalypts grow fast and provide farmers with firewood.

Social programs of industrial forestry programs

One company, Pizano SA, is well known for taking extra efforts in creating social programs. The program includes cleaning the city streets, building and running primary schools, and supporting extension programs to help local farmers to improve incomes. There was also a women's program to improve women's status, family programs to help reduce alcohol consumption by workers, house building, and creation of happy families. Male workers with contented families are happy in their work, resulting in reduced absenteeism. Furthermore, the company hosted a competition for the best looking, most efficient fire stoves. While these programs require money, they are also an asset of the project, as many workers and locals respect and support the Pizano forestry project. During the author's visit to the project area, he failed to find negative comments against the Pizano project.

An agroforestry program

In central Colombia, an agroforestry program by an electric company was visited. In Colombia, electric companies are required by regulation to reforest watershed regions. The intention of the program was good. It distributed free trees to local people to improve the watershed and the incomes of families. However, many trees ended in the backyards of farmers and few were planted. Of those planted, many died. Since the tree seedlings were given free, farmers took them, but planting them was too much trouble. The survival rate of trees distributed was probably 10% at best. The underlying cause of this low rate of survival probably started in poor project planning, including the planner not adequately understanding how farmers would treat free seedlings.

Cases in the United States of America

The author interviewed executives of 10 large forest-product companies in the USA, using a semi-structured questionnaire (Endo 1997). The study intended to examine:

(i) how do forest corporations (or their managers) measure and/or sense their social reputations?
(ii) what are the benefits (motivations) of having a good social reputation to corporations?
(iii) what are the social strategies of forest corporations?

As the interview allowed open-ended dialogue, the grounded theory mode of encountering new findings was achieved. Furthermore, during this study, the concept of symbolic interactionism was used as a guide to understand how and why executives see things as they do.

How do forest corporations measure and/or sense their social reputations?

Executives look at television and read newspapers to monitor their company's reputation. Some executives argued that customers are the best source of their social reputations. One company ran a social reputation survey and found that the company was better known in smaller cities in which they operated. *Fortune* magazine ratings and KLD social data base, which business researchers often use, were usually not important to the executives interviewed. The executives did not admit that environmental groups are an important source of company reputation. This may be because if they admitted paying attention to the views of environmental groups they would give the groups more legitimacy. However, executives of one company were quite proud of awards given to their company by environmental groups. In general, the executives appeared to care far more about their company's reputation than the author originally imagined.

Benefits of a good reputation

The executives considered that the benefits of a good reputation include increasing sales, improving the regulatory climate, attracting able employees, motivating employees, and fostering a favourable

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investment climate. In approximately half the companies, the executives noted that having public support by earning a good reputation would favour the company if it made a mistake. According to this view, companies have to earn a 'reservoir of good will'. Some executives answered that a good reputation raises the morale of employees. For some, a good reputation might result in a more flexible regulatory climate. 'Flexible regulatory climate' did not mean that the companies were trying to breach environmental standards. They were quite concerned that one mistake would waste all their efforts in earning a good reputation. Overall, they appeared willing to go beyond compliance, but if a mistake of not complying with a standard was made, they wanted to be excused for their normal good behaviour.

For being good, you will be attacked more

However, one problem of being responsible was observed and needs attention. Some executives stated that by doing good things (being responsible), they may be attacked more. It is ironical that if you say you are responsible, you may become a prime target of activists. From the activists' viewpoint, accusing environmentally/socially insensitive companies may not have any meaning because such companies may decline to respond. What activists need are responses and reactions from companies. Of course, some executives did not share this view. Some believed it was beneficial to try hard to do good things and to establish good relations with activists. Another issue preventing forest-product companies being more responsible is the lack of differentiation among such companies. Because many people do not differentiate one company from another, some executives are not motivated to earn a good reputation for the company.

Clear-cutting

For many executives, clear-cutting brought out radically polarised views and was a problem. No executives thought that clear-cutting, if applied correctly, is an environmental problem and compared it with harvesting a corn field. But forests are unique. In many people's minds, forests are where 'Bambi' lives. While nobody likes the visual effects of clear-cutting, foresters understand that sound forests will return a few years after clear-cutting,. However, many people, especially in urban areas, do not understand that clear-cutting is a method of regeneration. Except by stopping clear-cutting, there is no direct solution for avoiding criticism against it. Although executives considered clear-cutting should still be an option in forestry management, they realised that earning a good reputation could be more important.

Relationships between social ratings and the financial status of the companies

While this study did not try to make a rigorous comparison between social ratings and the financial status of companies, several observations were possible. First, companies which established conservation areas in collaboration with environmental groups tended to have relatively high return on equity (ROE) and low debt ratio compared with other companies. On the other hand, some companies that rely heavily on wood from public lands, despite accusations from the environmental community, had low financial returns. Possibly, their weak financial state may force them to rely on whatever forest resources they can access. These observations may indicate that a relatively strong financial situation may be a precondition for forest-product companies to undertake long-term social and environmental programs.

Cases in China

Field forestry workers in southern China

In eucalypts plantations in southern China, e.g. in Guangdong and Guangxi, there are two categories of field workers. The first category comprises local farmers. As Guangdong and Guangxi are located near the coast, living standards there are still higher than in more inland provinces, such as Hunan and Guizhou. For many local farmers, the work in the forest plantations is relatively hard and pay is low, so they avoid working in them if there is an alternative.

The second category includes workers who come from provinces in the interior of the country. Usually, forestry contractors employ field supervisors who, in return, are responsible for bringing a team of workers. A certain job (for example, land preparation and seedlings planting) is contracted for an amount of money. If the quality of work is poor, either money is deducted or they have to redo the work. Team leaders and their workers have to make their own living and eating arrangements. They often keep their living standards to the bare minimum, because less they spend the more they can take home. Their camps usually have a roof made of plastic sheeting and water is taken from nearby creeks. Electricity is usually non-existent and entertainment limited. A common entertainment is an illegal lottery in Hong Kong. Every Tuesday and Thursday afternoon,

winners are announced, and during these days the work is often disrupted.

Safety standards

Safety standards need improvement. For example, the author has observed a team of family members using machetes for weeding where the weed height exceeded 1.5 m. The workers were subjected to extremely risky conditions as they could accidentally run into and injure each other. In general, the use of safety equipment, such as helmets, hearing protection and safety glasses, is still relatively rare.

Discussion

These examples have illustrated various social dimensions of forestry projects. We must continuously earn good reputations or forest plantations may cease to exist. We all have to care. The following are some lessons and suggestions for future.

1. Listening what other people say about forestry projects is the first step in understanding and establishing relations between people and the projects.
2. There exists tremendous potential to better understand social aspects of forestry projects. Some initial issues may be:
   – what are the working conditions of forestry workers?
   – what do forestry workers think about their working conditions?
   – what are opinions of local people on forestry programs?
   – what are cost-effective training/education programs for forestry workers?
   – what are cost-effective ways a forestry project can establish good relations with local communities?
3. Project managers and foresters work under pressure. They may have little time to care about social issues. Furthermore, some managers may be intimidated by the possibility that the harder they work to improve their social/environmental practices, the more accusations they may receive. In other words, they perceive little incentive for rapidly improving their social reputation. Creation of systems to reward socially conscious forestry projects and managers may help to correct this.
4. While one can discuss implementing various social programs in forestry projects, it is

necessary that the projects stay competitive. If a project is not financially sound, it cannot generate resources to sustain programs. The most difficult challenge is 'how to make a forestry project people-friendly while maintaining or improving the project's competitiveness.'

Remarks

The content and opinions of this paper are of the author alone, not those of Guangxi Oji Plantation Forest Co. Ltd. Responsibility for the content of this paper rests solely with the author.

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Eucalypt Planting in Thailand

V. Luangviriyasaeng[1]

Abstract

Eucalypts are of considerable economic importance in Thailand. An estimated 480,000 ha of plantations, mainly *Eucalyptus camaldulensis*, have been established for production of woodchips, poles, sawn timber for general construction, and fuelwood. Over 200,000 ha have been established during the last decade. Current annual planting is 40,000 ha, mainly by private companies and a large number of small farmers. Rotations are 4–5 years and harvests from these plantations are mostly for the pulp and paper industry. Clonal plantations from selected trees are commonly used for industrial plantations, for high productivity and uniform growth. Many eucalypt plantations are variable in growth and stem form, with those planted using unimproved seed being poor. Some clones are more susceptible to fungal diseases. A breeding plan for *E. camaldulensis* in Thailand was developed with international support in 1991, and many progeny trials and seedling seed orchards of *E. camaldulensis* and *E. urophylla* have been established. Hybrid breeding of eucalypts is now under way for selection of disease-resistant clones and adaptability to a wide range of environments.

Eucalypts provide the most important domestic source of raw material for the pulp and paper industry of Thailand. The total area of industrial eucalypt plantation in 2001 was 480,000 ha (N. Laemsak, pers. comm. 2003), with a total production capacity of solid wood of 19 million tonnes. The plantation areas are distributed in all regions of the country, with the main planting areas being on the northeast (47%) and east (29%), with smaller areas in the north (13%), central (11%), and south (<1%) (Sunthornhao 1999). The current annual planting rate is 40,000 ha, mainly by private companies and a large number of small farmers, using a 4- or 5-year rotation.

The demand for eucalypt wood by major wood-based industries (i.e. pulp mills, chip mills, and medium-density fibre board (MDF) plants) in Thailand in 2003 is estimated to be 7.6 million t (N. Laemsak, pers. comm. 2003). The pulp industry is by far the largest consumer requiring 4.2 million t (55%), followed by the chip mills 2.1 million t (28%) and MDF plants 1.1 million t (15%). Other forms of utilisation (e.g. poles and sawn timber) account for the remaining 0.14 million tonnes (2%).

The current production capacity of short-fibre pulp from eucalypt wood is sufficient to meet the demand for at least the immediate future. This prediction is based on an assumption that the large number of small farmers will continue to plant eucalypts. However, many small farmers whose plantations were badly affected by an outbreak of leaf pathogens during the 1999 wet season have recently switched to other cash crops, such as cassava. In addition, the yield of many eucalypt plantations is low (MAI <12 t ha^{-1}), presumably due to low genetic quality of planting stock, making eucalypt planting an unprofitable and unattractive venture. There is an urgent need to reverse this trend or the wood-based industry will suffer a severe shortage of wood supply in future.

[1] Silviculture Research Division, National Park Wildlife and Plant Conservation Department, 61 Phaholyothin road, Chatuchak, Bangkok 10900, Thailand. Email: <Vitool@forest.go.th>.

Introduction of Eucalypts

The first of eucalypt in Thailand is believed to have been planted as an ornamental tree on private property in Bangkok in the early 1900s. Although there were some spot plantings in later years, it was not until 1950 that the Royal Forest Department arranged a first introduction of many species from Australia including *E. alba, E. citriodora, E. paniculata, E. saligna* and *E. grandis* for an arboretum planting in Chiang Mai province (Pothisaro 1985).

With assistance from FAO in 1964, 15 *Eucalyptus* species with pulpwood potential were introduced from Australia, and planted at four Forest Experimental Stations in the north (Chiang Mai), northeast (Si Sa Ket), west (Kanchanaburi) and south (Surat Thani). The species were *E. alba, E. miniata, E. botryoides, E. camaldulensis, E. citriodora, E. cloeziana, E. deglupta, E. grandis, E. maculata, E. paniculata, E. pilularis, E. robusta, E. saligna, E. tereticornis* and *E. tetrodonta.* Remnants of these plantings are still evident at these stations (Pousajja 1993).

New species/provenance trials were added in 1972 in Chiang Mai, after the Thai–Danish Pine and Fast-Growing Tree Improvement project was set up. Subsequently, *ex-situ* gene conservation stands of selected species such as *E. brassiana, E. camaldulensis* and *E. urophylla* were planted at a project substation in Surin. These stands became a seed production source for most of the early commercial and general plantings.

The results from the species introduction trials have indicated that the following species are suitable for planting in Thailand under different ecological environments.

- Species for dry (1000–1200 mm annual rainfall) lowlands: *E. brassiana*; *E. camaldulensis*; *E. citriodora*; *E. tereticornis.*
- Species for moist (1500 mm) sites: *E. urophylla.*
- Species for high-altitude sites: *E. grandis*; *E. saligna.*

Further trials set up with support from ACIAR and CSIRO Forestry and Forest Products during 1985–1986 confirmed the suitability of *E. camaldulensis* and *E. urophylla* for planting in many parts of Thailand. For *E. camaldulensis,* Petford, Queensland, was the most adaptable seed source as revealed by most experimental plantings. Many early plantations are believed to have used seed from this source.

Commercial Plantations of *E. camaldulensis*

The acute demand for wood has promoted a rapid increase in eucalypt plantings by farmers and private companies. Large-scale planting of *E. camaldulensis* started in 1983 (Thaiutsa and Taweesuk 1987). At first these new plantings provided a new opportunity for local villagers to operate nursery businesses. Seedlings produced by these nurseries were relatively cheap, and generally raised from locally available seed of unknown, but almost certainly poor, genetic quality. Plantations established with these seedlings were extremely variable in growth and form. However, in recent years most of these village nurseries have failed, as farmers are insisting on the very high quality seedlings that can be produced by larger and better nurseries operated by large companies.

Up to 80% of current nursery stock is produced by stem cuttings. Tissue-cultured seedlings account for 12%, and the remaining 8% is from seed (Thaiutsa 2002). Clonal plantations are impressive in growth and stem form. However, little is known about the extent of their genetic make-up and selection process, as most private companies generally do not disclose their information. From personal observations, however, it can be concluded that only a small number of clones has been used for the operational planting by private companies.

Disease Problems

Certain provenances of *E. camaldulensis* are known to be susceptible to a suite of foliar pathogens. Experience in Vietnam has shown that the Petford provenance is subject to severe infestation by a leaf blight *Cylindrocladium quinqueseptatum* in areas where annual rainfall is high (1500 mm and over) (Pham Quang Thu et al. 2000). Other provenances from far north Queensland (e.g. Laura River and Morehead River) are less susceptible.

During 1994–2000, eucalypt plantations across Thailand were surveyed for evidence of foliar pathogens as part of an ACIAR project. The most serious disease was the leaf and shoot blight caused by *Cryptosporiopsis eucalypti*, not the *Cylindrocladium quinqueseptatum* which was found in Vietnam (Old et al. 2002). An unusually high rainfall (>1500 mm) in the main eucalypt planting regions in 1999 caused an

outbreak of this disease, resulting in a loss of tens of thousands of hectares of clonal plantations, with certain clones being more affected. It is plausible that the original source of these clones is the Petford provenance, which was the most sought-after seed source due to its proven success in early trials. Plantations established from seedlings raised from seed were generally not affected during the 1999 outbreak.

Eucalypt Breeding Programs

A systematic breeding program for *E. camaldulensis* in Thailand commenced in 1991, with support from ACIAR and CSIRO Forestry and Forest Products (Raymond 1991). The program has been implemented by the Royal Forest Department in collaboration with other state forest enterprises. An extensive range of 300 individual parents from Queensland, the Northern Territory and Western Australia was used to establish large progeny trials cum seedling seed orchards. The results of these progeny trials when trees were 2 years old indicated considerable variation in growth performance among regions and provenances within regions despite the existence of variation between families within provenances (Pinyopusarerk et al. 1996). Provenances from Queensland were superior in growth rate to those from the Northern Territory and Western Australia. The results have provided important baseline data for selection of appropriate provenances and families for the second generation in the breeding program. A second-generation progeny trial has recently been established with seed from selected parents from the first-generation seedling seed orchards.

There is also an improvement program for *E. urophylla*. The Royal Forest Department, with assistance from the CSIRO Australian Tree Seed Centre, planted a seedling orchard comprising 121 families in 1989. Seed has been collected regularly from this orchard over the past 5 years. Some seed has been supplied to private companies. Second-generation seed was planted in 1998 and trees are showing much improved growth.

After the outbreak of foliar pathogen *C. eucalypti* in 1999, private companies have begun to pay more attention to the improvement program. At least two companies have imported a large number of individual families of *E. camaldulensis* and other species from Australia to set breeding populations with a broad genetic base.

Hybrid Breeding

Hybrid breeding of eucalypts is now under way for selection of disease-resistant genotypes and wide adaptability. The intraspecific hybrids of *E. camaldulensis* are most common. Clonal tests of interspecific hybrids between *E. camaldulensis* as female parents and other eucalypt species have been planted out. Some hybrid clones have already been used for commercial planting. The breeding strategy for eucalypt hybrids is not adequate because of the lack of information on the male and female parental trees.

Recent Developments

The improvement program for *E. camaldulensis* initially placed emphasis on rapid growth of straight and tall trees. An emerging problem with fungal diseases has stimulated interest in breeding trees for resistance to common diseases. Now there is increasing interest in breeding superior eucalypts that not only grow fast and tall and survive fungal diseases, but also possess wood with superior pulpwood properties. Such wood will produce much higher economic returns than the general run of wood that has not been produced from scientifically directed breeding programs. This work is strengthened with support from AusAID through the Thai–Australia Government Sector Linkages Program. The program aims to assist the government forest departments and private companies to produce genetically superior planting materials that will grow quickly and healthily, and will also produce considerable volumes of wood with desirable properties. An important part of this is to routinely use near-infrared (NIR) spectroscopy as a rapid method for the estimation of pulp properties of wood samples. This information will then be used to select trees with the desirable traits for propagation for operational plantations. CSIRO Forestry and Forest Products has assisted in the required training.

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Developing a Strategy for Sustainable Management of *Eucalyptus* Plantations in China

Xie Yaojian[1]

Abstract

Eucalypts are important plantation species in southern China, with currently 1.54 million hectares planted and more planned. The paper discusses strategies and measures for sustainable management of eucalypt plantations. These plantations have significant social, economic and ecological benefits. They can produce employment, have general economic benefits and can increase farmers' incomes. Scientifically managed eucalypt plantations have ecological benefits. Establishing plantations on degraded sites restores vegetative cover, increases biological diversity, enhances soil structure and the diversity of the soil flora and fauna, and improves the microclimate and local environment of the forest. Foresters should change the concept from giving priority to timber production to paying equal attention to both wood production and environmental protection, from intensive management to less intensive management, and from traditional continuous utilisation to sustainable management. Forestry and forest product certification is an effective way to promote sustainable development. Biological instability is the key problem in achieving sustainable management of eucalypt plantations. It is the result of: monocultures; incorrect species–site matching; and soil and climate changes. The following measures are suggested to correct the situation: (1) appropriate balance between species and site condition; (2) mixed-species plantations; (3) control of genetic variation; (4) scientific management of vegetation; (5) improved site preparation and planting techniques; (6) suitable wood-harvesting methods; and (7) control of pests and diseases.

'Eucalypt' is the general name of the *Eucalyptus* genus, which has 945 species and varieties within the Myrtaceae family (Wang Huoran 1999). Eucalypts are native in Australia, Papua New Guinea, a few islands of Indonesia, and the Philippines. Early in 1890, China began introducing eucalypts for planting in city parks, along railways, and other 'four sides' areas. However, until the 1950s, China introduced eucalypts mainly in Leizhou Peninsula (Qi Shuxiong 2002). At the beginning of the 1980s, systematic introduction and breeding trials of eucalypts started at Dongmen Forest Farm, Guangxi, with aid from Australia. This project was very important for the development of eucalypts in China.

Now eucalypts have become most important for developing fast-growing tree plantations in southern China. According to incomplete statistics, there are 1.54 million ha of eucalypt plantations in many provinces, including Guangdong, Guangxi, Hainan, Yunnan, Fujian, Sichuan, Jiangxi, Hunan, Guizhou and Chongqing (Qi Shuxiong 2002). There is great enthusiasm for developing eucalypt planta-tions; for example, the Government of Guangxi Autonomous Region plans to establish 40,000 ha each year.

This paper discusses strategies and measures for sustainable management of eucalypt plantations.

[1] China Eucalypt Research Center, Mid.30, Renmin Road, Zhanjiang, 524022, Guangdong, China.
Email: <xieyj@pub.zhanjiang.gd.cn>.

Social, Economic and Environmental Benefits of Eucalypt Plantations

Eucalypts have many advantageous features, such as rapid growth, high production and good economic benefits. Some of the social, economic and ecological benefits claimed are analysed below.

Social benefits

Eucalypt plantations can create employment in afforestation, forest management, the wood-pulp industry, fibreboard production etc. In particular, the short rotation period of eucalypt plantations offers more jobs than traditional long-rotation plantations. In general, one hectare of eucalypt plantation provides four jobs.

Eucalypt plantations can provide many products of value to the people, e.g. wood for papermaking, artificial boards, building and construction materials, and furniture-making and mine timbers. They also provide firewood for rural energy, and by-products such as essential oils and honey. Some eucalypts are good ornamental species and can be planted by roadsides or in gardens (Bai Jiayu and Gan Siming 1996).

Eucalypt plantations can increase a farmers' incomes, and help stabilise and increase the prosperity of rural populations.

Economic benefits

Generally, eucalypt plantations are more profitable than those of other tree species. So, in southern China, many foreign companies and some local enterprises are investing in establishing eucalypts. For example, they can make a profit of 2250–3000 yuan ha^{-1} yr^{-1} in the Zhanjiang area of Guangdong province (Table 1). However, in some other places plantations have made a loss, e.g. in Fujian 2 years ago, which dampened people's enthusiasm for planting eucalypts.

Environmental benefits

Plantations benefit the environment in many ways. Establishing plantations on degraded sites can restore vegetative cover, increase biological diversity, enhance soil structure and the diversity of the soil flora and fauna, and improve the microclimate and environment of the area. For example, in the early 1950s, Zhanjiang, Guangdong had very little vegetative cover so there was soil erosion, and the effects of the frequent typhoons and droughts were serious. The West Guangdong Forest Farm (now Leizhou Forestry Bureau) was set up in 1954 and it introduced eucalypts in 10 forest farms in 5 counties around Zhanjiang. By the early 1980s, 54,000 ha of plantation, of which 80% (43,000 ha) was eucalypts, had been established. Now, eucalypt plantations occupy almost all the low hilly plain, the flat land along the coast, and both sides of the railway and highway. The area planted to eucalypts on Leizhou peninsula has reached to 186,000 ha and, with other plantations, forests now cover 27.5% of the land area. The natural environment has improved significantly, e.g. rainfall has increased, evaporation has fallen, water and soil are better protected, and the effects of typhoons are less than before. Due to environmental improvement, agricultural production in Zhanjiang has increased markedly, and now Zhanjiang is well known as a 'national agricultural base city'.

The environmental benefits of plantations, which depend on proper management, include forming a biological corridor between natural protection districts, controlling run-off and soil erosion, building up protective forest and preventing sandstorms, and lowering the watertable in the seriously salt-affected area. Conversely, if the plantations are not managed properly they will have ecological problems. Fast-growing eucalypt plantations harvested on short rotations remove much more soil nutrients and water than other species, and their biological diversity is not so rich. The potential for run-off and soil erosion is high, and the soil can lose its fertility.

Concepts for Sustainable Development of Eucalypt Plantations

To realise sustainable development of eucalypt plantations, we must re-establish old concepts, particularly the following three:

1. Pay equal attention to wood production and environment protection. We should give up the concept that plantations are for only timber-production. All plants, including plantation trees, are part of an ecological system, so they should be managed sustainably (Zhang Shuogong and Zhu Chunquan 2001).

2. Manage plantations in an open system, i.e. they should not be considered as belonging only to the planter, they should also be regarded as an ecological resource for the community (Guan Baijun 2001).

3. Give equal attention to economic, social and ecological benefits: move from traditional continuous utilisation for wood production to sustainable management and development.

Forestry and Forest-Product Certification System

An effective way to promote sustainable development of eucalypt plantations is to have a certification system. In the past 10 years, the United Kingdom, the Netherlands, Germany, United States, Canada, India, and Malaysia have set up forestry and forest-product certification schemes to ensure sustainable management of forests. Forest certification is an important action for developing international trade in forest products, promoting sustainable development of forests, and improving the world environment (Liu Kailin 2002).

In China, forestry and forest-product certification is just starting. It is reported that 940 ha of forest at Changhua Forest Farm in Lin'an, Zhejiang was certified by SmartWood for the Forestry Stewardship Council (FSC) in April 2001. It was the first forestry unit in China to be certified by an independent body. This is a major development for Chinese forest certification. In 2001, the forest certification group SGS, authorised by FSC, carried out primary work of forest certification evaluation for an area of plantation belonging to Jiayao Forestry Development Corporation in Gaoyao, Guangdong, but certification has not yet been approved.

It is suggested that sustainable development of eucalypt plantations requires the application of a forest and forestry-product certification system.

Table 1. Economic analysis of costs and benefits of a typical eucalypt plantation.

Item		Calculate basis/number, unit price	Convert into money (yuan ha^{-1})
Benefit			
Rotation period		6 years	
Growing volume		225 m^3 ha^{-1}	
Available wood volume		157.5 m^3 ha^{-1}	
Value of wood		250 yuan t^{-1}	47,250
Costs			
Establishment and maintenance	Forestation investment	Soil preparation, basic fertiliser, seedling, planting, etc.	5,250
	Harvesting and transportation	78 yuan m^{-3}	12,285
	Land rent	25 yuan ha^{-1} yr^{-1}	2,250
	Annual interest	3%	945
	Subtotal		20,730
Taxes and charges	Forestation funds	10% income of wood sale	4,725
	Value-added tax	5.8% income of wood sale	2,740.5
	Special agricultural tax	8.8% income of wood sale	4,158
	Local educational surtax	(value-added tax + special agricultural tax) × 3%	207
	Local reconstruction tax	(value-added tax + special agricultural tax) × 7%	483
	Subtotal		12,313.5
Gross income			47,250
Gross cost			33,043.5
Gross profit			14,206.5
Annual profit			2,367.75

Note: All above data calculated according to the market price of eucalypt pulp timber in Zhanjiang, Guangdong in 2000.

Problems in Sustainable Development of Eucalypt Plantations

Biological instability

Biological instability is the key problem in achieving sustainable management of eucalypt plantations. The instability is manifested as follows: (i) some diseases and pests have a serious effect and are difficult to control; (ii) damage by severe weather events of wind and frost; and (iii) loss of soil fertility. Generally, the damage caused by pests and diseases and pests is not so serious as to be disastrous (Li Zhiyong 2000; Sheng Weitong 2001). However, wind causes serious damage especially in coastal areas subject to typhoons. Freezing damage has occurred in some areas and requires attention. In some eucalypt plantations, management deficiencies may lead to declining soil fertility, and practices need to be identified and implemented to counteract this problem.

Monocultures

Most plantations are monocultures. Compared with natural forests, a plantation's ecosystem and biological diversity is so simple that it is not well buffered against stressful events. In intensively managed plantations, genetic diversity may be low, especially when just one clone is planted over a large area. This could lead to serious disease and pest problems, as has occurred in agriculture and some forest plantations. In southern China, a single eucalypt clone has been planted over thousands of hectares in some places and there is a great risk of a major disaster. Furthermore, soil fertility is more difficult to maintain in monocultures of eucalypts as their leaves decompose slowly, in contrast to mixed species plantations where litter decomposition is more rapid.

Species–site matching

To plant the right species of tree in the right place used to be a basic ecological principle for plantations. If a tree species is planted in an unsuitable place, it will be poorly adapted to local conditions, so growth is slow, and the potential for damage by adverse climatic events or diseases and pests is increased. For example, the relatively frost-sensitive *E. urophylla* was planted at Xiaoguan, Guangdong and 13,000 ha of plantation suffered severely from the December 1999 frost event. A similar situation occurred with other species in the 1970s in Jiangxi, Hunan, and Zhejiang, and negatively affected people's enthusiasm for eucalypt planting.

Soil changes

In southern China, clear-felling, burning, intensive site preparation and tending have been practised in Chinese fir and eucalypt plantations. These practices often cause problems in the physicochemical quality of forest soil. A great deal of organic matter and nitrogen is lost in burning and harvesting debris, litter and other vegetation in site clearing, and when the soil is exposed by site preparation and tending much of it can wash away (Table 2).

Climate change

Climatic variability is an important factor in a plantation's biological instability. Unlike annual agricultural crops, forest plantations are grown for many years and have to endure extreme climatic events of heat, cold or drought that may occur at long intervals. Periodic, severe cold spells have inflicted serious damage on eucalypt plantations in subtropical areas of southeastern China, for example in the middle 1970s.

Quarantine

Quarantine is a key measure for preventing the spread of exotic diseases and pests. In the past, ignoring quarantine, or imperfect quarantine arrangements, resulted in the spread of diseases and pests, including some that caused very severe damage. For example, the spread of *Bursaphelenchus xylophilus* led to death of a large area of *Pinus* in Jiangsu, Zhejiang, Anhui, Guangdong and other areas. The spread of *Hyphantria cunea* led to major damage to plantations of many species, and introduction of a foreign longicorn beetle led to the destruction of *Populus* in Ningxia. Pests and diseases are an ever-present threat when large areas of a single species, such as eucalypts, are planted in an area.

Practices to Improve Biological Stability

Improving biological stability is basic to ensuring sustainable management of eucalypt plantations to retain long-term productivity and provide ecological benefits. So, forest plantations should be managed as an ecosystem. Ecosystem management includes a series of methods that are familiar in

ecology; for example, close matching of the species/variety to the site, appropriate patterns of mixed-forest, control of the genetic components, treating vegetation scientifically, improving afforestation technologies, and rational harvesting practices (Lin Sizu and Li Zhiyong 2001). In addition, support from state policies and attention to socioeconomics are important for sustainable management of eucalypt plantations.

Technology practices

Site-species/variety matching

Eucalypts were introduced into China more than 110 years ago, and now many species, varieties and clones have been studied extensively. In developing plantations, proper matching of species and site is essential for stability and full expression of growth potential. For instance, *E. urophylla × E. grandis* clones are adapted to the local site and climatic conditions in most of Guangdong, Hainan and southern Guangxi, so the plantations have stability and high productivity.

Before promotion and extension of a new variety, it is necessary to carry out critical long-term field trials to study the interaction between the new variety and the environment. With this experience, areas to which it is adapted can be defined. For example, the *E. urophylla × E. grandis* clones selected by Dongmen Forest Farm in Guangxi did not resist *Pseudomonas solanacearum* when introduced in Zhanjiang, Guangdong. Conversely, *E. urophylla* clones selected in Zhanjiang, Guangdong grew slowly when introduced to Guangxi.

Mixed plantations

Many natural forests have relatively diverse ecosystems and are rich in species, so their biological stability is good. When one species, or even one clone, is planted in large areas, the biological stability is reduced. It is a matter of fact that a mixed plantation is one important way to improve the sustainability of plantations. The technologies of mixed-tree plantations include: interactions between species, patterns of mixture, rotation period, and timber utilisation. Some experience has been gained in trials of a mixture of a *Eucalyptus* species and an *Acacia* species that resulted in increased productivity and more sustainable management (Zheng Haishu and Wen Qijie 1997). The mixture could adjust forest microclimate, make good use of sunshine, slow down wind and resist environmental stress. It could increase the activity of enzymes and micro-organisms to accelerate decomposition of the litter, assist nutrient cycling and increase productivity. However, the eucalypt/acacia mixture technique is not yet fully developed and requires further study. Other mixed species methods, such as planting shrubs and grass under trees, could be tested but may be difficult to apply because they increase plantation costs. A less costly method would be to retain some natural vegetation when establishing plantations.

Control of genetic variation

Forest-tree breeding selects highly productive and highly stress-resistant genotypes, but how these are deployed in the plantation areas is basic to maintaining long-term productivity. In China, tree

Table 2. Comparison of soil erosion caused by different site-preparation methods.

Site-preparation method	Annual rainfall (mm)	Vertical flow depth (mm)	Erosion (t ha^{-1})	Specification
Full-cultivation and deep-turnover	1335	11.5	5.33	Full-cultivation to at least 35 cm and removal of all vegetation.
Cultivation in trenches	1335	3.5	0.35	Trench width 60 cm, trench spacing 167 cm. Removal of grass between trenches.
Strip cultivation	1335	1.0	0	Band width 100 cm strip. Retain all vegetation between strips.
Pitting	1335	0.2	0	Hole 40 × 40 cm, row spacing 167–200 cm, retain vegetation.

Based on Xiang Dongyun (1999).

breeders have often given priority to rapid growth and high wood-productivity features in selecting and breeding, so the output of eucalypt plantations has improved greatly, say by 10–25%, and some clones have improved even more. However, the stress-resistance features, especially resistance to drought, cold, pests and diseases, have been given less attention and so there is still much work to be done.

In developing clonal plantations, a single clone should not be deployed over large areas or the risk of loss from diseases, pests and severe weather events will be significantly increased. Clones can be mixed within blocks, or blocks of single clones can be mixed on the plantation estate. Some experts have recommended at least 20 clones should be used to improve the stability of plantations. Also, clones should be changed over time, as one clone used in several rotations could become more prone to damage by diseases and pests and have an adverse effect on soil fertility.

Vegetation management

It is important to take care of vegetation scientifically in plantations, because of the simplicity of the plantation ecosystem. Careful vegetation management can contribute to improving the microclimate, increasing biological diversity, and improving or maintaining soil fertility. Protection of existing vegetation in plantations, or in the overall plantation estate area, can provide natural vegetation corridors and help increase biological diversity. Secondary forests with considerable biological diversity are often abundant around plantations, so they should be protected as much as possible to improve the ecology and environment of plantations. Vegetation under trees can be developed and managed by controlling plantation density. Wider spacing of eucalypts will favour greater development of understorey vegetation, but in some areas farmers have decided it is beneficial to plant trees densely, some even planting 60,000–70,000 trees ha^{-1}. According to our research, the vegetation in eucalypt plantations mostly amounts to 20–30 species.

Improved silvicultural techniques

Incorrect methods of site preparation have commonly led to run-off and soil erosion and loss of soil nutrients. In southern China, clearing the site by burning and intensive soil cultivation has resulted in major losses of organic matter and nitrogen, and exposed the soil to erosive forces. This silvicultural method on granite and sandy shale soils in Fujian resulted in severe erosion, with 30–40 t ha^{-1} of soil lost, including 600 kg ha^{-1} of nutrients. In countries such as Brazil, Germany and New Zealand, minimum cultivation techniques are now used, with only chemical herbicide to kill grass and small holes for planting. Disturbance of the site environment should minimal, so that the environment can easily recover. A method called 'no-burning site preparation' has been tried for eucalypt plantations at Ivory Hill Forest Farm, Xijiang Forest Bureau, Guangdong. Instead of burning, herbicide was applied, and the planting places prepared without leaving the soil exposed from open pits. The results were very good. The soil humus layer was 30–40 cm deep, there was no water and soil erosion, and no forest fire risk. In 2-year-old eucalypt plantations, there was no significant difference in growth between the old and new methods, but from the point of view of sustainable management, the no-burning and minimal cultivation method was more effective.

Harvesting methods

Eucalypt plantations in China are mainly used for industrial purposes, so most are clear-felled when harvested. Harvesting is the most significant factor affecting the forest's environment. Many scientists support stopping complete cutting, and recommend selective harvesting, especially for protection forests.

Selection felling has been the theoretical base for the method of 'no dominant felling'. Selection felling can involve cutting down a single mature tree or felling small groups. The cutting method harvested trees by layer according to height and preserved a certain number of old trees. During the course of felling, dying and diseased trees were removed. After cutting, the canopy density should be about 0.4.

When industrial plantations on flat areas are clear-felled, each cutting area should not be too large, and the vegetation should be protected. Branches should be left on site and some fertiliser applied to restore soil fertility. How to manage harvesting to achieve sustainable management of eucalypt plantations is worth serious study.

Control of diseases and pests

Instead of controlling diseases and pests by applying chemical sprays, we should make efforts to grow sustainable, healthy plantations that have good resistance to diseases and pests. In China,

many seedlings and cuttings are transported long distances, and if quarantine practices are ignored, pathogens and noxious insects will be widely distributed. So, quarantine measures should be strengthened, and quarantine policy and practices strictly applied.

Socioeconomics

Besides the above technical measures, socioeconomic methods and policies should be adopted to ensure sustainable development and management of eucalypt plantations. For instance, government needs to establish a long-term plan for encouraging plantation development and adopt incentive measures such as increasing government investment, giving financial subsidies, and providing loans at favourable interest rates. The government can support the 'stock cooperative system' to encourage people to join in management of plantations and establish a reasonable system for distribution of benefits. Such measures will enable eucalypt plantations to be developed harmoniously in social, ecological and economic aspects.

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Scenarios for a Commercial Eucalypt Plantation Industry in Southern China

Xu Daping[1]

Abstract

The current distribution and likely future expansion of eucalypt plantations in southern China are described in this paper. As the demand for wood and paper will increase strongly in the next 10 years, the market for eucalypt wood in China is very optimistic. The key question for the expansion of eucalypt plantations in southern China is whether the price of the eucalypt wood produced locally is competitive internationally. Scenarios and economic analysis of different plantation establishment and management regimes are also included in this paper. It is concluded that site selection, fertilisation and weed control are the key factors that affect the economic benefit from commercial eucalypt plantation investment. It is predicted that 30% of productivity of eucalypt plantations in southern China will be from genetic improvement, and 70% will be from plantation establishment and management. Tax cuts in the near future will make most of the well-managed eucalypt plantations in southern China profitable. Research needs for commercial eucalypt plantations are also discussed in this paper.

Eucalypts were introduced into Guangdong province, China in the late nineteenth century (Hu Tianyu 2002). Today, there are about 1.5 million ha of eucalypt plantations in southern China (Table 1). However, most of these plantations are slow-growing with low productivity. In Hainan, where natural conditions are the most favourable for eucalypts, average mean annual increment (MAI) of plantations is about 9 m^3 ha^{-1} (Huang Jincheng 2000). The average MAI of eucalypt plantations in southern China is only 6–8 m^3 ha^{-1} (Xu et al. 2000b), about one-third of the average productivity (20 m^3 ha^{-1} yr^{-1}) of eucalypt plantations in the world (Brown et al. 1997). Moreover, productivity of eucalypt plantations is very variable, from 2 to 70 m^3 ha^{-1} yr^{-1}, which suggests there is great potential for improving productivity of eucalypt plantations in southern China.

According to the 'White Book on Forestry in China – 2002', the total forest area in China was 160 million ha, fifth in the world. Total standing volume was 12,500,000,000 m^3, seventh in the world. However, total area of tree plantations in China was 47 million ha, the largest in the world and about one quarter of the world total. About 5 million ha of tree plantations are established or replanted every year in China. According to statistical data from customs, total log imports in 2002 were 24.3 million m^3, mainly from Russia, Malaysia, Gabon, Papua New Guinea, New Zealand and Germany; total sawn timber imports were 5.4 million m^3, mainly from Indonesia, the USA, Thailand, Malaysia, Russia, Brazil and Canada. Total pulp and paper input in 2002 was 12.4 million t, of which recycled paper was 6.9 million t, pulp and paper 5.3 million t, and newspaper 0.2 million t. Wood resource shortage is a major problem in China because the stand volume of forests per person is only one eighth of the world average, about 10 m^3 per person (Zhang 2000). Wood consumption in China is 0.12 m^3 per person, much lower than the world average 0.68 m^3 per person. The average stand volume of all forests in China is only 78 m^3 ha^{-1}, much less than 133 m^3 ha^{-1} in neighbouring Japan and the 266 m^3 ha^{-1} in Germany (Wang 1999). After the logging ban on natural forests in China in 2000, the annual timber production of 12.4 million m^3 from natural forests (Figure 1) has had to be replaced by

[1] Research Institute of Tropical Forestry, Chinese Academy of Forestry, Longdong, Guangzhou, China 510520. Email: <gzfsrd@pub.guangzhou.gd.cn>.

wood from tree plantations (Zhang 2000). The projected wood shortage in 2010 in China will be over 56 million m^3 if the forest productivity cannot be increased (Wang 1999). Current imports of logs, sawn timber and board are about 20 million m^3 annually (Figure 2). Paper and pulp consumption in China was 35 million t in 2000, second largest in the world (Cai and Chen 2000). But the consumption per person is only 28 kg yr^{-1}, half of the average in the world. It is predicted that, by 2010, annual paper and pulp consumption will be 36–43 kg per person and total national consumption will be 50–60 million t with an annual growth rate of 4.0–5.8% (Cai and Chen 2000). If pulp and paper imports follow the same pattern as in the last 11 years (Figure 3), imports in 2010 will be about 26 million t. The State Forest Administration plans to establish 2.6 million ha of high yield pulpwood plantations in the next 10 years. To control water pollution to the main river systems, the government has closed thousands of small pulp and paper factories (<5000 t yr^{-1}) using non-wood materials. As a result, larger pulp and paper factories (>500,000 t yr^{-1}) using eucalypt chips will soon be established in southern China to meet the strong domestic demand for paper. The demand for eucalypt pulpwood will increase greatly in the next 5 years, so that more plantations must be established in the near future and/or productivity of eucalypt plantations increased.

Eucalypt Plantation Development in Southern China

One scenario is that the area of eucalypt plantations will be 2 million ha in 2005–2008 and their MAI will be increased to 10 m^3 ha^{-1} as a result of genetic improvement and implementation of better management techniques. Annual wood production will be about 15 million m^3. About 50–60% of the eucalypt wood production will be used for pulp and paper production, and 2 million t of paper will be produced annually. The other 40–50% eucalypt wood will go to plywood, medium or high density fibreboard (MDF or HDF) and sawn timber (Figure 2).

Figure 1. Total wood production in China, 1980–2001.
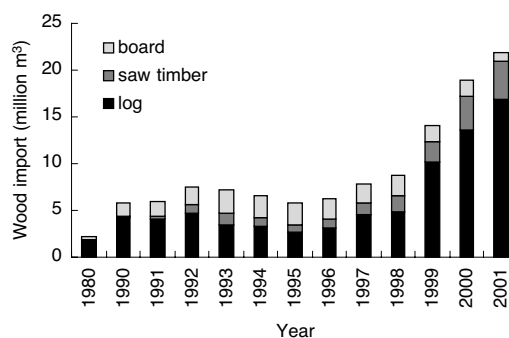
Figure 2. Total wood imports into China 1980 to 2001.

$y = 1.2626x - 2512$
$R^2 = 0.9474$
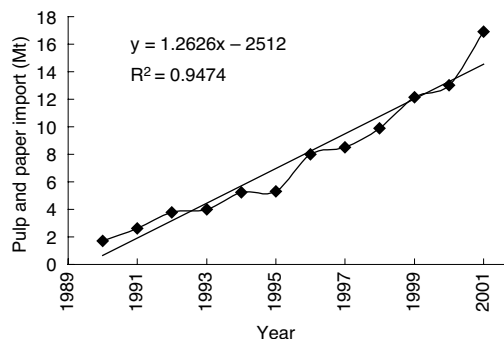
Figure 3. Pulp and paper imports to China 1990– 2001.

Today, annual plywood production in China is 22 million m^3, the largest in the world. Clearly, there is no problem for marketing eucalypt wood. The main challenge is to make the price of eucalypt wood produced in China internationally competitive.

Table 1. Area of eucalypt plantations in southern China.

Province	Guangdong	Hainan	Guangxi	Yunnan	Fujian	Sichuan	Others	Total
Area ('000 ha)	570	352	339	154	53	47	30	154,500

From Qi Shuxiong (2002)

The cost of producing eucalypt wood (per m^3 with bark) on site is about 200–250 RMB (2001–2002) (1US\$ = 8RMB). This is about twice the cost in Brazil and much higher than acacia wood in Indonesia. The only way to reduce eucalypt wood costs is to increase productivity. Taking a plantation on a moderately fertile site as an example, the total cost in a first rotation is 10,668 RMB. If the MAI is 15 m^3 ha^{-1}, the wood volume harvested is about 55 m^3 ha^{-1} and the value about 11 000–13 750 RMB ha^{-1}. Usually, taxes on eucalypt wood are 33–35% (about 16% plantation management fee, 8% agricultural tax, 8% no grain agricultural product tax and 1–3% other taxes). Zhou Zaizhi et al. (2002) reported that 37–40% of total wood volume goes to tax in Suixi county, Zhangjiang, Guangdong province. Net income of the eucalypt plantation in a first rotation is 7260–9075 RMB ha^{-1}. No grain agricultural product tax will be levied this year so net income will be 8140–10,175 RMB ha^{-1}. In some regions, the 16% plantation management fee can be reduced to 8% for foreign investment companies so their net income will be 9020–11,275 RMB ha^{-1}. Clearly, it is very difficult to make money from the investment in first rotation eucalypt plantations.

The response of the second rotation coppice of eucalypt plantations to fertilisation is usually less than in the first rotation (Xu et al. 2000a; Jiang et al. 2002) and with reduced fertilisation costs the overall cost of the second rotation is dramatically reduced. The productivity of the second rotation eucalypt coppice is about 90–120% of the productivity of the first (Xu et al. 2000a; Jiang et al. 2002) and the profit for second rotation crops will be about 5000 RMB ha^{-1} on moderately fertile sites (Table 2).

Taking a plantation on a fertile site as an example, total cost for the first rotation is 12,525 RMB (Table 3). If the MAI is 22.5 m^3 ha^{-1}, the final volume of harvested wood is about 84 m^3. The value of the wood is

Table 2. Cost scenario for eucalypt plantations on a moderately fertile site.

Rotation	Activity	Cost (RMB ha^{-1})	Accrual (RMB ha^{-1})
First	Land rent	2250	237 (5% interest rate)
	Plantation establishment	6000[a]	776 + 213 + 127 + 65 = 1181 (5% interest rate)
	Harvest	1000	
	Total	9250	1418
Second	Land rent	2250	237 (5% interest rate)
	Plantation establishment	1500[b]	323 (5% interest rate)
	Harvest	1000	
	Total	4750	560

[a] 450 RMB for seedlings, 750 for site preparation, 900 for base manure fertilisers, 750 for tree planting and fertilisation, 750 for re-fertilisation 4 months after planting, 750 for re-fertilisation in second year, 600 for weed control in second year, 750 for re-fertilisation in third year and 300 for others. [b] 300 RMB for thinning coppice, 600 for fertilisation, 450 for weed control and 150 for others.

Table 3. Cost scenario for eucalypt plantations on a fertile site.

Rotation	Activity	Cost (RMB ha^{-1})	Accrual (RMB ha^{-1})
First	Land rent	3750	394 (5% interest rate)
	Plantation establishment	6000[a]	1181 (5% interest rate)
	Harvest	1200	
	Total	10 950	1575
Second	Land rent	3750	394 (5% interest rate)
	Plantation establishment	1500[b]	323 (5% interest rate)
	Harvest	1200	
	Total	6450	717

[a] 450 RMB for seedlings, 750 for site preparation, 900 for base manure fertilisers, 750 for tree planting and fertilisation, 750 for re-fertilisation 4 months after planting, 750 for re-fertilisation in second year, 600 for weed control in second year, 750 for re-fertilisation in third year and 300 for others. [b] 300 RMB for thinning coppice, 600 for fertilisation, 450 for weed control and 150 for others.

about 16,800–21,000 RMB ha^{-1}. Net income of the eucalypt plantation in the first rotation is 11,088–13,860 RMB ha^{-1} after full tax payment. Net income without the no grain agricultural product tax would be 12,432–15,540 RMB ha^{-1}, higher than the investment. Net income for a foreign investment company will be 13,776–17,220 RMB. The total cost of the second rotation coppice will be 7167 RMB ha^{-1}. Hence, the investment for first rotation eucalypt plantations on fertile lands will make money with a profit of more than 7000 RMB.

On a poor site, the total cost of the first rotation is 9224 RMB (Table 4). If the MAI is 10 m^3 ha^{-1}, the final wood harvest is about 37.5 m^3. The value of the wood is about 7500–9375 RMB ha^{-1}. The investment will lose money on this rotation. The total cost for the second rotation coppice is 3866 RMB ha^{-1}. The profit from the second rotation coppice will be about 2500–3000 RMB.

In these three scenarios, a fixed investment for plantation establishment is used. However, this investment package will be suitable for a fertile site. For moderately fertile and poor sites, investment increment will change the profit from the first and second rotation plantations. If fertilisation and weed control can be improved with an additional investment of 2500 RMB ha^{-1}, the profit is likely to increase by 2000–5000 RMB ha^{-1}. This will make eucalypt plantation investment on moderately fertile sites profitable and allow the investment on poor sites break-even. It will increase profits in the second rotation.

It is concluded that site selection is very important for the profitability of the eucalypt plantation industry in southern China. Where feasible, only fertile and moderately fertile sites should be considered for investment.

Table 4. Cost scenario for eucalypt plantations on a poor site.

Rotation	Activity	Cost (RMB ha^{-1})	Accrual (RMB ha^{-1})
First	Land rent	1125	118 (5% interest rate)
	Plantation establishment	6000[a]	1181 (5% interest rate)
	Harvest	800	
	Total	7925	1299
Second	Land rent	1125	118 (5% interest rate)
	Plantation establishment	1500[a]	323 (5% interest rate)
	Harvest	800	
	Total	3425	441

[a] 450 RMB for seedlings, 750 for site preparation, 900 for base manure fertilisers, 750 for tree planting and fertilisation, 750 for re-fertilisation 4 months after planting, 750 for re-fertilisation in second year, 600 for weed control in second year, 750 for re-fertilisation in third year and 300 for others. b 300 RMB for thinning coppice, 600 for fertilisation, 450 for weed control and 150 for others.

Table 5. Impact of P application levels on income of the plantation.

Treatment	P application (kg ha^{-1})					
	0	13	52	104	208	312
	Yuan ha^{-1}					
Establishment cost	4,500	4,500	4,500	4,500	4,500	4,500
P fertiliser and application	0	200	800	1,600	3,200	4,800
Total cost	4,500	4,700	5,300	6,100	7,700	9,300
Cost + interest[a]	6,181	6,456	7,280	8,379	10,577	12,774
Wood value	3495	10,185	15,354	14,610	18,285	18,315
Net income	−2,686	3,729	8,074	6,231	7,708	5,541

[b] Annual interest was 5%, the total time was 6.5 years.

Table 6. Impact of fertilisation regimes on economic profit of *Eucalyptus urophylla* plantations in Enping, Guangdong province

Returns and costs	Treatment									
	$N_{25}{:}P_{22}{:}K_{21}$	$N_{25}{:}P_{44}{:}K_{42}$	$N_{25}{:}P_{66}{:}K_{84}$	$N_{50}{:}P_{22}{:}K_{42}$	$N_{50}{:}P_{44}{:}K_{84}$	$N_{50}{:}P_{66}{:}K_{25}$	$N_{100}{:}P_{22}{:}K_{84}$	$N_{100}{:}P_{44}{:}K_{21}$	$N_{100}{:}P_{66}{:}K_{42}$	$N_{0}{:}P_{0}{:}K_{0}$
Stand volume (m^3 ha^{-1})	102.1	115.5	100.1	117.7	98.7	114.7	100.1	106.1	141.1	36.1
Wood volume (m^3 ha^{-1})	71.5	80.9	70.1	82.4	69.1	80.3	70.1	74.3	98.8	25.3
Cost of establishing (Yuan ha^{-1})	1,986	2,153	2,361	2,115	2,323	2,323	2,372	2,370	2,539	1,688
Harvest + transport. (Yuan ha^{-1})	5,146	5,821	5,045	5,932	4,974	5,781	5,045	5,347	7,111	1,819
Taxes (Yuan ha^{-1})	6,432	7,277	6,306	7,415	6,218	7,226	6,306	6,684	8,889	2,274
Sale of wood (Yuan)	21,441	24,255	21,021	24,717	20,727	24,087	21,021	22,281	29,631	7,581
Net income	6,981	8,034	6,244	8,301	6,164	7,709	6,228	6,810	9,947	1,039

Note: Annual interest was 6.4%; the total tax was 30% of wood volume; wood price at the chip factory was 300 RMB m^{-3}; harvesting and transportation cost is 72 RMB m^{-3}; wood volume is 70% of stand volume (from Liang et al. 2002).

Investment and Other Factors Affecting Eucalypt Plantation Development

So far, great gains have been made in genetic improvement. The gap between the best clones that are used for eucalypt plantation industry now and new improved clones will not be very large, probably about 30% of total productivity increment. However, the gap between poor and good plantation establishment and management will be very large, possibly about 70% of total productivity increment. Also, some of the benefits of tree breeding will be lost if the trees are grown in suboptimal conditions in the plantation. Therefore, more funding support should be applied to find better plantation establishment and management techniques. Unlike clone improvement, plantation establishment and management techniques are more complicated and site-specific. Adequate plantation establishment and management techniques can be selected only by field managers, so training for field managers will also be very important.

High taxes on eucalypt wood have been a major constraint for the development of eucalypt plantations in southern China but now many local governments have reduced such taxes. For example, in Zengcheng, Guangzhou, the fee for plantation management (16% of the total value of the wood) was reduced. In Zhangzhou, Fujian province, tax is collected according land area instead of wood production. This policy change will encourage greater investment in eucalypt plantations. In Zhanjiang, Guangdong province, tax is collected on a fixed price that is much lower than the market price. I suggest the fee for plantation management should be collected according area rather than total wood production. This will dramatically increase investment for eucalypt plantations, and the tax for government will not be reduced. In southern China, there is inadequate land available to meet the demand for eucalypt plantations, so increasing investment in existing eucalypt plantations will help solve the wood shortage problem. It will also encourage private involvement and investment in eucalypt plantations.

After the policy change, most of the increased investment will go to plantation management, probably to site preparation, fertilisation and weed control. In one study, we found that highest economic profit among different phosphorus (P) application treatments was the middle level fertilisation, 52 kg P ha^{-1} (Table 5). Another study by Liang et al. (2002) in Enping showed that N_{100}:P_{66}:K_{42} was the best fertilisation regime producing the best economic return (Table 6).

There is still no information on impacts of weed control and site preparation on investment profit. More study is needed to find best plantation management techniques.

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Benefit–Cost Analysis of Eucalypt Management for Sustainability in Southern China

Zhou Zaizhi[1] and W. Loane[2]

Abstract

This paper reports an economic analysis for a project investigating management of eucalypt plantations in southern China for improving sustainability and productivity. The analysis evaluated benefits and costs of the key options for more sustainable management, comparing their net benefit with that of a traditionally managed plantation as a benchmark. Estimates of physical productivity were based on benchmark studies by local scientists. As an example of crop rotation between agricultural crops and eucalypt trees, watermelons were grown for one year on a former eucalypt site, followed by a crop of eucalypts for woodchips over a 5-year rotation. As residues were ploughed back into the soil to improve soil quality, woodchip productivity increased, while the watermelons were sold as a profitable commercial crop. Annual equivalent net benefit for this approach was estimated to be considerably higher than for a standard plantation. A similar positive result was obtained with a pineapple crop rotation for two years before the eucalypts. Another option considered was retaining all litter and residues on site. It was assumed that this would allow a continuation of the first-rotation productivity for four rotations, instead of the decline of 47% observed over that period. The cost of this was the loss of sale of by-products, and costs for chopping and rolling residues. The benefit–cost ratio just for the changes was high at 2.9. These interim results suggest several options are available that retain or restore organic matter on the site, and not only improve the sustainability of plantations but also show better economic returns than that of a traditionally managed plantation. However, the distributional implications, in terms of the social groups gaining or losing, need special attention. The forest owner makes monetary gains from increased revenue, while local villagers and harvest contractors who lose access to litter and forest by-products could be worse off. Measures to compensate the low-income groups who lose would be necessary to ensure that the plantation reforms have desirable effects on welfare and social sustainability.

The economic study reported here is part of a broader project investigating management of forest plantations in China and Australia to avoid resource depletion and environmental detriment. A particular issue is the concern that depletion of soil nutrient reserves in plantation soil is causing a decline in productivity with successive rotations. Plantation management and tending practices, such as litter collection and whole-tree harvesting, may be a factor in this.

To examine these problems and alternative management options, a collaborative project was initiated between the Research Institute of Tropical Forestry, Guangzhou, China, and the Forest Science Centre, Department of Natural Resources and Environment, Victoria, Australia, with funding from ACIAR. Other research partners in the project include the South China Institute of Botany, the China Eucalypt Research Centre, CSIRO Land and Water and the University of Melbourne. More details can be found on the project website at <www.eucalypt.net>.

[1] Research Institute of Tropical Forestry, Chinese Academy of Forestry, Longdong, Guangzhou, China 510520.

[2] Forest Science Centre, Department of Sustainability and Environment, PO Box 137, Heidelburg, Victoria 3084, Australia.

Management Options

A number of potential management options to over-come the sustainability problems were identified, with the assistance of local forestry officers and scientists at a workshop at Leizhou Forest Bureau (LFB) in March 2001. Several of these options were selected for further economic analysis here, giving priority to those that appeared to be most directly related to retention of site fertility, and those for which reasonable data were available. They can be divided into two broad groups.

Plant nutrient input:
- planting agricultural crops or nitrogen-fixing tree species between eucalypt rotations
- intercropping — mixed plantings of eucalypts and agricultural crops or acacias.

Retaining biomass:
- leaving harvest residues (branches and bark) and roots and stumps of trees
- leaving litter on site.

Economic analysis of the sustainability options required data on the productivity of plantations with and without such management practices, as well as the costs and other benefits of each. The analyses here are based on data from published reports of studies by Chen Xiao (1996), Wang Shangming (1997), Wu Xueshi (1995), and Yu Xuebiao et al. (1999), and Yu and Long Teng (1999) in the Leizhou Peninsula in southern China. This was supplemented by plantation management data provided by the Leizhou Forest Bureau.

Benefit–Cost Analysis Methodology

An economic benefit–cost analysis (BCA) was carried out in order to compare key options for more sustainable management. This involved estimating the aggregate benefits and costs in monetary terms for each management option, and comparing the net benefit with that of a traditionally managed plantation as a benchmark. The opportunity cost of land was not included in costs, so the net benefits can be regarded as returns to land.

Net benefits and costs in time periods were compared by discounting them back to the starting period, using a discount rate of 6% per annum, based on current interest rates on bank loans in China of about 5.8% for borrowings over more than 5 years.

Net present value (i.e. total of all discounted net benefits) is a criterion commonly used for comparing the economic merit of different options. However, in this case, the **annuity value** is the primary criterion used.

If B_1, B_2...is a set of money amounts (net benefits) over n years, and r is the discount or interest rate, then the net present value (NPV) of the amounts is:

$$NPV = \sum_{t=1}^{n} \frac{B_t}{(1+r)^t}$$

The annuity equivalent is the amount which, if paid as a constant amount every year, would have the same discounted present value, and is given by:

$$A = \frac{r}{1-(1+r)^{-n}} \times NPV$$

NPVs cannot be validly compared between projects over different time periods, whereas the annuity converts them all to a common basis of one year. Hence, it is better for comparing forestry projects of different lengths, and for comparing them with annual agricultural crops.

The internal rate of return (IRR) is another useful criterion as it shows the annual percentage return on capital. The IRR equals the discount rate which would make the NPV (or annuity) of a project equal to zero. If the IRR of a project is greater than the discount rate (or cost of capital), the project must have a positive NPV and is economically worthwhile. The benefit–cost ratio (BCR; ratio of gross discounted benefits to gross discounted costs) is also used in this paper.

Results

Standard plantation benchmark

The standard plantation of *Eucalyptus urophylla* was estimated to be profitable at even modest productivity levels around 12 m^3 ha^{-1} yr^{-1} on 5-year rotations, given the good returns from woodchips on the export market. The price of standing trees was taken to be 148 yuan m^{-3} (US\$1 = about 8.28 yuan). This is based on the wood price for the whole tree, including bark, reported in Wang Shangming (1997), understood to be for the standing tree after deducting costs for logging, transport, chipping etc. from the price of woodchips.

Based on LFB management standards, the costs were mainly establishment costs of 3500 yuan ha^{-1} over the first 3 years, of which the fertilising cost of 2500 yuan was the biggest item.

On the better sites with the U6 eucalypt clone, mean annual increment in wood productivity (MAI) around 29 m^3 ha^{-1} can be attained, which produces net benefits with an annuity equivalent of 3030 yuan ha^{-1}, or an IRR of 65%. At a MAI of 21 m^3 ha^{-1}, the annuity is still high at 1980 yuan ha^{-1} and IRR of 51%. These are very high returns by most standards.

The standard plantation benchmark involves the common practice of whole-tree harvesting and litter collection. Thus, economic benefits are obtained both from the main product — chipwood, which is converted into chips for export by the forest owner — and from various by-products. Wood with diameter down to 2.5 cm, and length 0.5–2 m, is used for chipping, so that almost all wood is used for chips. About 59% of chips are obtained from stem logs and 41% from branches and twigs.

The stumps and roots belong to the forest owner and are dug out and sold to local middlemen, who sell them to local mills for producing charcoal or boiler fuel. In some areas, harvesting contractors have the right to take the stumps. Leaves and twigs can be taken by the harvesting farmers free of charge, for daily household uses such as cooking. Litter is often collected through the rotation by local farmers and villagers, without charge. In some areas, the price of litter is 5 yuan t^{-1}. It has value to villagers as a fuel that is cheaper than gas, the next best alternative.

Because whole-tree harvesting removes soil nutrients along with the organic matter, it can be expected to reduce site fertility and productivity. This approach was associated with a decline of 47% in productivity (stem only) over 18 years, from 12 m^3 ha^{-1} yr^{-1} in the first rotation to 8 m^3 ha^{-1} yr^{-1} in the fourth rotation, as observed on an LFB study site in Hetou (Yu Xuebiao et al. 1999). Using the productivity data from that study, the annuity value was initially 747 yuan ha^{-1} in the first rotation, and had declined to 78 yuan ha^{-1} by the fourth rotation.

Agricultural crop rotations

To evaluate some options for more sustainable management, data were used from studies of crop rotations (or shifting management) with eucalypts and agricultural crops, namely (i) watermelons and (ii) pineapples.

Watermelon rotation

Watermelons were grown for 1 year on a former eucalypt site, followed by a crop of *E. urophylla* for woodchips over a 5-year rotation (Chen Xiao 1996). The watermelons were sold as a commercial crop after only 3 months growth, while the residues were ploughed back into the soil to improve soil quality.

Woodchip productivity in the following rotation, averaged across two sample plots, was about 11% higher compared with a standard site (MAI of 23.5 m^3 ha^{-1} compared with 21.0 m^3 ha^{-1}), apparently due to soil improvement. A partial offset against these benefits was the deferral of the subsequent eucalypt crop by one year. The cost of delaying the income from the next wood harvest is measured in the BCA by the reduction in the discounted value of the harvest, as the later harvest is discounted back one more year to the starting date. At a discount rate of 6% per annum, the cost of deferral is less than the increase in wood revenue, so there is some net gain on wood, but the watermelon profits make the main contribution to the economics of the option.

The revenue from watermelons in Chen's study was 18,000 yuan ha^{-1}, based on yield of 22,500 kg ha^{-1} and selling price of 0.8 yuan kg^{-1}. Costs were reported to be 11,200 yuan ha^{-1}, giving a substantial profit. If attainable in repeated seasons, it would be a more profitable use of the land than plantations. However, agriculture is not the core business of forest agencies, but rather a complement in this case to enhance its forestry business. The watermelon profitability would not necessarily be attainable in all seasons and other sites.

On the combined enterprise of eucalypts and watermelons over the 6-year rotation, the annual equivalent net benefit was 3160 yuan ha^{-1}. This was considerably higher than the annual net benefit of the standard plantation of 1980 yuan ha^{-1}. The improvement was primarily due to the watermelon profits in the first year which contributed 88% of the increase in net benefit, while the increased woodchip revenue contributed the rest.

Looking only at the changes from the base case, the ratio of benefits to costs was 1.7, which indicates a clear margin of superiority for the agricultural rotation approach.

Pineapple rotation

In a study of pineapple–eucalypt rotations, the pineapple crop occupied the site for 2 years before the eucalypt rotation of 5 years (Wang Shangming

1997). Gross revenue from pineapple harvests was reported to be 25,300 yuan ha^{-1}, against costs of 15,000 yuan ha^{-1}. This gave a substantial profit in its own right, but was also associated with an increase in productivity of the subsequent eucalypt crops by an average of 18% across four species in the sample plots. As a partial offset to these benefits, the eucalypt crop was delayed by 2 years, giving rise to an interest cost on deferred income.

Taking the combined crop returns in the biomass retention option, the annual net benefit over 7 years was 3670 yuan ha^{-1}, compared with 2700 yuan ha^{-1} for the benchmark plantation case. About 90% of the increase was due to the pineapple profits, with the rest due to the increased wood revenue. Looking only at the changes from the base case, the ratio of benefits to costs was again 1.7.

Intercropping

Another approach involves intercropping — planting nutrient-providing plants between the rows at the same time as the eucalypts are planted. Scientific studies have examined intercropping with several alternative crops — watermelons, pineapples and mitangcao (Yu Xuebiao and Long Teng 1999) (Table 1). The spacing of the eucalypts for intercropping was 1.5×3 m, with the agricultural crop grown between the 3 m rows. As eucalypts may grow rapidly and close their crowns over the site, it may be difficult to grow other crops between the trees unless the rows are wide.

Taking watermelon as an example, the annual net benefit with intercropping over 6 years was 2600 yuan ha^{-1}, compared with 980 yuan ha^{-1} for the standard plantation. The ratio of benefits to costs for the changes only was 1.8.

In the case of pineapple intercropping with *E. urophylla*, the improvement in wood productivity was 12.9% — higher than after watermelon. Pineapples normally progress to higher yields in their third and fourth years. However, in this study the pineapple crop was costly, with output value of only 400 yuan ha^{-1} against costs of 4200 yuan ha^{-1} due to poor management (Wu Xueshi 1995). Overall, this trial was uneconomic.

The net benefit of mitangcao was also low because it is grown only for 'green manure'; that is, to plough in for fertiliser, and yields no product to sell, Neither did it show a significant increase in wood productivity.

Biomass retention

The other important option analysed was the retention of litter and residues on site. It was assumed that, under this approach, the productivity level of the first rotation would be continued through subsequent rotations, but at the cost of the loss of use of by-products such as roots, stumps, barks, branches and litter. Table 2 shows the contributions of different parts to total biomass over the four rotations and their contribution to total nitrogen over the first rotation (Yu Xuebiao et al. 1999), and the value of by-products assumed in the analysis (based on LFB data).

While the stemwood makes up most of the biomass and has the highest commercial value, the other components hold the majority of the N store and so are most important for site fertility (Table 2). Leaves and litter have a particularly high N content compared with their commercial value.

The assumption that productivity is maintained by biomass retention is based on the idea that site fertility is maintained through a combination of retaining harvest residues, and adding fertiliser and organic inputs, such as bagasse, to make up for the loss of nutrients in harvested wood.

The retention approach contrasts with the common plantation practice of whole-tree harvesting and litter collection. Under this benchmark approach, wood productivity was assumed to follow the path observed in the data from Yu Xuebiao et al. (1999) —

Table 1. Effects of different intercropping options on woodchip productivity.

Agricultural crop	Species	Control (base-case)	Intercropping	% increase in MAI
		Mean annual increment woodchips (m^3 ha^{-1})		
Pineapple	*E. urophylla*	11.49	12.97	12.9
Watermelon	*E.* Leizhou No. 1	13.45	14.23	5.8
Mitangcao	*E. urophylla*	13.08	13.12	0.3

declining by 47% over four rotations. Alternatively, if all biomass is removed, it may be possible to maintain site fertility through a greater application of fertilisers, but this option is not evaluated here.

Annual net benefit of the biomass retention option over four rotations each of 5 years was 655 yuan ha^{-1}, compared with 495 yuan ha^{-1} for the benchmark case, indicating that the biomass retention option is substantially better in economic terms. The change in management raised the plantation's BCR from 1.62 for the standard management to 1.82 for biomass retention.

Table 2. Contributions of different components to total biomass over four rotations and their contribution to total nitrogen (N) over the first rotation[a] and the value of by-products assumed in the analysis.[b]

Component	% of total biomass	% of total N	Price (yuan t^{-1})
Stem	79	41	148 (yuan m^{-3})
Bark	7	11	35
Branches	3	3	7.5
Leaves	3	34	5
Stump and roots	3	4	80
Coarse roots	4	6	–

[a] Based on Yu Xuebiao et al. (1999); [b] based on LFB data.

The change in cash flows had the following components:

1. increase in chipwood revenue, with a present value of 2820 yuan ha^{-1}, an increase of 20%
2. extra costs for rolling and chopping harvest residues to facilitate establishment of the next rotation, with a present value of 60 yuan ha^{-1}
3. loss of by-products, with a present value of 900 yuan ha^{-1}.

The increase in chipwood revenue outweighs the other costs, including loss of by-products, for several reasons:

1. chipwood in Leizhou has a far higher value per tonne
2. chipwood (stem wood) is a far higher proportion of the total tree biomass than the other by-products

3. potential percentage improvement in wood production through saving nutrients is large.

The BCR for just the changes was 2.9, and the annual equivalent benefit of the change was 160 yuan ha^{-1}.

There is uncertainty as to the expected productivity level, due to the scarcity of scientific data on the benefits of biomass retention. Hence, some sensitivity tests were run, varying the extent of productivity change. If retention allows productivity to recover only 50% of the decline suffered in the standard plantation, the annuity value of the retention option would still be 535 yuan ha^{-1}. If retention allows productivity to recover only 30% of the decline suffered in the standard plantation, the annuity value of the retention option would be about 485 yuan ha^{-1} — the same as the standard plantation. This suggests that the retention option would still be better within a wide margin for error in the productivity assumption.

Distributional effects

The changes due to biomass retention involve net benefits to the forest owner of 2760 yuan ha^{-1}, with net costs to villagers through lost litter of 35 yuan ha^{-1}, and net costs to harvest contractors who collect stumps, roots and other harvest residues of 785 yuan ha^{-1}.

These costs to losing groups were a relatively small proportion of total benefits, but they tend to be concentrated on the lower-income people who may suffer greater hardship from a reduction in income. Although the total benefits are higher from biomass retention, it is not possible to say that the change would be good for the economic welfare of the population as a whole, unless the poorer groups were compensated to avoid actual losses.

Some options for compensation would be:

For harvest contractors:
- compensating for loss of by-products by paying them a higher price for their harvesting work.

For villagers:
- allowing them to collect litter, while compensating for its effect on fertility and soil structure by increasing inputs of inorganic and organic fertilisers;
- allowing them to take wood from the culling of small weak stems, while leaving litter to provide ground cover (preventing collection)

• providing more jobs for them in plantation tending.

Partial approaches to retention are possible; for example, higher priority could be given to retaining harvest residues, while allowing litter collection, as harvest residues are a greater part of biomass, compensation for harvest contractors may be easier to arrange, and those collecting litter may be more economically vulnerable.

The distributional effects of the agricultural rotation and intercropping options are of less concern, since the costs and benefits of the wood revenue and the agricultural crops both accrue to the forest owner.

Conclusions

The results to date suggest several options are available that not only improve the sustainability of plantations but also show positive economic returns.

Options involving retention of tree biomass, such as roots, stumps, bark, branches and litter, are worthwhile to avoid or reduce the significant reduction in fertility and productivity otherwise occurring under conventional practices. However, at this stage there are few scientific data comparing productivity levels of different systems, or indicating how much applied fertiliser might be needed to supplement the biomass retention option.

If litter collection and whole-tree harvesting are stopped, measures to compensate the low-income groups who lose income from by-products would be necessary to ensure that the plantation reforms have desirable effects on welfare and social sustainability. Possible measures include:

1. paying harvesting contractors a higher price for their harvesting work to compensate for their loss of by-products
2. allowing villagers to take wood from the culling of small weak stems, as compensation for preventing litter collection
3. allowing villagers to collect litter while compensating for its effect on fertility and soil structure by increasing inputs of inorganic and organic fertilisers.

Rotations involving plantings of watermelons and pineapples before the eucalypt rotation also gave positive results, partly through increasing wood productivity but mainly through profits on the agricultural component. Although the watermelons and pineapples were highly profitable in the sample plots, it cannot be expected such crops will be so profitable on all sites and in all seasons. The study at least suggests this is a promising approach to pursue further.

Further analysis is to be conducted, using the plantation growth model 3PG to simulate a wider range of scenarios.

Acknowledgments

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Eucalypt Domestication and Breeding — Past Triumphs and Future Horizons

S.P. MacRae[1]

Abstract

An overview of past achievements and future directions in eucalypt domestication and breeding is presented. Examples of value recovery from genetic (conventional and molecular) and tree breeding in the fast-growing plantation forestry industry are given, including the use of clonal propagation technology to capture and enhance genetic gains and fast-track value recovery from breeding programs. Strategies for the development and deployment of improved genetic resources within effective time frames, for sustainable high productivity and quality plantations for specific end-uses are discussed. Attention is also focused on the need for close integration of molecular and conventional gene technologies. This integration will substantially enhance and speed-up genetic improvement and sustainability of breeding programs through improved faster selection in conventional breeding programs, faster deployment of genetically improved material to plantations and a deeper understanding of the genes controlling commercially important traits such as wood properties in forest trees.

Concomitant with a 1.5% increase in the world's population is a 1.3 to 2% annual increase in global demand for wood products, which translates to a 30–50% increase in the next 20 years (FAO 1995; McLaren 1999; White and Martin 2001). This increase in demand is occurring simultaneously with a decrease in the total area of forests in the world and increasing pressure to conserve much larger areas of the world's natural forests for purposes other than wood production. The value of plantations as a source of wood products to help meet global demand is therefore well recognised (Hagler 1996; Sedjo and Botkin 1997; Spears 1998; Sedjo 1999; Fox 2000).

Today around 10% of the world's wood consumption comes from plantation forests. This value is increasing and could reach 50% within a relatively short time, depending upon the rate of plantation establishment and the productivity of those plantations (White and Martin 2001). Calculations have shown that plantations covering only 5% of the world's forested area and with average growth rates of 10 m^3 ha^{-1} yr^{-1} could meet the world industrial wood requirement. Only half this area would be needed if the plantation productivity were doubled to 20 m^3 ha^{-1} yr^{-1} (Hagler 1996; Sedjo 1999; White and Martin 2001).

As a result, over the past few decades, there has been an increasingly strong recognition worldwide of the importance of domestication, genetics and tree breeding in improving 'fast-growing' hardwoods and softwoods. Forestry and forest-product companies and government organisations are therefore investing greater amounts in genetics and tree breeding to increase plantation productivity and meet the demands for fibre and wood resources.

There is little doubt that genetically improved plantations consistently outperform genetically unimproved plantations. The capture, enhancement

[1] CSIRO Forestry and Forest Products, PO Box E4008, Kingston, ACT 2604, Australia.
    <Email: Sharmane.MacRae@csiro.au>.

and transfer of genetics gains from breeding programs to plantations, though, is dependent on a number of factors including:

(i) breeding strategies — selection intensity and technique in the breeding program

(ii) deployment strategies — method of delivery of gains to plantations, including clonal forestry

(iii) plantation management — silvicultural practice and environmental issues.

These factors will undoubtedly drive value recovery from genetics and tree breeding.

This paper presents an overview of two of the major cornerstones to value recovery from genetic and trees breeding, namely project-based breeding strategies and deployment strategies.

1. Project-based breeding strategies aim to maximise genetic gains through integration of results from conventional and advanced genetic technologies to develop site-matched genotypes with improved fibre and wood production and quality for specific end uses. Close integration of molecular and conventional gene technologies can enhance and speed-up genetic improvement and sustainability of breeding programs through improved faster selection in conventional breeding programs. This, in turn, will result in faster deployment of genetically improved material to plantations. Breeding strategies alone will not ensure value recovery.

2. Efficient deployment strategies are essential for delivery of improved stock from the breeding program to plantations within effective time frames. This will include the use of clonal propagation technology to capture and enhance genetic gains and fast-track value recovery from breeding programs.

In addition, the components of value recovery — increased plantation productivity and uniformity, improved product quality and uniformity, increased tolerance to diseases and pests and increased return on investment — will be presented.

Breeding Strategies

All genetics programs have a beginning, but tree breeding is an activity that tends to continue indefinitely and sometimes aimlessly. Breeding strategies for both hardwoods and softwoods have evolved considerably over time, to meet changing internal and external market demands. The trend today is to implement project-based breeding strategies, with defined goals, good planning and communication, and set time frames (defined end) for delivery to plantations through well-defined deployment strategies, involving seed orchards and clonal forestry (MacRae and Cotterill 2000; Cotterill 2001).

Breeding strategy goals should be simple, straightforward and focused on the fundamental economic and environmental objectives of the company or organisation. They should encompass production, wood/fibre quality and genetic diversity.

Production

The production goals should involve as few traits as possible, because the more traits under selection the lower the gain in each trait. Where there are favourable genetic correlations it may be possible to consider a larger number of traits, as selection on one trait will lead to indirect gains in other traits. However, adverse or unfavourable genetic correlations tend to complicate breeding strategy because selection on one particular trait may lead to unfavourable changes in other important traits. The extent of the adverse genetic correlations will govern whether it is possible to select on a group of favourably associated traits while preventing deterioration in another adversely correlated trait. Strong adverse genetic correlations, however, usually leave no option but to develop multiple populations (such as multiple nucleus populations). Hybrid crosses among the different nucleus populations may help overcome the adverse correlations in future generations of tree improvement.

Wood/fibre quality

Two approaches seem to drive genetic improvement of wood and fibre quality.

Intermediate end use approach

This involves selection for a uniform and consistent wood quality that represents an 'intermediate' profile range in terms of wood, fibre, pulp or paper specifications for the particular species being improved. For example, selection in Stora Enso Celbi's Project D95 was for a consistent intermediate quality of *E. globulus*-type pulp. When D95 plantations begin to be harvested in 2005, the company expects a substantial improvement in consistency of the pulpwood supply to Celbi's mill (Cotterill 2001).

Importantly, many companies supply their industrial facilities with wood grown in 'own' plantations

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and also wood purchased from 'outside'. The wood from outside market sources is almost always more variable in quality than 'own' wood, due to differing levels of genetic improvement, age of harvest and so on. Own-plantation production reduces the reliance on 'market' wood and increases and improves uniformity and consistency.

Special-purpose approach

This involves developing 'breeds' (nucleus populations, discussed later) of trees having special wood and fibre properties and other traits such as disease and insect tolerance. For example, 'high wood density' breeding populations are reasonably common in forestry. Other companies are developing specific breeds for specific paper or solid wood end-uses. For example, Celbi is creating different nucleus populations to achieve short-term gains, particularly in wood, pulp and paper properties (Cotterill 2001).

Genetic diversity

There is invariably a trade-off between maximising genetic gain and maintaining sufficient genetic diversity to guarantee continued genetic improvement and sustainable, improved plantations. The risk to plantations due to failure to withstand new pests or diseases, or unusual climatic events such as drought or cold, is inevitably high if sufficient genetic diversity is not ensured. A 'DNA diversity index' which integrates: (i) number of families or clones, (ii) genetic relationship among families or clones based on DNA fingerprints, and (iii) variation in areas planted to particular families or clones in a plantation estate has been formulated to monitor and manage genetic diversity in plantations (MacRae and Cotterill 2000).

In any breeding strategy, it is important to remember that achieving goals, such as substantially increasing plantation productivity, depends heavily on reliable testing, selection, mating and, of course, planning. The creation and utilisation of outstanding families must, ultimately, be the cornerstone of any breeding strategy aimed at producing new and ever-improving genetic material for family (seed multiplication) or clonal forestry. In breeding projects that serve clonal forestry, it is the outstanding families from which superior clones can be selected for cuttings propagation. Achieving rapid gains in programs that serve mass-pollination family forestry requires creating outstanding full-sib families for the mass-pollinations.

Use of nucleus and cluster-breeding strategies (Cotterill 2001) in project breeding of eucalypts and pines is briefly reviewed.

Nucleus Breeding

Background

Nucleus breeding as a strategy for genetic improvement in fast-growing hardwood and softwood plantation species, in particular *Eucalyptus* and *Pinus*, began in the late 1980s (Cotterill et al. 1988) and is quite widely used today. Selecting trees with the highest breeding values and then crossing those selections in many combinations creates the nucleus population. This crossing of best parents with best parents is intended to produce outstanding full-sib families and individual trees, thereby maximising short-term improvement. Longer-term and more gradual genetic progress is secured in a 'main' breeding population that is less intensively selected and maintained with a much larger effective population size.

Influence of additive and non-additive genetic behaviour

Of significance in nucleus breeding is the fact that *Eucalyptus* and *Pinus* species have apparently different relative levels of additive versus non-additive genetic control.

Genetic behaviour of Pinus *species*

Nucleus breeding strategies are widely used for a number of pine species, namely *P. radiata, P. pinaster* and *P. elliottii*, in countries such as South Africa, Australia and New Zealand. The additive genetic behaviour of these three *Pinus* species grown in South Africa was studied by Cotterill et al. (1987). The important conclusion from this study was that the breeding values of parents of the three *Pinus* species provided a reasonable guide to the subsequent growth and form of their full-sib families. Under predominantly additive genetic control, the crossing of parents with 'best' general combining abilities (GCA) will often produce the best full-sib families. Breeding programs with *P. radiata* in both Australia and New Zealand using nucleus breeding strategies have resulted in similar outcomes and significant genetic gains.

Genetic behaviour of Eucalyptus *species*

The genetic control of growth of *Eucalyptus* species appears to be relatively strongly influenced by non-additive specific combining abilities (SCA). Under a non-additive genetic model, crosses among lower breeding value parents (that may be in the main breeding population) can deliver better performing full-sibs than crosses among high breeding value parents (in the nucleus). This situation occurs when high SCA present in particular crosses leads to families that perform better than the original parents. Having better families in the main population than in the nucleus would, of course, create a nonsense of nucleus breeding. In the case of *E. globulus*, for example, it has been observed that high SCA effects can be particularly evident in wide intraspecies crossing of genetically divergent (widely unrelated) parents (Cotterill 2001).

It should be stressed that, regardless of the non-additive genetic effects, there is clearly sufficient additive genetic variation expressed in *E. globulus* to achieve substantial genetic gains from each cycle of selection (Borralho et al. 1992a,b). The cumulative genetic gains that are passed from one generation to the next depend mainly on additive genetic effects.

In summary, the short-term gains from nucleus breeding depend on the basic additive genetic assumption that crossing high breeding value nucleus parents will produce the best possible families and individual trees for future utilisation. In this sense nucleus breeding requires reasonably strong additive genetic control of the traits under selection.

Multiple nucleus populations

As already mentioned, strong adverse genetic correlations usually leave no option but develop multiple populations; perhaps multiple nucleus populations. Each nucleus population would be superior for a group of favourably correlated traits and weak in other traits. As part of Project 3D, Stora Enso Celbi has employed multiple nucleus populations for wood properties that are under strong additive genetic control in *E. globulus* (Cotterill 2001). Similarly, State Forests of New South Wales will use multiple nucleus breeding for this purpose.

Cluster Breeding

Concept

Clusters of control-pollinated families having common female parentage are created from matings based on key or dominant females (Cotterill 2001). Like nucleus breeding, the cluster strategy is intended to maximise short-term gains and focus investment where it can have the most benefit. Cluster breeding is better suited to utilising non-additive genetic variation compared with nucleus breeding. The cluster strategy requires a main breeding population to secure longer-term and more gradual genetic progress and large effective population size.

There is definitely no need for any predefined mating pattern (i.e. dialleles or factorials) in creating the clusters. The main criterion in choosing male partners for the dominant females is perhaps to ensure distant genetic relatedness and the widest possible crossings (MacRae and Cotterill 2000).

Choosing dominant females

Potentially dominating females must be chosen wisely and the following factors can be important under different situations.

Production traits

Female and male parents of high GCA for production traits occur in almost all eucalypt breeding programs and those individuals should obviously be used to maximum advantage in control pollinations.

Rooting ability (clonal forestry)

Clones of proven superior rooting ability and field performance can themselves serve a key role as dominant female parents in crossing programs aimed at generating new families and clones for future clonal plantations. Such clones would obviously include the tried-and-tested favourites from existing commercial plantations of that company or other companies. The strong rooting characteristics of the parent will, it is hoped, be inherited, and create good families with individual trees amenable to vegetative propagation.

Flowering ability (mass-pollination forestry)

Choosing female parents is a particularly important aspect of any control-pollination program in breeding for commercial multiplication by mass-pollination. Almost all species of eucalypts exhibit large clone-to-clone variation in flowering potential. Some

clones can consistently produce large numbers of flowers per tree and high seed yields per capsule, while others maybe infertile. Control-pollination programs usually end up with a few females that flower very well dominating the full-sib families that are generated. Domination by these better flowering female parents is part and parcel of cluster breeding for mass-pollination forestry. The better flowering nature of the females ensures that the families selected on production traits (growth, wood quality) will be amenable to mass pollination.

Effective population size and continuing genetic gain

One potential problem with using dominant females is that they can have an adverse influence on effective population size in future generations of improvement. The dominant females can defeat the goal of one genetics project serving as the foundation for the next. As with nucleus breeding, the cluster strategy requires a main breeding population to secure longer-term genetic progress and maintain large, effective population size. From one generation to the next, parents would be moved from the main population into the clusters (Cotterill et al. 1988).

Stora Enso *Eucalyptus* plantation projects are based in Portugal, Brazil and Thailand, and the company has been breeding *Eucalyptus* since the mid-1960s. Stora Enso's pure bred and hybrid breeding strategies are based on developing outstanding families using control-pollination and intensive genetic selection of elite clones from these families for future plantations. Opportunities exist for very substantial improvement in wood productivity and quality by selecting the best families and the best trees (clones) within a species (Cotterill and MacRae 1996; MacRae and Cotterill 1996; Cotterill 1997; Cotterill and Brolin 1997; MacRae and Cotterill 1997, 2000).

Plantation management practices, including silviculture, weed control and pest and disease control, will have a major impact on realisation of genetic gains.

Advanced Genetic Technologies (Biotechnology)

Biotechnology today offers tree breeders a range of potentially valuable tools that may be broadly categorised as molecular-genetic and gene-modification technologies.

Molecular-genetic technologies

Molecular markers are used in DNA fingerprinting (for clonal identification and variety registration), genetic diversity assessment and management, marker-aided crossing and genome mapping (QTL mapping and marker-aided selection). DNA and EST (expressed sequence tag) sequencing are used in gene discovery research. The benefits of research using these technologies include increased genetic gain per unit time through more efficient and faster selection in conventional breeding programs, faster deployment of genetically improved material to plantations and a deeper understanding of the genes controlling commercially important traits such as wood properties.

Marker-aided crossing

Achieving a genetic goal such as doubling pulp production of *Eucalyptus* plantations depends very heavily on using control-pollination to generate outstanding families. It is actually these outstanding families that provide the elite clones or seedlings for establishing improved plantations. Choosing females is a key aspect of the control-crossing program (MacRae and Cotterill 2000).

One of the most important lessons learned from Stora Enso Celbi's genetics Project D95 was that crossing genetically divergent ('widely' different) populations of *E. globulus* consistently produced the most outstanding full-sib families; the technique is called 'wide-crossing'. DNA fingerprints reflect the genetic relatedness (diversity) of potential parents in a crossing program and can guide geneticists towards the widest possible crosses. Marker-aided crossing is currently being used in Stora Enso *Eucalyptus* control-crossing programs, ensuring that the best possible full-sib families are produced. It is from these families that elite clones are selected.

DNA diversity index

As already mentioned, DNA fingerprints can provide an accurate guide to genetic diversity among the parents in a breeding program. Maintaining adequate genetic diversity in breeding programs is fundamental to the long-term adaptation, health and sustainability of *Eucalyptus* plantations. Forestry and forest-products companies, such as Stora Enso, have included genetic diversity of their forests and plantations as a key part of their plantation environment policy.

In the past, tree breeders have simply counted the number of clones or parents involved in a breeding project to get a rather crude measure of genetic diversity. However, this counting system does not take account of just how closely related are the genetic materials being used in breeding and plantation programs. Nor does counting the number of clones take account of the representation of different clones in terms of hectares actually planted. DNA fingerprints can give an objective evaluation of genetic diversity.

A unique 'diversity index' has been developed to monitor the genetic diversity of *Eucalyptus* plantation estates. The diversity index integrates three key parameters: (i) number of clones in the plantation, (ii) genetic relationship among clones based on DNA analyses, and (ii) variation in area planted with different clones —

Diversity index = f(number of clones, relatedness coefficient, variation in area).

The higher the index, the higher the effective genetic diversity of the annual establishment over the plantation estate (MacRae and Cotterill 2000).

Marker-aided selection

Many companies and research organisations around the world are investing in marker-aided selection research focused primarily on wood morphological and wood chemical properties that determine key solid wood (e.g. CSIRO Australia) and paper qualities (e.g. Stora Enso) such as density, strength, opacity, porosity and bulk. Reasons for the special interest in wood properties are: (i) wood and paper properties are of fundamental economic importance; (ii) delays can occur in conventional breeding, because trees must be reasonably mature before wood samples can be collected and used for direct measurement of paper properties; and (iii) most wood properties are strongly inherited in *Eucalyptus* and *Pinus* species and this gives a higher probability of detecting correlations between the wood and the DNA markers.

Genetic modification technology

While recombinant DNA techniques and genetic engineering are controversial, the technology offers opportunity to greatly enhance genetic progress by adding new genes into already selected elite clones. The process does not involve sexual reproduction, and the desirable trait therefore remains intact, as does the 'genetic background' of the tree. The intro-

duced gene adds value to an already desirable genetic background. Inserted genes may also include genes that do not occur naturally in the *Eucalyptus* genome, allowing advantage to be taken of previously inaccessible characteristics by overcoming taxonomic barriers. It is important to note that the full potential of genetic engineering will be realised only through its integration into conventional tree breeding and clonal programs. Possibilities are opening up to improve economically important traits that cannot be modified by conventional means within a reasonable time frame.

Many commercial forestry and forest products companies, like Stora Enso, have made the decision not to use genetic engineering technology to modify and improve its fibre resources (MacRae and Cotterill 2000).

The progress made in gene transfer technology for *Eucalyptus* in the 1990s has opened real possibilities for integrating this technology into conventional *Eucalyptus* breeding programs. Many research groups worldwide are currently focused on searching for new genes and developing reliable protocols for gene transfer in *Eucalyptus* (MacRae 1997; MacRae and Van Staden 1999). Examples of commercial interest that are being studied are genes for herbicide (glyphosate) tolerance, lignin content and composition, cellulose (cellulose binding domain (CBD) genes) and insect tolerance (*Bacillus thuringiensis* toxin gene). No transgenic *Eucalyptus* is available commercially today. Before transgenic *Eucalyptus*, or pine species for that matter, carrying any of these genes can be commercialised, extensive testing and risk evaluation is necessary and ethical considerations are essential.

Deployment Strategies

The simplest part of tree breeding can be achieving the gains in a breeding population (i.e. identifying good genetic material in field trials). This step involves well-known quantitative genetic technologies such as progeny/clonal testing and efficient selection. The most difficult step is usually to multiply a few outstanding families or individuals that have been identified in trials to produce, from a few superior tested trees, the millions of plants in nurseries for commercial plantation estate establishment.

The responsibility of breeding projects does not end with creation (identification and selection of outstanding families and clones) of improved germ-

plasm; it ends only when improved genetic material is deployed into plantations. This point about delivery may seem obvious, but there are still too many companies with high-performing material in field trials and relatively unimproved material entering their commercial plantations. One important measure of a good tree breeder is the deviation in genetic quality of material in trials and the material in the commercial nursery at any point in time. Deployment strategies are therefore an important component of value recovery from tree breeding.

The connections or networks between genetics projects and other operational parts of the company are absolutely critical to the process of getting improved material from trials to plantations, and in the final industrial utilisation of improved material after harvest. There must be close cooperation between the genetics program, nursery, laboratory, seed orchards, forest regions and mill. These connections have little to do with genetics and very much to do with personal relationships, leadership and information flow.

Seed orchards offer one method for multiplying outstanding individuals to capture and enhance gains from the breeding program and transferring these gains to plantations. The other method of capturing and enhancing genetic gain involves vegetative propagation (MacRae and Cotterill 1997).

Open-pollinated orchard seed

Open-pollinated seed orchards are a commonly used way of capturing genetic gains for commercial deployment of a number of *Eucalyptus* and *Pinus* species. Superior trees are brought together in an orchard area and allowed to cross-pollinate naturally to produce improved seed. In the case of *E. globulus*, 20 to 40% gains in productivity can be expected compared with genetically unimproved seed. Genetic gains are, however, lower than those from mass-pollination because there is no control over what particular parent is cross-pollinated with what other parents and, hence, less gain from intraspecific hybrid vigour.

Control-pollinated seed

The technique of controlled-pollination is commonly used in tree breeding to produce relatively small quantities of seed (a few grams) for genetic trial purposes. For certain *Eucalyptus* species, mass controlled-pollination is an viable means to commercial

deployment of elite full-sib families. It should be noted, however, that this deployment method is not possible with many commercial plantation species.

Nevertheless, in the case of *E. globulus* mass-pollination it is possible to multiply outstanding full-sib families for commercial plantations. This technique was first used by Stora Enso (Leal and Cotterill 1997). It has been improved by Harbard et al. (1999) and is now widely used for *E. globulus* in Chile, Australia, Portugal and elsewhere. The cost-effectiveness of mass-pollination can depend almost entirely on orchard site selection and breeding strategies designed specifically for mass-pollination. Domination of good-flowering female parents is not necessarily a bad thing in breeding strategy for mass-pollination ('cluster' breeding; discussed earlier). The good-flowering characteristics of the female help ensure that the full-sib families eventually selected will be amenable to mass-pollination (Cotterill 2001).

Clonal plantations

The other methods of capturing gain involve vegetative propagation by stem cuttings, mini-cuttings or *in vitro* micropropagation. In the past 10–15 years, the selection and cloning of *Eucalyptus* has had considerable impact on plantation productivity. In particular, vegetative propagation has facilitated the used of interspecies hybrids. Clonal forestry also offers opportunities to fast-track interim genetic gain into plantations.

In Brazil for example, clonal *Eucalyptus* plantations have operational growth rates in the range of 30–50 m^3 ha^{-1} yr^{-1}. Genetic trial growth rates of over 70 m^3 ha^{-1} yr^{-1} have been achieved.

Genetics and nursery

Perhaps the most common reason for delays in getting improved genetic material from trials to plantations is sub-optimal communication and cooperation between genetics and nursery/seed orchard personnel. It is worth discussing separately the cooperation needed for successful multiplication by cuttings versus seed.

Cuttings propagation

Cuttings propagation is often used to multiply *Eucalyptus* and *Pinus* species for commercial plantations. The major companies and organisations involved in clonal forestry of *Eucalyptus*, particu-

larly in the tropics, almost invariably have extensive clonal field trials and, in general, the more recent the trials, the more outstanding the clones. For example, genetically advanced material in clone trials established in the 1990s is almost always better than clones in earlier trials. However, the bulk of the nursery production of a particular company may still be based a handful of clones that were developed and tested in the 1980s. The 1990s clones are nowhere to be seen in the commercial nursery or, if they are there, it is in small quantities. Of course, there are also many examples of the well-managed companies using 1990s clones.

Total production and cost of cuttings are the main drivers for nursery managers. For this reason most nursery managers prefer using clones that are tried-and-tested as far as nursery performance is concerned — the 'good old clones'. It is invariably the tree breeder who must upset the *status quo* and push to get newer and better field performing clones into commercial production. In clonal forestry the delay in getting reasonable numbers of newly tested clones into plantations is often the main impediment to a fast-moving genetics program.

In the case of pine, cuttings propagation is used as a tool to mass propagated elite full-sib families for commercial deployment.

Connection with inventory

When improved material goes into plantations it is, of course, essential that the inventory group map areas of each clone or family. It is also important to use inventory measurements in the final appraisal of genetic gains. Different clones and families may require different volume functions.

Connections with plantation management

Plantation management strategy, including silviculture and weed control, has a major influence on realising genetic gains in plantations. Undoubtedly, the full genetic potential of improved germplasm will not be realised if germplasm is planted off-site and poor plantation management practices are implemented.

Connections with harvesting

In order to take commercial advantage of genetic differences in wood properties, the different clones or families must be harvested separately and delivered to the mill either individually or in batches of similar wood properties. Problems such as insufficient areas of particular clones or families in harvest compartments, or perhaps poor inventory records of genetic identity, will effectively prevent the company from using genetic differences in wood properties, even if they want to. It is not uncommon to see genetic effort go to waste because material was not planted in such a way that made possible the extraction of individual trees or batches of clones of similar wood quality.

Value Recovery

It is easy to demonstrate the adage that 'time is money'. For example, the internal rate of return (IRR) on the investment in Stora Enso's Project D95 has been estimated at 32% based on an investment over 8 years from 1987 to 1995, and estimated increased returns from the first D95 plantations to be harvested in 2005 (MacRae and Cotterill 2000). If D95 could have been shortened by, say, 2 years the IRR would have increased to 50% due to cost savings and the earlier availability of wood from plantations (Cotterill 2001).

In order to maximise economic returns, the genetics project should be designed to deliver partially improved genetic material for an intermediate gain into plantations well before the project completion date. For example, the State Forests of New South Wales 2002–08 tree improvement program is a 6-year project that will begin to deliver material of intermediate gain into plantations within a 3-year time frame.

The key components of value recovery from genetics and tree breeding include: (i) increased genetic gains; (ii) increased plantation productivity and uniformity; (iii) improved product quality and uniformity; and (iv) economic gains.

Increased genetic gains

The value recovery from genetics and tree breeding through increased genetic gains can best be described using a few examples. Intensive breeding and genetic selection of *E. globulus* families under Stora Enso's Project D95, between 1987 and 1995, has increased by up to 70% the productivity (t pulp ha^{-1} yr^{-1}) of their latest *E. globulus* plantations (MacRae and Cotterill 2000).

Stora Enso is engaged in a joint-venture company located in southern Bahia, Brazil. The plantations are all clonal and dominated by *E. grandis* 'natural

hybrids' of Rio Claro origin and 'Urograndis' (*E. grandis × E. urophylla*) of Aracruz origin. An intensive hybrid-breeding program, which integrated conventional and molecular genetic technologies, was initiated in 1998. The goals of this project include increasing by 50% the bleached kraft pulp production per hectare per year of plantations established from January 2006 onwards, compared with pre-1998 plantations. Strong interim gains have already been achieved.

An example of increased interim genetic gains from a solid wood *E. pilularis* breeding program is that initiated by State Forests of New South Wales in Australia. Growth and form assessments of 3-year-old trees in family trials have identified superior parent plus trees and 20 families with significant volume gains (up to 31%) across two sites compared with routine seedling controls.

Over the past few decades, there has been increasing recognition of the contribution that advanced genetic technologies can make in conventional breeding. The benefits of these technologies include: increasing genetic gains per generation; reducing the lead time (generation or project time) and thereby maximising gains per year; and other issues such as genetic diversity and plant variety registration. Table 1 lists new technologies and identifies the main areas in which each technology will enhance genetic improvement of *Eucalyptus*.

Gains per generation

It is evident from Table 1 that new technologies such as marker-aided crossing (via DNA fingerprinting) and gene transformation can enhance the genetic gains achieved from one generation (cycle) of genetic selection. For example, marker-aided crossing assists the geneticist in ensuring that the best possible full-sib families are produced in the control-

crossing program. Without the aid of DNA markers, it is likely that the potentially best ('widest', discussed previously) control crosses will not be made and substantial potential gain is lost.

Gene transformation represents another technology that can substantially enhance genetic gains (Table 1); in this case by adding new genes into already selected elite clones. As mentioned previously, gene transformation remains a few years away in practical application.

Advanced genetic technologies such as marker-aided selection should be quite effective in improving wood traits, which tend to be more strongly inherited than, say, growth (discussed previously in this section).

Gains per unit time

Advanced genetic technologies such as marker-aided selection and gene transformation can be effective in reducing the lead time to complete one generation (Table 1). For example, marker-aided selection may facilitate early evaluation of paper properties using DNA taken from clones or families at the seedling stage of development.

It is important to clarify that, in this paper, a genetic project is assumed to extend over one complete generation (which is invariably the case). Consequently, the 'generation time' is the 'lead time' that a genetic project will require to deliver genetic gains.

Reduced lead time

Under conventional technologies, one generation of breeding *E. globulus* may require at least 14 years to produce mass control-pollinated seedlings for plantation establishment. The integration of conventional *plus* advanced genetic technologies may require only 8 years to complete a full breeding cycle; 60% of the generation time (project lead time) under

Table 1. New gene technologies and their contribution to enhancement of conventional technology.

New gene technology	Enhancement of conventional technology		
	Genetic gain per generation	Lead time (genetic gain year^{-1})	Other (e.g. diversity and registration)
DNA fingerprinting			Yes[a]
Marker-aided crossing	Yes[a]		
DNA diversity index			Yes[a]
Marker-aided selection		Yes[b]	
Gene transformation	Yes[a]	Yes[a]	

[a] 'Yes' indicates the contributions new gene technologies can make to conventional tree breeding in increasing genetic gains per generation, reducing the lead time (generation or project time), as well as other issues such as genetic diversity and plant variety registration.
[b] Marker-aided selection integrated with conventional index selection.

conventional breeding. This reduction in generation time has a very significant impact on genetic gains per unit time and, therefore, returns on investment in genetic improvement (discussed next).

Enhanced gains per unit time

Dividing the previously mentioned gains per generation by the generation (project) time highlights the potential of new technologies to maximise genetic gains per year of improvement. For example, projections are that a 90% gain in pulp production per generation under conventional and advanced genetic technologies can be achieved in an 8-year generation. This would give an 11% gain in pulp production for each year of the genetic improvement project. This is more than double the corresponding gain per year under conventional technology only (i.e. 70% gain per generation over 14 years translates to a 5% gain increase per project year).

Increased plantation productivity and uniformity

D95 seedling families can be expected to produce 70% more pulp per hectare per year than genetically unimproved *E. globulus*. Improved form and uniformity of genetically improved plantation trees will benefit harvesting and wood costs.

Improved product quality and uniformity

Quality

Product quality traits for both paper and solid wood products are time-consuming and costly to measure and are best measured at rotation age. Nevertheless, for certain plantation species (e.g. eucalypts) measurements of these traits at half rotation correlate well with those at full rotation, facilitating earlier selection on wood and fibre properties in breeding programs.

Stora Enso Project D95 quality achievements provide a good example here. The main D95 objective of doubling pulp production came with one important 'restriction', namely that the quality of *E. globulus* pulp was to be maintained at existing levels.

Figures 1 and 2 show examples of hand sheet properties for the six *E. globulus* parents evaluated by Stora Corporate Research as part of Project D95. The parents are all involved in control-pollinations to produce full-sib seedling families for plantations establishment. It is evident from Figures 1 and 2 that all of these *E. globulus* parents are intermediate in

terms of key paper properties such as tensile index and porosity (Cotterill and MacRae 1996).
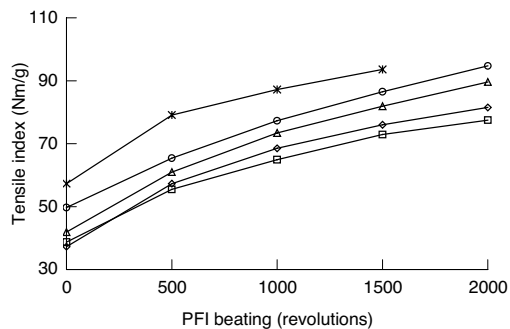
Figure 1. Means of different *E. globulus* parents for tensile index of hand sheets across increasing levels of PFI refining in the laboratory. The trees were grown on one site in Portugal and harvested at 9 years of age.
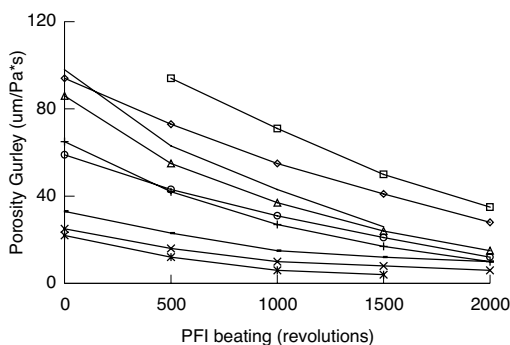
Figure 2. Means of different *E. globulus* parents for hand sheet porosity across increasing levels of PFI refining. The trees were grown on one site in Portugal and harvested at 9 years of age.

Wood uniformity

The most important aspect of any breeding program focusing on wood quality will be a substantial improvement in the uniformity and consistency of pulpwood. The consistency of any commercial forestry company's overall wood supply will be improved through improved uniformity and volume of its own, plantation-grown pulpwood.

Increased tolerance to disease and pests

Breeding for pest and disease tolerance is an important component in any breeding program, and the ben-

efits will be reaped in the long-term health and sustainability of plantation. An example of achievements in this area is the selection by State Forests of New South Wales of *Ramularia* shoot-blight-tolerant *Corymbia variegata* seed sources from a large family trial.

Economic outcomes

Forestry and forest-products companies are major investors in tree breeding and genetics worldwide and, as a result, details of economic returns are confidential. However, from the limited published data available, there is little doubt that large returns can be achieved. An example already mentioned is the internal rate of return of 32% achieved by Stora Enso investment in *E. globulus* tree breeding.

Conclusions

Conventional genetic improvement programs with fast-growing plantation trees, such as *Eucalyptus* species, have the capacity to produce large gains in commercially important traits such as wood fibre production and quality, and to develop and deploy improved softwood and hardwood planting stock within effective time frames, for sustainable, high productivity and quality plantations for specified end uses. Molecular genetic technologies offer tree breeders valuable tools that can further increase genetic gain per unit time through more efficient (more accurate) and faster selection, faster deployment of genetically improved material to plantations and a deeper understanding of the genes controlling traits such as wood properties.

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Genetic Improvement of Tropical Eucalypts in China

Bai Jiayu, Xu Jianmin and Gan Siming[1]

Abstract

About 1.54 million ha of *Eucalyptus* plantations have been set up in Guangdong, Hainan, Yunnan and Fujian provinces and in the Guangxi region. Their productivity has been about 5–10 m^3 ha^{-1} yr^{-1}, much lower than in some other countries such as Brazil where growth rates as high as 100 m^3 ha^{-1} yr^{-1} have been recorded. One reason is that superior species, provenances, families and clones of *Eucalyptus* have not been planted on a large scale. This paper briefly outlines the steps taken for introduction of new lines of *Eucalyptus* and genetic improvement in several internationally supported projects. As a result, the general productivity of plantations has increased significantly in the past 10 years to about 20–25 m^3 ha^{-1} yr^{-1}, and has reached as high as 60 m^3 ha^{-1} yr^{-1}.

Eucalypts have been grown in China for about 100 years. Systematic study of eucalypts began in the 1980s, and since then there has been much progress in selecting species, provenances and families for plantation improvement. In the early 1980s, an Australian International Development Assistance Bureau project, involving the Queensland Department of Forestry, supported eucalypt plantation research at Dongmen, Guangxi. From 1985 to 1992, the Australian Centre for International Agricultural Research provided support for a cooperative project between CSIRO Forestry and Forest Products and the Chinese Academy of Forestry (CAF), to select better-performing eucalypts for southern China. Now 63 species, 258 provenances and 572 families have been tested. From these, improved planting material with potential productivity around five times that of the formerly widely planted *E. citriodora* (now *Corymbia citriodora*) have been selected.

Four other important research projects have assisted the progress in genetic improvement of eucalypts in China. The World Bank Loan Project included 'Research and extension of cultivation technology on fast-growing and high-yielding *Eucalyptus* plantation' in the National Afforestation Project (NAP) (1991–1995) and its successor FRDPP (1996–2001). A National Key Project, 'Improved variety selection and cultivation technology on *Eucalyptus* tree species for pulpwood' (1996–2000), and a State Science Fund Project, 'Construction of genetic linkage maps of *E. urophylla* and *E. tereticornis*' (1997–2000), further assisted tree-improvement research.

In recent years, the use of interspecific hybrids has increased. Dongmen State Forest Farm, Guangxi has planted *E. camaldulensis* × *E. urophylla* because it grows rapidly on infertile soils and is wind firm. The Research Institute of Tropical Forestry (RITF) has made 1760 intraspecific and interspecific combinations, using mainly *E. urophylla, E. grandis, E. tereticornis* (including *E.* 12ABL) and *E. camaldulensis.*

As a result of all these activities, genetic improvement assisted by vegetative propagation has helped

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[1] Research Institute of Tropical Forestry, Chinese Academy of Forestry, Longdong, Guangzhou 510520, China. Email: <gzfsrd@pub.guangzhou.gd.cn>.

increase the general productivity of plantations in the past 10 years to about 20–25 m^3 ha^{-1} yr^{-1}. Productivities as high as 60 m^3 ha^{-1} yr^{-1} have been reached.

This paper briefly outlines the steps taken to introduce of new lines of *Eucalyptus*, and subsequent genetic improvement to improve plantation productivity. More detailed accounts of particular aspects of the tree-improvement program can be found in Bai Jiayu (1988, 1993, 1994), Chen Binglin and Yang Juntao (1988), Gong Mingqing (1990), Li Danqing (1990), Li Haijia (1990), Eldridge (1991), Hong Weiluo (1991), Cao Yuehua (1992), Li Chuanchao (1992), Hong Jusheng (1993) and Xu Jianmin et al. (2001).

Objectives

The overall objectives of the tree-improvement programs were to identify species and/or provenances worth planting and to advance breeding studies through:

1. selection of adaptable and productive new species to replace inferior species currently planted
2. identification of the best provenances of successful species
3. progeny testing and selection to supply good reproductive material (seed or cuttings) for establishing seed orchards
4. hybridisation and clonal reproduction and selection to increase productivity of eucalypt plantations
5. establishing potential species breeding populations and developing of effective technology for seedling seed orchards (SSOs) and clonal seed orchards (CSOs) to produce improved high-quality seed to meet the demand of the NAP and FRDPP projects in the development of large-scale plantations
6. construction of genetic linkage maps of *E. urophylla* and *E. tereticornis* by using RAPD molecular markers, and study of quantitative traits loci (QTLs) associations.

Trees Species/Provenances Selection

Scientists from the CSIRO Australian Tree Seed Centre, aided by climatic analyses of different localities, helped Chinese scientists choose for testing 59 eucalypt species, including 572 families in 246 provenances. Most trials were in the form of complete or incomplete randomised block designs.

Based on the initial trial results and subsequent hybrid breeding activities, 18 superior species, including 63 provenance/families and clones, have been confirmed and deployed in large-scale eucalypt plantations in southern China (Table 1).

Progeny Trials

1. *Eucalyptus tereticornis* – 100 families from 14 provenances tested at Yangxi county, Guangdong

After 7 years of testing, the best provenances were 13659, 16547,16547,16558 and 13544 from Queensland, and 13398 and 16547 from Papua New Guinea. Poor provenances were from New South Wales. The 22 best families were selected. Family no. 50 had the highest productivity, with a mean annual increment (MAI) of 28.8 m^3 ha^{-1}. Highest basic wood density at age 6 years was 548 kg m^{-3} in family no. 21. Fibre properties of 11 superior families are shown in Table 2.

2. *Eucalyptus. urophylla* – 196 families from 17 provenances tested at Yangxi county, Guangdong

After 7 years, the best provenances were 17564, 17565, 17566 and 17567 from Mt Mandiri, Mt Lewotobi and Mt Egon, Flores Island, Indonesia. Poor provenances were from Jawagahar (17574) and Andalan (17573). The MAI of the best 15 families was over 20 m^3 ha^{-1}. The best family was no. 67 with a MAI of 29.1 m^3 ha^{-1}. Family no. 56 had the highest basic wood density, 537 kg m^{-3}, at age 6 years. Fibre properties of 10 superior families are shown in Table 3.

Cross-Breeding

The Research Institute of Tropical Forestry (RITF) has made 1760 intraspecific and interspecific combinations using mainly *E. urophylla, E. grandis, E. tereticornis* (including *E.* 12ABL) and *E. camaldulensis*. RITF has established 270 hybrid progenies in 25 experiments in Guangdong, Hainan, Jiangxi and Fujian provinces, and MAIs greater than 30 m^3 ha^{-1} have been recorded. Fifty-one hybrid progenies (including TH9113, TH9117, TH9224, TH9211...U 5C, U 5T) have been selected. The highest productivities of hybrid clones were, respectively, LH4, LH5 and LH6 selected from TH9211 hybrid, with MAIs of 47.0 m^3 ha^{-1}, 46.0 m^3 ha^{-1} and 47.0 m^3 ha^{-1} at 3 years of age.

Table 1. Eucalypts recommended for large-scale plantations in different regions of south China with examples of their growth potential and wind resistance.

Region	Species / Serial no. / Source	Age (yr)	Height (m)	Dbh[a] (cm)	Volume (m³ ha⁻¹)	Wind resistance
East Hainan, (frequent typhoons)	*E. urophylla* 12895, Mt Mandiri, Indonesia (Indo.)	5	13.82	12.54	128.34	good
	E. camaldulensis 14918, Laura, Queensland (Qld)	5	12.38	8.69	77.71	
	E. tereticornis 13418, Sirainumu, Sogeri, Papua New Guinea (PNG)	5	11.48	9.05	74.04	
	E. tereticornis 13443 Kennedy River, Qld	5	12.66	8.24	69.26	
Northwest Hainan	*E. urophylla* 12895, Mt Mandiri, Indo.	4	11.42	10.66	129.26	
	E. tereticornis 13660, Helenvale, Qld	4	10.44	9.10	100.51	
	E. urophylla × *E. grandis* DH32-29, Dongmen, Guangxi	3	21.10	13.6	117.59	poor
	E. urophylla × *E. grandis* DH30-1, Dongmen, Guangxi	1	9.40	7.88	40.95	good
	E. urophylla U6, Zhanjiang	1.5			27.77	good
	E. urophylla × *E. tereticornis* TH9224, Chinese Academy of Forestry, Research Institute of Tropical Forestry (CAF, RITF)	1.0	8.32	7.20	31.20	good
Southwest Hainan (semi-drought area)	*E. tereticornis* 13443, Kennedy River, Qld	5	10.60	8.76	80.47	
	E. camaldulensis 14106 Gilbert River, Qld	5	10.34	8.77	77.98	
	E. camaldulensis 15062, Katherine, Qld	5	10.02	8.32	72.10	
	E. camaldulensis 14847, Petford, Qld	5	10.54	8.42	71.35	
	E. camaldulensis 14918, Laura, Qld	5	10.27	8.60	70.66	
	E. urophylla U6, Zhanjiang	2.5			68.97	good
	12ABL B, Hainan	9			321.67	good
West Guangdong (hilly areas)	*E. urophylla* × *E. grandis*, Brazil	2	9.65	8.72	104.02	medium
	E. urophylla 12362, Dili, East Timor	2	9.05	7.73	72.09	medium
	E. urophylla 15982, Mt Wuko, Indo.	2	8.83	7.84	71.95	medium
	E. urophylla 12895, Mt Mandiri, Indo.	2	8.70	7.78	66.65	medium
	E. urophylla 12898, Mt Boleng, Indo.	2	8.25	7.52	59.88	medium
	E. 12ABL W5, Zhanjiang	3	11.51	8.27	71.657	good
	E. urophylla U6, Zhanjiang	3			97.62	good
	E. urophylla × *E. grandis* DH32-29, Dongmen	3	14.31	9.63	104.11	good
	E. urophylla × *E. tereticornis.* TH9211-LH4, CAF, RITF/Leizhou F.B.	3	12.69	11.87	141.00	good
	E. urophylla × *E. tereticornis.* TH9211-LH5, CAF, RITF/Leizhou Forest Bureau (F.B.)	3	12.59	11.04	138.00	good
	E. urophylla × *E. tereticornis* TH9211-LH6, CAF, RITF/Leizhou F.B.	3	13.77	12.73	141.00	good
	E. urophylla × *E. camaldulensis* TH9117-LH28, CAF, RITF/Leizhou F.B	3	11.64	11.72	100.00	good
	E. grandis × *E urophylla* CH1, Leizhou F.B.	3			126.67	medium
	E. urophylla F₂ SSO CAF, RITF/ Leizhou F.B.	2.5	13.0	10.56	100.46	medium

Table 1. (cont'd) Eucalypts recommended for large-scale plantations in different regions of south China with examples of their growth potential and wind resistance.

Region	Species / Serial no. / Source	Age (yr)	Height (m)	Dbh[a] (cm)	Volume (m³ ha⁻¹)	Wind resistance
Central Guangdong (low hills and with little wind)	*E. urophylla* 14532 Mt Lewotobi, Indo.	1.2	5.01	4.04		
	E. grandis × *E urophylla* 15356, Brazil	1.2	5.03	4.04		
	E. camaldulensis B21, Petford, Qld	1.2	5.44	3.47		
	E. tereticornis 15825, Laura River, Qld	1.2	5.00	3.32		
	E. camaldulensis 14918, Laura, Qld	2	6.10	4.33		
	E. tereticornis 13443, Kennedy River, Qld	2	5.96	4.19		
	E. urophylla 14534, Mt Egon, Indo.	5	13.49	10.61	110.11	
	E. cloeziana B47, Qld	5	10.81	8.21	53.93	
	E. urophylla U9, CAF, RITF	4.5	16.23	15.34	202.83	medium
	E. urophylla U11, CAF, RITF	4.5	15.39	14.06	166.16	medium
	E. urophylla F$_{1.5}$ SSO, CAF, RITF	3.0	14.0	12.20	103.15	medium
Eastern Guangdong (hill region) and South Fujian	*E. camaldulensis* 12897, Irvinebank, Qld	1.3	5.21	4.29		good
	E. camaldulensis 13801, Katherine, Northern Territory (NT)	1.3	5.09	4.35		good
	E. camaldulensis 14338, Petford area, Qld	1.3	5.07	4.21		good
	E. tereticornis 13443, Kennedy River, Qld	1.3	5.20	4.04		good
	E. tereticornis 13544, 40 km N of Gladstone, Qld	1.3	4.45	3.83		good
	E. urophylla 14532, Mt Lewotobi, Indo.	4	10.2	8.89	87.45	good
	E. grandis 18698		19.5	18.1	316.15	
	E. grandis 18702		16.7	15.6	207.88	
	E. urophylla U23, CAF, RITF	3.5	15.08	14.71	174.31	good
	E. urophylla U53, CAF, RITF	3.5	13.79	13.32	141.70	good
	E. urophylla F$_{1.5}$ SSO, CAF, RITF	1.5	9.50	7.60	27.16	medium
South Jiangxi (north tropical region)	*E. urophylla* 12362 S Dili, East Timor	2	7.65	6.24	52.76	poor
	E. tereticornis 13443, Kennedy River, Qld	2	8.29	5.93	49.08	medium
	E. camaldulensis 14106. Gilbert River, Qld	2	7.90	5.35	37.91	medium
	E. dunnii 15956, Dead Horse Track, New South Wales (NSW)	4	11.7	10.3		good
	E. dunnii 16894, Teviot Falls State Forest, Qld	4	15.0	10.5		good
	E. grandis 18146	2.5	7.36	7.43		good
Yunnan (Chuxiong and the southwest of Baoshan)	*E. smithii* 16373	6	12.6	11.9	93.23	
	E. globulus ssp. *maidenii* 17769	6	13.5	11.1	83.17	
	E. nitens 16619	6	10.3	9.4	50.05	
	E. globulus ssp. *bicostata* 17777	6	10.8	9.6	54.74	

[a] Diameter at breast height

Table 2. Wood fibre properties of superior families samples of *E. tereticornis* at age 6 years.

Family no.	Position of wood sample	Fibre length (FL)	Fibre width (FW) (μm)	Double cell wall thickness (D) (μm)	Diameter of cavity (d) (μm)	L/W	2W/I	d/diam. of cell
51	Sapwood	1017	17.70	5.58	12.12	57	0.40	0.68
	Heartwood	993	16.55	5.33	11.22	60	0.48	0.68
50	Sapwood	1033	14.93	5.19	9.74	69	0.57	0.61
	Heartwood	948	14.72	4.94	9.78	64	0.51	0.66
63	Sapwood	1077	13.38	4.43	8.95	80	0.49	0.67
	Heartwood	921	14.56	4.86	9.70	63	0.50	0.67
47	Sapwood	1089	13.00	4.25	8.75	84	0.49	0.67
	Heartwood	977	13.75	5.24	8.51	71	0.61	0.62
98	Sapwood	1033	14.08	4.30	9.78	73	0.44	0.69
	Heartwood	948	15.72	5.18	10.54	60	0.49	0.67
46	Sapwood	1038	12.75	4.63	8.12	81	0.57	0.64
	Heartwood	921	13.60	4.96	8.64	67	0.57	0.64
17	Sapwood	1057	13.48	5.20	8.28	78	0.63	0.61
	Heartwood	914	13.40	4.21	9.19	68	0.46	0.69
21	Sapwood	955	12.80	4.75	8.05	75	0.59	0.63
	Heartwood	897	12.36	4.27	8.09	73	0.53	0.65
60	Sapwood	1062	11.83	5.03	6.80	89	0.57	0.73
	Heartwood	907	11.92	4.00	7.92	76	0.51	0.66
96	Sapwood	1105	13.08	4.12	8.96	84	0.46	0.69
	Heartwood	972	13.66	4.79	8.87	71	0.54	0.65
88	Sapwood	1018	13.00	4.11	8.89	78	0.46	0.68
	Heartwood	1022	12.74	5.20	8.54	80	0.60	0.67

There are six nurseries with an annual production of more than 10 million cuttings of new eucalypt hybrid clones in south China.

Eucalyptus Breeding Base

Six breeding bases with seven *Eucalyptus* species and with a total area of 240 ha have been established in Xinhui, Yangxi, Leizhou Forest Bureau, Dongmen Forest Farm and Danzhou Forest Farm (Hainan). In Xinhui city (Guangdong), there is a second generation *E. urophylla* SSO, a *E. urophylla* nuclear-breeding population, and the main *E. grandis* breeding population.

Up to 2000, 60 ha of SSOs and CSOs of *E. urophylla, E. grandis, E. tereticornis* and *E. globulus* had been established, and their annual seed yield of more than 200 kg represents 20–30% of seed requirements each year.

High-yield technologies to ensure high-quality seed production have been applied in the *E. urophylla* SSO. Thinning was the main measure, but other treatments included fertilisation, pruning and paclobutrazol (PP333) application.

Thinning increased seed productivity by 60% compared with the unthinned control. Application of fertiliser ($N_{100}P_{150}K_{50}$) to thinned stands increased seed productivity by 132% over the control (unthinned, unfertilised). A further increase in seed yield up to 202% over the control occurred where paclobutrazol was applied to thinned and fertilised stands.

Table 3. Wood fibre properties of superior families samples of *E. urophylla* at age 6 years.

Family no.	Position of wood sample	Fibre length (FL)	Fibre width (FW) (μm)	Double cell wall thickness (D) (μm)	Diameter of cavity (d) (μm)	L/W	2W/I	d/diam. of cell
2	Sapwood	977	18.00	4.32	13.68	54	0.32	0.76
	Heartwood	1149	15.48	4.60	10.88	74	0.42	0.72
56	Sapwood	1016	19.44	5.12	14.32	52	0.36	0.74
	Heartwood	1122	16.38	5.04	11.34	68	0.44	0.69
68	Sapwood	1017	19.44	4.45	14.94	52	0.30	0.77
	Heartwood	1237	16.38	4.68	11.70	75	0.40	0.71
101	Sapwood	960	17.88	5.26	12.61	54	0.42	0.71
	Heartwood	1122	17.10	5.22	11.88	66	0.44	0.69
149	Sapwood	995	16.56	4.50	12.06	66	0.37	0.73
	Heartwood	1107	17.64	5.22	12.42	63	0.42	0.70
194	Sapwood	1042	16.84	4.86	11.98	62	0.47	0.68
	Heartwood	1130	16.20	5.12	11.08	70	0.41	0.71
196	Sapwood	964	17.10	5.22	11.88	56	0.47	0.68
	Heartwood	1032	17.28	5.40	11.88	60	0.45	0.69
199	Sapwood	984	14.40	5.22	9.18	68	0.56	0.64
	Heartwood	1068	17.28	4.84	12.44	62	0.39	0.72
200	Sapwood	944	18.00	5.58	12.42	52	0.45	0.69
	Heartwood	1019	14.40	4.50	9.90	71	0.45	0.69
208	Sapwood	925	18.36	6.12	12.24	50	0.50	0.67
	Heartwood	1060	15.30	4.88	10.62	69	0.46	0.69

Biotechnology

From 82 progenies of a single *E. urophylla* × *E. tereticornis* F1 hybrid, two medium-density genetic linkage maps for *E. urophylla* and *E. tereticornis* were constructed using RAPD molecular markers. The RAPD linkage map of *E. urophylla* comprised 16 linkage groups with 129 framework markers and 64 accessory markers, a total map distance 1741.3 cM, 91.0% coverage of the genome, and an average between-marker distance of 13.36± 8.97 cM. In *E. urophylla,* locations were determined of three QTLs controlling seedling height and one QTL of seedling branch number.

The RAPD linkage map of *E. tereticornis* also comprised 16 linkage groups, with 96 framework markers and 64 accessory markers, a total map distance 992.1 cM, 91.0% coverage of the genome, and an average between-marker distance of 10.4 ± 8.55 cM. In *E. tereticornis,* locations were determined of four QTLs controlling seedling height.

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Improvement of Eucalypts for Reforestation in Vietnam

Le Dinh Kha, Ha Huy Thinh and Nguyen Viet Cuong[1]

Abstract

Eucalypts are one of the most important groups of plantation species for the supply of industrial raw materials in Vietnam. The estimated area of eucalypt plantations at the end of 2001 was 348,000 ha. Seedling seed orchard (SSO) and seed production areas (SPA) have been established for priority species including *Eucalyptus urophylla, E. camaldulensis, E. tereticornis* and *E. pellita* at a number of locations. The most promising clones from the SSOs and SPAs have also been selected, vegetatively propagated and tested in the field. A molecular marker study to evaluate genetic diversity of *E. urophylla* indicated that fast-growing provenances have higher out-crossing rates. Integration of plus tree selection with hybridisation and field testing has given very positive results. Interspecific hybrids such as the combinations *E. urophylla* × *E. camaldulensis, E. camaldulensis* × *E. urophylla, E. urophylla* × *E. exserta, E. exserta* × *E. urophylla* have outperformed their parental species in terms of volume growth by 100–300%. Some of these hybrids are now being tested in large-scale field trials in different ecological zones of Vietnam. Results of field trials show growth rates of some locally devµeloped hybrid clones were significantly higher than those of imported clones, making them very promising for reforestation programs. Preliminary results of studies on pulp properties indicate pulp potential and paper quality of hybrid clones are similar or slightly better than those of their parents.

Eucalypts are one of the most important groups of plantation species for the supply of industrial raw materials in Vietnam. Their wood is used for pulp and paper, particle board, construction and furniture. Eucalypts are widely planted along canal banks in the Mekong Delta, along dams, rice paddy boundaries and roadsides, and as wind breaks in the Red River Delta. They are also widely planted in many places throughout the country as scattered trees. Moreover, eucalypts provide much of the fuelwood for most of rural areas of Vietnam. Together with acacias, eucalypts have significantly contributed to the improvement of income and living standards of rural people in lowland areas, particularly in central and central-northern Vietnam. The area of eucalypt plantations Vietnam at the end of 2001 was estimated as 348,000 ha (MARD 2002). This figure does not include the row plantings and scattered trees referred to above.

Eucalyptus camaldulensis and *E. robusta* were the first species introduced into Vietnam by the French in 1930. Eighteen other species were then introduced for trials in Da Lat (Central Highlands) in 1950, and among these, *E. microcorys* proved to be very promising. In 1960, *E. exserta* was introduced and widely planted in northern Vietnam, and it was considered an important species for re-greening bare land and denuded hills. The area planted to this species during the 1960s was 40,000–50,000 ha.

From 1975 onwards, species and provenance trials for a number of eucalypt species were established in different ecological zones of Vietnam. Based on these trials, the most promising species and provenances have been identified, and these are now used as the main planting materials for plantation establishment.

[1] Research Centre for Forest Tree Improvement Forest Science Institute of Vietnam, Hanoi, Vietnam.

With funding support from ACIAR and the Australian Agency for International Development (AusAID), and the cooperation of CSIRO scientists, seedling seed orchards (SSOs) and seed production areas (SPAs) have been established for priority species including *E. urophylla, E. camaldulensis, E. tereticornis* and *E. pellita* at a number of locations. The most promising clones from the SSOs and SPAs have also been selected, vegetatively propagated and tested in the field.

In the early 1990s, within the framework of technological cooperation with China, some highly productive eucalypt clones were imported for planting. At the same time, locally selected clones with high productivity and adaptability have been used in reforestation programs.

In recent years, very positive results have been gained by integration of plus tree selection with hybridisation and field testing. Interspecific hybrids created recently by the Research Centre for Forest Tree Improvement (RCFTI) have outperformed their parental species, in terms of volume growth, by 100–300%. Some of these hybrids have been recognised by the Ministry of Agriculture and Rural Development (MARD) as technologically advanced germplasm, and they are now being tested in large-scale field trials in different ecological zones. Results of field trials show that growth rates of some of the locally developed hybrid clones are significantly higher than those of the imported clones, making them very promising for reforestation programs.

Preliminary results of studies on pulp properties indicate that the pulp potential and paper quality of hybrid clones is similar to, or slightly better than, those of their parental species.

Species and Provenance Testing

Species/provenance testing is a means to exploit effectively the existing natural variation for tree-improvement programs. Provenance trials can be set up by using bulk provenance seedlots, or provenance–progeny trials can be integrated with SSO establishment.

Provenance trials using bulk seedlots

In 1930, *E. camaldulensis* and *E. robusta* were introduced to Vietnam by the French. From 1950 to 1958, 18 species were introduced and tested at Lang Hanh (Lat. 11°45'N; Long. 108°23'E; altitude 900 m) in Lam Dong province, Among those species tested were *E. botryoides*, *E. camaldulensis*, *E. cinerea*, *Corymbia citriodora*, *E. globulus*, *E. longifolia*, *E. maidenii*, *E. microcorys*, *E. punctata*, *E. resinifera*, *E. robusta* and *E. saligna*. Mean annual increment of these species averaged 1.1–1.4 m for height and 1.4–3.8 cm for diameter (Nguyen Van Tai and Nguyen Van Thon 1971). The fastest-growing species at Lang Hanh were *E. globulus*, *E. microcorys* and *E. saligna,* which had MAIs of 2.4–3.8 cm for diameter. Data collected by RCFTI in 1989, from trials at Lang Hanh and Mang Linh (alt. 1500 m), showed that *E. microcorys* and *E. saligna* were the fastest-growing species (Table 1). The 50-year-old trees of these species still exist and form a very beautiful plantation. Regrettably, some very large trees have recently been cut down.

After 1975, and in particular from 1980 onwards, several species/provenance trials were set up at different ecological zones of Vietnam. The 12 most widely tested species were *E. camaldulensis, E. tereticornis, E. urophylla, E. cloeziana, E. pellita, E. grandis, E. brassiana, E. exserta, E. microtheca, E. deglupta, C. citriodora* and *C. torelliana.*

Table 1. Growth of *Eucalyptus microcorys, E. saligna* and *E. robusta* at Lang Hanh and Mang Linh (1989 data).

Species	Planted	Lang Hanh			Mang Linh		
		Height (m)	Diameter (cm)	Volume (m^3)	Height (m)	Diameter (cm)	Volume (m^3)
E. microcorys	1950	31.7	35.5	1.636	27.5	42.0	1.905
E. saligna	1950	29.7	40.4	1.904	25.8	43.5	1.917
E. robusta	1951	18.3	30.0	0.621	22.5	30.2	0.806

In the first trials, due to the lack of a comprehensive set of seedlots, poor trial protection and monitoring, some premature conclusions were drawn. Consequently, serious problems have occurred. An example was the case of the Petford provenance of *E. camaldulensis*, which was identified as an outstanding performer in the early 1990s (FSIV 1990; Hoang Chuong 1992). Results of species/provenance trials at later ages showed that the growth rate of this provenance was only mid-ranked and it was seriously damaged by dieback diseases, particularly in southeastern Vietnam and Thua Thien, Hue (Sharma 1994; Pham Quang Thu et al. 1999). The most promising provenances of *E. camaldulensis* in Vietnam are Laura River, Kennedy River and Morehead River (Queensland) and Katherine (Northern Territory) (Le Dinh Kha and Doan Thi Bich 1991; Le Dinh Kha et al. 2001), while the best provenance of *E. tereticornis* tested during the 1990s was Sirinumu Sogeri (Papua New Guinea) (Hoang Chuong 1996).

The species/provenance trial at Dong Ha (Lat. 16°50'N, Long. 107°05'E, alt. 50 m) could be considered as a typical trial for testing adaptability and growth rate of some eucalypts species for the lowland of northern Central Vietnam (Table 2).

Data in Table 2 show that, of the species and provenances tested, the best for this region are *E. urophylla* from Lembata (Indonesia); *E. cloeziana* Queensland provenances from Herberton, Helenvale, Woondum and Cardwell; and *E. pellita* Queensland provenances from Kuranda and Helenvale. Provenances of *E. camaldulensis, E. tereticornis* and *E. grandis* were slower growing. While *E. grandis* is well-adapted and fast-growing in highland areas (over 1200 m), *E. camaldulensis* and *E. tereticornis* were poorly represented in this trial, with some of the best-performing provenances of these species not included. However, it should be noted that these two species are the main planting species for southern provinces from Quang Tri southwards. *E. urophylla* and *E. pellita* not only grow rapidly in Quang Tri but also in northern and southeastern provinces of Vietnam and are the most promising two species for the lowland areas of Vietnam.

A fairly representative set of 23 provenances of 8 eucalypt species was tested at Lang Hanh (alt. 900 m) and Mang Linh (alt. 1500 m) in the highlands of Da Lat in 1992. At 18 months, the fastest-growing provenance at Mang Linh was *E. urophylla*, Mt Egon, Flores, Indonesia (23081) with a volume index Iv = $D^2H = 3.94$. It was followed by an *E. saligna,* Da Lat landrace (Iv = 3.18), Blackdown, Queensland (Qld),

(Iv = 2.34)*;* and *E. grandis* Paluma, Qld (Iv = 2.45). Slower-growing provenances were *E. camaldulensis,* Emu Creek, Petford, Qld, and *E. tereticornis,* Mt Garnet, Qld, with volume index values of 1.10 and 0.68, respectively.

At age 4 years in the trial at Lang Hanh, the fastest-growing provenance was *E. grandis,* Paluma, Qld (Iv = 172.18). It was followed by *E. pellita* from Helenvale, Qld, Kiriwo, PNG and Bloomfield Qld (Iv = 119.27–150.26); *E. saligna,* Blackdown, Qld (Iv = 134.48) and *E. urophylla*, Mt Egon, Indonesia (14531) (Iv = 120.47). Slow-growing provenances were *E. camaldulensis*, Kennedy River, Qld (Iv = 72.74) and Katherine, NT (Iv = 58.0).

Data collected in 2003 for the trial established in 1992 at Lang Hanh showed that:

E. microcorys (Da Lat land race):H = 22.5 m, dbh = 21.4 cm, V = 0.405 m³

E. saligna (Da Lat land race):H = 25.1 m, dbh = 27.7 cm, V = 0.756 m³

In a provenance trial of *E. urophylla* in central-northern Vietnam (alt. 100–200 m) the fastest growing provenance was Ulubahu (alt. 150 m, Wetar Island), followed by Alor (alt. 800–1200 m). For trials where these provenances were not included, the most promising provenances were from Lewotobi, Flores and Mt Egon, Flores (Nguyen Duong Tai 1994). In Côte d'Ivoire, the most promising provenances of *E. urophylla* were from low elevations in Indonesia (Wencelius 1983). *Eucalyptus urophylla* was the fastest-growing species in a species/provenance trial at Mang Giang in the Central Highlands of Vietnam (Lat. 13°59'N, alt. 900 m).

It can be concluded that *E. urophylla* and *E. pellita* are not only valuable for planting in the lowlands but also for higher elevations in the northern part of the Central Highlands. The land races of *E. microcorys* and *E. saligna* at Da Lat are also promising for planting in the Da Lat area.

Provenance trial integrated with SSO establishment

Seedling seed orchards of *E. camaldulensis, E. pellita, E. tereticornis* and *E. urophylla* have been set up in different locations. These plantings were established initially as provenance–progeny trials, and are assessed and selectively thinned as they develop. They are very important not only to supply seed but also for selecting the most promising provenances and plus trees for use in future tree-improvement programs.

Table 2. Growth of *Eucalyptus* species and provenances tested at Dong Ha (Quang Tri province) (1/1991–7/1999).

Seedlot	Species/provenance		Diameter$_{1.3}$ (cm)		Height (m)		Volume (dm³)	
			$\bar{x}$	v (%)	$\bar{x}$	v (%)	$\bar{x}$	v (%)
23645	*E. urophylla*	Mt Lembata Indo.	11.4	19.3	13.2	15.9	154.4	5.7
23081		Mt Egon Indo.	9.3	21.8	10.7	9.1	84.0	9.1
23042		Mt Lewotobi Indo.	9.0	23.2	10.5	18.3	82.8	9.8
		Mean	9.9	21.4	11.5	14.4	107.1	8.19
14236	*E. cloeziana*	Herberton Qld	10.5	20.1	12.7	17.9	136.3	6.5
12602		Helenvale Qld	10.3	15.2	11.6	13.3	119.2	7.3
17008		Woondum Qld	10.3	23.2	11.6	14.3	108.2	7.8
14422		Cardwell Qld	10.3	20.5	11.3	20.4	101.9	7.6
12205		Maitland Qld	10.1	17.7	11.0	15.2	96.8	7.8
12202		Paluma Qld	10.0	17.2	11.0	11.6	96.0	8.1
13543		Monto Qld	9.6	21.9	10.9	15.3	90.7	8.8
12207		Bakerville Qld	9.6	20.6	10.8	10.6	89.1	8.7
14427		Blackdown Qld	9.5	17.7	10.7	9.0	88.1	8.7
		Mean	10.0	19.3	11.3	14.2	102.9	7.93
15255	*E. pellita*	Kuranda Qld	10.2	18.6	11.3	12.6	100.3	7.9
14211		Helenvale Qld	10.2	16.8	11.1	14.9	100.3	8.1
16122		Kiriwo PNG	10.1	20.6	11.0	17.4	97.8	8.2
13998		Coen Qld	9.7	17.6	10.9	12.6	95.5	7.8
16120		Keru PNG	8.9	25.2	10.2	17.0	77.5	10.3
13826		Bloomfield Qld	8.4	22.1	9.8	17.2	66.1	11.5
		Mean	10.1	18.6	11.1	14.3	99.4	8.01
13661	*E. tereticornis*	Mt Molloy Qld	8.9	20.1	10.2	17.6	73.7	11.1
13660		Helenvale Qld	8.8	21.4	10.2	18.6	72.1	10.7
13666		Mt Garnet Qld	8.4	19.7	10.0	17.7	69.7	11.1
		Mean	8.7	20.4	10.1	18.0	71.8	10.98
13289	*E. grandis*	Mt Lewis Qld	8.8	18.5	10.1	9.7	71.9	9.9
16583		Atherton Qld	8.0	22.7	9.1	16.8	58.2	12.6
16723		Paluma Qld	7.9	23.1	8.8	25.6	54.3	13.3
14838		Cardwell Qld	7.5	23.5	8.7	21.2	47.2	14.4
		Mean	8.1	21.9	9.2	18.3	57.9	12.6
16720	*E. camaldulensis*	Petford Qld	8.2	21.9	9.5	17.0	64.8	11.5
13695		Normanton Qld	8.0	22.9	9.1	17.5	56.7	12.9
		Nghia Binh Vietnam	7.8	27.2	8.7	16.5	53.5	14.4
15049		Bullock Creek Qld	7.2	22.2	8.6	18.3	45.4	15.7
16553		Wrotham Qld	6.4	26.1	7.6	15.9	30.3	21.5
12968		Burdekin River Qld	6.2	21.8	7.4	20.2	27.2	22.1
15325		Camooweal Qld	6.1	23.1	7.4	17.0	25.5	22.5
15323		Julia Creek Qld	5.9	18.2	7.2	15.9	22.3	23.7
13817		Leichhardt River Qld	5.5	22.3	6.6	16.8	18.3	29.2
		Mean	6.8	22.9	8.0	17.2	38.2	19.3
			Fpr < 0.001		Fpr < 0.001		Fpr < 0.001	
			S.e.d = 0.933		S.e.d = 1.153		S.e.d = 23.42	

Two SSOs of *E. urophylla* were established in 1996–1997 at Van Xuan, Phu Tho province (Lat. 21°30'N) and at Cam Qui in Ba Vi district, Ha Tay province (20°20'N). Data collected in 2000 indicated: (i) at Cam Qui, where the site is quite poor and the soil is very shallow and gravelly, the most promising provenances are Lewotobi, Flores and Waikui, Alor; provenances from Pantar, Wetar, and elsewhere in Flores grew more slowly; (ii) at Van Xuan, where the site is better, with soil depth exceeding 50 cm, the most promising provenance was Waikui, Alor, followed by Uhak, Wetar. Lewotobi and Mt Egon provenances from Flores grew more slowly. In general, provenances Waikui, Baubillatung and Piritumas are promising at both sites. Ranking of Lewotobi and other provenances depends on site conditions.

Eucalyptus camaldulensis provenance testing integrated within an SSO was conducted at Chon Thanh, Binh Phuoc province of southeastern Vietnam, using 155 families of 7 promising provenances. Data collected in December 1999 indicated that the most promising provenances there were Laura River (Qld), Kennedy River (Qld) and Morehead River (Qld). These were less-affected by dieback disease. Petford provenance was the poorest performer in this SSO (Nguyen Tran Nguyen 1999). This result should be compared with the Dong Ha trial (Table 2), where Laura, Kennedy and Morehead River provenances were not included and Petford provenance was the best of the *E. camaldulensis* provenances tested.

Plus tree selection and clonal testing

Plus tree selection and clonal testing were conducted by RCFTI, and FRC at Phu Ninh. In addition, some highly productive eucalypt clones were imported from China by organisations such as FRC and the Forest Tree Seed Enterprise at Ho Chi Minh City (Central Seed Company).

Table 3. Growth of some fast-growing families in *Eucalyptus urophylla* seedling seed orchards (SSOs) at Van Xuan and Cam Qui.

Van Xuan SSO (11/1996–7/2000)					Cam Qui SSO (6/1997–1/2000)				
Provenance	Family no.	Diameter$_{1.3}$ (cm)	Height (m)	Volume (dm^3)	Provenance	Family no.	Diameter$_{1.3}$ (cm)	Height (m)	Volume (dm^3)
SSO mean value		8.5	8.8	30.7	SSO mean value		8.5	8.9	27.9
Uhak	126	12.0	11.4	72.7	Lewotobi	29	10.2	10.2	47.4
(Wetar)	122	11.5	10.9	67.1	(Flores)	56	10.1	10.2	44.2
	124	10.4	10.5	54.1		48	9.9	11.2	44.0
	137	10.2	10.9	52.5		35	9.7	10.0	43.3
	131	10.6	10.5	52.2		27	9.6	11.2	42.7
	138	10.0	10.8	50.7		53	9.6	10.7	41.8
	136	10.5	10.1	50.7		26	9.6	10.2	41.7
						38	10.0	9.9	40.3
						32	9.5	9.9	39.3
Waikui	139	10.6	11.9	58.9	Egon	92	9.7	9.6	37.9
(Alor)	141	9.9	10.3	48.1	(Flores)	77	9.9	9.5	36.9
						75	9.2	9.3	35.9
Piritumas	148	10.5	10.2	52.3	Mandiri	15	9.4	10.0	36.9
(Alor)	147	9.8	10.0	42.1	(Flores)				
Baubillatung	154	9.5	8.7	44.3	Piritumas	159	9.6	9.1	36.5
(W. Pantar)	165	9.8	9.4	42.4					
					Baubillatung	153	9.5	9.5	35.8
Lewotobi	23	10.4	9.9	46.4					

Selecting plus trees in SSOs

From SSOs of *E. urophylla,* some fast-growing families and plus trees have been selected in Van Xuan, Phu Tho province and Cam Qui, Ha Tay province (Table 3), and vegetatively propagated for clonal testing.

A study using DNA markers to assess genetic diversity of the *E. urophylla* SSO at Cam Qui showed out-crossing rates of the fast-growing provenances and families higher than those of the slower-growing provenances (Tran Ho Quang 2001).

From the SSO of *E. camaldulensis* at Chon Thanh, some fast-growing individual trees with volume growth 2.5–3.5 times the average value of the best families and provenances, and free of dieback disease, have been selected and propagated by cuttings for clonal testing. At age 18 months, some fast-growing and disease-free clones have been selected in the clonal trial at Binh Thuan. Volume index (D^2H) of the three best clones in this trial was in the range 73.2–85.4, while the volume index of average growing clones was 30.0–30.9 and that of the poorest clones only 3.5–7.0 (Table 4; Ha Huy Thinh 2003).

Plus tree selection in production forests

In 1993, a clonal trial for 38 clones of *E. camaldulensis* selected from production forests was established at Cam Qui. Plus trees were selected from 4-year-old plantations. Diameter and tree height of all selected plus trees exceeded the average value of the plantation by more than 1.5 standard deviations. A randomised complete block design with 3 replicates and 10 trees per plot was used and spacing was 3×2 m.

The planting site had thin, infertile soil developed from laterite. In addition to the 38 selected clones, there were four control treatments: a natural hybrid between *E. exserta* and *E. camaldulensis* (EC), and seedlings from commercial seedlots of *E. camaldulensis* (control), *E. exserta* (Ex) and *E. urophylla* (U).

Data collected at age 7 years (Table 5) showed stem volume of 8 among 38 selected clones was higher than that of *E. urophylla.* Stem volume of 11 of the clones was higher than the best natural hybrid clone (EC3), 26 clones were higher than *E. camaldulensis* (control) and the remaining 12 clones were poorer than the control.

The two fastest-growing clones were nos 22 and 7 and their stem volumes (calculated with form index coefficient $f = 0.5$) were 102 dm^3 and 80 dm^3/tree, approximately two times higher than *E. urophylla* and three times higher than the *E. camaldulensis* control. Growth rates of these two superior clones were significantly higher than natural hybrid clones between *E. exserta* and *E. camaldulensis.* This trial has demonstrated the necessity to field-test clonal selections.

Plus tree selection and clonal testing for *E. urophylla* were also conducted by FRC Phu Ninh (FRC Phu Ninh 1998). At age 39 months, two fast-growing clones, namely PN2 and PN14, have been identified.

Table 4. Growth of *Eucalyptus camaldulensis* clones selected from Chon Thanh seedling seed orchard in a clonal trial at Binh Thuan (2002–2003).

Clone no.		Diameter$_{bh}$ (cm)	Height (m)	Volume index
1. Fast clones	55	4.1	4.7	85.5
	121	4.0	4.4	73.9
	160	4.0	4.4	73.2
2. Average clones	87	3.4	2.7	30.9
	187	3.4	2.7	30.1
	51	3.0	2.7	30.0
3. Poor clones	179	1.3	2.4	7.0
	130	1.2	2.3	6.4
	126	1.0	2.3	3.5
	$F_{pr.}$	<0.001	<0.001	<0.001
	LSD	1.02	0.75	28.3

Table 5. Growth of *E. camaldulensis* clones compared to seedlings of *E. urophylla*, *E. camaldulensis* and *E. exserta* and some hybrid clones at Ba Vi, Ha Tay province (9/1993–10/2000).

Clone no.[a]	Diameter$_{1.3}$ (cm)		Height (m)		Volume (dm^3)	
	$\bar{x}$	v (%)	$\bar{x}$	v (%)	$\bar{x}$	v (%)
C22	12.0	9.9	17.5	8.3	103.0	4.0
C7	11.1	15.0	16.8	10.4	80.6	4.2
C12	10.9	5.6	13.1	4.6	57.4	5.8
C24	10.7	13.9	15.4	8.7	75.9	5.3
C26	10.7	9.7	15.0	6.5	70.0	5.3
C19	10.0	15.4	15.1	12.6	64.4	6.3
C21	9.7	12.4	17.3	7.5	66.5	5.9
C29	9.5	12.2	14.4	9.8	54.9	6.6
U	10.2	17.8	11.3	16.1	52.2	7.9
EC2	9.9	14.6	11.5	9.4	49.2	7.6
EC1	7.9	9.1	9.1	2.0	24.3	10.4
Control	7.6	19.9	10.8	14.3	29.0	11.8
Ex	7.8	23.3	8.2	19.7	25.4	13.4
EC3	7.4	19.5	8.9	11.8	23.4	12.9
C36	5.7	17.0	9.9	11.7	14.4	19.0
C42	3.9	8.7	7.2	15.6	3.6	45.2
	Fpr <.0001		Fpr <0.001		Fpr <0.001	
	S.e.d = 0.967		S.e.d = 1.269		S.e.d = 32.68	

[a] C = *E. camaldulensis*, U = *E. urophylla* (seedlings), EC = *E. exserta* × *E. camaldulensis*, Ex = *E. exserta* (seedlings), Control = *E. camaldulensis* (seedlings), v = coefficient of variation.

Stem volume in these two clones was significantly higher than control treatments and imported clones U16 and GU from China (Table 6). Clone PN2 is very seriously affected by leaf blight disease caused by *Phaephleospora destructans* (Nguyen Hoang Nghia 2003).

Hybridisation and Field Testing of Hybrids

In 1991, plus trees of *E. urophylla* (U), *E. camaldulensis* (C) and *E. exserta* (E) were selected and grafted to enable flowering under controlled conditions. During 1996–2000, studies on flowering phenology, pollen collection and storage, and controlled pollination techniques were conducted for all three species. By controlled pollination, reciprocal hybridisation between the three species has been conducted and more than 70 inter- and intraspecific hybrid combinations have been made.

These hybrids and a controlled pollination within *E. urophylla* (UC, CU, UE, EU, CE, EC and UU) were field-tested at different sites including Thuy Phuong, Ha Noi (deep fertile alluvial soil), Ba Vi, Ha Tay province (shallow infertile hillside soil) and some other locations.

Data in Table 7 show that all hybrid combinations between *E. urophylla*, *E. camaldulensis* and *E. exserta* grew faster at all planting sites, than open-pollinated, non-hybrid offspring of the trees used as the hybrid parents (Le Dinh Kha and Nguyen Viet Cuong 2000, 2001).

Growth of hybrid combinations can be classified into the following groups (suffixes refer to parent tree numbers):

(i) fast growing hybrid combinations for hill sites, deep and fertile soils in the Red River delta and acid sulfate soils in Kien Giang (Mekong Delta) – $U_{15}C_4$, $U_{29}E_1$, $U_{29}E_2$ and E_2U_{29}

(ii) fast-growing hybrid combinations for deep and fertile soils in the Red River delta and acid sulfate soils in Kien Giang – $U_{29}C_3$, $U_{29}C_4$ and possibly $U_{29}U_{27}$

(iii) fast-growing hybrid combinations for hill sites at Ba Vi and Dong Ha: $U_{29}E_1$, $U_{29}E_6$, E_4U_{29}, $U_{29}U_{26}$ and $U_{29}U_{24}$.

Generally, the hybrid combination UC grows well on the deep soils of the Red River delta and seasonally waterlogged, acid sulfate soils in Kien Giang. Hybrid combinations UE and EU are usually fast-growing on hill sites. Hybrid combinations EC and CE are the slowest among combinations created. Their growth is only slightly better than the open-pollinated offspring of their parent trees.

Growth of hybrids and their parent species at an age of 3 years at Thuy Phuong and Ba Vi trials could be considered as typical example of heterosis–planting site interaction. Survival at both trials is high (85–100%). At age 3 years, stem volume of the three fastest-growing hybrid combinations at the Thuy Phuong trial was 135–155 dm^3/tree, and that of the three poorest growing parental species 14.5–46.0 dm^3/tree. At Ba Vi, the corresponding volumes were 37.1–40.0 dm^3/tree and 8.7–16.9 dm^3/tree (Table 7). This indicated that growth of the fastest-growing hybrid combinations at Thuy Phuong is 10 times higher than the slowest-growing parent species, while at Ba Vi, the corresponding ratio was only 3.5. Thus, growth of hybrid trees at Thuy Phuong was not only faster than that at Ba Vi, but also the degree of heterosis was also higher (Le Dinh Kha and Nguyen Viet Cuong 2000, 2001).

There are 10 hybrid combinations with stem volumes 27–140% higher than the best production seedlot (U_{Egon}) at the Thuy Phuong trial, while at Ba Vi only 6 hybrid combinations had volume growth better (23.6–45.5%) than U_{Egon}. This indicated that site conditions and silviculture measures are not only important for plantation productivity but also for expression of the heterosis effect in tree improvement.

Another cause of variation in heterosis performance is reciprocal effects, as demonstrated by the stem volume of hybrid combinations E_4U_{29} and $U_{29}E_4$ at age 3 years:
- at Thuy Phuong – $U_{29}E_4$ = 104.1 dm^3/tree; E_4U_{29} = 75.0 dm^3/tree
- at Ba Vi – E_4U_{29} = 37.0 dm^3/tree; $U_{29}E_4$ = 30.4 dm^3/tree.

A study on hybridisation for *E. deglupta* and *E. pellita* indicated also that reciprocal hybridisation would significantly influence the growth of hybrids (Glori 1993). This suggests volume growth of hybrids created by reciprocal hybridisation differs markedly between planting sites. Heterosis is influenced by both genetic and environmental factors. Whether the role of genetic factors (in this case cytoplasmic inheritance) or environmental factors is more important in the expression of heterosis depends on specific conditions.

Another important characteristic of hybridisation is the change of hybrid combination rankings in growth at different planting sites (Figure 1). At the Thuy Phuong trial, the fastest growing type is the UC hybrid combination. The order from fast to slow growing hybrid combinations was UC > UE, UU, EU > U > EC > C, E. At Ba Vi, the fastest growing combination was UE and the order in volume growth there was UE, UU, EU > UC > U, EC > C, E. Thus, while the fastest-growing hybrids on the deep and fertile soils are UC combinations, reciprocal hybrid combinations UE and EU are more promising on poor and degraded sites. The EC hybrid combinations are slow growing on both sites and superior only to open-pollinated seed of the parents and commercial seedlots (Figure 1). As *E. exserta* grows more slowly than the two other species, so growth of hybrid combinations CE

Table 6. Growth of some *E. urophylla* clones at two sites in central -northern Vietnam at age 39 months (FRC 1998).

Clone	Soc Dang			Gia Thanh		
	Diameter at base (cm)	Height (m)	Volume[a] (dm^3)	Diameter at base (cm)	Height (m)	Volume* (dm^3)
PN2	9.1 a	10.5 a1	22.5 a	9.4 a	11.4 a	26.6 a
PN14	8.6 ab	10.1 ab	19.6 a	8.9 a	10.6 a	22.0 a
U16	7.8 c	10.1 ab	16.0 b	8.1 b	8.5 bc	14.4 b
GU	7.6 c	9.6 bc	14.5 b	7.7 bc	8.1 b	14.3 b
Control	7.8 c	9.8 bc	15.9 b	7.5 c	7.9 bc	11.5 b

[a] Cylindrical volume.
Treatments with different letters significantly different (P<.05)

and EC is usually poorer than other hybrid combinations. It suggests heterosis is influenced by the genetic relationship of pollinated parents and also dependent on growth characteristics of the parental species.

Research on paper potential for some samples of EC, UC, UE and EU hybrids and the parents showed that wood density of the hybrids is equivalent or higher than the parents, cellulose content is higher and pulp yield and mechanical properties of paper produced from hybrid wood is equivalent to the parents. Stem volume in the hybrids is always markedly higher than that in their parents, so paper potential of the hybrids is also higher than that of their parents (Le Dinh Kha et al. 2001).

Field Trial of Selected Hybrid Clones

From field trials of hybrid combinations, more than 30 individual hybrid trees from 8 different combinations have been selected and recognised as technologically advanced germplasm by MARD. Rooted cuttings from selected hybrid trees were used for establishing clonal trials in several ecological zones of Vietnam.

Preliminary results of clonal testing showed that growth of some selected hybrid clones was better than selected clones PN2 and PN14 from FRC, and imported clones U6 and GU8 from China. The most

Table 7. Growth of hybrid combinations at Thuy Phuong and Ba Vi (1998-2001).

	Thuy Phuong (Ha Noi)				Ba Vi (Ha Tay)		
Hybrid.	Diameter$_{1.3}$ (cm)	Height (m)	Volume (dm^3)	Hybrid	Diameter$_{1.3}$ (cm)	Height (m)	Volume (dm^3)
U29C3	16.3	14.7	155.13	U29E1	9.2	11.6	40.0
U29C4	15.4	14.4	139.74	U29E6	9.1	11.2	37.2
U29U27	15.5	14.6	134.81	U29U26	8.9	11.5	37.1
U29E1	14.5	14.1	119.51	E4U29	8.8	11.6	37.0
U29E4	13.4	14.3	104.13	U29E7	8.8	11.4	36.0
U29E7	13.4	14.6	103.55	U29E2	8.8	10.9	34.0
E1U29	13.5	14.3	102.93	U29U24	8.7	10.9	33.8
E2U29	12.6	14.4	91.19	U29C4	8.3	11.1	30.7
U29E6	12.9	13.7	90.48	U29U27	8.3	10.6	30.5
U29U26	12.5	13.2	82.23	U29E4	8.3	11.0	30.4
E4U29	11.5	13.5	75.00	E2U29	8.3	10.7	29.7
U27	11.7	13.1	74.49	E1U29	8.1	10.7	29.2
U29E2	11.5	11.8	72.70	UEgon	7.7	10.3	27.5
U29U24	11.1	13.8	68.23	Ct	7.3	10.9	23.8
E1C3	11.3	12.5	65.07	U27	7.3	9.3	22.3
UEgon	11.3	12.4	64.55	E1C3	7.0	9.8	20.1
E2C3	10.5	11.5	56.02	E4C4	6.7	9.9	18.9
U26	10.9	11.5	55.55	ULem	6.4	8.7	17.9
ULem	10.3	11.7	52.40	E1C4	6.5	9.6	17.7
E4C4	9.6	12.3	49.34	CKen	6.2	9.7	16.9
E1C4	9.8	11.8	48.13	E2C3	6.3	8.3	14.1
U29	9.8	11.4	46.01	E2	5.9	8.5	14.1
CKen	9.2	10.2	35.08	E4	5.5	8.9	12.6
Ct	9.3	9.0	30.21	U29	5.6	8.2	11.0
E2	7.9	10.3	25.55	E1	5.0	7.6	8.7
E4	6.6	9.5	21.65				
E1	5.8	8.3	14.47				
Fpr	<0.001	<0.001	<0.001	Fpr	<.001	<.001	<.001
				LSD	0.8	1.1	7.3
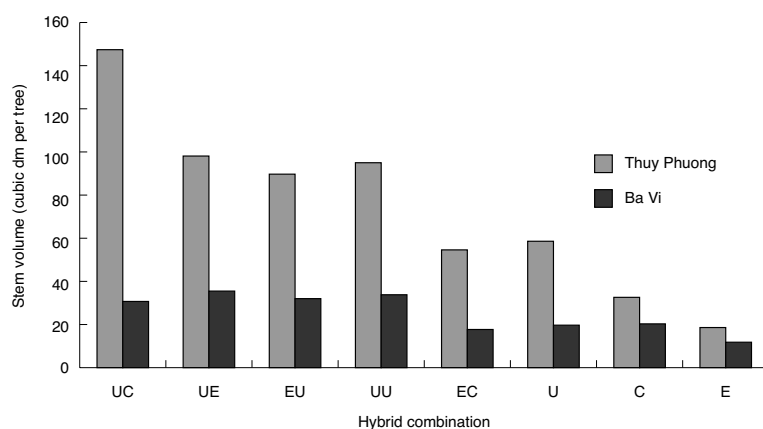
Figure 1. Stem volume of eucalypt hybrid combinations a 3 years old at Thuy Phuong and Ba Vi, Vietnam.

promising hybrid clones belong to the combinations $U_{29}E_1$, $U_{29}E_2$, $U_{15}E_4$, C_2U_{17} and $U_{29}C_3$ (Table 8). Similar results were obtained from the clonal trials at other sites. This suggests that artificial hybridisation plays a very important role in eucalypt improvement programs.

In addition to the above-mentioned research, significant achievements in vegetative propagation by cutting and tissue culture techniques have been successfully conducted for mass propagation of superior eucalypt clones. These technological advances have been transferred to different forest production units, bringing about a major advance in propagation and mass production of superior eucalypt germplasm for planting.

Conclusion

Following initial introduction of eucalypts to Vietnam in 1930, certain eucalypt species have become some of the most important species for planting. Despite long-lasting wars and many other difficulties, thanks to the efforts of Vietnamese forest scientists with the kind assistance and research cooperation of overseas forest scientists and international institutions, in particular SIDA–SAREC (Sweden), ACIAR, AusAID, CSIRO and China, there have been considerable achievements in research on eucalypt improvement in Vietnam. At present, in addition to the imported and highly productive eucalypt clones, the most promising provenances of the main

Table 8. Growth of selected hybrid clones at Tam Thanh (Phu Tho province) 12 months after planting (2002–2003).

Hybrid clone	Diameter at breast height (cm)		Height (m)		Iv		Survival (%)
	$\bar{x}$	$v\%$	$\bar{x}$	$v\%$	$\bar{x}$	$v\%$	
U29E1.24	4.1	6.1	4.4	5.0	73.96	23.5	97
U15E4.83	4.0	7.7	4.5	7.6	72.00	27.2	100
U29E2.5	4.0	10.7	4.4	6.1	70.40	28.5	100
C2U17.91	3.9	9.5	4.5	6.7	68.44	30.2	100
U29E1.23	3.8	11.7	4.2	8.3	60.65	36.7	100
U29C3.2	3.6	2.8	4.5	5.4	58.32	7.7	97
U29E2.34	3.8	15.7	3.9	11.7	56.31	4.7	100
GU8	3.6	9.6	3.9	6.0	50.54	26.1	100
PN2	3.2	7.9	3.1	5.1	31.74	5.1	97
U6	3.0	8.1	3.0	5.4	27.00	5.4	100
PN14	2.9	10.5	2.8	3.9	23.55	3.9	93

eucalypt species used for planting in Vietnam have been identified, and some highly productive hybrids that are more resistant to pests and diseases have been developed. Suitable vegetative propagation methods, such as cuttings and plant tissue culture, have been developed for mass production of superior planting materials used in reforestation programs. New achievements in biotechnology have been successfully applied to tree-breeding activities in Vietnam.

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Growth and Genetic Improvement of *Eucalyptus pellita* in South Sumatra, Indonesia

E.B. Hardiyanto[1]

Abstract

Four sub-lines of open-pollinated progeny tests of *Eucalyptus pellita* from Papua New Guinea (PNG) and Indonesia were established at PT. Musi Hutan Persada, South Sumatra, Indonesia to ascertain their growth potentials and genetic improvement for pulp plantations. In each sub-line, families tested came from the same provenance. The following sub-lines and families were included in the trials: North Kiriwo, PNG (39 families), South Kiriwo, PNG (48 families), Serisa Village, PNG (34 families) and Muting, Irian Jaya, Indonesia (50 families). Height and diameter growth were measured at 1, 2, 5 and 7.5 years of age. At 7.5 years old, the mean height growth ranged from 24.1 to 25.8 m, while that of diameter varied from 20.6 to 21.5 cm depending on sub-line. There were significant differences between families within sub-lines for height and diameter growth. Individual heritability estimates for height were moderate (0.10–0.29), while those of diameter were low to high (0.08–0.42). Comparable family heritability estimates ranged from 0.45 to 0.75 for height and from 0.48 to 0.77 for diameter. Genetic correlations between height and diameter growth were generally high (0.52–0.99). Age–age genetic correlations were high both for height (0.77–0.98) and diameter (0.59–0.99), indicating the opportunity for early selection. Starting at 3 years of age all sub-lines were progressively thinned to convert them into seedling seed orchards. Growth potential of *E. pellita* was lower than that of *Acacia mangium* grown at the same site.

The area of plantation forests has increased steadily in many parts of the world, including in Indonesia and other Southeast Asian countries. In Indonesia alone, there are more than 1.8 million ha of newly established industrial plantation forests in the islands other than Java (Ministry of Forestry 2001). Most current plantation forests are dominated mainly by short-rotation plantations of acacia, particularly *Acacia mangium*, for pulp and paper industries.

PT. Musi Hutan Persada (MHP) located in South Sumatra, Indonesia began to establish its *Acacia* plantations in 1990 on unproductive sites formerly dominated by alang-alang (*Imperata cylindrica*) grass. Some 193,500 ha have been planted, mainly with *A. mangium*. A species trial conducted at the company site in the early 1980s confirmed the superiority of *A. mangium* over other species. The species was selected due to its good characteristics: it is adapted to, and grows well on, the inherently acid and poor red-yellow podsolic soils dominating the company plantation sites and in a lowland humid environment. Its wood is excellent for pulp and paper making. The pulping properties of *A. mangium* wood are comparable to those of *Eucalyptus*. Lately the wood of *A. mangium* has been popular for other purposes, such as furniture making.

However, relying on a single species for multiple products is probably not a good strategy. Consequently, MHP is trying to find backup species. One of the species being tested is *Eucalyptus pellita*. This paper reports the growth performance of this eucalypt, and its potential genetic improvement, at the company site in South Sumatra.

[1] PT. Musi Hutan Persada, Jl. Residen Abdul Rozak 99, Palembang 30114 Indonesia.
 Email: <ekobhak@indosat.net.id>.

Materials and Methods

Seed collection

Seed collected from natural stands in Papua New Guinea (PNG) were purchased from the Australian Tree Seed Centre, while seed from Irian Jaya was obtained from the Faculty of Forestry, Gadjah Mada University. Details of the seed collection are given in Table 1.

Trial establishment and experimental design

The progeny tests were divided into four sub-lines according their natural distributions (Table 1). Sub-lines N. Kiriwo, S. Kiriwo and Serisa Village were planted in Pendopo District, whereas the Muting sub-line was planted in Subanjeriji District, about 70 km from the Pendopo. Both sites are located at low altitudes in a humid environment with a mean annual temperature of 25°C. The rainy season occurs from October to April, while the dry season is from June to September, but light rains are frequent during the dry season. The soil at both sites is red-yellow podsolic or Ultisol (Soil Survey Staff 1992) derived from sedimentary parent materials of tuff. Site characteristics are shown in Table 2. At both sites, the existing vegetation was felled and cleared using bulldozers and the sites were disc-ploughed using a farm tractor.

Seeds were sown in September 1995 and transplanted into polybags (6 × 17 cm) containing topsoil as potting medium. The trials were outplanted in December 1995 and January 1996, at Pendopo and Subanjeriji, respectively, and given 30 g urea (46% N) and 70 g triple-superphosphate (14% P) per tree at planting. Regular weeding (manual and herbicide) kept the trees free from weeds.

The progeny tests were thinned at 2 years of age, leaving 3 and 2 trees at Pendopo and Subanjeriji, respectively. Pedopo was thinned again at 4 and 5.5

Table 2. Site characteristics and trial design.

	Site	
	Pendopo	Subanjeriji
Altitude (m)	80	60
Latitude (°S)	3°17'	3°39'
Longitude (°E)	103°52'	104°00'
Soil texture	Clay	Clay
Annual rainfall (mm)	2700	2600
Previous vegetation	Scrub	Burned *Acacia mangium* plantation
Sub-line	N. Kiriwo, PNG S. Kiriwo, PNG Serisa Village, PNG	Muting, Irian Jaya, Indonesia
Date of planting	January 1996	December 1995
No. of replicates	14	12
Plot size	5 trees	4 trees

years, each thinning removing 1 tree in each plot, finally leaving the best tree in each plot. Subanjeriji was thinned again at 5 years, removing 1 tree and leaving the best tree in each plot.

Measurement and analysis

The progeny tests were measured for tree height and stem diameter at ages 1, 3, 5 and 7.5 years. The data were then analysed using analyses of variance based on the following linear model:

$$Y_{ijk} = \mu + B_i + F + \varepsilon_{ijl}$$

where Y_{ijk} is the individual tree observation, μ the overall mean, B_i the effect of the ith block, F_j the effect of the jth family and ε_{ijk} the residual error.

Table 1. Details of seed collection of *Eucalyptus pellita* tested in the progeny trials.

Description	Populations			
	S. Kiriwo, Papua New Guinea	N. Kiriwo, Papua New Guinea	Serisa Village, Papua New Guinea	Muting, Irian Jaya, Indonesia
Latitude (°S)	8°25'	8°20'	8°36'	7°21'
Longitude (°E)	141°30'	141°32'	141°26'	140°36'
Altitude (m)	45	45	45	40
Number of families	48	39	34	50

Data analyses followed methods described by Williams et al. (2002). Residual maximum likelihood (REML) analysis within the statistical package Genstat 5 (Payne et al. 1993) was used for estimation of family means and variance components. Heritabilities were estimated using the following formulas:

individual tree heritability

$h^2 = 2.5\sigma^2_f /(\sigma^2_f + \sigma^2_{fb} + \sigma^2_e)$

with $S.E.h^2 \cong (2.5\ \sigma^2_f)/ (\sigma^2_f + \sigma^2_{fb} + \sigma^2_e)$

family heritability

$h^2_f = \sigma^2_f / (\sigma^2_f + \sigma^2_{bf} /b + \sigma^2_e/nb)$

with $S.E.h^2_f \cong (2.5\ \sigma^2_f)/ (\sigma^2_f + \sigma^2_{bf} /b + \sigma^2_e/nb)$

where σ^2_f is component of variance due to family, σ^2_{bf} the component of variance due to block × family interaction, σ^2_e residual error, b the harmonic mean number of blocks per family and n the harmonic mean number of trees per family. The variance component of block (σ^2_b) is not included in the denominator of the formulas of heritabilities, implying that the estimated heritabilities are appropriate to selection on block-adjusted data (Cotterill 1987). The coefficient of relationship was assumed to be 1/2.5 instead of the normal 1/4 for half-sib family analysis, assuming an average rate of outcrossing of 70% for Eucalyptus species in the natural population (Moran and Bell 1983; Griffin and Cotterill 1988).

The standard error of component of family variance ($S.E.\sigma^2_f$) was calculated by the method of Anderson and Bancroft (1952):

$S.E.\sigma^2_f = [2/k^2 \Sigma_i(MS_i)^2 / (df_i + 2)]^{0.5}$

where k is the coefficient of family mean square, MS_i, the ith mean square used to estimate the nth component and df_i the number of degrees of freedom for MS_i.

Genetic correlations (r_g) between height and stem diameter were calculated from estimates of additive genetic variance and covariance, according to Falconer (1981). Phenotypic correlations were estimated as simple correlation coefficients (Falconer 1981).

Results and Discussion

Growth

Survival in all progeny trials was generally good, ranging from 79 to 91% in the first year, and from 75 to 82% in the second year (Table 3). The lower survival rate of the sub-line Muting was due to animal browsing. Trees exhibited a high degree of apical dominance, a very low incidence of forking, and were generally healthy.

Mean tree height and stem diameter are shown in Table 3. Growth of *E. pellita* was generally good for

Table 3. Height and diameter growth of *Eucalyptus pellita* in South Sumatra.

Characteristics and ages	S. Kiriwo, PNG		N. Kiriwo, PNG		Serisa village, PNG		Muting, Irian Jaya, Indonesia	
	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
Survival (%)								
1 year	87		91		89		79	
2 years	79		79		82		75	
Tree height (m)								
1 year	3.3	1.32	3.8	1.30	4.1	1.38	4.1	1.19
2 years	8.1	2.07	9.8	2.05	9.6	1.96	8.0	2.55
5 years[a]	19.2	2.62	19.7	2.69	20.3	2.56	–	–
7.5 years[b]	24.1	3.31	25.0	3.57	25.8	3.92	–	–
Stem diameter (cm)								
1 year	3.7	1.22	4.3	1.14	4.5	1.22	4.2	1.28
2 years	7.4	2.24	8.1	2.43	8.3	2.41	7.2	2.02
5 years[a]	14.7	2.71	15.7	2.81	16.0	2.76	16.6	2.71
7.5 years[b]	20.6	3.11	21.5	3.49	21.6	3.74	–	–

[a] Two trees per plot. [b] One tree per plot.

all sub-lines and much faster than at approximately the same age in other trials in Australia (Harwood et al. 1997), Laos (Pinyopusarerk et al. 1996) and Western Samoa (Woods and Peseta 1996), but comparable with those reported from a trial in Sabah (Harwood et al. 1997). Growth of *E. pellita* was slower than that of *A. mangium* growing at the same site. *Acacia mangium* (Muting, Irian Jaya provenance) planted at the same time in the adjacent plot in Subanjeriji was height 9.4 m and diameter 9.8 cm at 2 years of age (Khomsatun et al. 1999). The height and diameter of *A. mangium* (Kiriwo, PNG provenance) planted at the same compartment at Pendopo at 5.5 years old (without thinning) were 22.6 m and 18.2 cm (Hardiyanto et al. 2000). Slower growth of *E. pellita* compared with *A. mangium* on the same site has been recorded elsewhere (Turvey 1995; Kurinobu et al. 1996; Pinyopusarerk et al. 1996; Harwood et al. 1997)

In the present trials, *E. pellita* had better and healthier growth than other *Eucalyptus* species tested on the plantation site. No symptoms of leaf diseases, which are generally observed on *E. urophylla* and *E. urophylla* × *E. grandis* planted on this site, have been observed on *E. pellita*. These two species show excellent growth in the first two years, but then their growth declines due mainly to leaf diseases, such as leaf spot caused by *Pestalotia* sp., *Alternaria* sp. or *Macrospoma* sp., and leaf rust caused by *Puccinia* sp. (Rahayu 1996; S. Rahayu, pers. comm.). Other tropical eucalypts on the MHP site (*E. deglupta* and *E. brassiana*), though free from serious leaf disease, have grown very poorly. At lowland tropical sites with year-round high temperatures and high humidity, and with no or only a short-dry season, as at the MHP site, fungal diseases grow continuously without disruption on their life cycles. *Eucalyptus pellita* has also been more resistant to foliar diseases than other *Eucalyptus* species planted in humid tropical environments elsewhere (Harwood et al. 1997; Harwood 1998; Hardiyanto and Tridasa 2000).

Heritability estimates

Both height and diameter growth showed highly significant family effects in every sub-line and age of assessment. Individual tree heritabilities for height were moderate for all sub-lines, ranging from 0.12 to 0.29, while those for diameter were also moderate, ranging from 0.08 to 0.23. Standard errors were rela-

tively low in all cases, ranging between 0.008 and 0.024. Family heritabilities for height and diameter were also considered moderate, ranging from 0.45 to 0.75 for height, and from 0.48 to 0.77 for diameter. The magnitude of heritability estimates for height and diameter were similar in all sub-lines. These heritability estimates were calculated for a single site and therefore may be biased upwards by the presence of genotype–environment interactions. The assessment age (1–5 years) does not seem to affect the heritability values. It is worth noting that the heritability assessed at 5 years old may be overestimated due to selective thinning at 2 years of age (Matheson and Raymond 1984).

Published data on heritability estimates for *E. pellita* are still scarce. Heritabilities in these trials (Table 4) were comparable with those reported from open-pollinated progeny trials of other *Eucalyptus* species at similar ages (Eldridge et al. 1993), ranging from 0.07 to 0.43 for height, and from 0.11 to 0.46 for diameter. Estimated heritabilities here were lower than those reported by Kurinobu et al. (1996) from an open-pollinated progeny trial of *E. pellita* in South Kalimantan assessed at 20 months: there, individual tree heritabilities for height and diameter were 0.47 and 0.28, respectively. The use of coefficient of relationship of 1/4 by Kurinobu et al. (1996) in the heritability calculation resulted in higher values of heritabilities, even though the seeds were collected from natural stands.

Genetic and phenotypic correlations

Height and diameter had strong, positive genetic correlations at ages 2 and 5 years (Table 5). Phenotypic correlations between these traits followed the corresponding genetic correlations, but were marginally lower than those of genetic correlations. High genetic correlations between height and diameter have been recorded in other *Eucalyptus* species, e.g. *E. nitens*, 0.65 (King and Wilcox 1988), and *E. globulus*, 0.55 (Volker et al. 1990). High genetic correlation between height and diameter indicates simultaneous selection of these traits is possible, and selection for diameter, the trait easier to measure, will bring a substantial positive response for height.

Age–age genetic correlations for height and diameter were generally high, ranging from 0.77 to 0.99 for height, and from 0.59 to 0.99 for diameter. Genetic correlations between 2 and 5 years were higher than between 1 and 5 years, indicating early

selection at 2 years of age will be more efficient (Table 6). Results of the present study show an opportunity for selecting at a very young age (2 years), and it is possible to take advantage of the early selection as *E. pellita* starts flowering at about 2–3 years old.

Future directions

These results indicate that the growth rate of *E. pellita* is fairly good, despite being slower than *A. mangium*. Height and diameter growth are under a moderate level of genetic control. Therefore, this species offers good opportunities for substantial genetic improvement of these traits. As mentioned previously, the progeny trials were all progressively thinned to convert them into seedling seed orchards, eventually leaving only the best tree in each plot. The seedling seed orchards have produced seed that could be used for operational plantations. Individual seed collection from the best tree in every family of each sub-line has also been made for use in the second generation of progeny tests. However, the future of breeding work on *E. pellita* at MHP will depend upon the extent of future operational planting in the company. Currently, *A. mangium* is the principal species for pulpwood at MHP. Perhaps an alternative use of *E. pellita* would be production, on a short (12–15 year) rotation, of small logs for sawing and veneer. This could alleviate the shortage of wood from natural forests that will occur within the next few years in South Sumatra.

Table 4. Individual tree heritabilities for height and diameter of *Eucalyptus pellita* in South Sumatra.

Sub-line and age (year)	Height		Diameter	
	h^2	h^2_f	h^2	h^2_f
N. Kiriwo, PNG				
1	0.19 ± 0.015	0.62 ± 0.044	0.21 ± 0.016	0.63 ± 0.043
2	0.12 ± 0.009	0.46 ± 0.051	0.16 ± 0.012	0.65 ± 0.048
5	0.20 ± 0.016	0.55 ± 0.082	0.18 ± 0.014	0.53 ± 0.071
S. Kiriwo, PNG				
1	0.16 ± 0.014	0.65 ± 0.047	0.15 ± 0.013	0.61 ± 0.048
2	0.17 ± 0.015	0.66 ± 0.050	0.19 ± 0.016	0.75 ± 0.048
5	0.29 ± 0.024	0.60 ± 0.077	0.19 ± 0.017	0.58 ± 0.087
Serisa Village, PNG				
1	0.12 ± 0.011	0.61 ± 0.054	0.13 ± 0.012	0.62 ± 0.052
2	0.10 ± 0.008	0.49 ± 0.062	0.08 ± 0.008	0.57 ± 0.063
5	0.13 ± 0.012	0.45 ± 0.098	0.13 ± 0.012	0.48 ± 0.081
Muting, Indonesia				
1	0.25 ± 0.018	0.75 ± 0.041	0.15 ± 0.011	0.64 ± 0.040
2	0.12 ± 0.009	0.65 ± 0.050	0.23 ± 0.017	0.77 ± 0.053
5	–	–	0.42 ± 0.030	0.73 ± 0.047

Table 5. Genetic and phenotypic correlations between height and diameter at 1, 2 and 5 year(s) old of *Eucalyptus pellita* in South Sumatra.

Sub-line	Genetic			Phenotypic		
	1 yr	2 yr	5 yr	1 yr	2 yr	5 yr
N. Kiriwo, PNG	0.99	0.97	0.94	0.93	0.81	0.68
S. Kiriwo, PNG	0.98	0.97	0.93	0.93	0.82	0.65
Serisa Village, PNG	0.99	0.89	0.52	0.92	0.81	0.66
Muting, Indonesia	0.97	0.89	–	0.82	0.52	–

Table 6. Age–age genetic correlations of *Eucalyptus pellita* in South Sumatra.

Sub-line	Age–age genetic correlation	
	Height	Diameter
N. Kiriwo, PNG		
1 and 5 years	0.88	0.79
2 and 5 years	0.77	0.85
S. Kiriwo, PNG		
1 and 5 years	0.84	0.85
2 and 5 years	0.86	0.94
Serisa Village, PNG		
1 and 5 years	0.79	0.59
2 and 5 years	0.98	0.99
Muting, Indonesia		
1 and 5 years	–	0.67
2 and 5 years	–	0.89

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Performance at Dongmen, Guangxi of *Eucalyptus grandis* from Improved and Unimproved Sources

Li Hongwei,[1] Shen Wenhui,[1] Wang Guoxiang[2] and R.E. Pegg[3]

Abstract

As part of the activities under the tree-improvement plan, a series of family-in-provenance trials for several species was established at Dongmen, Guangxi (22°15'N, 107°40'E and altitude 150 m asl). The 1988 and 1990 experiments reported here involved, respectively, 200 and 168 families of *Eucalyptus grandis* from-tree improvement programs in several countries, collections from natural forest in Australia and local selections. Part of the 1988 experiment was replicated at Qinlian (21°50'N, 109°05'E and 50 m asl) on a sandy soil with nutrient levels inferior to those at Dongmen. Growth was so poor that the site was cleared at about 2 years after planting. Performance of provenances from northern Queensland was good (as in other provenance trials in China). Apart from that from the Windsor Tableland, northern Queensland provenances outperformed the seedling seed orchard (SSO) and natural forest provenances from Coffs Harbour and the SSO source from the Transvaal, South Africa. The very good performance of the Florida and Aracruz material is probably a reflection of the advanced stage of tree improvement reached in those two programs. Performance of seedlots introduced into China from external tree-improvement programs is difficult to predict. Four trees were selected from the 1990 experiment and from grafting in the espalier area for use in the controlled pollination program at Dongmen. Two of these came from the Aracruz SSO and one from the Florida material.

Eucalyptus grandis is an important species in Dongmen and other areas of Guangxi Zhuang Autonomous Region, China, not as a pure species, but because of its value in hybrid combination with *E. urophylla*. Several hybrids between these two species are planted as clones in large areas of southern China.

Eucalyptus grandis was one of four species (with *E. urophylla*, *E. tereticornis* and *E. camaldulensis*) selected for inclusion in the tree-improvement program at Dongmen (Nikles 1987). Introduction of the *E. grandis* × *E. urophylla* hybrid from Aracruz, Brazil to Dongmen in 1984, stimulated the interest in

eucalypt hybrid production (especially combinations involving *E. grandis*) in southern China. As part of the tree-improvement plan, provenance and family trials were established at Dongmen with several species, including *E. grandis,* between 1986 and 2001. In some family trials, seedlots from tree-improvement programs in other countries were included.

In this paper, we compare the performance of E. grandis seedlots introduced from tree-improvement programs in other countries with that of unimproved Australian families in provenance collections, and open-pollinated progeny from Dongmen selections in two family trials at Dongmen.

Methods

Two trials were established at Dongmen Forest Farm, Guangxi (latitude 22°15'N, longitude

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[1] Dongmen Forest Farm, Fusui County, Guangxi 532108, China.

[2] Rm 401, Building 19, Renmin Dadao Zhong, Zhanjiang 524022, China

[3] 3 Thulimbah Street, Coopers Plains, Queensland 4108, Australia.

107°40'E, altitude 150 m asl). Mean annual rainfall is 1213 mm, with a summer peak in distribution. The climate is classified as subtropical, although winters can be quite cold. Mean annual temperature is 21.3°C. Dongmen does not experience heavy typhoon damage because it is located about 90 km from the south China coast.

Soils at Dongmen, derived from sedimentary material, are acid latosols with low available phosphorus. The A horizon in many areas has been severely eroded by past land-management practices.

The sites of the two experiments previously grew eucalypt plantations that were harvested and the stumps removed. The sites prepared by one pass of a D7 tractor with three rock rippers, followed by one pass with a winged ripper. The topography is gently sloping. Planting espacement in each experiment was $3 \text{ m} \times 2 \text{ m}$ (1667 plants ha^{-1}). Fertiliser was applied at a rate of 100 kg ha^{-1} N, 50 kg ha^{-1} P and 50 kg ha^{-1} K (N100P50K50) about 2 weeks after planting.

The two experiments have a non-contiguous, single tree plot design.

1988 experiment

This experiment was located at Jiu Cheng Branch Farm. It contained 200 families with 30 replications per family. There were four sets each of 50 families. One plant from each of 50 families was grouped to form a set. Seedlots were from eight northern Queensland provenances, the Coffs Harbour (Australia) seedling seed orchard (SSO), a SSO at Tzaneen, Transvaal, South Africa and from six Dongmen selections. Details of provenances are given in Table 1.

One set of 50 families was also established at Qinlian Forest Farm (21°50'N, 109°05'E, 50 m asl) on a sandy soil with much lower organic carbon and nutrient status than the soil at Dongmen.

The Jiu Cheng experiment was thinned to approximately 50% stocking on a silvicultural basis at 2.5 years of age. It was felled in the mid 1990s and replaced with a new plantation. Data examined in this paper are from a measurement at age 5 years 4 months.

1990 experiment

This experiment is located at Qu Duo Branch Farm. It contains 168 families with 30 replications per family. There are two sets each of 84 families. One plant from each of 84 families was grouped to form a set. Seedlots were from four northern Queensland provenances plus a large collection from the Windsor Tableland (northern Queensland), several locations in the Coffs Harbour area, Aracruz (Brazil) SSO, a SSO at Tzaneen, (South Africa), Florida and from 12 Dongmen selections. Details of the provenances in the experiment are given in Table 2. Because six families from northern Queensland are from four provenances, and 28 families from Coffs Harbour are from 16 seedlots, representation of families per provenance is low. In this paper, these data have been amalgamated under broad 'northern Queensland' and 'Coffs Harbour' provenances.

The experiment was unthinned when measured at age 4 years 5 months, but survival was fairly poor, with an experiment average of only 62.5%.

Table 1. Details of seedlots by provenances used in the 1988 *Eucalyptus grandis* family trial at Jiu Cheng Branch Farm.

Seedlot[a]	Provenance	Latitude	Altitude (m)	No. of families
S14393	25–36 km S.E. of Mareeba	17°06'S	900	11
S14420	12 km S. of Ravenshoe	17°42'S	860	19
S14423	Baldy State Forest 194, near Atherton	17°18'S	1000	25
S14709	W. of Wondecla	17°23'S	980	7
S14710	S. of Ravenshoe	17°42'S	920	12
S14714	W. of Kennedy	18°12'S	605	6
S14716	N.W. of Townsville	19°01'S	880	5
B111	Windsor Tableland	16°11'S	1100	50
S15641	Coffs Harbour SSO	30°08'S	100	20
SSB1	SSB No. 1 Tzaneen, Transvaal	30°10'S	750	39
Dongmen	OP progeny from Dongmen selects	22°15'N	150	6

[a] S refers to seedlots from the CSIRO Australian Tree Seed Centre and B to seed from Queensland Department of Forestry.

Table 2. Details of seedlots by provenances in the 1990 *Eucalyptus grandis* family trial at Qu Duo Branch Farm.

Seedlot[a]	Provenance	Lat.	Alt. (m)	No. of families
FLO	Florida, USA	27°00'N[b]		24
B111	Windsor Tableland	16°11'S	1100	37
BRZ	Aracruz, Brazil	19°48'S	30	44
SSB 1	SSB No. 1 Tzaneen, South Africa	30°10'S	750	17
Dongmen	OP progeny from Dongmen selects	22°15'N	150	12
	Various Coffs Harbour locations	30°12'S[b]		28
	Various northern Queensland locations	18°00'S[b]		6

[a] B refers from Queensland Department of Forestry.
[b] Approximate coordinates

Results

1988 experiment

At 1 year of age, the mean height and diameter at breast height (dbh) for the set at Qinlian were only 1.26 m and 0.46 cm, respectively, compared with figures for the same set at Dongmen of 2.53 m and 1.75 cm. Growth at Qinlian continued to be very poor, so the experimental site was cleared.

Thinning to a nominal 50% achieved an actual experiment average of 46.8%. Variation in survival between families was great, but was small between provenances. Fifteen families were eliminated by a combination of poor initial survival and inferior growth. Ranking of provenances at 5 years and 4 months is shown in Table 3, where volumes have been adjusted to the average experiment survival of 46.8%. Data quoted do not include any volume for thinned stems, but an inspection of that statistic showed ranking is not affected by such inclusion.

The families were ranked to observe the distribution of families by provenances. This is shown in Table 3. Unfortunately, no individual tree selections were made in this experiment before it was felled.

1990 experiment

Ranking of provenances at 4 years and 5 months is shown in Table 4, where volumes have been adjusted to the average experiment survival of 62.5%.

During an exercise in 1998 to select candidates for inclusion in the Dongmen espalier area, this experiment was examined closely. The top 10 families were identified, and the individual tree measurement data records searched for potential candidates before field inspection. Four trees were selected and grafted in the espalier area for use in the controlled pollination program at Dongmen. Two of these came from the Aracruz SSO, one from the Florida material and one was of unknown origin, being a magnificent tree located in the isolation section of the experiment, where family identity had not been recorded.

Discussion

The presence of natural hybrids in the progeny of the Dongmen selects in the 1988 experiment and in the Aracruz provenance in the 1990 experiment inflated the performance of these sources to some extent. In the case of the Dongmen selects, the hybrids appeared to be with either *E. tereticornis* or *E. camaldulensis*. In the Aracruz source, the pollen contaminant was definitely *E. urophylla*. However, we consider the rankings would be little altered by removing the hybrid effects.

The difference in the level of performance of the progeny of the Dongmen selects between the two experiments is difficult to explain. There were, however, only two selects common to the two experiments.

The performance of the northern Queensland provenances was good, apart from that from the Windsor Tableland. These provenances outperformed the SSO and natural forest provenances from Coffs Harbour and the SSO source from South Africa. This result is in accordance with the statement of Wang Huoran et al. (1994) that 'seed from North Queensland is preferable for planting in China because of higher growth rates'. We cannot explain the poorer performance, relative to other northern Queensland sources, of the Windsor Tableland provenance.

Table 3. Ranking of provenances in the 1988 *Eucalyptus grandis* family trial at age 5 years 4 months, showing number of families surviving, number of families in the top 20 for volume production, height and dbh development, along with standing volume.

Seedlot[a]	Provenance	No. of families surviving	No. of families in top 20	Mean height (m)	Mean dbh (cm)	Volume (m³ ha⁻¹)
Dongmen	Dongmen selects	6	3	14.2	12.8	71.21
S14716	Townsville	5	1	13.7	11.9	59.38
S14420	S. Ravenshoe	15	3	13.4	11.5	54.71
S14710	S. Ravenshoe	9	2	12.9	11.4	51.49
S14423	Baldy State Forest	22	3	13.0	11.2	50.32
S14714	Kennedy	5	1	13.1	11.2	50.31
S14709	Wondecla	7	–	12.6	11.2	48.74
S14393	Mareeba	11	1	12.7	10.9	46.74
B111	Windsor Tableland	48	5	12.6	11.0	46.64
SSB 1	Tzaneen SSO	37	–	11.8	10.8	42.40
S15641	Coffs Harbour SSO	20	1	12.7	10.4	42.16

[a] S refers to seedlots from the CSIRO Australian Tree Seed Centre and B to seed from the Queensland Department of Forestry.

Table 4. Ranking of provenances in the 1990 *Eucalyptus grandis* family trial at age 4 years 5 months, showing height, diameter and standing volume.

Seedlot[a]	Provenance	No. of families in top 10	Mean height (m)	Mean dbh (cm)	Volume (m³ ha⁻¹)
FLO	Florida	1	15.0	11.7	83.54
BRZ	Aracruz SSO	5	15.1	11.6	83.44
	Miscellaneous northern Queensland	2	14.8	11.6	81.87
B111	Windsor Tableland	1	13.9	10.6	63.68
SSB 1	Tzaneen SSO	–	14.1	10.5	63.18
Dong.	Dongmen selects	1	14.0	10.1	57.70
	Miscellaneous Coffs Harbour	–	13.9	9.7	53.82

[a] B refers to seed from Queensland Department of Forestry.

The very good performance of the Florida and Aracruz material is probably a reflection of the advanced stage of tree improvement reached in those two programs.

Coffs Harbour sources consistently performed poorly in the two experiments, even though in the 1998 experiment the seed came from the SSO. The same can be said of the South African SSO.

There is always variation between families within provenances (and, of course, between trees within families) as is shown by some families from the poorer provenances ranking quite highly. Such variation allows for selection of some of the better trees from the poorer families or provenances for inclusion in the next generation of the breeding population.

Whether or not introductions from tree-improvement programs in other countries are worthwhile is a contentious issue. However, in these two experiments we can see that the performance of such material is somewhat unpredictable. It can be argued that introducing such material may provide a means of widening the genetic base of the breeding population. It could be concluded as a result of these two experiments that introduction into China of further material from Coffs Harbour (and maybe from any provenances in New South Wales) is unlikely to be rewarding. However, there is always the possibility of finding outstanding individuals even in the poorer provenances. For example, the pollen parent for the widely used *E. urophylla* × *E. grandis* clones DH33-9, DH32-27 and DH32-28 was from a Coffs Harbour seed collection.

Production of any hybrids involving *E. grandis* for the low nutrient, sandy sites near the south coast of China will probably require selection of the *E. grandis* parents elsewhere, as the species does not develop satisfactorily on such areas.

Conclusions

The two experiments demonstrate the generally good growth rates of northern Queensland provenances of *E. grandis* in China. Results are is in accordance with other observations in China (Wang Huoran et al. 1994).

Introductions of individual tree seed lots from advanced tree-improvement programs in other countries are valuable for adding to the breeding population, but actual performance of the seedlots is unpredictable.

Acknowledgment

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Variation in Growth and Wood Density of *Eucalyptus urophylla*

Luo Jianzhong[1]

Abstract

Twenty-seven families representing six provenances of *Eucalyptus urophylla* were sampled from a provenance–family trial in China to examine genetic variation in growth and wood density. Growth data were collected annually from ages 3 to 7 years and wood density data annually from ages 3 to 6 years. For growth traits, significant differences between provenances developed by 5 years of age, but significant differences between families did not develop until age 6 years. Differences observed in wood density between provenances and between families-within-provenances were significant at all ages. Heritabilities for diameter at breast height and volume were generally very low (0.10), but that for wood density was moderate to strong (0.34–0.60). There were low negative correlations (about –0.10) between tree volume and wood density. Juvenile–mature correlations of growth traits and of wood density were high (0.70).

Eucalyptus urophylla and selected hybrids of this species grow rapidly and produce good quality pulpwood under favourable conditions. They are important sources of raw material for pulp and paper industries in Brazil, Indonesia, South Africa and southern China. The natural distribution of *E. urophylla* is in Indonesia with some of the largest populations occurring on the islands of Alor, Flores, Pantar and Wetar. Pryor et al. (1995) suggested populations on Wetar are a separate species, *E. wetarensis*, due to the special characters of their capsules and other traits. Wetar Island is the easternmost of the islands with natural stands of *E. urophylla*.

Eucalyptus urophylla is thought to have first been introduced into China in the late 1970s. As a result of its good growth in various trials, planting of the species increased rapidly and widely in southern China. However, the genetic base of this species available within China to support ongoing tree improvement was, until recently, quite limited. To help address this problem, the China Eucalypt Research Centre introduced large numbers of new seedlots to establish a provenance–family trial cum breeding population in 1995 in the southwest of Guangdong province.

Methods

Seedlots

The complete trial contained 143 open-pollinated families representing 12 provenances. The study reported here used 27 of these families representing six provenances from three islands (Table 1). Families used in this study were selected on the basis of generally good growth rate and stem form, and all were of above-average volume at age 3 years. Twelve of these families represented three of the provenances that would be classified as *E. wetarensis* according to Pryor et al. (1995). However, this newer classification has not been widely accepted interna-

[1] China Eucalypt Research Centre, Renim Dadao Mid 30, Zhanjiang, Guangdong 524022, China.
Email: <luojianzh@21cn.com>..

tionally (CABI 2000). In this report all provenances will be referred to as *E. urophylla*.

From each of the 27 families studied, 5 trees were randomly selected, with a maximum of 1 tree per replicate, and their growth rate and wood density assessed. A clone of *E. urophylla* (MLA), which was included in the trial as a control, was also assessed for growth and wood density.

Site

The trial is located in JiJia Forest Farm of Leizhou Forestry Bureau in the far southwest of Guangdong province (latitude 21°50'N, longitude 110°30'E., altitude 20–30 m asl). The soil is a deep-red-coloured, coarse-grained, clay silt with a heavy texture. Over most of the site, the soil is very deep and roots are able to extend several metres into the B and weathered C horizons. The soil is generally low in available P and S.

Mean annual temperature is 23.5°C. Mean temperature in July, the hottest month, is 28.9°C, and in January, the coldest month, is approximately 16.0°C. Mean annual precipitation is 1885 mm, with more than 80% of this occurring during a distinct wet season from May to September (summer).

Trial design

The trial used a randomised complete block design with eight replicates. In each replicate, families were represented as a 4-tree row plots. Trees were initially spaced at 2.0 m between trees within rows and 3.0 m between rows (1667 trees ha^{-1}).

Site preparation, planting and management

The trial was planted in July 1995 and has received three thinnings. The first, in August 1997, involved a within-plot thinning with the best 2 trees per 4-tree row plot being retained, as judged subjectively on tree diameter, stem form, branch size, and disease and insect resistance. In September 1998, a second within-plot thinning was conducted to leave only the single best tree in each plot. In October 2000, the poorest trees in the poorest families (approximately one-third of the remaining trees) were removed to convert the trial into a seedling seed orchard.

Assessments

All trees identified for this study (see above) were assessed annually in July–August for total height (ht) and diameter at breast height (dbh) between mid-1998 (age 3 years) and mid-2002 (age 7 years). In addition, bark-to-bark increment cores were taken annually from each of the trees in this study between mid 1998 and mid 2002 (cores of 5 mm diameter). These cores were taken at heights of approximately 1.3 m above the ground.

Volumes of the sample cores were measured using the water displacement method, and the oven dry weight of each core was then determined after drying at 105°C for 10 hours. The volumes and oven-dry weights were used to determine basic densities as follows:

$$D = (W/V) \times 1000$$

where D is basic density in kg m^{-3}, W is the oven dry weight of the core in grams and V is the water-saturated volume of the core in cm^3.

Conical tree volumes were estimated according to the following equation:

$$Vol = 1/3 \times \pi \times (dbh/2)^2 \times ht \times 0.10$$

where: Vol = is the individual tree volume in dm^3, π = 3.1416, dbh = diameter at breast height in cm and ht = total height in m.

Table 1. Details of the seedlots in the *Eucalyptus urophylla* trial at JiJia Forest Farm.

Seedlot no.[a]	No. of families	Location	Latitude (°S)	Longitude (°E)	Altitude (m)
17840	4	Wai Kui, central Alor Island	8°14'	124°44'	540
17841	4	Piritumas, W. Alor Island	8°19'	124°31'	355
17843	4	Baubillatung, W. Pantar Island	8°20'	124°02'	285
17830[b]	1	NW of Ilwaki, Wetar Island	7°54'	126°26'	490
17831[b]	9	N of Ilwaki, Wetar Island	7°52'	126°27'	515
17836[b]	5	SW of Uhak, NE Wetar Island	7°39'	126°29'	350

[a] Seedlot numbers of CSIRO's Australian Tree Seed Centre.

[b] Indicates seedlots classified as *E. wetarensis* by Pryor et al. (1995).

Data analysis

To examine the genetic variability of the traits, analyses of variance were carried out based on the following linear model:

$$Y_{ijk} = \mu + R_i + P_j + F_{k(j)} + e_{ijk}$$

where:

Y_{ijkl} is the measurement of the individual tree representing family k within-provenance j in replicate i

μ represents the overall mean

R_i represents the effect of replicate i

P_j represents the effect of provenance j

$F_{k(j)}$ represents the effect family k which is nested within provenance j

e_{ijk} represents the residual error with a mean of zero.

Computation of provenance and family-within-provenance means, and analyses of variance, were carried out using the ANOVA procedure in GENSTAT 5.32, following procedures described by Williams et al. (2002).

Within-provenance individual tree heritabilities ($h_i{}^2$) were calculated using the REML procedure in GENSTAT, following procedures described by Williams et al. (2002). For all the analyses, provenances and replicates were treated as fixed effects, while families-within-provenances were treated as random. The heritabilities were estimated according to the equation:

$$h^2 1/r \times \sigma^2{}_f / (\sigma^2{}_f + \sigma^2{}_m)$$

where

r   is the coefficient of relationship

$\sigma^2{}_f$ is the variance between families-within-provenances

$\sigma^2{}_p$ is phenotypic variance $(= \sigma^2{}_f + \sigma^2{}_m)$

$\sigma^2{}_m$ is the variance between plots.

The coefficient of relationship used in this computation was assumed to be 0.4, rather than the value of 0.25 often used for half-sib families. The value of 0.4 was chosen based on the assumption that open-pollinated families of *E. urophylla* from natural stands, like those of many other eucalypt species, would carry a degree of inbreeding resulting from selfing and neighbourhood inbreeding, and thus would not be true half-sibs (Eldridge et al. 1993; Burgess et al. 1996).

Genetic correlations between traits were calculated from variances and covariances obtained using a mixed-model analysis carried out at the individual tree stratum and following methodologies described by Williams et al. (2002).

Results and Discussion

Growth

Growth of trees studied in the trial at JiJia Forest Farm was excellent, with an overall mean dbh and volume at age 3 years of 13.7 cm and 77.5 dm^3, respectively. By age 7 years, these averages had increased to 22.5 cm and 324 dm^3, respectively. Clearly, *E. urophylla* is well-adapted for productive plantations in the environment represented by JiJia Forest Farm.

Surprisingly, the control clone (MLA) at 3 years averaged only 12.8 cm in dbh and 70.3 dm^3 in volume, and at age 7 years only 20.9 cm and 286 dm^3, respectively (Table 2). This clone has been used extensively for establishment of short-rotation pulp-wood plantations in southern Guangdong, as it had a reputation for good growth. However, this trial clearly shows that its growth is inferior to that of the average of good natural stand provenances.

Significant differences ($p \leq 0.05$) in mean dbh between the provenances did not develop until age 6 years (Table 3). Differences between families-within-provenances for mean dbh were not significant at any age. As reliable differentiation between the provenances studied was not obtained till age 6 years, it seems that selection of the superior provenances should wait until at least that age. However, the number of provenances studied here is relatively small with respect to *E. urophylla*'s natural distribution. In a trial in the southern Philippines that included 208 families of 16 natural stand provenances of this species, Arnold and Cuevas (2003) found, at about age 3 years, large significant differences in dbh between both provenances and families-within-provenances.

At age 3 years, the best performing provenance for dbh growth was 17841 which averaged 14.0 cm and 83.5 dm^3, respectively (Table 2 and Figure 1). However, by age 6 years this provenance was ranked in only fourth place for dbh and provenance; 17843 had emerged as the best provenance.

The pattern of variation of mean tree volume was similar to that of dbh (Table 4 and Figure 2). Significant differences ($p \leq 0.05$) between provenances developed from age 6 years. At age 7 years, differences between families-within-provenances for mean tree volume were also significant.

Table 2. Provenance means at ages 3 and 7 years for diameter at breast height (dbh), volume (Vol) and ranks by volume, along with mean sample core wood basic densities (Den) at ages 3 and 6 years, for *Eucalyptus urophylla* in the trial at JiJia Forest Farm.

Seedlot	Dbh3 (cm)	Den3 (kg m^{-3})	Vol3 (dm^3)	Vol3 (rank)	Den6 (kg m^{-3})	Dbh7 (cm)	Vol7 (dm^3)	Vol7 (rank)
17840	13.6	450	79.9	3	490	23.0	343	2
17841	14.0	450	83.5	1	490	21.8	271	6
17843	13.6	390	74.0	4	440	24.4	388	1
17830	12.0	440	59.0	6	500	21.5	296	5
17831	13.9	430	80.0	2	500	22.3	319	3
17836	13.5	420	73.3	5	480	21.6	313	4
MLA (clone)	12.8	430	70.3		470	20.9	286	

Table 3. Results from analyses of variance for diameter at breast height (dbh) from annual assessments between the ages of 3 to 7 years in the *Eucalyptus urophylla* trial at JiJia Forest Farm.

Source of variation	Degrees of freedom	Dbh3 f pr	Dbh4 f pr	Dbh5 f pr	Dbh6 f pr	Dbh7 f pr
Provenances	5	0.221	0.210	0.074	0.001	0.002
Families-within- provenances	26	0.589	0.657	0.433	0.348	0.140

Table 4. Results from analyses of variance for individual tree volume (Vol) from annual assessments between the ages of 3 to 7 years in the *Eucalyptus urophylla* trial at JiJia Forest Farm.

Source of variation	Degrees of freedom	Vol3 f pr	Vol4 f pr	Vol5 f pr	Vol6 f pr	Vol7 f pr
Provenances	5	0.182	0.251	0.056	0.002	0.006
Families-within- provenances	26	0.437	0.287	0.154	0.291	0.001

Table 5. Results from analyses of variance for wood core density (Den) from annual assessments between the ages of 3 to 6 years in the *E. urophylla* trial at JiJia Forest Farm.

| Source of variation	Degrees of freedom	Den3 f pr	Den4 f pr	Den5 f pr	Den6 f pr
Provenances	5	0.001	0.003	0.001	0.001
Families-within-provenances	26	0.009	0.001	0.001	0.001

Wood density

There were large significant differences in core wood mean basic density between both provenances and families-within-provenances at all ages studied (Table 5). At age 3 years, the core wood mean basic density across all the trees sampled was 427 kg m^{-3} and provenance means ranged from 390 kg m^{-3} (provenance 17843) up to 450 kg m^{-3} (provenance 17840) (Table 2).

By age 6 years, core wood mean basic density had increased to 488 kg m^{-3} and provenance means ranged from 440 kg m^{-3} (provenance 17843) to 500 kg m^{-3} (provenances 17830 and 17831) (Table 2). At the family level, the magnitude of variation at age 6 years was much greater with core wood mean basic densities in families ranging from 431 kg m^{-3} up to 578 kg m^{-3} (data not shown). Clearly, for the *E. urophylla* material studied in this trial, the magnitude of the variation between provenances and between families-within-provenances for wood basic density is, to age 6 years, much greater than that for volume.
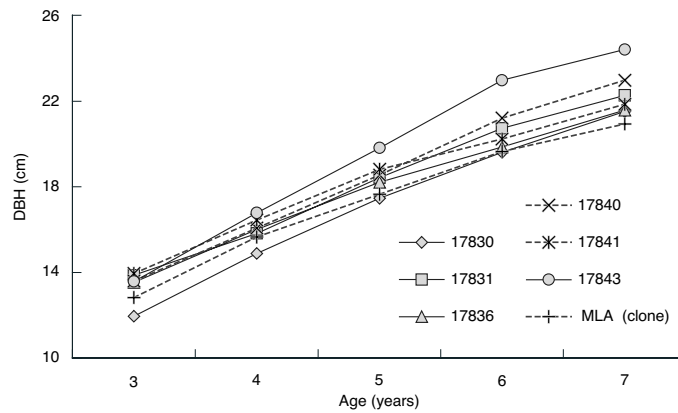
Figure 1. Diameter at breast height (dbh) by age for the different provenances in the *Eucalyptus urophylla* trial at JiJia Forest Farm.
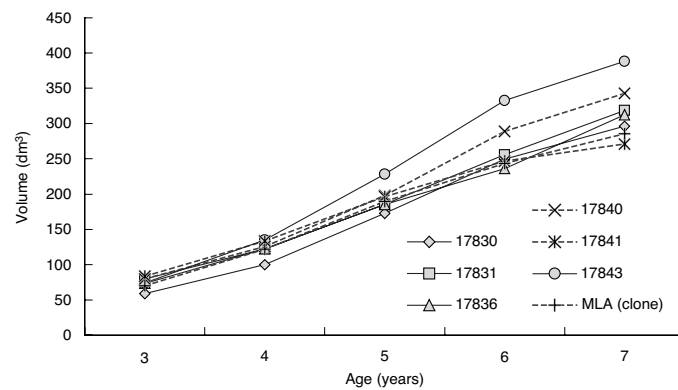
Figure 2. Tree volume by age for the different provenances in the *Eucalyptus urophylla* trial at JiJia Forest Farm.

Wood density is a very important trait with respect to the value of eucalypt wood for pulp production (Downes et al. 1997). The correlations between wood basic density and screened pulp yield are generally very strong and, as most eucalypt timber in southern China is sold on the basis of weight, density has a particularly strong influence on economic returns to eucalypt plantation growers. As substantial variation was observed in wood basic density in this trial, it will be very important that wood basic density be a key trait in the selection of material to be used for establishment of *E. urophylla* pulpwood plantations.

That core wood basic density increased steadily from age 3 to 6 years (Figure 3), by an average of approximately 20 kg m^{-3} yr^{-1} family is also very important to both growers and wood processors. Due

to this increase, and by inference the increase in mean, whole tree wood basic density, any reduction of rotation length below 6 years would substantially reduce economic returns to growers. For wood processors, the 6-year-old timber should be significantly more profitable than younger material, due to the correlations between density and pulp yields.

Estimates of heritabilities and genetic correlations

For the growth traits (dbh and volume), within-provenance individual tree heritabilities (h_i^2) of dbh and volume were generally very low (Table 6). The heritabilities observed for core wood basic density were much higher, and ranged from 0.34 at age 3 years up to 0.60 at age 6 years.

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The finding that heritabilities for wood traits were much stronger than those for dbh and volume in this *E. urophylla* trial is consistent with results obtained for many other eucalypt species (see, e.g. Eldridge et al. 1993; Raymond 2000). Due to such heritabilities, it can be expected that much greater genetic gains would be achieved by selection on wood basic density than on growth.

Table 6. Within-provenance individual-tree heritabilities among different traits of *E. urophylla* in the provenance-family trial at JiJia Forest Farm.

| | Age (yr) | | | | |
	3	4	5	6	7
Diameter (dbh)	0	0	0.01	0.07	0.10
Tree volume	0.01	0.03	0.13	0.08	0.15
Wood core density	0.34	0.43	0.47	0.60	– –

Age–age genetic correlations were estimated for dbh and wood density. In general, the correlations were high and ranged from 0.66 to 0.86 (Table 7). As the age difference increased, the age–age correlations showed a small but progressive decrease. Genetic correlations between tree volume and sample core wood basic density at different ages were low (Table 8).

Most of the eucalypt plantations in Guangdong province are grown for pulpwood, on short rotations of up to 6 years. Consequently, for the ages examined in this study, the 6-year assessment equates to full rotation age and the 3-year assessment to half rotation age. The age–age genetic correlations between these ages were relatively strong for both wood core basic density and for dbh (r = 0.70 and 0.73, respectively). If the correlations for growth were considered alone, they might suggest that relatively early age selections (i.e. half rotation age) could be relatively efficient. However, as the growth differences between the families and provenances were not significant at the earlier ages, selection for growth clearly needs to be delayed till the later ages (e.g. 6 years), when some genetic differentiation can be observed. In contrast, early age selection should be efficient for improving wood density, as the early age differences for this trait were substantial and significant.

Genetic correlation estimates between traits give an indication of the opportunity for indirect selection and of the impact of selecting for one specific trait over other key traits. In this study, genetic correlations between tree volume and wood basic density were negative. This also is consistent with estimates published for genetic correlations between tree growth and basic density from eucalypt trials elsewhere (Raymond 2000). However, as the magnitude of these genetic correlations was low for this *E. urophylla* trial, it should be possible achieve improvement in either one of the traits with no significant reductions in the other, by employing multiple trait index selection methodologies (Cotterill and Dean 1990).
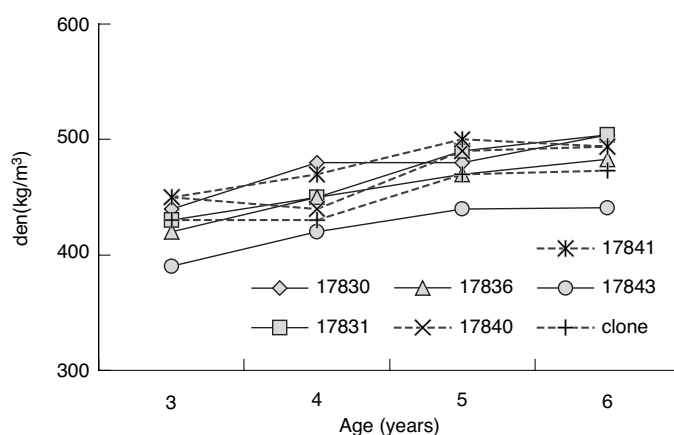
Figure 3. Sample core wood density (den) by age for the different provenances in the *E. urophylla* trial at JiJia Forest Farm.

Table 7. Age–age genetic correlations for diameter at breast height (dbh) and for sample core basic density (Den) in the *Eucalyptus urophylla* provenance–family trial at JiJia Forest Farm.

	Dbh3–dbh4	Dbh3–dbh5	Dbh3–dbh6	Dbh3–dbh7
Age–age genetic correlation	0.86	0.79	0.73	0.66

	Den3–Den4	Den3–Den5	Den3–Den6	
Age–age genetic correlation	0.82	0.81	0.70	

Table 8. Genetic correlations between tree volume and sample core wood basic density at different ages in the *Eucalyptus urophylla* provenance–family trial at JiJia Forest Farm.

	Vol3–Den3	Vol4–Den4	Vol5–Den5	Vol6–Den6
Genetic correlation	−0.11	−0.06	−0.10	−0.12

Conclusions

Differences of growth traits were not significant at early ages, and heritabilities of these traits were relatively low. A factor in this may be that the families studied were selected on the basis of all being faster growing. Nonetheless, as age increased, growth diverged, and the differences between both provenances and families-within-provenances became significant.

As the magnitude of heritabilities for wood density was much greater than those for growth, the genetic gains achievable by selection on wood density, and hence benefit to growers, would be much greater than what could be provided by selection on growth. Also, as strong genetic differentiation in wood density was evident from an early age, with large significant differences between both provenances and families-within-provenances and moderate to strong age–age genetic correlations, substantial genetic improvement of this trait should be achievable through early selection. In contrast, the lack of early age genetic differentiation for growth necessitates delaying selection for growth to around full rotation age (i.e. 6 years for pulpwood plantations in southern China).

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Progeny Test of Open-Pollinated Families of *Eucalyptus urophylla* on Multiple Sites

**Xu Jiamin,[1] Li Guanyou,[1] Lu Zhaohua,[1] Bai Jiayu,[1] Lu Guohuan[2]
and Wang Shangming[3]**

Abstract

Growth traits at age 3 years of 81 families of *Eucalyptus urophylla* in a five-site progeny test were analysed. Tree height, stem diameter and volume had significant differences between families and sites, and family × site interaction was strong. Six excellent families were selected from different sites, and five superior families from Danzhou (Hainan), and Leizhou, Xinhui, Heyuan and Raoping in Guangdong province. Results of tests provided a basis for upgrading seed supply and roguing seed orchards. With this selection rate, seed collected from the superior families for afforestation areas was estimated to have a genetic gain in volume production of 3.37–10.57%. If the seed orchard were rogued and these superior families retained, genetic gain in volume would be doubled.

Eucalyptus urophylla has become a major plantation tree species in southern China since its introduction and research on provenances–families developed during the 1980s. The management phases have involved seed orchards*,* second generation seed orchards and clonal seed orchards through early selection of mother trees. The second breeding population and research trials on families will provide a basis for improved generations. With three levels of seed orchard, *Eucalyptus* breeding and gains must improve rapidly. To select superior provenances/ families of multiple-site or single-site adaptability, it is important to analyse growth on different sites. Few research reports are available of this topic for *E. urophylla* in China. We consider that the best strategy for breeding and improving eucalypts in southern China is to rely on multiple generations, to use interspecific hybrid breeding to achieve proven clones, and then to direct the genetic gains to production plantations (Xu et al. 2002). Eucalypt seed orchards on multiple sites fit this strategy. The aim of this study was to identify new families/clones that can grow quickly in a consistent manner over large areas of southern China.

Materials and Methods

Eighty-one progenies were tested from selections from plus trees of a first-generation seedling seed orchard in Daze town, Xinhui City, Guangdong (23°34'N, 110°05'E, altitude 45 m). Details of the progeny in the test of open-pollinated families are in Table 1.

The five test sites are located in Guangdong and northern Hainan.

1. Danzhou Forest Farm Danzhou City, Hainan Island (19°24'N, 109°39'E) has a tropical oceanic monsoon climate, a mean annual temperature of 24°C, no frosts, a mean annual rainfall of 1600 mm and a distinct dry season

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[1] Research Institute of Tropical Forestry, Chinese Academy of Forestry, Guangzhou 510520, Guangdong, China.
[2] Forestry Bureau of Xinhui City, Xinhui 529000, Guangdong, China.
[3] Leizhou Forestry Bureau, Suixi 524348, Guangdong, China.

from November to April. There are 2–3 typhoons over class 10 each year. Soils are latosols developed from granite.

2. Hetou Forest Farm, State Leizhou Forestry Bureau, Guangdong (20°18'–21°30'N, 109°39'–110°38' E) has a tropical monsoon climate, a mean annual temperature of 23.5°C and a mean annual rainfall of 1855 mm. There are 2–3 typhoons each year, between July and October. Soil type is a shallow-sea deposit laterite.

3. Duruan Town, Xinhui City of Guangdong (23°34'N, 113°05'E) has a southern subtropical climate, a mean annual temperature of 22.3° C, no frosts and a mean annual rainfall of 1750 mm. The site is a gently sloping field with a granitic red soil.

4. Zhongxin Town, Heyuan City, Guangdong (24°23'N, 114°40'E), between the Longxian basin of Wengyuan and Dengta basin of Wuhua, has a southern subtropical climate, a mean annual temperature of 20.5°C and a mean annual rainfall of 1695 mm. The site is a gently sloping field with a purple red soil.

5. Raoping County Forest Research Institute, Raoping County, Guangdong (23°40'N, 116°56'E) has a southern subtropical climate, a mean annual temperature of 21.4°C, an extreme minimum temperature of 0.8°C and 349 frost-free days. The mean annual rainfall is 1470 mm

and the crimson soil is deep and friable. The predominant species are leguminous plants with wild groundnuts in the understorey.

Soil properties at each site are shown in Table 2.

A randomised complete block design with four replications and plots of 2 rows × 5 trees was used. The numbers of families tested at Danzhou, Leizhou, Xinhui, Heyuan and Yaoping were 81, 49, 36, 36 and 38, respectively. Tree height and stem diameter (dbh) of all trees were measured, and survival rate recorded after 6 months. At 1, 2 and 3 years, height and dbh were measured. A single tree volume index can be calculated by the equation (McKenney et al. 1991):

$$SV = \frac{1}{3} \times H \times dbh^2$$

Correlation can be analysed by SAS software (Chen Zixing and Xu Xishui 1997). The estimated genetic gain (DG) is given by the equation (Hodge and White 1992):

$$\Delta G = (\bar{x} - \bar{X}) \times h_f^2 / \bar{X}$$

In this equation: 'ΔG' is the percentage of genetic gain, 'x' is average volume of progeny of selected families, 'X' is an average weighted volume of all families, 'h^2' is family heritability.

Table 1. Provenances/families of *Eucalyptus urophylla* in the trials.

Progeny no.	Seed lot no.	Number of families	Provenance[a]	Lat. (°S)	Long. (°E)	Altitude (m)
49, 52	12897	2	Mt Mandiri	8°33'	122°35'	830
51	13010	1	Ulanu River	8 °20'	124°27'	700
48, 66–74	14531	10	Mt Egon	8 °38'	122°27'	515
50, 75, 76	14532	3	Mt Lewotobi	8° 31'	122°45'	398
53, 55	14533	2	Flores Island	8°31'	122°45'	340
23, 44–47, 54, 56–65, 77–84	14534	23	Mt Egon	8° 38'	122°27'	500
85	15089	1	Mt Egon	8° 38'	122°27'	500
115–124	16682	10	Mt Egon,	8° 38'	122°27'	415
93–97	17565	5	Mt Lewotobi	8°32'	122°48'	375
98–109	17567	12	Mt Egon	8°38'	122°27'	450
110–111	17570	2	Bangat	8°38'	122°27'	330
112	17572	1	Iling Gele	8°37'	122°27'	600
113–114	17573	2	Andalan	8°36'	122°28'	725
91–92	B2-3	1	–	–	–	–
86–90	Mixed [b]	5	Mixed provenances	–	–	–

[a] All provenances from natural stands in Indonesia except B2-3 from Brazil plantations.
[b] Mixed provenances including 14531, 14532, 12895, 12987.

Table 2. Soil analysis at the five *Eucalyptus urophylla* test sites.

Soil property	Test sites				
	Danzhou	Leizhou	Xinhui	Heyuan	Raoping
pH	5.10	3.80	4.10	4.45	5.02
Humus (g kg^{-1})	0.541	4.700	7.200	11.17	20.43
Total N (g kg^{-1})	0.028	0.250	0.320	0.440	0.682
Total P (g kg^{-1})	0.026	0.040	0.060	0.274	0.234
Total K (g kg^{-1})	0.190	1.210	1.080	3.388	13.19
Available N (mg kg^{-1})	21.63	33.14	41.37	52.80	71.61
Available P (mg kg^{-1})	0.23	0.42	0.88	2.40	2.21
Available K (mg kg^{-1})	1.38	4.50	8.83	23.67	46.17
Available B (μg g^{-1})	0.213	0.370	0.315	0.514	0.632
Dissociative 1/2Ca^{+2} (mmol kg^{-1})	0.44	0.54	0.38	−	−
Dissociative 1/2Mg^{+2} (mmol kg^{-1})	0.24	0.68	0.56	−	−

Results

Territorial multispot variance analysis

Thirty-six families tested at three sites were analysed by multispot variance analysis. The fixed model was used and families for which there were no data were deleted. Results are in Table 3. There are highly significant differences between families and sites, and the interaction of families × sites for every growth statistic at 2 and 3 years was also significant. Indications are that there is a high degree of adaptability and inherent differences between families. The families with strong adaptability and fast growth can be identified through selection.

Comparing the growth of families at all sites

Duncan's multiple range test was used in an analysis of 36 families on five sites (Table 4). There are significant differences in height, dbh and volume at five sites at 2 years. Growth is highest at Leizhou and Heyuan with Yaoping next; at Danzhou and Xinhui, growth is lower. There are still significant differences between sites at 3 years, but the ranking has changed. The order of volume production at the five sites is: Raoping > Leizhou > Heyuan > Xinhui > Danzhou. The volume at Raoping is highest at 0.06571 m^3 individual^{-1} and is 2.05 times that at Danzhou (0.03207 m^3 individual^{-1}). Because the family × site interaction is highly significant, it is essential that families are evaluated at every site.

Selection of superior families at five sites

Growth variance analysis of three sites at 3 years (Table 5) indicates that there are highly significant differences in height, dbh and individual volume of families. The growth statistics have significant differences between blocks and in the family × block interaction at all sites except for dbh at Leizhou and height at Raoping. So the growth status and selection of superior families should be further analysed.

Duncan's multiple range test divides family volumes at three sites at 3 years into different groups (Table 6). Raoping, Leizhou, Heyuan, Xinhui and Danzhou can be divided into 8, 8, 10, 13 and 9 groups, respectively. Forty-three families ranking above No. 15 were selected at five sites to account for 53% of all tested families. There were six families: 44, 47, 50, 66, 68 and 88, ranked above No. 15 in at least three sites. No. 68 was superior at four sites and No. 47 at five sites.

Early results of *E. urophylla* provenance/family research indicate provenances of seed lots 14534, 14531, 16882 and 17567 from Mt Egon, Flores Island, Indonesia are suited to southern China and are superior provenances in high growth (Liang et al. 1994; Wu et al. 1995; Xu et al. 1996). To improve the genetic quality of the seed orchard at Daze, Xinhui, families from these four provenances were used. Table 6 shows that the progeny from provenances 14534, 14531, 16682 and 17567 grow well. Thirty-three families were selected ranked above No. 15 and amounting to 76.7% of superior selected families. These superior families should be retained when thinning in the next phase.

Table 3. Impact of variance analysis at multiple sites planted to *Eucalyptus urophylla*.

Source of variance		DF	F value [a]		
			Height	Diameter	Volume
2 years	family	35	7.99**	8.82**	9.76**
	site	4	230.78**	93.97**	156.13**
	family × site	140	3.52**	3.95**	4.16**
3 years	family	35	3.25**	4.66**	3.86**
	site	4	294.60**	246.53**	272.94**
	family × site	140	1.83	1.74*	1.71*

[a] * and ** indicate significance at the 5% and 1% levels respectively. P < 0.05 indicates difference was significant.

Table 4. Duncan's multiple range test of growth of *Eucalyptus urophylla* between different sites.

Property	2 years			3 years		
	Site	Average	Duncan's T test[a]	Site	Average	Duncan's test
Height (m)	Leizhou	10.7098	a	Raoping	13.2233	a
	Heyuan	9.7579	b	Leizhou	12.6823	b
	Raoping	9.6798	b	Danzhou	10.8821	c
	Danzhou	9.1217	c	Heyuan	10.8588	c
	Xinhui	8.4360	d	Xinhui	10.1212	d
Diameter at breast height (cm)	Leizhou	9.0219	a	Raoping	12.0375	a
	Raoping	8.6763	b	Leizhou	11.7080	a
	Heyuan	8.5654	b	Xinhui	9.9087	b
	Danzhou	8.1044	c	Heyuan	9.5821	bc
	Xinhui	7.9517	c	Danzhou	9.4508	c
Single tree volume index (m³)	Leizhou	0.029461	a	Raoping	0.065712	a
	Raoping	0.024753	b	Leizhou	0.059638	b
	Heyuan	0.024295	b	Heyuan	0.034106	c
	Danzhou	0.020408	c	Xinhui	0.033283	c
	Xinhui	0.018658	d	Danzhou	0.032073	c

[a] Scores with the same letter are not significantly different at the 5% level of probability.

Estimate of genetic gain of families at different sites

From an analysis of variance with data of 27 families at four sites (Raoping, Leizhou, Xinhui, and Heyuan), family heritability for growth statistics can be calculated. By using a mixed model with sites and blocks as fixed effects and others as random effects, and using average volume as a selection index, genetic gain could be estimated according to different selection ratios (see Table 7). At Leizhou, heritabilities were height (0.3197), diameter (0.2481) and volume (0.3421).

Genetic gain for tree volume can be increased at different selection ratios to reach 4.86–12.78% at a 1/5 selection ratio. Six families with broad adaptability,

44, 47, 88, 50, 66 and 68, were selected in at least three sites (ranked above No. 15). Families with narrow adaptability were selected on volume production. Families with narrow adaptability are: at Raoping, 23, 94, 47, 53 and 113; at Leizhou, 47, 108, 71, 99 and 121; at Heyuan, 88, 109, 66, 69 and 98; and at Xinhui, 53, 50, 88, 47 and 45. Genetic gain for provenance selection is related to selection methods. In Table 7, the genetic gains are as calculated before thinning. By thinning and eliminating poor families and keeping excellent families in seed orchards, the formula for calculating genetic gain would be:

$$\Delta G = 2(\bar{x} - \bar{X}) \times h_f^2 / \bar{X}$$

i.e. genetic gain is doubled.

Table 5. Analysis of variance of growth of *Eucalyptus urophylla* at three sites at 3 years old.

Site	Source of variation	DF	F value[a]		
			Height	dbh	Volume
Raoping	Block	3	2.31	8.08**	4.65**
	Family	37	4.20**	2.35**	2.99**
	Family × block	111	1.92**	1.65**	1.76**
Leizhou	Block	3	67.30**	0.83	7.71**
	Family	48	1.87**	2.03**	2.06**
	Family × block	144	1.56**	0.95	1.05
Heyuan	Block	3	83.53**	12.25**	28.73**
	Family	35	5.18**	2.44**	2.71**
	Family × block	105	3.44**	1.26	1.85**
Xinhui	Block	3	105.29**	40.49**	49.56**
	Family	35	8.36**	4.64**	4.96**
	Family × block	105	2.59**	1.19	1.51**
Danzhou	Block	3	7.30**	4.25**	8.23**
	Family	80	2.90**	1.70*	2.57**
	Family × block	240	0.97	0.70	0.98

[a]   * and ** indicate significance difference at the 5% and 1% levels respectively.

Table 6. Superior families of *Eucalyptus urophylla* on five sites at 3 years old.

Site	Factor	Identification numbers of the top ranked 15 families according to volume growth at 3 years old
Raoping	Top 15 families	23, 94, 47, 53, 113, 70, 88, 66, 68, 44, 107, 69, 75, 45, 50
	Testing grouping	8
Leizhou	Top 15 families	47, 108, 71, 99, 121, 100, 109, 55, 66, 52, 72, 59, 98, 113, 116
	Testing grouping	8
Heyuan	Top 15 families	88, 109, 66, 69, 98, 71, 90, 107, 83, 68, 81, 47, 87, 94, 50
	Testing grouping	10
Xinhui	Top 15 families	53, 50, 88, 47, 45, 69, 44, 71, 101, 81, 68, 111, 70, 64, 90
	Testing grouping	13
Danzhou	Top 15 families	73, 57, 72, 76, 44, 54, 68, 90, 61, 87, 48, 47, 102, 64, 83
	Testing grouping	9

Table 7. Volume genetic gain in *Eucalyptus urophylla* at three sites at 3 years old.

Sites	Genetic gain of volume in selected ratio (ΔG%)				
	1/2 selected ratio	1/5 selected ratio	Six families of broad adaptability	Part sites superior families	Six families of broad adaptability + part sites superior families
Raoping	5.33	10.18	5.42	12.39	8.59
Leizhou	2.73	4.86	1.46	6.02	3.74
Heyuan	3.62	5.14	2.14	5.30	3.37
Xinhui	7.43	12.78	8.49	14.42	10.57

Discussion

Results of multiple-site progeny testing of superior families in a *E. urophylla* seed orchard show that there are highly significant differences in growth statistics between families and sites, and family × site interaction is also highly significant. The order of volume growth of 3-year-old families at five sites is: Raoping > Leizhou > Heyuan > Xinhui > Danzhou, and it indicates that *E. urophylla* is adapted not only to the tropical region but also to the subtropical region. The area of north Guangdong (south of 24°23'N) with hilly topography, and the plains of eastern Guangdong are ideal districts in which to develop high yielding plantations of *E. urophylla*. The production potential in these districts should be no lower than that of the main *E. urophylla* planting region of western Guangdong.

Some families have relatively different growth rates on different sites, so different superior families should be selected to suit a particular region. In this test, nos 44, 47, 50, 66, 68 and 88 are families with broad adaptability. Superior families well adapted to different regions are: to northern Hainan, 73, 57, 72, 76 and 44; to Leizhou Peninsula, 47, 108, 71, 99 and 121; to the central region of Guangdong, 53, 50, 88, 47 and 45; to the northern part of Guangdong, 88, 109, 66, 69 and 98; and to eastern Guangdong, 23, 94, 47, 53 and 113.

Multiple-site testing of progeny from a seed orchard shows that the progeny originating in provenances 14534, 14531, 16882 and 17567 from Mt Egon, Flores Island, Indonesia grow well at the five test sites. Thirty-three families ranked above No. 15 were selected, and account for 76.7% of superior selected families. The testing provides an important basis for thinning the *E. urophylla* seed orchard in Daze, Xinhui, and it also provides a basis for directing seed from individuals in this orchard to afforestation regions with different environmental conditions. If collection and segregation of seed by site adaptability on the basis of broad and narrow adaptability or using a selection ratio of 1/5 to define superior families, the genetic gains for volume are 3.37–10.57% and 4.86–12.78%, respectively.

Through thinning to eliminate poor families and retain superior families in seed orchards, the genetic gain for volume can be increased to 6.74–21.14% and 9.72–25.56%, respectively.

Selection of families with broad or narrow adaptability and the retention of the same groups when progeny testing, can provide a useful basis for genetically upgrading *E. urophylla* seed orchards. To upgrade the breeding population, one strategy that might be considered is the establishment of *E. urophylla* clonal seed and cross-breeding orchards using vegetative material collected from superior families. Another strategy is to establish second-generation *E. urophylla* seed orchards using seed collected from superior families. In both these options, care must be taken to ensure the genetic base is not too narrow.

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Selection of Cold-Tolerant Eucalypts for Hunan Province

Lin Mujiu,[1] R. Arnold,[2] Li Bohai[1] and Yang Minsheng[3]

Abstract

Hunan province has a subtropical monsoonal climate. While it experiences long, very hot and humid summers, its winters can be relatively cold and, in occasional years, severe cold periods (days of continuous sub-zero temperatures) can be encountered when masses of cold air flow in from the northwest. The combination of hot moist summers and cool to occasionally very cold winters can be particularly testing to the adaptability of exotic species such as eucalypts. Eucalypts were first introduced to Hunan in the 1920s, and a range of planting initiatives over the next 50 years generally ended in widespread failure due to use of inappropriate species and provenances. After surveys of these in the mid 1980s revealed a few plantings had not only survived but grown very well, Hunan Forestry Department proceeded to establish a number of species–provenance trials throughout central and southern Hunan. The results from five of these trials are presented and discussed. The trials reported demonstrate that selected provenances of *Eucalyptus dunnii, E. saligna, E. camaldulensis* and *E. tereticornis* have potential for plantation establishment in some Hunan environments. Across the trials, *E. dunnii* and *E. saligna* have generally shown the best growth and adaptation to the extremes of Hunan's environment. A number of other species, such as *E. benthamii,* also have potential, based on the combination of success in some of the trials and the species' climatic profiles that have been developed elsewhere. However, it emphasised that all of the trials reported are relatively young (<7 years old) and the results must be regarded as preliminary. In the future, attention will also need to be focused on soil, nutritional and silvicultural management, and wood quality, for eucalypt plantations to be successful in Hunan.

Hunan province is situated immediately to the south of the middle reaches of the Changjiang (Yangtze) River. It has an area of 210,500 km^2 and ranges in latitude from 24°39' to 30°08' N and in longitude from 108°47' to 114°15' E. It adjoins the province of Hubei to the north, Jiangxi to the east, Guangdong to the southeast, Guangxi to the southwest, and the provinces of Chongqing and Sichuan to the west. Topographically, mountains rising to over 1000 m above sea level to the east, south and west bound the province, but it is open to the low-lying country to its north.

Hunan has a subtropical monsoonal climate and experiences long, very hot and very humid summers, with mean maximum temperatures of the hottest month (July) generally being above 30°C. Even so, there is a clear distinction among all four seasons, and winters can be relatively cold, with the mean minimum temperature of the coldest month (January) averaging only 3–8°C and absolute minimum temperatures being around –6 to –10°C. In the north, there is an average of over 100 frost days a year, while in the south the average is only around 60 days.

[1] Forestry Science & Technology Extension Station, Hunan Provincial Forestry Department, 338 Ziyuan Road, Changsha City, Hunan 41007, China.
Email: <faefdh@public.cs.hn.cn>.

[2] CSIRO Forestry and Forest Products, PO Box E 4008, Kingston, ACT 2604, Australia.
Email: <roger.arnold@csiro.au>

[3] China Eucalypt Research Centre, 30 Mid Renmin Road, Zhanjiang, Guangdong 524022, China.
Email: <cerclb@pub.zhanjiang.gd.cn>.

Maximum precipitation occurs during spring and early summer, with total annual rainfall averaging around 1400 mm, though there is less in the north than the south. Late summer and early autumn (July–September) is often a period of high temperatures and little precipitation, despite persistently high humidity.

Northern parts of Hunan, which are lower in altitude and exposed to the north, generally experience more extreme weather conditions in both summer and winter than do southern parts of the province. In some winters, severe cold periods (days of continuous sub-zero temperatures) can be encountered when masses of cold air flow in from the Gobi Desert and Siberia to the northwest. These inflows of chilled air can result in substantial losses to agricultural, horticultural and even forestry crops. The extreme contrasts that are a feature of Hunan's climate (i.e. frequent winter frost with occasional advective freezes, high summer temperatures and summer rainfall, which are combined with high humidity yet later summer drought) can be particularly testing to the adaptability of exotic species such as eucalypts (Arnold and Luo 2002).

Soils of sites available for forest plantations in Hunan are generally deep (>1.5 m), well drained and permeable, with profiles characterised by reddish-brown heavy clay loam surface layers overlying dark-red, well-structured light clays (Laffan 2002). Depending on the content of free iron, the soils are classified as either red dermosols or red ferrosols. Most of the soils are derived from substrates of either sandstone, siltstone or limestone and, across much of the province, soils of forest plantation sites have been severely degraded by sheet erosion with subsoils now exposed on the surface. These soils are strongly acidic and poor in organic material. The main soil limitation is generally their low level of nutrients that, together with the high content of iron oxides in some red soils, necessitates repeated applications of fertilisers to achieve good growth rates. Although there are good quality, less acidic alluvial soils on Hunan's northern plains, these are primarily devoted to growing rice and a variety of other crops.

Eucalypts were probably first introduced into Hunan in 1926. In the 1950s and 1960s, some extensive plantings were undertaken by forestry, railway and road departments with most plantings being, as one might expect, along railways and roads. These plantings used a wide range of species and seed sources, but were primarily *Corymbia citriodora* and *Eucalyptus exserta,* which thrived in the warmer coastal areas of more southern provinces. However, most of the species and seed sources used proved to be poorly adapted to Hunan's testing environment and there were widespread failures (Turnbull 1981). Nonetheless, investigations in 1986 revealed that some species had survived and even prospered. Remnants of various plantings were found in 78 of the province's counties, with the most common species being *E. camaldulensis*, *E. robusta* and *E. botryoides*. Of these, the most productive and best adapted has been *E. camaldulensis* with some of the 40-year-old trees averaging over 25 m in height and up to 63 cm in diameter at breast height (dbh).

Since the mid 1990s, Hunan Forest Department has developed a more scientifically based domestication program for eucalypts in Hunan, and now pays attention to both the environmental amplitudes of species introduced and the socioeconomic conditions of regions for plantation establishment. Much of this work has been undertaken in close collaboration with Australian researchers, and a wide range of new species and provenances has been introduced over the past 10 years from Australia

Eucalypt Species–Provenance Trials in Hunan

Since the mid 1990s, Hunan Forest Department has established numerous field trials and demonstration plantings using a wide range of eucalypt species and provenances obtained from natural stands in Australia. This paper presents extracts from the results from five of the more important trials.

1997 species–provenance trial — selection for growth and cold tolerance

This trial was established in June 1997, approximately 6 km west of Chengzhou city in southern Hunan, and includes 14 provenances representing 7 species (Table 1). It is located on a low hill site with a gentle northern slope at an elevation of 246 m asl. The site features a deep 'red soil' (>3 m) derived from slate–shale of medium fertility. This site was previously occupied by regrowth scrub comprising a mixture of species. The trial comprises a randomised complete block design with 4 replicates, 64 tree plots (8 × 8 trees) and a between-tree spacing of 2.0 × 2.0 m. The site was spot cultivated by hand, planting holes dug and 300 g compound fertiliser (NPK) was

incorporated into the soil at the base of each planting hole before planting.

In December 1999, when the trial was approximately 30 months old, Hunan experienced a severe cold event. In Chengzhou City near the trial, the minimum temperature dropped to –7.9°C. The impact of this freeze was particularly bad, as the weather in the preceding weeks had been unseasonably warm. Three months after the cold event, an assessment was made of the trial for both growth (dbh and total height) and cold damage (approximately age 33 months) of all remaining trees. Cold damage was assessed visually using a simple 4 point scale. A score of 1 was assigned to very heavily damaged and dead trees, score 2 to moderate to heavily damaged trees showing significant resprouting/recovery, score 3 to lightly damaged trees, and a score of 4 to very lightly damaged or undamaged trees.

Results

Eucalyptus badjensis (17774) sustained almost no visible damage from the freeze (Table 1). Provenances of *E. tereticornis*, *E. dunnii* and *E. saligna* showed reasonable resilience to the freeze, with fewer than 10% of trees killed and mean cold damage scores generally greater than 2.5. In contrast, all trees of *E. microcorys* (13971) were killed and the locally sourced material of *E. camaldulensis*, for which the original Australian origin(s) is uncertain, proved to have relatively poor cold tolerance. For *E. grandis*, the natural stand seed lot (15921) with 31% mortality showed markedly poorer cold tolerance than the seed orchard seed lot (18146) with just 8% mortality.

For the combination of growth and cold tolerance, *E. saligna* (16620), *E. dunnii* (15965) and *E. tereticornis* (17430) and (16439) were some of the best. Despite the very good cold tolerance of *E. badjensis* (17774), its growth was relatively poor to age 33 months in this trial. The best growth in the trial was by the seed orchard material of *E. grandis* (18146) and, despite its apparently poor cold tolerance, the locally sourced *E. camaldulensis* also grew very well.

1997 species trial — selection for growth

This trial was established in May 1997 at Xiadeng Village of Longbo Town in ShuangPai County in southern Hunan. It included five species (Table 2) and although the seed was provided through the China Eucalypt Research Centre from the CSIRO Australian Tree Seed Centre, the exact details on the specific set of seed lots included in this trial have been misplaced. The trial is on a low hilltop site approximately 400 m asl. The site features a deep, yellow dermosol soil (>3 m) derived from slate–shale parent of medium fertility (M. Laffan, unpublished data). This site had been occupied by low scrub. The trial comprises a randomised complete block design with 3 replicates, 20 tree row plots and a between tree spacing of 2.0 _ 2.0 m. The site was disc ploughed, planting holes dug by hand and 250 g of superphosphate was incorporated in the soil at the base of each hole before planting.

All trees remaining in the trial were assessed in August 2002, at approximately age 5 years, for dbh and total height.

Results

At age 5 years, there were no trees surviving of *E. globulus* or *E. grandis*. Although the reasons for this were not directly evident from the assessment, results from other plantings in the area have indicated that *E. globulus* is not adapted to the combination of high summer temperatures and high humidity, or to cold as severe as that encountered in December 1999. All the *E. grandis* are thought to have been killed in the cold of December 1999 and/or succumbed to late summer/autumn drought.

Eucalyptus saligna, E. dunnii and *E. tereticornis* had survivals to age 5 years of over 80% and have proven reasonably well adapted to the local environment. *E. saligna* showed the best growth overall, while average height and diameter for *E. dunnii* and *E. tereticornis* were approximately 20% less (Table 2).

1996 species trial

This trial was established in May 1996 in DaoXian County in southern Hunan. It included *E. globulus, E. nitens, E. saligna* and *E. dunnii* provided through the China Eucalypt Research Centre from the Australian Tree Seed Centre (see Table 3). The trial is on an open, level site at approximately 300 m asl. The site features a red ferrosol soil (>3 m) derived from limestone of low natural fertility (M. Laffan, unpublished data). This site had previously been occupied by low-quality pasture. It comprises a randomised complete block design with 3 replicates, 10 tree row plots and a between tree spacing of 2.0 × 2.0 m. The site was strip ploughed, the planting holes dug by hand and 250 g of fused calcium magnesium phosphate incorporated into the soil at the bottom of each hole as base fertiliser before planting.

Table 1. Seed source details with their average growth to age 33 months along with their average cold damage scores and percentage mortality from the December 1999 cold event in the eucalypt species provenance trial near Chengzhou City in Hunan.

Seedlot[a]	Species	Provenance details				Means and (rankings)			
		Locality	Latitude (° 'S)	Longitude (° 'E)	Alt. (m)	Height (m)	Dbh (cm)	Cold damage score	Trees killed by cold (%)
15956	E. dunnii	Dead Horse Track, NSW	28 25	152 20	650	5.1 (6)	5.6 (4)	3.1 (4)	7.2 (8)
18231	E. dunnii	Koreelah State Forest, NSW	28 18	152 30	575	4.1 (12)	4.5 (10)	3.2 (3)	4.4 (4)
18264	E. dunnii	Yabbra Plains Rd, NSW	28 37	152 29	500	4.4 (10)	4.7 (8)	3.1 (5)	6.3 (6)
17555	E. dunnii	Moleton–Kangaroo State Forest NSW	30 05	152 54	420	4.7 (8)	4.8 (7)	2.7 (9)	8.2 (10)
17733	E. dunnii	Spicers Gap, Qld	28 04	152 22	650	4.2 (11)	4.5 (9)	3.2 (2)	7.4 (9)
Landrace	E. camaldulensis	Dukou, Sichuan, China				5.4 (3)	5.1 (6)	2.8 (6)	18.2 (12)
17430	E. tereticornis	Loch Sport, Vic.	38 04	147 35	10	4.8 (7)	5.2 (5)	2.7 (8)	4.1 (3)
16349	E. tereticornis	Atherton–Wongabel, Qld	17 19	145 28	780	5.4 (4)	4.4 (12)	2.3 (11)	2.7 (2)
17761	E. tereticornis	Spicers Gap SF, Qld	28 03	152 24	675	4.6 (9)	4.1 (13)	2.7 (10)	6.9 (7)
18146	E. grandis	Coffs Harbour Seed Orchard, NSW	30 08	153 07	100	7.4 (1)	7.4 (1)	2.0 (12)	8.3 (11)
15921	E. grandis	Kempsey Tan Ban SF NSW	30 52	152 51	50	5.4 (5)	6.1 (3)	1.9 (13)	31.0 (13)
13971	E. microcorys	NNE of Kendall, NSW	31 34	152 47	40	2.6 (14)	2.0 (14)	1.0 (14)	100.0 (14)
17774	E. badjensis	Glenbog State Forest, NSW	36 36	149 26	1050	4.1 (13)	4.5 (11)	3.9 (1)	0.0 (1)
16620	E. saligna	Yadboro State Forest, NSW	35 20	150 12	60	5.8 (2)	6.2 (2)	2.7 (7)	4.5 (5)

[a] All seedlots, except for the 'landrace' lot of *E. camaldulensis*, were supplied by CSIRO's Australian Tree Seed Centre.

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Table 2. Average growth of eucalypt species to approximately age 5 years in the trial established in 1997 in ShuangPai County, southern Hunan.

Species	Means and (rankings)	
	Height (m)	Dbh (cm)
E. dunnii	9.0 (3)	11.2 (2)
E. globulus	n.s.[a]	n.s.
E. grandis	n.s.	n.s.
E. saligna	11.2 (1)	13.1 (1)
E. tereticornis	9.1 (2)	11.0 (3)

[a] No survivors.

In 1998, this trial had a severe drought of about 5 months from June to November (summer–autumn). In December the following year, there was severe cold with temperatures in the area falling rapidly to –7.0°C. When approximately 6 years old in August 2002, the remaining trees were assessed for dbh and total height.

Results

None of the *E. globulus, E. grandis* or *E. nitens* survived to age 6 years. It is likely that *E. globulus* and *E. nitens* succumbed to the combination of high summer temperatures and high humidity, and possibly the drought in 1998. *Eucalyptus grandis* would most likely have either been killed in the drought of 1998 and/or the cold of December 1999.

Both *E. dunnii* and *E. saligna* survived the 1998 drought and 1999 cold reasonably well, with survivals of over 70% to age 6 years. Growth of both species was reasonable, with *E. saligna* (16620) performing

slightly better than *E. dunnii* (17733) (Table 3). Both species had average height increments of over 2.0 m yr^{-1} and diameter increments over 2.3 cm yr^{-1}.

2001 species–provenance trials (two sites)

Two large eucalypt species–provenance trials were established in April 2001, as part of a Chinese–Australian collaborative project 'Development of germplasm and production systems for cold tolerant eucalypts for use in cool regions of southern China and Australia'. One site, located at Yongzhou City Forestry Research Institute, is representative of southern Hunan plantation environments. The other is located at Shaoyang City Forestry Research Institute and represents central Hunan plantation environments.

The Yongzhou site is on a gentle southeasterly slope. The soil is a red dermosol of silty clay loam to silty clay texture (M. Laffan, unpublished data). Previously, the site was occupied by citrus orchards. Site preparation comprised manual spot cultivation and planting holes of $50 \times 50 \times 50$ cm were dug. Into the soil at the base of each planting hole, 2000 g of rapeseed compost, 500 g pig manure and 500 g phosphorus fertiliser were incorporated.

The Shaoyang site is an undulating hilltop site with a red dermosol soil of clay loam to light clay texture. This site had previously been occupied by scrub comprising a mixture of *Sassafras tzumu, Camellia oleifera* and *Pinus massoniana*. Planting holes of $80 \times 80 \times 70$ cm were dug after full surface cultivation. Fertilisation was carried out by incorporating Four kg of rapeseed compost and 500 g phosphorus fertiliser were incorporated into the base of each planting hole before planting.

Table 3. Average growth of eucalypt species to approximately age 6 years in the 1996 trial in DaoXian County, southern Hunan.

Seedlot[a]	Species	Provenance details				Means and (rankings)	
		Locality	Latitude (° ' S)	Longitude (° ' E)	Alt. (m)	Height (m)	Dbh (cm)
17733	*E. dunnii*	Spicers Gap, NSW	28 04	152 22	650	13.0 (2)	13.8 (2)
Landrace	*E. globulus*	Yunnan, China				n.s.[b]	n.s.
18146	*E. grandis*	Coffs Harbour Seed Orchard, NSW	30 08	153 07	100	n.s.	n.s.
18264	*E. nitens*	Blue Range Rd, Vic.	37 24	145 48	1000	n.s.	n.s.
16620	*E. saligna*	Yadboro State Forest, NSW	35 20	150 12	60	13.7 (1)	14.7 (1)

[a] All seedlots, except for the 'Landrace' lot of *E. globulus,* supplied by CSIRO Australian Tree Seed Centre.
[b] No survivors.

At both sites, the trials were randomised complete block designs, with five replicates. Plot size was 20 trees (4 rows of 5 trees) with a between tree spacing of 2.0 × 3.0 m. The seed lots for the trial were supplied by CSIRO's Australian Tree Seed Centre and details are provided in Table 4.

In the summer following establishment there was a significant drought in southern Hunan. During the period from 21 June to 25 August 2001, almost no rain fell in the region at a time of very high summer temperatures (maximum temperatures up to 44°C in Yongzhou City). This situation had a noticeable impact on survival and early growth in the Yongzhou trial. In contrast, rainfall during the summer of 2001 in the Shaoyang area was close to normal. In August 2002, at approximately age 15 months, both trials were assessed for survival and, on all surviving trees, dbh and total height were measured.

Results

Overall survival and growth to age 15 months was markedly better at Shaoyang than at Yongzhou. This difference is attributed primarily to the drought encountered around Yongzhou in the first summer after establishment.

At Yongzhou, *E. dunnii* (18264) and *E. benthamii* (18787) had the best survival (Table 5). Poorest survival at this site was by *E. badjensis* (19606) and *E.*

dalrympleana (12563 and 18692). At Shaoyang, all but *E. dalrympleana* (12563 and 18692) and *E. smithii* (16916) had greater than 80% survival.

Rankings for height and diameter growth between the two sites were similar. *E. dunnii* (17555) had the best growth overall, with *E. dunnii* (18264) and *E. benthamii* (18787) also growing very well at both sites. Two *E. smithii* provenances included in the trials had good growth at Yongzhou but were only mediocre at Shaoyang. The growth of the locally selected *E. camaldulensis* clone (C34) was generally inferior at both sites, although it did produce above average diameter at Shaoyang. The three provenances of *E. dalrympleana* (12563, 16514, 18692), *E. badjensis* (19555) and *E. viminalis* (14920) all grew relatively poorly to age 15 months at both sites.

Discussion and Conclusions

From the trials reported above it is apparent that selected provenances of *E. dunnii, E. saligna, E. camaldulensis* and *E. tereticornis* have good potential for plantation establishment in some Hunan environments. Across the trials, *E. dunnii* and *E. saligna* generally grew best and proved reasonably well adapted to Hunan's extremes of hot humid summers, frequent winter frosts and occasional severe cold events caused by freezing air masses moving in from the north.

Table 4. Details of seedlots included in the eucalypt species–provenances trials established in 2001 at Yongzhou and Shaoyang in Huna.

Seedlot[a]	Species	Provenance details				
		Locality	State	Latitude (° ' S)	Longitude (° ' E)	Alt. (m asl)
19555	*E. badjensis*	Glenbog	NSW	36 29	149 19	1100
19606	*E. badjensis*	Deua National Park	NSW	35 59	149 40	960
18787	*E. benthamii*	Kedumba Valley	NSW	33 49	150 23	140
12563	*E. dalrympleana*	Nundle State Forest, Tamworth	NSW	31 27	151 15	1250
16514	*E. dalrympleana*	Mt Canobolas, Orange	NSW	33 22	148 58	1080
18692	*E. dalrympleana*	Brindabella	ACT	35 23	148 49	1150
17555	*E. dunnii*	Moleton–Kangaroo State Forest	NSW	30 05	152 54	420
17917	*E. dunnii*	Koreelah State Forest	NSW	28 18	152 30	575
18264	*E. dunnii*	Yabbra Plains Road	NSW	28 37	152 29	500
16916	*E. smithii*	12 km NE Orbost	Vic.	37 34	148 29	370
19819	*E. smithii*	Wingello State Forest	NSW	34 44	150 10	600
14920	*E. viminalis*	Cotter Catchment	ACT	35 38	148 50	1100
18308	*E. viminalis*	S Tallaganda State Forest	NSW	35 58	149 35	900
19817	*E. viminalis*	Glenbog State Forest	NSW	36 38	149 26	1000
C34	*E. camaldulensis*	clone from plus tree selected in Hunan				

[a] All seedlots, except for the clone of *E. camaldulensis,* were supplied by CSIRO Australian Tree Seed Centre.

Table 5. Average survival, height and diameter at breast height (dbh) to age 15 months of seedlots in the eucalypt species–provenances in the trials established in 2001 at Yongzhou and at Shaoyang in Hunan.

Seedlot no.[a]	Species	Provenance means and (rankings) at Shaoyang			Provenance means and (rankings) at Yongzhou		
		Survival (%)	Height (m)	Dbh (cm)	Survival (%)	Height (m)	Dbh (cm)
19555	E. badjensis	87.0 (7)	3.5 (11)	2.9 (13)	53.6 (10)	2.7 (13)	2.3 (12)
19606	E. badjensis	82.5 (11)	4.1 (5)	3.7 (8)	41.7 (15)	3.1 (9)	2.8 (9)
18787	E. benthamii	93.3 (2)	4.4 (3)	4.6 (2)	69.0 (2)	3.8 (4)	4.4 (1)
12563	E. dalrympleana	50.0 (15)	2.5 (15)	2.2 (15)	46.4 (13)	2.1 (15)	1.6 (15)
16514	E. dalrympleana	91.5 (4)	2.7 (14)	2.6 (14)	55.1 (7)	2.1 (14)	1.8 (14)
18692	E. dalrympleana	78.3 (13)	3.3 (13)	3.0 (12)	42.7 (14)	2.8 (11)	2.6 (11)
17555	E. dunnii	87.0 (6)	5.0 (1)	4.6 (1)	60.7 (4)	4.1 (1)	3.8 (3)
17917	E. dunnii	85.0 (9)	4.0 (6)	3.9 (5)	59.3 (5)	3.4 (6)	3.3 (6)
18264	E. dunnii	86.0 (8)	4.6 (2)	4.4 (3)	70.5 (1)	4.0 (2)	3.9 (2)
16916	E. smithii	59.6 (14)	3.9 (9)	3.3 (10)	54.4 (8)	3.7 (5)	3.4 (5)
19819	E. smithii	90.6 (5)	4.1 (4)	3.7 (7)	52.3 (12)	3.9 (3)	3.5 (4)
14920	E. viminalis	80.9 (12)	3.3 (12)	3.0 (11)	62.7 (3)	2.9 (10)	2.7 (10)
18308	E. viminalis	93.0 (3)	4.0 (7)	3.8 (6)	54.3 (9)	3.1 (8)	2.9 (8)
19817	E. viminalis	82.7 (10)	3.8 (10)	3.6 (9)	52.5 (11)	3.3 (7)	3.0 (7)
C34	E. camaldulensis	97.0 (1)	3.9 (8)	4.0 (4)	56.0 (6)	2.8 (12)	2.2 (13)

[a] All seedlots were supplied by the CSIRO Australian Tree Seed Centre, except for the clone of *E. camaldulensis*.

Table 6. Climatic parameters for Hunan province and known climatic requirements for viable plantations of various eucalypt species[a] based on both their native habitats and successful plantation environments.

Climatic parameter	Hunan[b]	Eucalyptus benthamii	E. camaldulensis	E. dunnii	E. globulus	E. grandis	E. saligna	E. tereticornis	E. viminalis
Altitudinal range (m asl.)	100–800	30–150	20–700	60–1800	0–2400	0–2400	0–2100	0–1000	0–1400
Mean annual rainfall (mm)	1200–1700	500–2500	400–2500	750–1950	500–1500	900–2500	500–1500	500–3000	500–2500
Rainfall regime	summer	summer	summer, winter or uniform	summer, uniform	winter, bimodal	winter, bimodal, uniform	summer, winter or uniform	summer, winter or uniform	winter, uniform, bimodal
Dry season duration (months)	0–2	0–5	0–8	0–5	0–7	0–5	0–7	0–8	0–5
Mean annual temperature (°C)	15–20	13–17.	13–28	14–22	9–21	9–21	10–22	10–27	4–17
Mean maximum temp. of hottest month (°C)	27–30	>27	21–41	24–31	19–31	23–36	23–34	22–40	21–32
Mean minimum temp. of coldest month (°C)	3–8	>4	0–22	–1 to 17	0–15	3–20	–1 to 17	–2 to 19	–4 to 9
Number of days of frost	30–65	10–25	0–50	0–60	0–60	0–15	5–50	0–25	5–60
Absolute minimum temp. (°C)	–5 to –9	>–10	>–9	>–10	>–8	>–6	>–9	>–8	>–12

[a] Sources of data on climatic requirements of the eucalypt species were CAB International (2000) and Jovanovic and Booth (2002).
[b] Parameters provided for Hunan are for target plantation environments in the province.

It is instructive to consider the results from the trials examined above in respect to climatic profiles that have been developed for the various species, based on both their native habitats and successful plantation environments (Table 6). It has been well established elsewhere that *E. globulus* is a species primarily suited to mediterranean-type environments which feature dry summers and cool moist winters (CABI 2000; Jovanovic and Booth 2002). Thus, it is not surprising that this species has generally failed in Hunan. However, it is inappropriate to consider climate as the sole determinant of species adaptability; of soil and other environmental factors must also be taken into account. For instance, *E. grandis* prefers moist, well-drained, deep, loamy soils of alluvial or volcanic origin. It cannot tolerate long periods of drought or sites on dry, stony, skeletal soils or those with relative little moisture-holding capacity (CABI 2000). It is likely to have been the combination of minimum temperatures at the lower limit of *E. grandis*'s tolerance along with the species inability to tolerate drought that together led to its failure in some of these Hunan trials.

Clearly, the future selection of eucalypt species–provenances for testing in Hunan must be based on what is already well-known about their environmental preferences. Information in Table 6 relates well to observations from Hunan trials. In addition, this and information available on a range of species not included in the table, indicate that a number of eucalypt species warrant further testing in Hunan, especially *E. benthamii*.

The trees in all the trials examined here have been relatively young (i.e. age 6 years or less). While they have clearly shown species such as *E. globulus*, *E. microcorys* and *E. grandis* are not adapted to Hunan's environment, the trials are generally too short to draw definitive conclusions about the successful species and provenances. This is especially true in the case of the 2001 species–provenance trials at Shaoyang and Yongzhou — at the time of assessment neither of these trials had experienced one of the cold events/advective freezes which typically limit the success of many exotic species in Hunan province. Once trees in the trials reach merchantable sizes, it will also be important to carry out analyses of their wood properties — the trees must not only grow well they must produce timber of value to potential end users.

Following on from the selection of superior eucalypt species and provenances for plantation establishment in Hunan, attention will now need to be given to tree improvement and mass production of superior individuals by way of seed, rooted stem cuttings and/or tissue culture. This will require development of breeding populations and seed orchards of the key species as a priority in Hunan. A shortage of local production capacity for seed of eucalypt species and provenances adapted to the cooler areas of south-central China, such as Hunan, has been a major barrier to expansion of cold-tolerant eucalypt plantations in such areas (McKenney et al. 1991; Arnold and Luo 2002; Arnold and Xiang 2003).

Successful development of large areas of eucalypt plantations in Hunan will require detailed understanding and intensive management of soil types and nutrition in the target plantation environments (M. Laffan, unpublished data). Similarly, quality silvicultural management will be an absolute requisite for the combination of genetic and site potentials to be fully realised in this new environment for eucalypt plantation development. Direct adoption of silvicultural regimes employed in China's tropical and subtropical coastal eucalypt plantations may not be appropriate in Hunan — the species, target end products, sites and market access are widely different.

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Review of Cold-Tolerant *Eucalyptus* Improvement in Fujian Province

Lan Hesheng,[1] Qiu Jingqing,[1] Xie Guoyang,[1] Huang Delong,[2] Zhao Shirong[3] and Lin Wenge[4]

Abstract

Some cold-tolerant *Eucalyptus* species or provenance/family trials established in Fujian province since the late 1980s are reviewed. Results confirmed the feasibility of successful eucalypt plantations in northwestern Fujian. Species such as *E. grandis, E. saligna* and *E. dunnii* grew well and were most cold-tolerant. Growth of *E. camaldulensis* was comparatively fast in young stands but slow in older stands, so its performance should be tested for a longer period. All provenance/family trials showed considerable variance of growth and cold tolerance among trees, families and provenances. Variance among trees seems to be greatest. It suggested that cold-tolerant *Eucalyptus* improvement has high potential to increase volume growth of plantations. Integration of plus tree selection and rapid clonal propagation is an effective method to greatly increase genetic gain.

As a key timber-production area in southern China, Fujian has the highest forest coverage rate in the country, with 7.35 million ha of forests, covering 60.5% of the total land area, and with a total standing volume of 417 million m^3. Fujian is suitable for eucalypt planting and introduced eucalypts at an early date. Eucalypts have been evaluated, and interest in plantations has increased gradually in recent years. Eucalypts have become the most important species in short-rotation forestry. According to the Forestry Plan of Fujian, 12,000 ha of eucalypt plantation will be established this year, which accounts for almost half of total area of high-yielding forest to be planted in 2003.

Eucalypt improvement is not very advanced, due to a late start and little support. There has been no eucalypt seed-orchard development or breeding, and none of the popularly planted clones has been selected locally. This has severely hampered the development of eucalypts in Fujian, especially in the northwest of the province. However, cold-tolerant eucalypt improvement has gained momentum in recent years, and systematic introduction and provenance/family trials have been initiated. Recently, more than 30 species have been introduced of which 6 are in provenance/family trial stands. This research will provide scientific data to select suitable species for the northwest, and also consolidate the gene resources and foundation for sustainable improvement for cold-tolerant eucalypts in Fujian.

Eucalyptus Introduction Trials

More than 260 species have been introduced into Fujian since the first introduction in 1894, but most introductions have been haphazard (Shi and Zhou 1994). Large-scale introductions began in the late

[1] General Forest Seed & Seedling Station of Fujian Province, Fuzhou 350003, China.
[2] Yongan State-owned Forest Farm, Yongan, Fujian 366000, China.
[3] Weimin State-owned Forest Farm, Shaowu, Fujian 3540006, China.
[4] Yongan Forestry Group Co., Yongan, Fujian 366000, China.

1980s and some 30 species been brought in since then. Some species trials experienced the very cold weather in 1999. Most analyses of the species trials have focused on growth and cold tolerance, except for the work of Chai et al. (1993), which reported variance of basic density and fibre length among 45 provenances of 4 species.

Species trial in central Fujian

In 1987, a trial including 15 species was established in a complete randomised block design in Tuoshi State-owned Forest Farm, near Fuzhou. Growth measurements were made in 2000 (Table 1) and showed major differences between species, e.g. volume growth of the best species (*E. cloeziana*) is 25 times greater than that of the slowest (*E. cinerea*). Although growth in the trial is not as good as other trials due to poor soil fertility, there are six species in which annual height and diameter breast height (dbh) growth surpass 1 m and 1 cm, respectively. Of these species, *E. cloeziana* is the fastest-growing, followed by *E. grandis*, *Corymbia citriodora* (*E. citriodora*), *E. resinifera*, *E. tereticornis* and *E. urophylla*. The trial had very light frost damage in 1999, with the highest cold injury index of 3 due to relatively light cold air flow in the vicinity of Fuzhou. *Eucalyptus pellita*, *E. microcorys*, *C. torelliana* and *E. camaldulensis* suffered the most serious damage, with about one-third of the trunk injured by the cold, while the

six fastest-growing species had little damage, except *E. urophylla* with cold injury index 2.

Species trials in northwestern Fujian

Species trials were established in Yongan in 1994 (11 species), 1998 (11 species) and 2001 (13 species).

Growth details and cold injury index of the 1994 trial are in Table 2. The trial was established in a completely randomised design with four replications, and with a hybrid clone (*E. grandis × E. urophylla*) as the control. There was variability in growth and cold tolerance among the species (Huang et al. 2003). *Eucalyptus grandis* grew fastest, with an average annual height growth of 3 m and dbh of 3 cm. It had high cold tolerance as it only suffered light cold injury (index 2) during the cold event of 1999 in which the lowest temperature was –5.6°C. There were 7 days with the lowest temperature below 0°C. The hybrid clone had the second best growth but suffered serious cold damage (index 4) with almost half the trees killed. *Eucalyptus saligna* also showed favourable growth as the third fastest with average annual height growth of 3 m and quite good cold tolerance (index 3). *Eucalyptus camaldulensis* and *E. pilularis* had the best cold tolerance but poor growth, while *E. nitens* had intermediate cold tolerance and slowest growth.

Table 1. Growth of a eucalypt species trial at ca 13 years old[a] at Tuoshi, Fuzhou.

Species	Ht (m)	Dbh (cm)	Cold index	Mean annual growth		Volume (m³)
				Ht (m)	Dbh (cm)	
E. cloeziana	16.0	20.4		1.23	1.57	0.2405
E. grandis	18.1	18.5		1.39	1.42	0.2238
C. citriodora	14.1	16.9	1	1.08	1.30	0.1455
E. resinifera	14.0	15.9		1.08	1.22	0.1279
E. tereticornis	14.6	13.8		1.12	1.06	0.1005
E. urophylla	15.7	13.0	2	1.21	1.00	0.0959
E. saligna	11.9	11.3		0.92	0.87	0.0540
E. microcorys	10.3	11.1	3	0.79	0.85	0.0458
E. pellita	9.0	10.6	3	0.69	0.82	0.0365
E. exserta	9.0	9.8		0.69	0.75	0.0312
E. propinqua	9.1	8.7		0.70	0.67	0.0249
E. paniculata	8.9	8.7		0.68	0.67	0.0243
C. torelliana	9.5	7.8	3	0.73	0.60	0.0200
E. camaldulensis	9.1	6.5	3	0.70	0.50	0.0139
E. cinerea	7.0	6.1		0.54	0.47	0.0094

[a] Planted September, 1987, measured May 2000, soil classification: third grade.

A species trial was established in Yongan Forestry Group Co. in 2001, as a part of the ACIAR Sino-Australia cooperative project, and initially there are great differences in survival and growth among the species. *Eucalyptus grandis, E. dunnii* and *E. camaldulensis* had good growth and better survival. *Eucalyptus globulus, E. nitens, E. radiata* and *E. smithii* had poor survival and growth, and trees continue to die.

Species trial in northern Fujian

Less introduction work has been done in northern Fujian than in other areas. In 1998, a species trial of 11 species was established in Weimin State-owned Forest Farm, Shaowu. The trial was designed as completely randomised blocks with four replications and 25 trees per plot. Trees in the trial survived and grew well, with average survival of most species above 40%, except *E. radiata* (4%), at 2 years after planting (Table 3). *Eucalyptus nitens* had 42% survival and was ranked seventh for growth among the 11 species. The trial suffered serious damage from the cold event in 1999, in which the lowest temperature was –8° C. There were 7 days with the lowest temperature below 0°C. Almost all trees were seriously damaged, and the survival decreased sharply. Some species, such as *E. smithii* and *E. radiata,* failed completely, and others, e.g. *E. nitens, E. quadrangulata, E. badjensis* and *C. maculata* (*E. maculata*) had very few survivors. *Eucalyptus benthamii, E. dunnii* and *E. dorrigoensis* had better growth, and survival while *C. maculata*

grew rapidly at an early stage but slowed quickly after the cold event, due to its poor cold tolerance. *Eucalyptus radiata* had very poor survival since planting and this may be due to poor adaptability.

Provenance/Family Trials

The first provenance/family trial in Fujian was established in the late 1980s with *E. grandis* and was followed by similar trials of *E. dunnii, E. pellita, E. smithii, E. saligna* and *E. camaldulensis.* There are more than 1400 families of six species included in these trials. Some of the trials experienced the cold event in 1999.

Provenance/family trial of *E. grandis*

The provenance/family trial of *E. grandis* has achieved satisfactory results (Wang et al. 1989; Chai et al. 1993; Huang et al. 2001; Qiu et al. 2002). Some 500 families have been tested in southern and northwestern Fujian. The results showed significant or highly significant variation in growth, cold injury and form among the provenances and families. Cold tolerance of provenances is correlated with their origins, with those originating from higher latitude or altitudes appearing more cold tolerant. Table 4 shows growth data of the *E. grandis* provenance/family trial planted in 1997 and including 202 families. The family mean growth in eight groups is higher than that of the two controls, i.e. routine *E. grandis* seeds

Table 2. Growth and cold tolerance of eucalypt species trial at ca. 5 years old[a] at Yongan.

Species	Ht (m)	Dbh (cm)	Vol. (m³)	Mean annual growth			Cold index	Deaths (%)
				Ht	Dbh	Vol.		
E. grandis	19.5	17.7	0.2036	3.25	2.95	0.0339	2.18	12.7
E. grandis	18.6	17.2	0.1834	3.10	2.87	0.0306	1.58	5.4
E. grandis ×E. urophylla	18.2	17.0	0.1753	3.03	2.83	0.0292	3.98	47.9
E. saligna	17.9	16.9	0.1704	2.98	2.82	0.0284	2.96	23.1
E. urophylla	15.0	14.4	0.1037	2.50	2.40	0.0173	4.83	85.4
E. propinqua	13.6	12.8	0.0743	2.27	2.13	0.0124	3.28	27.7
E. pilularis	13.3	12.4	0.0682	2.22	2.07	0.0114	1.44	3.1
E. maidenii	12.1	10.4	0.0436	2.02	1.73	0.0073	1.83	6.7
E. triantha	10.6	9.9	0.0346	1.77	1.65	0.0058	5	100
E. camaldulensis	10.2	10.0	0.0340	1.70	1.67	0.0057	1.19	0
E. globulus	10.0	8.3	0.0230	1.67	1.38	0.0038	2	10.3
E. nitens	8.0	7.7	0.0158	1.33	1.28	0.0026	1.72	5.6
Average	13.9	12.9	0.1	2.32	2.15	0.0157	2.7	27.3

[a] Planted March 1994, measured December 1999, cold injury assessed January 2000, soil classified second grade.

and a *E. urophylla* × *E grandi*s clone, except in group 7, in which the controls are higher. This suggests that selected *E. grandis* will grow faster than *E. urophylla* × *E grandi*s hybrid clones in a cooler region such as Yongan, northwest Fujian. Also, it suggests substantial benefits from genetic improvement of *E. grandis*. Further, the trial results showed the growth variance among seedlots is lower than that of families and the latter lower than that of trees. It suggests the improvement gain differs among three levels, i.e. provenance, family and trees.

Provenance/family trial of *E. dunnii*

The trial was established in 1998 with 214 families of six provenances and grew very well. The best family averaged 4 m tall and 5.5 cm ground diameter

at the end of the planting year. However, the cold event in 1999 seriously damaged the trial and most trees suffered index 3 to 4 cold injury. There were 7 days with the temperature below 0°C, the lowest being –7° C in Shunchang, near the trial site. Initial analyses (Lan et al. 2003) showed variance of growth and cold tolerance among the families is significant but less than variance among trees within families. The results suggested that provenances from New South Wales (NSW) maybe better than those from Queensland, as the best provenances were located at Yabbra and Koreelah (NSW). Although the control *E. nitens* had the highest cold tolerance, (index 1 to 2 cold injury), it grew much more slowly and had an unhealthy crown with many dead leaves. The recovered stand also had good growth with the survival

Table 3. Growth and survival of a eucalypt species trial 19 months and 31 months after planting[a] at Weimin, Shaowu.

Species	19 months			31 months			Best tree at 31 months	
	Survival (%)	Ht (m)	Dbh (cm)	Survival (%)	Ht (m)	Dbh (cm)	Ht (m)	Dbh (cm)
E. benthamii	52	2.41	1.8	28	6.4	7.9	10.0	12.2
E. dunnii	66	2.42	2.1	24	6.0	7.4	10.0	13.0
E. dorrigoensis	36	2.46	1.7	18	6.2	7.1	7.5	15.9
E. nobilis	54	1.92	1.2	30	4.8	5.5	7.3	11.0
E. nitens	42	2.22	1.9	8	5.0	5.1	6.6	8.3
E. quadrangulata	43	2.43	2.0	3	1.7	4.7	7.5	6.7
E. badjensis	57	2.17	1.3	13	3.6	3.8	6.4	7.9
C. maculata	69	3.32	2.3	12	3.6	3.3	6.6	6.8
E. radiata	5	1.35	1.0	0	–	–	–	–
E. smithii	61	2.44	1.7	0	–	–	–	–

[a] Planted May 1998.

Table 4. Growth of *Eucalyptus grandis* family trial in Yongan at ca. 6 years old.[a]

Group	Family mean			Mixed seeds of *E. grandis*			*E. urophylla* × *E. grandis*			Best family		
	Ht (m)	Dbh (cm)	Vol (m³).	Ht (m)	Dbh (cm)	Vol (m³).	Ht (m)	Dbh (cm)	Vol (m³).	Ht (m)	Dbh (cm)	Vol (m³).
1	10.4	10.8	0.047	10.9	10.2	0.038	11.7	11.5	0.065	14.2	14.7	0.104
2	11.0	11.9	0.066	10.3	11.0	0.056	9.7	10.0	0.043	13.8	12.8	0.095
3	12.4	12.8	0.234	10.4	10.9	0.153	8.4	9.0	0.071	14.1	14.4	0.324
4	10.2	11.5	0.053	10.1	11.4	0.047	9.0	10.3	0.031	11.4	13.3	0.075
5	11.1	12.1	0.060	11.5	11.2	0.050	11.0	11.0	0.039	12.6	13.7	0.081
6	9.2	10.8	0.041	8.2	9.0	0.026	7.3	8.0	0.018	10.0	11.9	0.054
7	8.4	11.7	0.043	7.5	10.6	0.030	9.3	13.7	0.063	9.3	13.9	0.065
8	11.7	12.0	0.073	9.3	7.9	0.032	9.7	9.3	0.022	15.2	14.9	0.144

[a] Planted March 1997, measured in January 2003.

about 55% and mean dbh 8.5 cm (best 13.3 cm) measured in September 2003. The trial was damaged seriously again twice by snow in late 2002.

Provenance/family trials of other species

A trial of *E. pellita* established in May 1998 grew rapidly after planting, but all trees were killed or severely frost-damaged in the following year. Although 60% sprouted in 2000, the sprouts have frequently suffered cold injury in recent years. It can be concluded with certainty that *E. pellita* can not be planted in northwestern Fujian. The *E. smithii* trial also grew well after planting, but has suffered 'dried up' disease since June 1999 which caused the survival to fall sharply to 40% in September 1999. This may be the result of the hot and wet summer climate. No tree survived the 1999 cold event. Trials of *E. saligna* and *E. camaldulensis* established in 2002 are growing well but need to be tested for a longer period.

Discussion

Feasibility of *Eucalyptus* planting in northwestern Fujian

Low temperature is the main factor limiting eucalypt planting in the cool area of northwestern Fujian. Although Fujian's coastal region is one of the most suitable regions to grow eucalypts due to its warm climate, the land available for plantations is very limited, as most fertile land is used for fruit and other crops. On the other hand, in northwestern Fujian there is plenty of hilly land with good fertility, but the climate is too cold for growing most hybrid clones of *E. urophylla × E. grandi*s. There is much debate about the feasibility of eucalypt plantations in northwestern Fujian. In the trials in Fujian in recent years, some species, such as *E. grandis, E. dunnii* and *E. saligna,* grew very well and showed good cold tolerance. *Eucalyptus grandis,* in particular, grows better than the hybrid clone. For *E. camaldulensis,* both growth and cold tolerance differ among the trials, i.e. comparatively fast in young trials to slow in older trials and from poorest cold tolerance (Fuzhou trial) to good cold tolerance (Yongan trials). Perhaps this variability corresponds its broad distribution in Australia, and we conclude that it needs more observation over a longer period. *Eucalyptus benthamii* grew best in the Shaowu species trial and this suggests more experimental work is required to test its high poten-

tial. So the trials confirmed the possibility of successfully growing eucalypts in northwestern Fujian, subject to selecting cold tolerant species. Of the potential species, *E. grandis* and *E. saligna* could be planted in the area with annual mean temperature of 18–20°C, the lowest temperature above –3° C and altitude less than 400 m. *Eucalyptus dunnii* could be planted in more northern parts with annual mean temperature 16–18° C and the lowest temperature above –5° C. Some other species, such as *E. camaldulensis* and *E. benthamii,* need to be tested for a longer period.

Influence of rainfall pattern in the species' natural distribution on introduction

The eucalypt trial results confirm the guiding and practical value of 'Matching climates theory' for eucalypt introductions (Hong et al. 1997). In the trials, the winter-rainfall-type species, such as *E. globulus, E. nitens, E. radiata* and *E. smithii,* have poor survival, even if they survive well in the first year. For example, in the supplementary trial with 13 species established in 2001, *E. nitens* and *E. globulus* had only 40% survival 2 months after planting, and trees are continuing to die. So the rainfall pattern at the species' origin is very important in deciding which species to introduce. It is not satisfactory to introduce winter-rainfall-type eucalypts into Fujian with its hot and wet summers.

Selection gain and select levels

Huang et al. (2003) reported a significant negative correlation between growth and cold tolerance, i.e. the provenances with better growth had lower cold tolerance. In our trial, there was no correlation between growth and cold tolerance, but there was between cold tolerance and provenance location (Qiu et al. 2002; Lan et al. 2003). Also, most *E. grandis* families grew faster than the *E. urophylla × E. grandi*s hybrid clone. It confirmed that high genetic gain could be achieved by cold-tolerance improvement, especially in cooler areas. All the provenance/family trials agreed that growth variance among trees is highest compared with that among provenances or families, and it suggested plus tree selection may achieve the greatest genetic gain. For the species like *E. grandis,* the efficient way to speed up improvement may be integration of plus tree selection and clonal propagation.

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Genetic Resources of Eucalypts and Their Development in Sichuan

Li Xiaoqing and Hu Tianyu[1]

Abstract

More than 130 species of *Eucalyptus* have been introduced into Sichuan in the past 100 years. Over 40 species survived and some have played an important role in forestry development in the province. About 47,000 ha of short-rotation industrial plantations have been established with *E. grandis* and *E. maidenii*. Other eucalypts that could be developed in Sichuan include *E. saligna, E. smithii, E. dunnii, E. deanei, E. nitens, E. camaldulensis, E. cloeziana* and *E. youmanii*.

Sichuan province is situated in western China and is the most northerly area where eucalypts have been introduced and grown in China. The province is situated between latitudes 26°61'N and 34°26'N and longtitudes 97°26'E to 101°30'E, and has altitudes between 260 m and 7000 m. The land slopes from northwest to southeast, with the Sichuan basin in the east and the plateau in the west. Agriculture takes place mainly in the east and southeast, and this is also the main area for eucalypt growing.

More than 100 species of *Eucalyptus*, such as *E. camaldulensis, E. globulus* and *E. robusta*, were introduced from Australia, India, South Africa and Algeria from 1910 to 1980. These eucalypts were planted in Gelesan, Chengdu, Luzhou and Panxi, but few survived due to lack of management or natural selection. Especially in 1974, very many *E. robusta, E. globulus* and *E. botryoides* were damaged by severe cold, and few of the 10 species introduced from Algeria in 1973 and 1974 survived. Forty species of *Eucalyptus* were introduced from 1980 to 1990 and grown at the Experiment Farm of Tree Improvement of the Sichuan Academy of Forestry by the *Eucalyptus* Introduction Work Group of the State Bureau of Forestry in association with the China–Australia Dongmen Project. Thirty-five of these species still survive.

The 40 *Eucalyptus* species in Sichuan are listed in Table 1. Sixteen species, introduced between 1980 and 1997, that have been selected, tested and proved adaptable, fast-growing and with economic potential are: *E. camaldulensis, E. deanei, E. dunnii, E. grandis, E. kirtoniana, E. macarthurii, E. maidenii, E. nitens, E. paniculata, E. smithii, E. saligna, E. seeana, E. urophylla, E. youmanii,* and *Corymbia citriodora* and *C. maculata.*

The following are some observations on the introduction of eucalypts, based on our experience in Sichuan.

1. Eucalypts from high altitudes in the northeast of Australia and Indonesia, and elsewhere in the summer-rainfall area of eastern Australia, can be successful in the Sichuan basin, e.g. *E. grandis, E. dunnii, E. saligna, C. maculata, E. robusta* and *E. urophylla* (Indonesia).

2. Eucalypts from high latitude, winter-rainfall areas or dry areas, such as *E. globulus* and *E. nitens,* can be grown in hilly areas with a subtropical, cool climate in southwest Sichuan, but not in the Sichuan basin.

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[1] Sichuan Academy of Forestry, Chengdu, 610081, Sichuan, China.

Table 1. Growth of eucalypts introduced into Sichuan.

Species	Natural distribution			Introduced	Growth			
	Lat. (°S)	Alt. (m)	Rainfall type[a] (mm)		Age (yr)	Ht (m)	Dbh (cm)	Vol. (m³)
E. camphora	28–37	300–1500	w–u, 625–1000	1982	8	7.58	9.6	0.0303
E. macarthurii	33–34	350–900	u, 750–1500	1982	8	7.23	11.3	0.0409
C. torelliana	16–19	100–800	s, 1000–1500	1982	8	8.57	8.8	0.0279
E. cloeziana	16–26	60–170	s, 1100–1700	1982	8	9.25	9.6	0.0353
E. deanei	28–34	30–1000	u–s, 900–1500	1982	8	7.23	11.3	0.0409
E. exserta	17–28	0–400	s, 4500–1100	1981	9	15.54	13.8	0.1108
E. 12ABL				1981	9	14.00	12.4	0.0815
E. saligna	28–35	0–300	s–u, 1200–800	1981	9	17.08	18.9	0.2014
E. amygdalina				1981	9	15.40	13.2	0.1007
E. punctata	32–35	0–1000	u–s 625–1250	1981	9	13.74	12.1	0.0765
C. citriodora	22–26	80–300	s, 625–1250	1981	9	14.89	15.4	0.1338
E. erythrandra				1981	9	8.93	5.8	0.0124
E. smithii	33–38	0–500	u, 750–1250	1981[e]	9	11.88	11.3	0.0593
C. maculata	25–37	800	u–s, 625–1250	1981[e]	9	15.28	16.0	0.1461
E. rudis	27–34	0–220	w, 450–900	1981	9	11.98	12.8	0.0769
E. kirtoniana[b]	28–43			1980	10	13.58	16.6	0.1432
E. viminalis	28–43	0–1500	w–s, 625–1400	1980	10	11.27	11.7	0.0616
E. umbellata [d]	6–38	0–1000	s–w, 500–1500	1980	10	15.39	13.1	0.0991
E. camaldulensis	15–38	30–600	w–s 250–625	1980	10	15.9	14.1	0.1177
E. robusta	23–36	0–100	u–s, 1000–1500	1980	10	14.2	13.4	0.0969
E. globulus	38–43	0–330	w–u, 500–1500	1980	10	11.4	8.4	0.0322
E. maidenii	34–39	230–915	w–u, 750–1500	1980	10	15.7	15.2	0.1356
E. seeana				1980	10	15.4	15.4	0.1040
E. botryoides	32–39	0–300	625–1000,	1980	10	14.1	13.5	0.0977
E paniculata	30–36	0–500	u–s	1980	10	15.5	17.3	0.1743
E studleyensis[c]				1980	10	13.1	13.0	0.0960
E. grandis	26–32	300–1250	s, 1000–1750	1996	8	15.0	16.1	0.1530
E. urophylla	8–10	3000	s, 1000–1750	1996	8	14.4	16.9	0.1445
E. dunnii	28–30	150–800	s, 1000–1750	1996	8	14.4	15.1	0.1291
E. propinqua	24–33	0–350	875–1400	1996	8	14.0	14.1	0.1096
E. amplifolia	28–36	0–1000	u–s, 500–1000	1996	8	9.5	8.3	0.0259
E. pauciflora	29–43	0–1800	w–s, 625–1250	1996	8	4.3	2.1	0.0007
E. cinerea	33–38	500–800	w–u, 500–700	1996	8	5.6	5.4	0.0064
E. nitens	30–38	1000–1300	w–u, 750–1250	1996	5	3.2	2.7	0.0009
				1992[f]	5	18.0	25.0	0.4418
E. smithii	33–37	50–1150	u, 750–1700	1990[g]	7	21.5	20.0	0.3377
E. globulus	34–39	230–915	w–u, 750–1500		7	22.0	21.0	0.3810
E. youmanii	28–32	800–1500	u, 750–1250	1997[h]	5	6.7	6.5	0.0281
E. macrorhyncha	32–38	150–1000	w–u, 600–800	1997[h]	5	6.7	6.5	0.0207
E. grandis				1992[i]	3.5	9.5	8.7	0.0236
E. dunnii				1992[i]		8.7	7.8	0.4570
E. smithii				1992[i]		8.2	8.6	
E. camaldulensis				1980[j]	8	22	23	

[a] Range of mean annual rainfall and rainfall distribution: w = winter rainfall, s = summer rainfall, u = uniform rainfall.
[b] E. kirtoniana = reputed hybrid E. tereticornis × E. robusta.
[c] E. studleyensis = possible hybrid E. camaldulensis × E. ovata.
[d] E. umbellata = E. tereticornis;
[e] Renshou County, [f] Wenchuan County, [g] Huili County, [h] Penzhou City, [i] Fengdu County, [j] Panzhihua.

3. Eucalypts from uniform-rainfall areas in the mid-latitudes of eastern Australia may grow well in the subtropical cool climatic area and above 600 m in the Sichuan basin, e.g. *E. maidenii, E. smithii* and *E. youmanii*. *Eucalyptus camaldulensis* from arid and winter-rainfall provenances cannot be introduced successfully in the Sichuan basin and the hot, dry, river valley areas.

Eucalypt Planting and Utilisation

Main climatic characteristics of plantation areas

Eucalypts are grown in Sichuan between latitudes 26 and 32°N. They are grown in the basin, the plateau and hilly areas where it is neither very cold in winter nor very hot in summer. The lowest temperature is above 2–4°C.

Climates in the Sichuan basin are affected by monsoons of the Changjiang (Yangtze) River valley and the mountains of 1000–7000 m. These features result in a subtropical warm–moist monsoon climate with an annual average temperature 16–19°C. The lowest average temperature of the coldest month is 6–8°C, the lowest temperature is –6°C to 0°C, the accumulated temperature above 10°C is 4500°C, and the mean annual rainfall about 1200 mm.

In the hilly area, elevation ranges from 1500 m to 2400 m. The temperature of seasons does not vary greatly in this area, the main difference is between the dry and humid seasons. Annual average temperature is 15–19°C, the lowest temperature is –3.8°C, and mean annual rainfall is 900–1200 mm.

Areas below 1500 m altitude are classified as 'dry and hot river valley', and have a mean annual rainfall of 600–860 mm. The lowest temperature is 0°C.

The results of introduction and selection research with eucalypts in different areas over about 20 years are shown in Table 2.

Utilisation

Eucalypts have been used by the Sichuan Department of Forestry in many state plantation projects since the mid 1990s. Eucalypts were formerly used in 'four side' plantings, but now they are planted more extensively on bare mountains and cutover areas, and are steadily developing as a source of industrial wood. Thus, eucalypt wood utilisation is changing from use by farmers to industrial use. Economic, social and ecological benefits of eucalypts vary throughout Sichuan. Growth rates have not reached their full potential due to sub-optimal plantation management technologies, including lack of improved planting stock. Volume growth in eucalypt plantations is generally 18–22 m^3 ha^{-1} yr^{-1}, and the best is 45 m^3 ha^{-1} yr^{-1}.

Table 2. Localities where eucalypt species are grown in Sichuan.

Area	Main species	Adapted species or provenances
Hilly area in southwest Sichuan, below 1500 m	*E. camaldulensis*	*E. camaldulensis* (15223, 15411)[a]
Hilly area in southwest Sichuan, 1500–2400 m	*E. maidenii*	*E. smithii, E. nitens*
Sichuan basin hilly land in the upper reaches of Changjiang River Valley	*E. grandis* (14431, 17708) [a]	*E. urophylla, E. camaldulensis* (13923, 13928) [a]
Lowland of Sichuan basin edge	*E. grandis* (18146, 18277)	*E. dunnii*

[a] CSIRO Australian Tree Seed Centre seedlot number.

Seed Crop Management of *Eucalyptus globulus* — Development of Seed Crops and Their Readiness to Harvest in Individual Trees

J. Sasse,[1] M. Lavery,[2] H. O'Sullivan,[3] A. Ashton[4] and M. Hamilton[4]

Abstract

Seed-orchard managers must be able to reliably evaluate the readiness for harvest of individual trees within an orchard, to maximise production of viable seed. Flowering and seed crop development of *Eucalyptus globulus* were examined over 2 years to evaluate the effect of harvest time on germinability and seed yield. Capsules from two flowering seasons were harvested 30 to 66 weeks post-flowering from 12 trees of a single provenance in a commercial seed orchard. The 12 trees were categorised as early, average and late-flowering for each of the two flowering years. Seed was extracted immediately after harvest, and germination testing commenced 9 days later. Germinability, germinants per gram and germinants per capsule were estimated. Over the entire harvest periods, in crops from both years, germinability was between 80–100% and there was little difference between flowering groups. Flowering and seed yield were higher in the 2000 crop than in the 1999 crop, but seed yield (germinants per gram or germinants per capsule) was greater in the 2000 crop than in the 1999 crop. Seed yield also differed between flowering groups, with the late-flowering trees showing an increase in seed yield through time compared with a relatively stable, low yield from the early-flowering trees. Seed yield from late harvesting of late-flowering trees was higher than from early-flowering trees. These results suggest seed yield will be greater in average and later-flowering trees if harvests are delayed. Demand for early seed supply should be met, if possible, from early-flowering trees to avoid reducing potential seed supply. The results suggest seed orchard managers should include regular assessments of flowering time in their schedule, to enable estimation of genetic composition of seedlots and to schedule early harvesting if required.

Demand for seed of *Eucalyptus globulus* has grown rapidly in recent years in Australia as the rate of plantation expansion has increased. Establishment of new hardwood plantations in Australia peaked in 2000, when over 126,000 ha were planted, and is expected to be maintained at about 75,000 ha yr^{-1} for the near future (National Forest Inventory 2002). A large proportion of this expansion has occurred in southern Australia, in areas typically planted to *E. globulus* or *E. nitens.* Eucalypt plantations in southern Australia are usually planted in winter, with seedlings approximately 6 months old. Nurseries therefore normally begin sowing seed in December, using seed collected the previous summer (December–February), about 1 year after flowering (Boland et al. 1980). Increased demand for genetically improved seed has necessitated much more intensive management of existing seed orchards (including non-destructive seed collection) and

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[1] Forest Science Centre, Department of Sustainability and Environment, PO Box 137, Heidelburg, Victoria 3084, Australia. Email: <jo.sasse@nre.vic.gov.au>.

[2] Arianda Pty Ltd, 1 Wilkins St, Newport, Victoria 3015, Australia. Email: <mrlavery@arianda.com.au>.

[3] Silvagene Pty Ltd, PO Box 186, Collins Street West, Melbourne 8007, Australia.

[4] Forest Science Centre, Water Street, Creswick, Victoria 3363, Australia.

establishment of new seed orchards. One consequence has been that stocks in storage have been reduced, resulting in a need to harvest seed and supply it to nurseries within the same season.

There is significant variation between provenances of *E. globulus* in flowering time. Gore and Potts (1995) observed flowering in an open-pollinated base population trial of *E. globulus* over a period of 8 months. The average flowering period of individual trees was about 37 days, and the time of flowering of individuals was highly variable. Most variation in the start, peak and end of flowering was attributed to racial differences within *E. globulus* subsp. g*lobulus,* but there was also significant variation due to localities within races and between families within localities (Gore and Potts 1995). Races from the east coast of Tasmania and the Furneaux Group of islands flowered approximately 1 month earlier than races from Victoria and King Island. It is uncertain whether there are similar differences between families, localities and races in the time taken for the seed to mature. If capsules are immature when collected, seed recovery may be poor, because the capsules do not open properly, and if the seed is immature it may not store well or germinate satisfactorily (Lockett 1991). Thus, in seed orchards comprising trees from a range of sources, scheduling harvesting might be problematic.

Eucalypt fruit are usually regarded as mature when the capsules become brown and hard, the lines of dehiscence on the capsule become apparent, and the valves of the capsule begin to open (Boland et al*.* 1980). Seed within the capsule is mature if white embryos within dark seed coats are evident and brown chaff towards the top of the capsule can be seen when cut through. Immature seed has a milky embryo and lacks the dark seed coat. However, there are reports of seed in some species being viable much earlier than their visual and physical characteristics would indicate. Seed with a relatively soft and light-coloured seedcoat has been found to germinate in some instances. For example, viable *E. delegatensis* seed was obtained by Grose (1957) 2.5–3 months after flowering. Fruit of this species does not normally mature completely until 10–12 months after the time of flowering (Boland et al. 1980). Although viable seed can be obtained at relatively early stages of capsule development, increasing viability with increasing capsule maturity is generally observed (DCNR 1994). In one *E. regnans* operational seed collection season*,* there were 0.5 viable seeds per capsule in capsules collected in mid-December. In contrast, 2.8 viable seeds per capsule were found in capsules collected 2 months later in mid-February (DCNR 1994).

A study was undertaken in a commercial *E. globulus* seed orchard managed by Silvagene Pty Ltd, aimed at examining the influence of harvest time on seed yield from individual trees, and to determine how early harvesting could be conducted in years of extreme seed demand.

Methods

Experimental site

The experiment was conducted at Yeodene Seed Orchard, a *E. globulus* seed orchard managed by Silvagene Pty. Ltd and located southeast of Colac, in southwestern Victoria. Average annual rainfall at Yeodene is 864 mm with a late winter peak and summer minimum, and the average monthly maximum and minimum temperatures are 23.8°C and 11.3°C, respectively, in February, and 11.4°C and 3.8°C, respectively, in July (Esoclim; Hutchinson et al*.* 1999). Soils on the site are derived from Tertiary sediments that are part of the Demons Bluff Formation, from the Nirranda Group. The A1 horizon is a grey sandy loam to 40 cm depth. The B1 horizon comprises light-orange clay of about 60 cm depth, and the B2 horizon is light-red clay of about 130 cm depth.

Yeodene Seed Orchard was originally a combined species–provenance–progeny trial of approximately 3 ha, established in 1988, and converted to seed production in 1995. The original trial was planted at 3 × 4 m and contained *E. globulus* (6 provenances, 27 families), *E. nitens* (7 provenances), and *E. regnans* × *E. obliqua* (1 provenance). In 1995, the trial was culled of all *E. nitens* and *E. regnans* × *E. obliqua*, and the remaining *E. globulus* rogued on the basis of age 3 and 4 years height and diameter data. Further roguing within the *E. globulus* culled individual trees from within seedlots, on the basis of volume production and basic density traits. Roguing was biased towards retaining greater numbers of individual trees from the better families, but all families were retained (except three, each of which had only one tree in the trial). In total, over 60% of all *E. globulus* trees were culled. The orchard currently contains 313 trees from 6 provenances and 24 families, plus 3 trees of unknown origin. Paclobutrazol was applied via stem injection in 1995 and again by soil drench in 1999 to

enhance flowering. Seed collection commenced in 1994, before roguing of the *E. globulus*, and continued from 1997–98. Annual yield from the orchard has averaged approximately 7 million seeds, but varies considerably.

Selection of study trees

Twelve trees from a single provenance (Jeeralang) were selected for repeated harvesting, beginning 30 weeks post-flowering. Trees were limited to a single provenance to reduce the confounding effects of provenance on seed yield. The 12 trees were selected on the basis of flowering time during the 1999 flowering season, and estimates of capsule crop size, to ensure sufficient capsules would be available for sustained sample harvests. Weekly assessments of the proportion of buds to have flowered, for each tree in the orchard, were conducted throughout the 1999 and 2000 flowering season. In most trees, there was a single week in which over 50% of buds flowered, and this was defined as the week of peak flowering. For the trees within the provenance selected to study, three flowering times were defined: intermediate (week of peak flowering was the average for the provenance); early (peak flowering was 2 weeks [~ 1 standard deviation] earlier than average); and late (peak flowering 2 weeks later than average). Four trees with capsule crops of at least 1000–1500 capsules were selected from within each group.

Capsule collection, seed extraction and germination testing

In the first season, 11 harvests were conducted from 7 to 13 months post-flowering (i.e. 30, 32, 34–44, 46, 48, 50, 52, 56 weeks post-flowering, or from August to December 2000). In the second season, 14 harvests were conducted from 8 to 18 months post-flowering (August 2001–March 2002). At each harvest, approximately 100 capsules were hand-picked from the trees scheduled for harvest and placed into cloth bags. Seed was extracted immediately after harvest. Green capsule weight and capsule number were recorded, before hanging the cloth bag in an extractor set at 34°C for 72 hours. Extracted seed and dry capsules were separated using a 2.9 mm round-hole sieve, and the dry weights of extracted seed and capsules recorded. Extracted seed was then packaged for germination testing.

Germination testing commenced 9 days after harvesting, and followed modified International Seed Testing Association protocols. Enough seeds (approximately 200) were randomly extracted from each seedlot to conduct tests with four replicates each of about 50 seeds (each replicate was approximately 0.4–1.0 g). The remaining seed was stored for further testing. Germination was on moist filter paper in petri dishes, at 25°C with 12 hours light per day. Counts were made at 5 and 15 days, followed by a squash test. Germinability (proportion of viable seed that germinated), germinants per gram of seed, and chaff extracted and germinants per capsule were calculated.

Analysis

Data were summarised and analysed using Excel 97 (Microsoft) and Statview v5.0 (SAS Institute). Time since the week of peak flowering was calculated in days, and regression analysis was used to examine differences in germinability and seed yield over time between flowering groups and seasons. Slopes were compared using pairwise comparisons between groups within seasons and within groups between years.

Results

Flowering observations

The provenance selected for the experiment comprises 15% of the orchard and is the last provenance to flower. In 1999, trees of this provenance flowered from late October to early January, but most trees flowered for about 16 days in December, and the average week of peak flowering was in mid-December (Table 1). This is later than the bulk of the orchard, which reached its peak flowering about 1 month earlier. Flowering was more abundant in 2000 than in 1999. In the Jeeralang provenance, flowering in 2000 began about 2.5 weeks earlier and peaked about 2 weeks earlier, and the average duration was about 6 days longer, than in 1999. There were some changes in the sequence in which the trees flowered. Amongst those trees studied over the two years, five trees were reclassified for the second year (Table 1). Four of the five reclassified trees shifted later in the sequence, i.e. early to intermediate (1 tree), intermediate to late (2), or early to late (1), and the other tree shifted to an earlier sequence (late to intermediate). The more abundant flower crop of 2000 developed into a more abundant capsule crop than that of the previous year.

Table 1. Peak flowering dates of the 12 *Eucalyptus globulus* trees studied and classification into flowering groups for the 1999 and 2000 flowering seasons.

Tree	Flowering group and time					
	Early (1999) 1-Dec-99	Early (2000) <12-Nov-00	Average (1999) 15-Dec-99	Average (2000) 28-Nov-99	Late (1999) 29-Dec-00	Late (2000) >14-Dec-00
1	1-Dec-99	4-Oct-00				
2	1-Dec-99	8-Nov-00				
3	1-Dec-99			1-Dec-00		
4	1-Dec-99					15-Dec-00
5			15-Dec-99	Did not flower		
6			15-Dec-99	1-Dec-00		
7			15-Dec-99			15-Dec-00
8			15-Dec-99			15-Dec-00
9			4		29-Dec-99	Did not flower
10					29-Dec-99	5-Jan-01
11					29-Dec-99	5-Jan-01
12				7-Dec-00	5-Jan-00	
No. per group	4	2		3	4	5

Germinability

Germinability (the proportion of viable seeds that germinated) was mostly between 80 and 100% in both years, although it was generally higher in 2001 (~90%) than in 2000 (<80%). There were no significant trends with time, or differences between groups, except in the 1999 late-flowering trees, which had lower viability that increased through time (Figure 1). Seed from any group harvested less than about 320 days after flowering (~10 months) had much more variable germinability than that harvested later.

Seed yield

The number of germinants per gram of seed, and the number of germinants per capsule, varied both between years and between flowering groups.
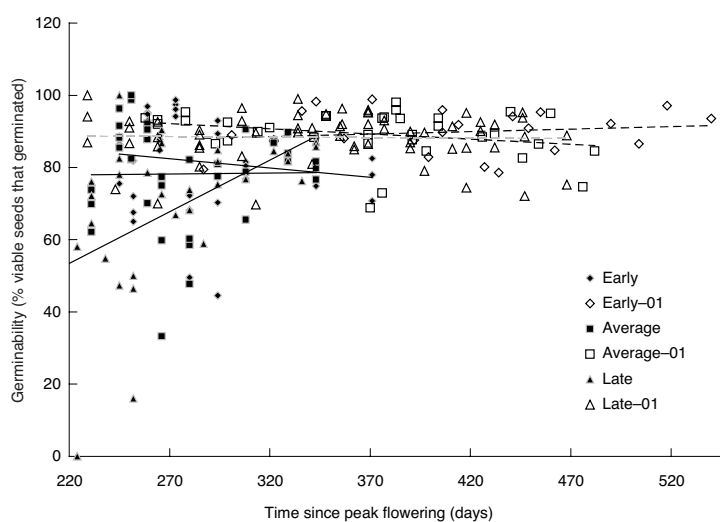
Figure 1. Germinability of seed extracted from each group of *Eucalyptus globulus* with time since flowering.

Average seed yields were greater in the 2001 harvest (103 germinants per gram, 10 germinants per capsule) than in the 2000 crop (24 seed per gram, 1.8 germinants per capsule). In both years, early-flowering trees had low yields that increased only slightly with time, and late flowerers had increasing yield through time (Figures 2 and 3). Average flowering trees were intermediate. Regression analysis of the germinants per capsule and the germinants per gram of seed is shown in Tables 2 and 3. The rate of change in yield differed between groups, but was the same for each group in the two years examined, except for the yield per capsule in the average flowering trees.
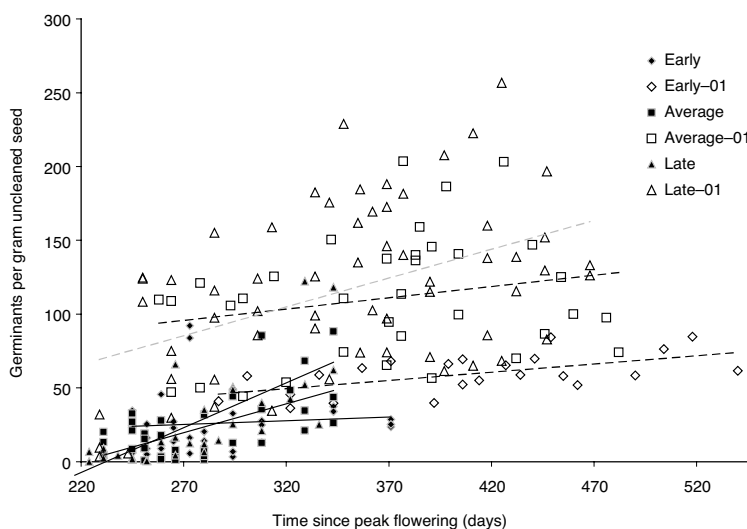
Figure 2. Seed yield (germinants per gram seed and chaff extracted) from each group of *Eucalyptus globulus* with time since flowering.
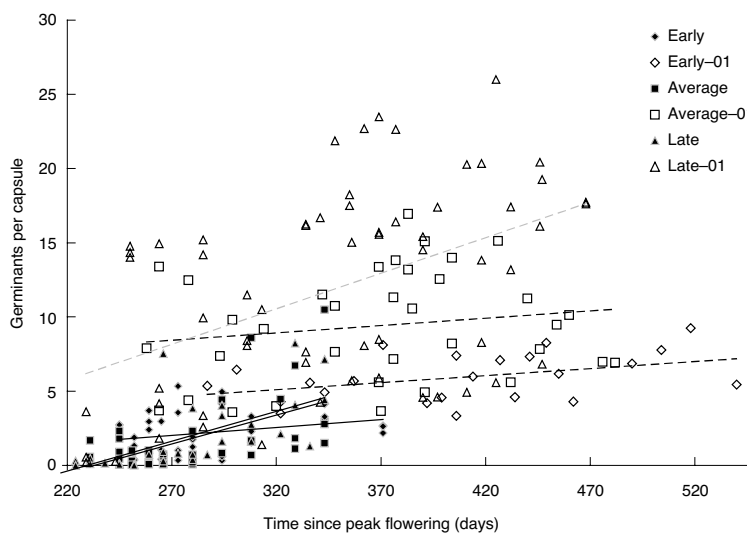
Figure 3. Seed yield (germinants per capsule) from each group of *Eucalyptus globulus* with time since flowering.

Discussion

Germinability was similar for each group within a single year's crop, and was higher in the year with a more abundant crop. In general, however, germinability was more variable in seed extracted from capsules harvested less than about 320 days (~10.5 months) since flowering. It did not vary much with time since flowering, except in the late flowering trees in the first year, which showed a significant increase in germinability between approximately 220 and 320 days. This suggests that seed that can be extracted from capsules has acceptable vigour, except possibly in late-flowering trees in a poor-flowering season.

Seed yield, however, whether measured as germinants per gram extracted or germinants per capsule, does change with time in average and late-flowering trees. Seed yield per gram increased with time at a similar rate for trees from average and late-flowering trees in both seasons, although absolute yields were higher in the year with the better flower crop. Seed yield per capsule showed a similar pattern, although the average-flowering trees changed less in the year with good flowering than the year in poor flowering. These findings suggest that, as time progresses, more viable seed can be extracted from the capsules of later-flowering trees, and that seed represented a greater proportion of the material extracted from the capsules. Extracted seed was not cleaned, so it is not possible to examine whether seed size changed with time, but this is unlikely, as if it did change, the findings suggest the extracted seed should get smaller with time.

Table 2. Summary of linear regressions describing response in viable seeds per gram of extracted material with time for each flowering group of *Eucalyptus globulus*. Comparisons between groups within years and within groups between years were made using pairwise comparisons based on a one-tailed t-test of $p < 0.05$.

Group	Intercept a	Gradient b	R^2 and significance[a]	Comparisons of slopes within year		Comparisons of slopes within groups	
Early 99	11.635	0.050	0.010 (ns)	A		A	
Average 99	−85.947	0.391	0.369 (***)		B	A	
Late 99	−140.848	0.607	0.569 (***)		B		A
Early 00	13.651	0.112	0.349 (**)	A		A	
Average 00	73.663	0.100	0.020 (ns)	A		A	
Late 00	−20.478	0.392	0.213 (***)		B		A

[a] ns = non significant; * = $0.01 < p < 0.05$; ** = $0.001 < p < 0.01$; *** = $p < 0.001$.

Table 3. Summary of linear regressions describing response in viable seeds per capsule with time for each flowering group of *Eucalyptus globulus*. Comparisons between groups within years and within groups between years were made using pairwise comparisons based on a one-tailed t-test at $p < 0.05$.

Group	Intercept a	Gradient b	R^2 and significance[a]	Comparisons of slopes within year		Comparisons of slopes within groups	
Early 99	−0.864	0.011	0.089 (ns)	A		A	
Average 99	−9.104	0.039	0.317 (***)	A		A	
Late 99	−9.225	0.040	0.459 (***)		B		A
Early 00	2.053	0.009	0.170 (*)	A		A	
Average 00	7.361	0.006	0.008 (ns)		B	B	
Late 00	−4.818	0.048	0.226 (***)		B		A

[a] ns = non significant; * = $0.01 < p < 0.05$; ** = $0.001 < p < 0.01$; *** = $p < 0.0001$.

The similarity in these trends between years of significantly different flower and capsule crops suggest that it is a consistent pattern. It appears that differences in flowering time of only 2 weeks between each group are expressed over a period of more than 6 months. A number of causes may contribute to the trend. It is possible that pollen flow, and therefore pollination, increased as flower development progressed. However, these trees were from the last provenance to flower in the orchard, and greater pollen flow and outcrossing would therefore be expected in earlier-flowering trees. It is possible that there are family effects on flowering and seed maturation time, although family identities were known and spread across all the flowering groups in both years. It may be that developmental times are linked, i.e. trees that require longer for flowers to develop also require longer for capsules and seeds to develop and mature. It is known that climatic effects can be important for developmental milestones to be reached and that accumulated temperature and/or rainfall thresholds must be met. However, climatic differences between periods of 2 weeks at flowering seem unlikely to explain differences observed 10–18 months post-flowering. At a general scale, it has been found that eucalypts with large bud and fruit volumes require longer maturation times (Keatley and Hudson 1998), but there has been little examination of developmental patterns at a within species or provenance scale. Closer examination of our data at an individual tree level (data not presented) suggests that the response observed in the groups was even stronger ($R^2 > 0.5$ in 8 of the 12 trees examined) in individual trees, although the grouping by flowering time was somewhat weaker. Most trees showed significant increases in seed yield over time, with rates of increase from ~0 (constant yield) to about 1.26 seed per gram per day. Some non-linear relationships could also be identified. Further work should be conducted to further explore these trends, including examining capsule and seed size in individual trees and studying trees from a broader genetic range.

Conclusions

Consistent differences were found across two contrasting flowering seasons between early, average and late-flowering trees in important seed production parameters. Seed yield, as measured by germinants per capsule or germinants per gram of seed, increased over time in later-flowering trees, but was approximately constant in early-flowering trees. Germinability was generally high in all seedlots, suggesting that seed extracted using routine techniques will usually have acceptable vigour. These findings suggest that, for maximum seed production, it is better to defer harvests rather than harvest early. In crops from years of poor flowering, harvesting early should be avoided. Demand for early seed should be met as far as possible from early-flowering trees, as this will have the least impact on potential seed supply.

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Spatial Variation in Capsule and Seed Crops within Crowns of *Eucalyptus globulus* Trees in a Seed Orchard

J. Sasse,[1] M. Lavery[2] and M. Hamilton[3]

Abstract

Demand for genetically improved seed for establishment of eucalypt plantations has increased the need to intensively manage seed orchards, including predicting current and future seed availability. This requires developing a technique to reliably estimate an individual tree's seed crop. A possible approach is to sample a limited number of capsules from a given point in the crown, estimate the number of seeds per capsule and multiply this figure by the estimated number of capsules in the crown. This experiment aimed to identify the most representative sampling point in the crown of the tree, and evaluate the 'cut-test', a technique currently in use for estimating the number of seeds per capsule. Capsules were harvested from 12 points around the crowns of 20 sample trees from a *Eucalyptus globulus* seed orchard and the number of seed per capsule estimated. The weight of extracted seed and the number of viable seed from 20 capsules at each point in the crown were measured. These results were then compared with the total yield of capsules and seed from each tree. Mean capsule weight increased up the crown, but there were no other significant differences in capsule or seed parameters between positions in the crown. The cut-test underestimated the number of seeds per capsule, and was not a reliable predictor of actual numbers of seed per capsule. Total capsule and seed yields were highly variable between trees. Further work is required to develop a technique to reliably estimate the number of capsules on the tree. Estimates of the number of seed per capsule are best made by harvesting a limited number of capsules from the zone of the crown carrying the bulk of the capsules, and extracting the seed. Family differences need to be more closely evaluated, and the feasibility of applying a mean family value for the number of seeds per capsule should be evaluated.

Demand for seed of *Eucalyptus globulus* in Australia has grown rapidly in recent years as the rate of plantation expansion has increased, requiring more intensive management of existing seed orchards (including non-destructive seed collection) and establishment of new seed orchards (Sasse et al. 2003). One consequence has been that the quantity of seed within existing orchards needs to be accurately predicted, in order to estimate current and future seed availability. Quantification of the relative contributions of individual trees to the bulked seedlot is also required to provide estimates of genetic improvement and predicted gain.

Techniques for estimation of seed crops of individual trees have been developed for use in native forest management (e.g. Harrison et al. 1990). These techniques aimed at predicting future seed supply, identifying suitable areas for seed collection, deter-

[1] Forest Science Centre, Department of Sustainability and Environment, PO Box 137, Heidelburg, Victoria 3084, Australia. Email: <jo.sasse@nre.vic.gov.au>.
[2] Arianda Pty Ltd, 1 Wilkins Street, Newport, Victoria 3015, Australia.
[3] Forest Science Centre, Water Street, Creswick, Victoria 3363, Australia.

mining a silvicultural system that is appropriate to seed availability, identifying, before harvesting, seed-trees that are suitable for retention, or determining the seed-tree distribution for adequate seed dispersal. Typically, these techniques are based on crown size, average capsule density and the number of viable seed per capsule (e.g. DNRE 1996a,b).

Species-specific relationships are used to determine the number of branchlets of capsule-bearing size from tree diameter. Trees are classified into one of six diameter classes and allowances are provided for crown damage. Average capsule density per branchlet is classified into one of five classes by comparing species-specific photographic guidelines with capsule density on randomly selected branches observed using a spotting scope or binoculars. A species-specific average is used for the number of viable seeds per capsule. This provides 30 categories of seed yield which are used to support silvicultural decisions. The estimated number of viable seed per tree within each category has a range of between ± 2000 to ± 27,000 for *E. baxteri*, between ± 2000 to ± 58,000 for *E. sieberi* and *E. globoidea*, and between ±1.0 to ±4.5 million for *E. regnans*. At best, these estimates are within ±10–20% of the category mean, and at worst are within ±33–67% of the category mean. Such an approach is inadequate for intensive seed orchard management, because the estimates of seed yield are generally not precise enough, and the use of tree diameters to determine crop size is confounded in seed orchards where the growth inhibitor paclobutrazol has been used to promote seed production.

It may be possible to more accurately estimate crop size by sampling a limited number of capsules from a given point in the crown, estimating the number of seeds per capsule and multiplying this figure by the estimated number of capsules in the crown. The first stage of this approach requires identification of the most representative sampling point in the crown of the tree, and development of a reliable technique for estimating the numbers of seed per capsule. In this experiment, capsules were harvested from 12 points around the crowns of 20 sample trees. The number of seeds per capsule was estimated using the 'cut-test', and the weight of extracted seed and number of viable seed from 20 capsules at each point in the crown were measured. These results were then compared with the total yield of capsules and seed from each tree. The aims were to evaluate the cut-test as a method of estimating the number of seed per capsule, and to identify whether there was a representative point in the crown where it is most appropriate to sample.

Materials and Methods

Experimental site

The experiment was conducted during the 1999 harvest at Yeodene Seed Orchard, a *E. globulus* seed orchard owned by the Treecorp Group and managed by Silvagene Pty Ltd. A full site description is given in Sasse et al. (2003).

Capsule harvest

Twenty trees were randomly selected from the orchard. No consideration was given to family identity or the size of the crop on each tree. Twelve sectors were defined for each tree: four aspects — north, south, east and west; and three tiers in the crown — upper, middle and lower. Sample collections were made at each of the 12 points in late January 1999. First, six capsules were selected at random and the number of seeds per capsule estimated using the cut-test. The cut-test was conducted by using secateurs to cut thin (~1 mm) slices horizontally through the capsule, starting at the disc. The number of seeds, defined as white embryos surrounded by dark testa, exposed by cutting was counted and recorded. Then, from the same point in the tree, 20 randomly selected capsules were collected and placed in a labelled sample bag. On seven nominated trees, 100 capsules were collected from each point. Sample bags containing the capsules were then refrigerated until extraction commenced about 1 week later. The remaining capsules on all trees were then harvested and individual tree collections kept separate during extraction and processing, to provide whole tree data on capsule and seed yield.

Seed extraction

Sample point collections were weighed green, and the number of capsules collected per sample point was counted and recorded. The capsules were then laid out on benches for drying for approximately 3 weeks. After drying, seed was extracted by placing each sample point collection within a sealed container and shaking the seed from the capsules. The seed and chaff were then separated from the capsules using a 2.9 mm round-hole sieve, and the dry weights

of extracted seed and capsules recorded. Seed samples were then packaged for germination testing.

Individual whole tree collections of capsules were weighed immediately following harvest in the field, and again before extraction. Each collection was placed in the extractor and tumbled at 34°C for between 24 and 72 hours. Dry weights of extracted seed, and of chaff and capsules, were recorded. Samples of extracted seed from each tree were then drawn from the bulk lot and packaged for germination testing.

Seed number and viability

The number of viable seeds per sample point was estimated by conducting squash tests on the entire seed sample. Samples were weighed, imbibed on moist filter paper in petri dishes at room temperature, and then squashed. The number of seed with firm white embryos was counted and recorded. For those samples with 100 capsules, and samples from the bulked whole tree collections, full germination tests were conducted in accordance with International Seed Testing Association procedures. The total sample was weighed, then four 1.0 g replicates spread over moist filter paper in separate petri dishes and placed in germination cabinets with lights at 25°C. Counts of germinated seed were conducted at 5 and 14 days. Any seeds that had not germinated by day 14 were squashed and sound seed counted as potentially germinable and added to the total seed number. The total number of seeds recorded in a germination test therefore equates to the number counted in a squash test, and viability is the proportion of all seed that germinated.

Analysis

The full data, including cut-test, capsule and seed weights and germination test results, from the sample point collections were collated and combined with the whole tree data. Some final whole tree data, such as total number of capsules, were derived by extrapolating from the sample point data. The data were summarised and analysed using Statview v5.0 and Genstat (1998) v4.1.

Variation in capsule and seed yield around the crown was evaluated by analysis of variance of the sample point data. Overall trends in capsule and seed yield were evaluated from the whole tree data. The suitability of the cut-test for estimating seed yield per capsule was evaluated by correlating the cut-test results with the actual number of viable seed extracted, as determined by the squash test results. Correlations between sample point data and whole tree data were conducted to identify the best sampling point for estimating seed yield.

Results

Sample point data

Tables 1 and 2 summarise the capsule and seed yield data by height and aspect. On average, the number of seeds per capsule estimated using the cut-test was just under 10 (9.7), compared to almost 18 (17.7) extracted from the sample capsules. The average capsule dry weight was about 1.7 g. The number of viable seeds per gram was about 124, and average viability was about 97%. Viability was uniform around the crown, and there was a slight, but non-significant, trend of increasing viability up the crown. The only parameter that varied significantly with position in the crown was average capsule weight, which increased significantly up the tree from about 1.5 to 1.9 g (dry weight). This difference was consistent across all aspects of the crown. Mean individual capsule dry weight was closely correlated with mean individual capsule green weight ($R = 0.97$, $p < 0.0001$), and individual capsule weight (green or dry) was negatively correlated with seeds per gram, although the correlation was low ($R \approx -0.35$, $p < 0.0001$). Individual capsule weight was also positively correlated with number of seeds per capsule ($R \approx 0.26$, $p < 0.0001$). The regression between cut-test mean and actual number of seeds per capsule was significant ($R^2 = 0.34$, $p < 0.0001$), but not strong enough to be useful for predictive purposes.

Whole tree yields

Capsule and seed yields from individual trees are summarised in Table 3. The size of the crop collected from individual trees varied between 5.9 and 48.7 kg (green weight) of capsules and 0.245 and 2.373 kg of seed. This equated to between 1900 and 17,600 capsules and 25,000 and 320,000 seed per tree. Thus, the number and weight of harvested capsules and seed varied about tenfold between trees. By comparison, the yield of seed per capsule and numbers of seed per gram was about half as variable, in the ranges of about 6–30 and 38–174, respectively. Average viability was 97% (range 80–100%).

Table 1. Mean capsule and seed yields by crown position for the 20 *Eucalyptus globulus* trees harvested at Yeodene Seed Orchard.

	Crown position			
	Lower	Middle	Upper	Overall
Cut-test mean	9.5. (4.0)[a]	9.8 (3.9)	9.7 (3.7)	9.7 (3.8)
Average capsule size (g green wt)	2.56 (0.80)	2.84 (0.99)	3.11 (1.11)	2.84 (1.00)
Average capsule size (g dry wt)	1.54 (0.45)	1.71 (0.55)	1.89 (0.61)	1.71 (0.56)
Seeds per capsule	17.1 (7.1)	17.4 (6.8)	18.7 (7.5)	17.7 (7.2)
Seeds per gram	124.5 (44.5)	122.2 (44.4)	126.1 (45.0)	124.3 (44.4)
Viability (%)	96.8 (4.0)	97.1 (3.7)	98.2 (2.1) [b]	97.4 (3.4)

[a] Standard deviations are shown in brackets. [b] One sample point was excluded as an outlier.

Table 2. Mean capsule and seed yields by aspect for the twenty trees harvested at Yeodene Seed Orchard.

	East	North	South	West	Overall
Cut-test mean	9.8 (4.0)[a]	9.9 (3.8)	9.4 (3.8)	9.6 (3.8)	9.7 (3.8)
Average capsule size (g green wt)	2.78 (0.92)	2.74 (1.00)	2.92 (1.02)	2.91 (1.07)	2.84 (1.00)
Average capsule size (g dry wt)	1.68 (0.53)	1.67 (0.58)	1.75 (0.55)	1.73 (0.59)	1.71 (0.56)
Seeds per capsule	17.5 (7.1)	18.4 (7.3)	17.4 (6.6)	17.7 (7.7)	17.7 (7.2)
Seeds per gram	122.6 (45.0)	132.1 (43.7)	121.0 (44.1)	121.5 (45.1)	124.3 (44.4)
Viability (%)	97.4 (3.9)	97.2 (3.6)	97.2 (4.0)	97.6 (1.9)[b]	97.4 (3.4)

[a] Standard deviations are shown in brackets. [b] One sample point excluded as an outlier.

Table 3. Mean capsule and seed yield data per tree for the twenty trees harvested at Yeodene Seed Orchard. Notes indicate the basis of the data.

	Mean	Std Dev.	Minimum	Maximum	Notes
Green weight of capsules (kg)	23.8	12.3	5.9	48.7	incl. sample collections
Dry weight of capsules (kg)	12.5	5.9	3.0	23.4	
Estimated number of capsules[a]	7877	4035	1907	17598	based on sample data
Weight of extracted seed (kg)	1.182	0.582	0.245	2.373	incl. sample collections
Average number of seed per gram	115.7	33.8	37.8	173.8	germination test results
Estimated number of seed ($\times 10^4$)[b]	13.888	8.653	2.578	32.073	calculated
Average number of seeds per capsule[c]	17.9	6.2	5.8	29.7	calculated
Viability (%)	97.1	4.2	80.5	100	germination test results

[a] No. capsules per tree = (mean capsule dry weight from all sample points x total dry weight of capsules from whole tree collection) + total no. capsules in sample point collection.
[b] No. seed per tree = weight of seed $\times$ seed per gram.
[c] No. seeds per capsule = total number of seeds / total number of capsules.

Correlations between capsule and seed yield parameters were examined and are summarised in Table 4. Green and dry weight of capsules, number of capsules and total weight and number of seeds were all highly correlated with each other, indicating that seed yield from an individual tree is highly correlated with the capsule yield. Although the number of viable seeds per gram was correlated with capsule number, the correlation was low and is possibly an artefact of the data. Correlations between total yield of seed and parameters based on the sample point data, such as the number of seeds per capsule, were similar to those of the sample point data. For example, as the number of seeds per gram decreased (and seed size presumably increased), there were fewer seeds per capsule and fewer seeds per tree.

Relationships between sample point and whole tree data

Table 5 shows the correlation matrix for sample point and whole tree results for those parameters likely to be practical as predictors of total seed yield. Correlations between mean individual capsule weight (green or dry) from different sampling heights and the total capsule yield or total seed yield (kg) from the entire tree were non-significant. Correlation between the cut-test mean and seeds per gram was moderate, but direct measures of extracted seeds per capsule and seeds per gram as measured by the squash test from the sample point data were better correlated with the average number of seeds per gram for the entire tree.

Table 4. Correlation matrix between capsule and seed yield parameters for whole tree data of the twenty trees harvested at Yeodene seed orchards, showing the correlation coefficient (R) for each comparison and its significance.

	GWT	DWT	CAPS	SDWT	SD/GM	SEED	SD/CAP
GWT: Green weight of capsules (kg)	1.000	0.984	0.899	0.958	0.089	0.796	0.062
DWT: Dry weight of capsules (kg)	***	1.000	derived	0.954	0.070	0.779	Derived
CAPS: Estimated number of capsules	***	derived	1.000	0.868	0.265	derived	−0.087
SDWT: Weight of extracted seed (kg)	***	***	***	1.000	0.108	0.855	Derived
SD/GM: Average number of seed per gram	ns	ns	***	ns	1.000	derived	Derived
SEED: Estimated number of seed ($\times 10^4$)	***	***	derived	***	derived	1.000	Derived
SD/CAP: Average number of seeds per capsule	ns	derived	ns	derived	derived	derived	1.000

Note: ns = non-significant, * represents $p = 0.01$–0.05, ** represents $p = 0.0001$–0.01, and *** represents $p < 0.0001$). Correlations are not presented for parameters derived from each other.

Table 5. Correlation matrix between sample point and whole tree capsule and seed yield results, showing the correlation coefficient R for each comparison and its significance.

Sample point yields	Whole tree yields				
	Total capsule green weight	Total capsule dry weight	Seed weight	Seed number	Seed per gram (germination test)
Mean capsule green weight	−0.094	−0.032	−0.064		
Upper	−0.046		−0.019		
Mid	−0.108		−0.086		
Lower	−0.140		−0.098		
Mean capsule dry weight	−0.128	−0.069	−0.116		
Upper		−0.037	−0.078		
Mid		−0.089	−0.131		
Lower		−0.086	−0.145		
Cut-test mean			0.091	0.325	0.457*
Number of seeds per capsule			0.134	0.450*	0.631**
Seeds per gram (squash test)			0.054	0.509*	0.964***

Note: * $p = 0.01$–0.05, ** $p = 0.0001$–0.01, and *** $p < 0.0001$).

Discussion

Whole-tree capsule and seed yields varied considerably between the 20 trees examined in this study. More detailed sampling of capsules from different points around the crown of the same 20 trees showed little variation in most capsule and seed yield parameters with position, with the exception of capsule size. This was accompanied by slight, but non-significant, increases in seed yield up the crown (germinants per capsule and germinants per gram). Patterson et al. (2001) found greater seed set at the top of three of five trees examined for patterns of outcrossing within a crown. They suggested that this was due to increased outcrossing. However, increased outcrossing is unlikely to explain larger capsule size, and these trends may reflect greater resource allocation to buds, flowers and capsules higher in the crown.

There are several potential causes for the variation in capsule crops observed across the 20 selected trees, including tree size and family effects. Although there appear to be differences between the families (data not presented), the sampling strategy was not designed to evaluate family differences. This shows that it is invalid to assume that a bulked seedlot from an orchard will have equal contributions of seed from each tree. Therefore, estimates of the genetic quality of a seed orchard seedlot must account for the differential contribution of seed from individual trees. This reinforces the need to estimate individual tree crops, ideally in the field, using a quick and reliable method. The total number of seed (S) in the crown of a tree is a function of the number of capsules (C) and number of seeds per capsule (sc). The relationship would be expected to take the form:

$$S = a + b \times (sc \times C).$$

Analysis (not presented) of this relationship using the total number of seed and estimated number of capsules from the whole tree data, and the number of seeds per capsule from the sample point data, suggested that this is a feasible approach to estimating seed crops. About 82% of the variation in total seed number was explained if the average number of extracted seed per capsule (from all sample points) was used, and about 65% of the variation was explained if the cut-test means were used. In both cases, the estimated number of capsules in the whole tree was derived from the dry weight of capsules collected, divided by the mean weight per capsule from the sample point data (Table 4).

Practical use of this kind of relationship would require accurate field-based estimates of both the number of seeds per capsule and the numbers of capsules within a tree. The cut-test is a poor estimator of the actual number of seeds per capsule. A direct measure of the number of extracted seed from a known number of capsules is more reliable. This might be achievable in the field by collecting a specified number of capsules, air drying for 24 hours, extracting manually (e.g. by shaking) and counting the seed. Alternatively, it might be possible to improve the accuracy of the cut-test by, for example, slicing through the capsule from the bottom upwards rather than from the disc, as most viable seed is at the base of the capsule. As there was no significant difference in the number of seeds per capsule between positions in the crown, sampling should be conducted in the zone of the crown that carries the most capsules.

A technique for accurately estimating the number of capsules per tree is also needed. Preliminary analysis (data not presented) of the 20 trees sampled in this experiment showed that the number of capsules on each tree was poorly correlated with tree size as measured by diameter at breast height ($R = 0.1$). This suggests that a more detailed assessment of individual trees will be necessary, perhaps including a count of the number of branches of different size categories and an assessment of the number of capsules borne on small branchlets. Estimation of the number of capsules would need to be conducted for the entire tree.

Differences in individual tree yields may be partly related to differences in capsule and seed size, and number of seeds per capsule, between families. Factors that influence capsule and seed crop size in individual trees are insufficiently understood. Some of these differences, such as capsule and seed size, are likely to be genetically controlled, and may be allometrically related to other parameters of the tree such as leaf, bud or flower size. Other differences, including the number of seed per capsule, may be related to factors that determine seed set, such as flowering time and the level of outcrossing. Some parameters, such as total capsule number, may be related to both flowering time and tree size. The dynamics and consequences of these and other factors need to be better understood if seed orchard management is to be optimised. The sample point data suggested differences between families, and although this needs to be more carefully evaluated, it

is likely that family-specific relationships for estimating seed crops should be developed. Estimates would need to be made for either all trees in the orchard, or a sampling strategy developed that reflects the family composition of the orchard.

Conclusions

The number of seeds per capsule in *E. globulus* did not vary between positions in the crown, although capsule size increased up the crown. Total seed yields varied considerably between individual trees, and family differences were likely. Techniques for estimating seed crops from seed orchards must therefore be based on individual trees, using estimates that account for family differences.

It should be possible to estimate the seed crop on an individual tree from the number of capsules on the tree and the average number of seed per capsule. Techniques need to be developed to reliably estimate the number of capsules on the tree. Estimates of the number of seed per capsule are best made by harvesting a limited number of capsules from the zone of the crown carrying the bulk of the capsules, and extracting the seed. Without further modification, the cut-test is not a sufficiently accurate predictor of seed per capsule. It may be sufficient to estimate the number of seed per capsule on a family, rather than individual tree, basis and apply a family mean to capsule crop estimates for each tree within the family in an orchard.

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Environmental and Cultural Influences on Flowering of *Eucalyptus dunnii*

R. Arnold[1] and Xiang Dongyun[2]

Abstract

Eucalyptus dunnii has become one of the preferred species for hardwood plantation establishment in many areas of south-central China and, in Australia, in northern coastal New South Wales and southeastern Queensland. However, it is a particularly shy-flowering species and this has limitations on plantation establishment and genetic improvement programs. Influences of geographic location and climate on flowering were examined in 17 planted stands of *E. dunnii* in China and Australia. Incidence of flowering is favoured by mean annual temperatures below about 16°C and stockings below 400 trees ha^{-1}, but there was no apparent association between age and flowering. Cultural treatments involving applications of high dosage fertiliser and paclobutrazol were tested in China and Australia to examine the potential for enhancing flowering and seed production in established seed orchards. Early results show that paclobutrazol, either alone or in combination with high dosage fertilisation, increased the proportion of trees initiating flower buds and substantially increased the number of flower buds per tree. Fertiliser did not affect initiation of flower buds. Neither treatment had any effect on initiation of flower buds in environments where untreated trees did not produce buds.

Eucalyptus dunnii Maiden (Dunn's white gum) is a tall forest tree native to limited areas in the northern coastal regions of New South Wales and the edge of southern Queensland (Benson and Hager 1993). As an exotic, the species has demonstrated adaptability to a wide range of soil types of good depth and moderate to high fertility (Herbert 1994), and it has proved better adapted to sites that are slightly too frosty for some more widely planted eucalypts such *E. grandis* or *E. urophylla* (Darrow 1996; CABI 2000; Johnson and Arnold 2000). Another of *E. dunnii*'s advantages is that it produces a versatile timber suited to production of a range of products from good quality pulp to quality sawn timber and veneers (CAB International 2000).

In Australia, trial plantings of *E. dunnii* on coastal sites in northern New South Wales during the 1970s and 1980s had high growth rates and often excellent stem form with fine branching. In several species trials, *E. dunnii* equalled or outgrew 'traditional' plantation eucalypts such as *E. grandis* and *E. pilularis* by age 15–18 years (Johnson and Stanton 1993). Such results helped to prompt larger-scale planting of *E. dunnii* in northern New South Wales and southeastern Queensland from the mid 1990s. It is now a priority plantation species in these areas, predominantly at higher altitude (>500 m asl) or low-lying, flat sites prone to frost. More than 15,000 ha of *E. dunnii* plantations have been established in the past 10 years.

Trials in China have shown *E. dunnii* to be a particularly promising plantation species for some summer rainfall areas of south-central China that are

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[1] Australian Tree Seed Centre, CSIRO Forestry and Forest Products; PO Box E4008, Kingston, ACT 2604, Australia. Email: <Roger.Arnold@csiro.au>.

[2] Forest Guangxi Forest Research Institute, 23 Yongwu Road, Nanning, Guangxi 530001, China. Email: <xiangdy@public.nn.gx.cn>.

also subject to winter frosts (Mannion and Zhang 1989; Wang et al. 1999; Arnold and Luo 2002). Indeed, it is now a priority species for establishment of new hardwood plantations in such areas. It is estimated that, during 2002, more than 3000 ha of *E. dunnii* plantations were established in northern Guangxi and Hunan provinces, and in 2003 it is estimated this will exceed 4500 ha.

Expansion of *E. dunnii* plantations in China is constrained by low levels of flowering and seed production. In the target environments for plantations, trees of 10 years of age and older are yet to start flowering, and several good quality seed orchards and seed production areas established as early as 1989 have not yet produced a single seed. Such flowering and seed production problems are common to many countries, and it has long been recognised as a shy-flowering species in its natural stands and when planted as an exotic (Boland 1984; Graca 1987). It often takes 10 years or more to start flowering and producing seed and, even then, its flowering and seed production can be low and irregular.

Vegetative propagation has enabled mass multiplication of selected stock of many tropical and subtropical eucalypts in China and elsewhere. Unfortunately, it is not an option for *E. dunnii*. Mass vegetative propagation of this species either by stem cuttings or by micropropagation is very difficult and not economically feasible for plantation establishment (CAB International 2000). Consequently, establishment of new plantations of this species has to rely on seed. Seed is imported from Australia to support the current *E. dunnii* establishment programs in China. Development of local seed production capacity is essential for longer term and larger scale expansion of these programs Also, genetic improvement of the species in China depends on the ability to mate and mass-produce improved planting material.

Attempts have been made in several countries to enhance *E. dunnii*'s flowering and seed production by cultural treatments. In Paraná State, Brazil, no increases in flowering were obtained from stem injections of gibberellic acid (GA), kinetin, ethrel (2-chloroethyl phosphoric acid [ethephon]) and/or application of NPK fertilisers with trace elements, for 2 years in succession (Graca et al. 1986). In South Africa, particularly strong flowering responses to a root drench of the growth-retarding chemical paclobutrazol were obtained (SAPPI 1997). Paclobutrazol is a broad spectrum, xylem-mobile

growth retardant that inhibits gibberellin biosynthesis and can reduce rates of cell division and expansion (Lever 1986). A secondary effect of paclobutrazol observed in some hardwood species, including a number of eucalypt species, is enhanced flowering intensity.

To examine the potential for enhancing *E. dunnii*'s seed production in both south-central China and southeastern Australia, a program of research was initiated jointly by CSIRO Forestry and Forest Products and Guangxi Forest Research Institute in the late 1990s. Between 1999 and 2002, a number of *E. dunnii* plantings in both countries were surveyed for reproductive buds, flowers and/or seed capsules to examine associations between environment and flowering. Also, two field trials in Australia and two in China were set up to test the flowering response of *E. dunnii* to fertiliser and paclobutrazol treatments. This paper presents and discusses the early results obtained from this work.

Methods

Environment and flowering

Between 1999 and 2002, 17 planted stands of *E. dunnii*, ranging in age from 3.5 to 18 years, were visited in the provinces of Yunnan, Guizhou, Guangxi and Hunan in south-central China and in the states of Victoria, South Australia, New South Wales and Queensland in Australia. For each of these, sites information about a number of parameters of geographic location and climate was obtained (Table 1). In each stand, trees were examined carefully for presence of flower buds, flowers and/or capsules. In Australia, all trees in each stand were examined. In China, all trees in smaller stands (i.e. <120 trees) were examined. In the case of larger stands, a randomly selected sample of 120 trees was examined. For each stand, the total number of trees with flower buds, flowers and/or capsules, total number of trees examined, age of the trees, and approximate stocking (trees ha^{-1}) were recorded.

To examine correlations between geographic location parameters and flowering in *E. dunnii*, correlation coefficients and the statistical significance of these were computed using the correlation procedure (PROC CORR) of the SAS statistical software package (SAS Institute 1989).

Cultural treatments for enhancing flowering

In Australia, fertiliser and/or paclobutrazol [(2RS,3RS)-1-(4-chlorophenyl)-4,4-dimethyl-2-(1,2,4 -triazol-1-yl) pentan-3-ol] treatments were applied to seedling seed orchards at Conargo and Mooney Swamp in southern New South Wales. Details of location, climate and soil for these sites are in Table 2. At Conargo, treatment plot size was 24 trees (8 rows × 3 trees) and at Mooney Swamp treatment plot size was 20 trees (5 rows × 4 trees). In both orchards, there were two complete replications of each of four treatments in a randomised complete block design (Table 3). Fertiliser applications were made in April 2000 (autumn). Paclobutrazol treatments were applied in late November–December 2000 (spring–summer).

In China the trials were carried out in seedling seed orchards at Satang Forest Farm near Liuzhou city and Guilin in northwest Guangxi province. Details of location, climate and soil for these sites are in Table 2. In both seed orchards, treatment plot size was 8 trees (2 rows × 4 trees) and there were three complete replications of each of five treatments in a randomised complete block design (Table 3). The first round of fertiliser applications was made in October–November 2000 (autumn) and the first round of paclobutrazol treatments in December 2000 (early winter). For treatments with two applications, fertiliser and paclobutrazol were applied again in April 2001 (mid-spring).

In January 2002, approximately a year after the paclobutrazol treatments, all trees in the cultural trials in the Australian seed orchards were examined (using binoculars) to record the number of flower buds and/or capsules on each tree. The number of each was assessed using a subjective scale as follows:

Score	Number of umbels (flower buds/capsule)
0	0
1	1 to 10
2	11 to 100
3	101 to 1000
4	1001 to 10 000

From mid 2001 (July) all trees in the cultural trials in the Chinese seed orchards were carefully scrutinised using binoculars for flower buds and/or capsules. This was repeated every 2 months until November 2002. No flower buds or capsules were observed on any trees in the trials (nor in areas of the seed orchard adjoining the trials).

Table 1. Summary of climatic and geographic location parameters, and correlations between these and the percentage of trees reproductively active, from surveys of 6 *Eucalyptus dunnii* stands in China and 11 in Australia.

Parameter	Country		Correlation (r) with percentage of trees reproductively active
	China	Australia	
Altitude (m)	30–1990	30–950	0.41[a]
Latitude	24° 28'–27°41'N	17°26'–37°45'S	0.28
Longitude	102°40'–113°07'E	140°47'–153°03'E	0.01
Mean annual temperature (°C)	15.5–20.5	12.2–19.9	–0.53[b]
Mean temp. hottest month (°C)	20.5–29.0	18.1–24.3	–0.29
Mean temp. coldest month (°C)	4.0–9.5	5.6–15.8	–0.27
Mean annual precipitation (mm)	900–1825	640–1900	–0.25
Age (years)	5–11	3.5–18	–0.04
Stocking (trees ha^{-1})	200–600	200–1150	–0.41[a]
Trees reproductively active (%)	0–60	0–70	not applicable
Number of trees examined per site	7–120	6–2400	not applicable
Number of sites	6	11	not applicable
Number of sites with actively reproductive trees	2	7	not applicable

[a] Correlation significant at $0.05 < p \leq 0.10$. [b] Correlation significant at $p \leq 0.05$.

Data analyses

The data on capsule and bud scores from the trials in the two Australian orchards were pooled for analyses across sites. This was carried out using plot mean data with SAS software (SAS Institute 1989) based on the following linear model:

$$Y_{ijk} = \mu + S_i + R_{j(i)} + T_k + e_{ijk}$$

where:

Y_{ijk} is the plot mean from the plot of treatment k in replicate j at trial site i

μ represents the overall mean

S_i represents the effect of trial site i

$R_{j(i)}$ represents the effect of replicate j at trial site i

T_k represents the effect of treatment k

e_{ijk} represents the residual error with a mean of zero.

Table 2. Site details for the seedling seed orchards in Australia and China where cultural trials were conducted to examine the potential to enhance flowering in *Eucalyptus dunnii*.

Parameter	China		Australia	
	Satang	Guilin	Conargo	Mooney Swamp
Latitude	24°28'N	25°20'N	35°17'S	35°30'S
Longitude	109°24'E	110°18'E	145°10'E	145°11'E
Altitude (m)	150	177	100	98
Mean annual temperature (°C)	20.5	18.9	15.2	15.2
Mean temperature hottest month (°C)	29.0	29.0	23.7	23.7
Mean temperature coldest month (°C)	9.5	8.5	8.7	8.7
Mean annual precipitation (mm)	1400	1825	1020*	1020*
Establishment year	1991	1991	1995	1995
Approximate stocking (trees ha^{-1})	400	400	310	310
Soil type	Heavy yellow sandy clay loam to light clay	Red silty clay loam, well drained	Heavy grey-brown clay loam, moderate drainage	Red sandy loam to red clay, well drained

Note: Total precipitation at Conargo and at Mooney Swamp seed comprises 420 mm yr^{-1} natural mean annual precipitation plus irrigation equivalent to approximately 600 mm yr^{-1}.

Table 3. Cultural treatments applied in the Australian and Chinese seedling seed orchards of *Eucalyptus dunnii*.

Location	Treatment
Australia – Mooney Swamp and Conargo New South Wales	*Control* – nothing applied *Paclobutrazol* – 1 g active ingredient per cm of circumference at breast height *Fertiliser* – 50 kg ha^{-1} P (in superphosphate) and 400 kg ha^{-1} N (in urea) *Fertiliser + Paclobutrazol* – 50 kg ha^{-1} P (in superphosphate) and 400 kg ha^{-1} N (in urea) with paclobutrazol at 1 g active ingredient per cm of circumference at breast height
China – Satang and Guilin, Guangxi	*Control* – nothing applied *Fertiliser (1 application)* – 60 kg ha^{-1} P (in superphosphate) and 300 kg ha^{-1} N (in urea) *Fertiliser (1 application) + Paclobutrazol (1 application)* – fertiliser at 60 kg ha^{-1} P (in superphosphate) and 300 kg ha^{-1} N (in urea) with paclobutrazol at 1 gm active ingredient per cm of circumference at breast height *Fertiliser (2 applications)* – total of 120 kg ha^{-1} P (in superphosphate) and 600 kg ha^{-1} N (in urea) *Fertiliser (2 applications) + Paclobutrazol (2 applications)* – total of 120 kg ha^{-1} P (in superphosphate) and 600 kg ha^{-1} N (in urea) with a total of 2 g active ingredient paclobutrazol per cm of circumference at breast height

For these analyses, sites and treatments were regarded as fixed effects, while replicates were regarded as random. The TEST option in the RANDOM statement of PROC GLM was used to obtain appropriate tests of hypotheses for these analyses of variance and to provide expectations of means squares, F ratios and probabilities for the appropriate tests of significance. Treatment means and stand errors of these means were estimated as least squares means (LSMEANS) from these analyses.

Results and Discussion

Environment and flowering

The range of environments in Australia and China where *E. dunnii* stands were surveyed for reproductive activity was quite wide (Table 1). Though the sites in China had a latitudinal range of only about 3°20', in Australia they ranged across approximately 20°20'of latitude. Altitudes ranged from 30 m to more than 1900 m above sea level, mean annual temperatures ranged from 12.2°C to 20.5°C and mean temperatures of the coldest months from 4.0°C to as high as 15.8°C. Stockings at the different sites varied from 200 trees ha^{-1} to as high as 1150 trees ha^{-1}.

Four stands in China and three in Australia had no reproductively active trees (i.e. carrying flower buds, flowers or capsules), and this ranged up to 70% of trees being reproductively active in one of the Australian stands and up to 60% in one of the Chinese stands. Interestingly, there was no correlation between age and flowering across the sites ($r = -0.04$; Table 1). In the youngest stand examined in Australia (3.5 years old), approximately 5% of trees were already reproductively active. Clearly, age was generally not a factor that limited flowering for the stands examined. Age has often been considered a key limiting factor to flowering by *E. dunnii*, and Boland (1984) concluded it would often take 10 years or more in many locations for *E. dunnii* to start to flower and produce seed.

The environmental parameter with the strongest significant correlation with reproductive activity in *E. dunnii* across the sites was mean annual temperature ($r = -0.53$), with lower means being associated with higher proportions of trees being reproductively active (Table 1). Other environmental parameters that showed significant ($0.05 < p \leq 0.10$) correlations with reproductive activity across the sites were alti-

tude ($r = 0.41$), and stand stocking ($r = -0.41$). Mean temperature of the hottest month, mean temperature of the coldest month and mean annual precipitation had weaker correlations that were also negative.

Environments favouring flowering of *E. dunnii* were generally those with a lower mean annual temperature and located at higher altitude. Lower stand stockings (below 400 trees ha^{-1}) also appeared to favour flowering. Lower mean temperatures for both the hottest and coldest months, along with lower precipitation, might also be beneficial. These results generally reinforce the findings of Graca (1987) from studies of 18 sites in Brazil, that flowering of *E. dunnii* tends to increase with increasing latitude and/or as mean temperature of the coldest month decreases.

Despite the apparent association between some of the environmental parameters such as mean annual temperature and flowering in *E. dunnii*, it must be understood that there will be distinct limitations to these associations. Trees need to first survive and grow well if they are to be able to flower and produce seed.

Environmental requirements for productive *E. dunnii* plantations, in terms of wood volume growth, are well understood (Table 4). While the environments of most of the stands examined were within these requirements, two in Australia were not. These had mean annual rainfall of only 650–710 mm and, interestingly, both had trees that were reproductively active from relatively young ages (3.5 years onwards). Clearly, the conditions required for 'productive' plantations are somewhat narrower than those required for the species to be able to survive and become established. In the future, when more experience and data are obtained, it may be possible to accurately prescribe climatic and other environmental requirements for prolific reproductive activity in *E. dunnii*. In addition to the climatic conditions it is likely that soils also have significant influence on the species' reproductive activity, though it was not possible to include them in this study.

Cultural treatments for enhancing flowering

There were no flower buds or capsules observed on any *E. dunnii* trees in the cultural trials in Guangxi during this study. As the trees were of a suitable age (>9 years at the start of the study in 2000), it is apparent that the environment there is not conducive to abundant early flowering by *E. dunnii*. This is despite the fact the environments of both sites are

well within the requirement of productive *E. dunnii* plantations (Tables 2 and 4). Indeed, growth at both sites has been very good with annual height increments of up to 3.4 m or more (Wang et al. 1999).

Table 4. Climatic requirements for viable plantations of *Eucalyptus dunnii* based on its native habitat and successful plantation environments.

Climatic parameter	Conditions required
Altitudinal range (m)	60–2400
Mean annual rainfall (mm)	750–2100
Rainfall regime	summer, uniform
Dry season duration (months)	0–5
Mean annual temperature (°C)	14–22
Mean maximum temperature of hottest month (°C)	24–31
Mean minimum temperature of coldest month (°C)	–1–17
Number of days of frost	0–60
Absolute minimum temperature (°C)	> –10

Source of data: CABI (2000); Jovanovic and Booth (2002); and Antoine Kalinganire (pers. comm.)

In the southern New South Wales trials, there was a reasonable level of reproductive activity before and during this study. However, there were no significant differences between treatments in these trials for either the percentage of trees with capsules or the average number of capsules (capsule score) in January 2002 (Tables 5 and 6). The capsules observed on the trees at that time had all developed from flowers initiated before application of the fertiliser and paclobutrazol treatments in 2000. It is assumed that these capsules represent the flowering/reproductive ability of untreated trees in those environments. However, whether or not any of the treatments affect capsule retention is yet to be examined (see below).

In contrast, there were significant differences between treatments for both the percentage of trees with flower buds and for the average numbers of flower buds on those trees in January 2002 in the New South Wales trials (Tables 5 and 6). These buds were initiated at some time during 2001, well after the fertiliser and paclobutrazol treatments were applied in 2000. In the control and the fertilised plots, 47.1% and 38.7% of trees had flower buds while for those treated with paclobutrazol or with paclobutrazol + fertiliser, 74.0% and 71.6% had flower buds, respectively (Table 6). Trees treated with paclobutrazol also produced substantially greater numbers of flower buds, with average scores of 2.56 and 2.42 in the paclobutrazol and paclobutrazol + fertiliser treatments, respectively, compared with average scores of only 1.79 and 1.84 in the control and in the fertiliser treatments.

As well as significant differences between the treatments in the New South Wales trials, there were significant differences between the two sites for average numbers of flower buds on those trees in the January 2002 assessment. However, although there was a greater intensity of flowering on those trees producing flowers at one of the sites (Mooney Swamp), there was no significant difference between the sites in the percentage of trees with flower buds (Table 5). Also, there was no significant site by treatment interaction for the percentage of trees with flower buds, or for the average numbers of flower buds on those trees, indicating that the responses to the treatments were similar across the two sites (Tables 5 and 6).

The above results indicate that paclobutrazol significantly increased both the number of trees initiating flower buds and the average number buds on those trees, but only in environments where untreated trees initiated flower buds. In the Guangxi trials, none of the untreated trees initiated buds and the application of paclobutrazol did not stimulate any initiation of flower buds. The results from the New South Wales trials generally concur with those of Griffin et al. (1993) who found increases in both the frequency of flowering and heaviness of bud crops in *E. globulus* and *E. nitens* following paclobutrazol applications.

In contrast to the responses to paclobutrazol applications, high doses of fertiliser did not significantly affect either the proportion of trees initiating buds or the average number of buds on these trees in the New South Wales trials. The means for the fertiliser and control treatments were similar, as were those for the paclobutrazol + fertiliser and the paclobutrazol treatments on these sites (Table 6). However, this research is still in progress and assessments of capsule retention rates, seed yields per capsule, seed weights and germination tests are planned, to examine actual seed yields and seed quality obtained from the different treatments. It may be that some effect of the fertiliser treatments will become evident from those data.

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Table 5. Mean squares from analyses of variance for percentage of trees carrying capsules, and mean score for capsule number on trees with capsules, along with mean squares for percentage of trees carrying flower buds and mean score for flower bud number on trees carrying buds, in the *Eucalyptus dunnii* flowering enhancement trials in southern New South Wales.

Source of variation	Trees with capsules[a] (%)		Average capsule score for trees with capsules		Trees carrying flower buds[b] (%)		Average bud score for trees with flower buds	
	df	MS[c]	df	MS	df	MS	df	MS
Site	1	0.294 ns	1	0.017 ns	1	0.181 ns	1	0.699 **
Replicate-within-site	2	0.030 **	2	0.521 ns	2	0.019 ns	2	0.011 ns
Treatment	3	0.011 ns	3	0.536 ns	3	0.125 ***	3	0.620 **
Site × treatment	3	0.007 ns	3	0.031 ns	3	0.033 ns	3	0.311 ns
Residual	6	0.003	6	0.093	6	0.008	6	0.066

[a] The capsules observed in this study developed from flowers initiated prior to application of fertiliser and paclobutrazol treatments in 2000.
[b] The flower buds observed in this study were initiated some time after the application of fertiliser and paclobutrazol treatments in 2000.
[c] MS = mean square; ns = not significant; ** = significant at $0.01 < p \leq 0.05$; *** = significant at $p \leq 0.01$.

Table 6. Treatment means and standard errors of the differences between treatment means across sites for the cultural trials on enhancing flowering in *Eucalyptus dunnii*, carried out in the seedling seed orchards in southern New South Wales.

Treatment	Treatment means across sites			
	Percentage of trees carrying capsules[a]	Average capsule score for trees carrying capsules	Percentage of trees carrying flower buds[b]	Average bud score for trees carrying flower buds
Control	12.9	1.82	47.1	1.79
Fertiliser	23.7	1.80	38.7	1.84
Paclobutrazol	23.3	1.96	71.6	2.56
Fertiliser + paclobutrazol	19.8	1.85	74.0	2.42
Standard error of difference between treatment means	7.7	0.18	8.9	0.25

[a] The capsules observed in this study developed from flowers initiated before application of fertiliser and paclobutrazol treatments in 2000.
[b] The flower buds observed in this study were initiated some time after the application of fertiliser and paclobutrazol treatments in 2000

Conclusions

Eucalyptus dunnii seed orchards and/or seed production areas should, for prolific flowering, preferably be located in areas with mean annual temperatures somewhat below 16°C and/or at altitudes of more than 800 m asl and managed at lower stand stockings.

The importance of locating *E. dunnii* seed production areas and seed orchards in such environments was demonstrated by the cultural research carried out in the Australian and Chinese seed orchards. The environment alone can have a far greater impact on flower initiation in this species than the cultural or management treatments examined. Cultural treatments can enhance both the percentage of trees initiating flower buds and the heaviness of flower bud initiation in favourable environments yet will have no effect if the environment is not naturally conducive to flowering in this species.

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Analysis of Genetic Heterozygosity in *Eucalyptus urophylla* and *E. tereticornis* Using RAPD Markers

Gan Siming, Shi Jisen, Bai Jiayu, Wu Kunming and Wu Juying[1]

Abstract

Five *Eucalyptus urophylla* × *E. tereticornis* crosses were used for RAPD analysis on genetic heterozygosity of the seven parental clones. Fifty-eight fragments were amplified with 9 single arbitrary primers, and 42 fragments (72.4%) were scored as polymorphic among the parents. Genetic distance between parents was calculated with RAPD data matrix. High levels of heterozygosity were revealed in the parents studied, with an average 28.0%, but the percentage of heterozygous loci varied with parent, from 16.2% to 39.5%. Implications for material selection in genetic linkage map construction are discussed.

Eucalyptus species (family Myrtaceae) are native to Australia, Indonesia and the adjacent islands. Where they are introduced for plantation forestry, it is largely due to their fast growth, multiplicity of uses and plasticity of adaptations (Jacobs 1979; Eldridge et al. 1993). *Eucalyptus urophylla* and *E. tereticornis* are two of the most important species in the genus. In China, substantial genetic gain in such traits as growth and wood properties has been demonstrated in field trials through recurrent selection and controlled pollination in the two species (Wu et al. 1996; Xu et al. 1996). These species and their hybrids are of great potential in establishing short-rotation and industry-oriented (e.g. pulp and paper making) plantations in a worldwide context, and great efforts have been placed on their multiple objective improvement, especially with a focus on integrating modern biological techniques.

A successful breeding program should take full advantage of a broad genetic base, particularly largely unimproved species such as forest trees, and genetic polymorphism and heterozygosity are always important indices used to monitor genetic diversity (Lanham 1996). Isozymes were initially used in plants for these purposes (Hamrick and Godt 1990), but their use was limited to some extent by the low amount of variability. The recent development of molecular marker technology has made it possible to conduct studies with more powerful assays, and random amplified polymorphic DNA (RAPD) is preferred because it is easy to analyse, requires very little DNA, samples the genome randomly, and does not need radioactivity handling facilities (Williams et al. 1990; Welsh and McClelland 1990; Martin et al. 1993; Gan et al. 1998). Though the reproducibility of RAPD markers is sometimes questioned, reliable results have been verified in many plant studies (Xiao et al. 1996; Lanza et al. 1997). Now DNA polymorphism and heterozygosity have been potently identified with RAPD markers in several species, such as intraspecific crosses of canola, *Brassica napus* (Marshall et al. 1994); cultivars of the shrub *Ribes nigrum* (Lanham 1996); and sibs of a single urediniospore-derived culture of the fungus *Cronartium quercuum* f. sp. *fusiforme* (Doudrick et al. 1993).

In the study reported here, we used RAPD markers and five interspecific crosses to detect the levels of

[1] Research Institute of Tropical Forestry, Chinese Academy of Forestry, Longdong, Guangzhou 510520, China. Email: <smggan@pub.guangzhou.gd.cn>.

polymorphism and heterozygosity in clones of *E. urophylla* and *E. tereticornis*. The implications for material selection in linkage mapping studies are discussed.

Materials and Methods

Plant materials

Three maternal clones of *E. urophylla* and four paternal clones of *E. tereticornis* were used in this study, from seedlings raised in 1989 with seeds collected in natural forests. Details of origin and code of the parental clones are shown in Table 1. The trees were conserved in the gene pool in Research Institute of Tropical Forestry, Chinese Academy of Forestry, and grafted in 1992. Controlled pollination took place in 1996 to produce five interspecific crosses, viz. crosses A, B, C, D and E (Table 1), and more than 10 sib seedlings per cross were then raised in the nursery from the seeds. For each cross, both parents and 10 sibs were used for RAPD analysis.

DNA extraction and RAPD assays

About 1 g of fresh, tender leaves per parent and 5-month-old sib seedlings was sampled and stored at –20ºC for subsequent DNA extraction. Preparation of DNA followed the procedure described in Doyle and Doyle (1990), amended by the addition of 5% poly-vinylpyrrolidone (PVP) and 2% 2-mercaptoethanol to the extraction buffer. DNA concentration was estimated by electrophoresis of agarose gel stained with ethidium bromide (EB) based on the fluorescence intensities of the sample.

RAPD was performed in thin-walled microcentrifuge tubes with Idaho Rapidcycler (Idaho Technologies). The amplification program and RAPD reaction mixture were in accordance with Gan et al. (2000). Twenty candidate primers (Operon Technologies Inc.), namely OPE01~OPE20, were used for primer screening against the seven parental DNA templates, and nine primers that could produce polymorphic, clear and stable fragments were eventually selected for formal amplification (Table 2).

Polymorphism and heterozygosity tests

RAPD genotypes of seven parents were scored for the presence/absence of amplification fragments, with one (1) representing presence and zero (0) absence of a fragment. Polymorphic markers among parents were recorded for polymorphism estimation. Genetic distance (GD) of different parent pairs was then calculated according to the method of Nei (1978). The number of heterozygous loci per parent was evaluated on the basis of the segregation across the sibs, and heterozygosity was calculated as the percentage of heterozygous loci taking of the total number of fragments amplified in each of the parental clones.

Results and Discussion

DNA polymorphism among parental clones

In total, 58 fragments were amplified with 9 primers selected from 20 candidates, including 42 (72.4%) being polymorphic and 16 persistent (non-polymorphic) among the seven parental clones tested

Table 1. Parental clones of *Eucalyptus urophylla* and *E. tereticornis* used in this study.

Parent	Clone code	Species	Seedlot no.[b]	Origin			
				Locality	Latitude	Longitude	Altitude (m)
P_{A1}[a], P_{E1}	13	*E. urophylla*	12897	Mt Wuko, Indonesia	8°33'S	122°35'E	830
P_{B1}, P_{C1}	03	*E. urophylla*	14531	Mt Egon, Indonesia	8°38'S	122°27'E	515
P_{D1}	10	*E. urophylla*	14534	Mt Egon, Indonesia	8°38'S	122°27'E	500
P_{A2}, P_{B2}	20	*E. tereticornis*	15825	Laura, Australia	15°44'S	144°41'E	140
P_{C2}	16	*E. tereticornis*	13443	Kennedy River, Australia	15°46'S	145°24'E	120
P_{D2}	21	*E. tereticornis*	15825	Laura, Australia	15°44'S	144°41'E	140
P_{E2}	18	*E. tereticornis*	13418	Sirinnmu, Sogeri Plateau, Papua New Guinea	9°30'S	147°26'E	580

[a] P_{A1} indicates the female parent of cross A, and P_{A2} the male in turn. [b] CSIRO Australian Tree Seed Centre seedlots.

(Table 2). The number of fragments varied with primer. Two unique primers, OPE09 and OPE13, could distinguish clearly between all the parents. The high level of polymorphism might be indicative of a relatively high level of polymorphism for the parents studied (Nei 1978). Figure 1 shows the RAPD profiles of seven parents amplified with two primers, OPE02 and OPE09.

Pairwise comparisons of RAPD data between parental clones resulted in a matrix of genetic distance (GD) (Table 3). The five crosses followed in parental GD a descending order A>E>B>C>D. This order was approximately the same as the clone fingerprints previously established with other primers (Gan et al. 1999).

Clone No. M 13 03 10 20 16 21 18 M 13 03 10 20 16 21 18 M

Primer OPE02   Primer OPE09
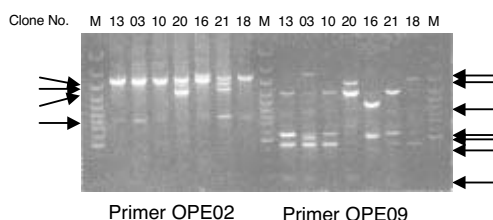
Figure 1. Amplification profiles of primers OPE02 and OPE09 against the seven parents. The arrows show the polymorphic fragments. M is the 100bp DNA ladder size standard (MBI) (with fragments representing 3000, 2000, 1500, 1200, 1031, 900, 800, 700, 600, 500, 400, 300, and 200bp from the top to the bottom).

Heterozygosity tests of seven parents

According to the dominant nature of RAPD markers, we could deduce the genotype *AA* or *Aa* at a locus from the presence of a RAPD fragment and recessive homologous *aa* from the absence. Thus, the fragment-specific parent could be genotyped as heterozygous *Aa* if the fragment segregated in the offspring in a Mendelian mode. In this way, the number and percentage of putative heterozygous RAPD loci (RAPDs) of each parent could be calculated (Table 4). The average of heterozygosity was calculated as the percentage that the total heterozygous loci took of the total number of fragments amplified for all the seven clones studied. Figure 2 shows the segregating markers among the sibs of each of the crosses amplified with primer OPE13.

Heterozygosity was defined as the percentage that heterozygous individuals took at a specific locus of the total individuals in a population (Nei 1978). It was originally a concept of population genetics and later extended to refer to the percentage of heterozygous loci at individual level (Marshall et al. 1994; Lanham 1996). In our observations, high levels of heterozygosity were revealed in the parental eucalypt clones, with an average 28.0% (72/257). Heterozygosity varied with parent, as P_{B1} (P_{C1}, Clone 03) ranked the first in percentage of heterozygous loci (39.5%), and P_{D1} (Clone 10) the last (16.2%). Levels of heterozygosity of eucalypts in this study were much higher than those estimated in a nearly isogenic line of canola (*Brassica napus*) (3.6% at the most)

Table 2. Primers used in formal amplification and the number of fragments amplified.

Primer	Sequence	Nt [a]	Np [b]	Nps [c] of each cross				
				A	B	C	D	E
OPE01	5' CCCAAGGTCC 3'	5	3	2	3	0	1	2
OPE02	5' GGTGCGGGAA 3'	5	4	3	4	1	0	3
OPE05	5' TCAGGGAGGT 3'	7	3	1	1	1	0	3
OPE08	5' TCACCACGGT 3'	7	6	3	1	0	0	0
OPE09	5' CTTCACCCGA 3'	9	7	1	3	2	1	2
OPE11	5' GAGTCTCAGG 3'	5	4	1	0	1	1	2
OPE13	5' CCCGATTCGG 3'	8	8	2	2	5	4	4
OPE17	5' CTACTGCCGT 3'	5	3	2	0	0	0	2
OPE19	5' ACGGCGTATG 3'	7	4	0	1	1	2	1
Total	9	58	42	15	15	11	9	19

[a] Nt is the total number of fragments.

[b] Np is the number of polymorphic fragments.

[c] Nps is the number of fragments polymorphic between both parents and segregant among the sibs per cross.

(Marshall et al. 1994), and were similar to those of *Ribes nigrum* (about 20%) (Lanham 1996).

Interestingly, heterozygous loci or their number varied in the same parental clone with cross (Table 4). For example, clone 03 showed 14 heterozygous loci in cross B, but 9 (one being exclusive) in cross C. This might be caused by (i) the inability of RAPD technology to detect heterozygous loci in case of $Aa \times Aa$, where the locus would not segregate in the sibs, and (ii) the use of an inadequate size of F_1 population as some factual segregating loci could not be observed in a small population. The ideal solution would rely on use of selfed populations. However, selfed crosses were difficult to obtain and tended to segregate aberrantly at a number of loci to due to self-incompatibility in most tree species (Dudley et al. 1991; Marshall et al. 1994). Therefore, the usual populations used were single outcross pedigree in related studies. In addition, the probability for detecting a heterozygous loci in a population could be given by the probability of a fragment being present in at least one sib as $1-(1/2)^{n-1}$ when $Aa \times aa$ (or $aa \times Aa$) and $1-(3/4)^{n-1}$ when $Aa \times Aa$, where n was the size of population. For a population of 10 sibs, the probability was 99.8% and 92.5%, respectively. So a population size of 10 sibs could be reliably effective for detecting possible segregating RAPD loci as was the case in this study.

In genetic mapping of highly heterozygous species, such as forest trees, the usual mapping population was F_1 pedigree and the strategy followed a pseudo-testcross configuration. In such a strategy, the marker available for linkage map construction should be present in the mapping parent (genotype Aa) but absent in another (genotype aa); and segregate 1:1 in the sibs in a Mendelian fashion (Carlson et al. 1991; Grattapaglia and Sederoff 1994). The high level of heterozygosity in eucalypt clones tested may indicate that testcross cases for RAPD markers were so common in eucalypts that the lack of codominance with RAPD might not represent such a disadvantage in genetic map construction.

Table 3. Nei's genetic distance between the seven parents.

Parent	P_{A1}, P_{E1}	P_{E2}	P_{B1}, P_{C1}	P_{C2}	P_{D1}	P_{A2}, P_{B2}
P_{E2}	0.7732(E)[a]					
P_{B1}, P_{C1}	0.4055	0.4447				
P_{C2}	0.5281	0.5725	0.6294(C)			
P_{D1}	0.4855	0.6190	0.5281	0.6678		
P_{A2}, P_{B2}	0.8303(A)	0.5725	0.6678(B)	0.4447	0.9732	
P_{D2}	0.5281	0.4855	0.3314	0.5281	0.5725(D)	0.5281

[a] The letter in brackets gives the cross in which both parents are involved in the genetic distance.

Table 4. Parental variations of heterozygous RAPDs in the five crosses tested.

Items	Cross E	Cross A	Cross B	Cross C	Cross D
Total number of RAPDs scored (Maternal total/Paternal total)	49 (38/40)	47 (38/35)	45 (38/35)	45 (38/37)	41 (35/34)
Number of parent-polymorphic RAPDs (Maternal-/Paternal-specific segregating RAPDs)	20 (9/10)	21 (9/6)	17 (10/5)	15 (7/4)	13 (5/4)
Number of RAPDs non-polymorphic between parents but segregating among sibs	4	3	4	2	2
Number of maternal heterozygous RAPDs (Percentage of the maternal total RAPDs)	9+4=13 (34.2%)		10+4+1[a] =15 (39.5%)		7 (20.0%)
Number of paternal heterozygous RAPDs (Percentage of the paternal total RAPDs)	14 (35.0%)	6+3+2[b] =11 (31.4%)		6 (16.2%)	6 (17.6%)

[a] The one heterozygous locus is detected exclusively in cross C.
[b] The two heterozygous loci are detected exclusively in cross B.

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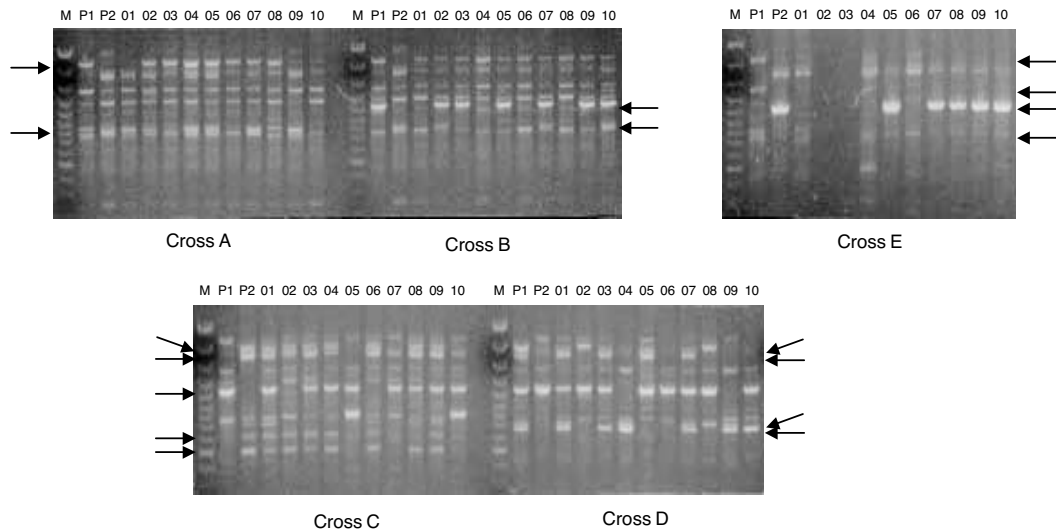
Figure 2. RAPD profiles of five crosses amplified with primer OPE13. The arrows show the fragments that are polymorphic between both parents and segregate among the sibs per cross. In each cross panel, M is the 100bp DNA ladder size standard (MBI) (order as Figure 1), P1 the female parent, P2 the male parent, and the rest 01~10 are sibs.

We suggest that preliminary screening of small samples of progeny be conducted to determine the parental polymorphism and heterozygosity before full-scale segregating analysis. In this respect, N_{ps} (Table 2) could be preferable in choosing a rational F_1 population and those fragments polymorphic between parents and segregant among sibs be potentially useful for genetic mapping in *E. urophylla* and *E. tereticornis*. Therefore, cross E (N_{ps}=19), followed with crosses C and D (N_{ps}=15), would probably be sound candidates for genetic mapping (with an appropriate number of sibs, e.g. 100 or more). Also, it might be inferred from this study that more than 300 primers could be selected out of 1000 candidate primers and about 500 markers be produced for genetic mapping of a typical eucalypt species. If these primers were used in combination, even more markers could be mapped (Carlson et al. 1991).

In summary, the results from the present study indicate that high levels of polymorphism and heterozygosity are reliably revealed in parental eucalypt clones with RAPD markers. They thus facilitate the construction of genetic maps for plant material preparation considerations.

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Soils Proposed for Eucalypt Plantations in Southern China: Properties, Distribution and Management Requirements

M. Laffan,[1] T. Baker[2] and Chen Shaoxiong[3]

Abstract

Nearly 50 million ha of mainly degraded red and yellow soils have been proposed for afforestation with cold-tolerant eucalypts in southern China. Landforms include undulating, rolling and steep hilly and mountainous land at varying elevations up to about 2000 m. Substrates are dominated by sedimentary and acid igneous rocks with sandstone, siltstone, limestone and granite occurring widely in the region. Mean annual rainfall varies from about 850 mm to over 1500 mm, with all areas showing a rainfall peak in spring–summer followed by a dry season in autumn–winter. High rainfall intensities in spring–summer are a feature of the climate. Both red and yellow soils are typically deep, well-drained, porous and easily penetrable by tree roots. Shallow and stony soils frequently occur on steep slopes, often in association with rocky outcrops. The soils have low levels of plant-available phosphorus and low to medium total nitrogen. Ratings of soil erodibility based on wet-sieving tests range from low to moderate. Since the soils generally have good physical properties, the main limitation affecting plantation growth is the low level of nutrients. There is also a significant risk of sheet and gully erosion resulting from the high rainfall erosivity, as well as a high landslide hazard on steep slopes underlain by deep soils and strongly weathered, relatively soft substrates. However, with appropriate fertiliser regimes and forest practices to minimise the risk of erosion and landslides, large areas, including gentle slopes as well as steep land, are considered suitable for plantation forestry. Sustainability of the plantations will be strongly reliant on manual forest practices that cause minimal soil disturbance.

Nearly 50 million ha of mainly degraded land have been targeted for a substantial expansion of eucalypt plantations in south-central China, stretching from Yunnan in the west to Fujian in the east. Land degradation has resulted largely from gully and sheet erosion, where topsoils have been removed by the effects of raindrop impact and run-off to expose subsoils and, in some extreme cases, the underlying bedrock. Landslides have also been responsible for severe loss of soils, particularly on sites where natural slopes have been undercut during construction of roads and railways. Major objectives of large-scale afforestation with cold-tolerant eucalypts are to help control and ameliorate severe soil erosion, derive long-term economic and social benefits to the local populace, and markedly increase the supply of wood products within China.

As part of a collaborative Australian–Chinese research project into cold-tolerant eucalypt plantations, three field visits to inspect soils and environmental features in southern China were made during

[1] Forestry Tasmania, 15960 Midland Highway, Perth, Tasmania 7300, Australia.
 Email: <michael.laffan@forestrytas.com.au>.
[2] Forest Science Centre, Department of Sustainability and Environment, PO Box 137, Heidelburg, Victoria 3084, Australia. Email: <tom.baker@nre.vic.gov.au>.
[3] China Eucalypt Research Centre, Zhanjiang, Guangdong, China. Email: <sxchen@pub.zhanjiang.gd.cn>.

2000–2003. The sites examined were all in eucalypt trials (species, species–provenance, provenance and provenance–family) or plantations in Yunnan, Guangxi, Hunan and Fujian provinces. The soils and sites were considered representative of much of the area proposed for afforestation with eucalypts.

This paper summarises the results of the field inspections (Laffan 2003) and laboratory analysis of soil samples, and interprets the information in relation to plantation potential and management requirements of the various soils and sites.

Site Data and Methods

Thirty sites were inspected to describe soil profile features and environmental attributes. At all sites, the climate is dominated by cool, dry winters and warm to hot summers. Periods of sub-zero temperatures and/or snowfalls can be expected to occur about once or twice every decade. The rainfall is spring–summer dominant and is characterised by high intensities and totals, particularly rainfall associated with typhoons and other deep low-pressure systems. Mean annual rainfall ranges from about 850 mm in Yunnan to over 1500 mm in Fujian. Soil moisture deficits typically occur in late summer–autumn.

Topography is highly variable and includes undulating, rolling and steep hill and mountain slopes at elevations ranging from several hundred metres to over 2000 m. The geology of the region is dominated by sedimentary and acid igneous rocks, with the most commonly occurring substrates including sandstone, siltstone, limestone and granite.

Surface (0–10 cm) soil samples were collected from numerous sites to analyse a range of nutrients and other chemical properties including pH, electrical conductivity, total nitrogen, carbon and phosphorus, available phosphorus and nitrogen, exchangeable calcium, magnesium, potassium and sodium, and phosphate retention. Subsoils (60–90 cm) from some sites were analysed for free iron.

In Yunnan, six soils were sampled for wet-sieving tests to determine water-stable aggregates and derive a rating of soil erodibility. A modified version of the wet-sieving method used in the laboratory for testing Tasmanian forest soils (Laffan et al. 1996) was developed specifically for use in the field. This method relies on manual end-over-end shaking of soil and water in a small jar, adding the resultant slurry to a 0.25 mm sieve placed over a container, washing with a known volume of water and weighing the slurry and

water in the container to arrive at the proportion of water-stable aggregates > 0.25 mm. A rating of soil erodibility was made using the results of water-stable aggregates in conjunction with assessments of soil drainage class, permeability and stone content as described in Laffan et al. (1996).

Properties and Distribution of Soils

Soil profile characteristics

Dominant soils in the region are broadly described as red and yellow soils. Both are invariably well drained with gradational or uniform-texture profiles. Red soils predominate throughout the region. They occur preferentially on undulating and rolling hill and mountain slopes on a wide range of substrates that are mostly strongly weathered. The soils are nearly all relatively deep (> 1.5 m) and permeable, with profiles that are easily penetrable by tree roots. Profiles that have been severely degraded are characterised by reddish-brown or red, clay loam surface layers overlying red, well-structured, light clays in subsoils. The red colours in surface layers result from previous sheet and gully erosion of the darker-coloured topsoils. Red soils that have not been severely degraded typically have strong brown or dark reddish-brown surface soil layers. Subsoil structure generally comprises moderately developed 20–50 mm angular blocky, breaking to moderately or strongly developed 5–10 mm and 2–5 mm polyhedral structure. Some profiles have weakly structured or massive subsoils, but they are porous and able to be readily penetrated by tree roots. Profiles with sandy loam surface and subsurface layers overlying clay loams were observed at several sites in Yunnan province.

Many of the red soils have high contents of free iron oxides in subsoil layers, as evidenced by laboratory analysis and by marked iron staining of fingers when determining field textures. However, there does not appear to be any relationship between iron oxide content and type of substrate (Table 1). Soil depth and stone content are variable, but appear to be dependent largely on topography, with shallow and stony soils occurring mainly on steep slopes and slightly or non-stony soils prevalent on easy slopes. Steep slopes underlain by limestone substrates are particularly variable, with pockets of deep soils occurring in a complex pattern with shallow soils and numerous exposed rocky outcrops.

Yellow soils cover a smaller area than red soils and their distribution appears to be strongly related to topography. They occur predominantly on steep slopes and less commonly on easy slopes where substrates are typically only weakly or moderately weathered. Most yellow soils are permeable, but depth and stoniness are highly variable, reflecting the relatively weak degree of weathering of underlying substrates. Typical profiles are characterised by brown silt loams or fine sandy/silty clay loams overlying well-structured, silty clay loams or light clays.

On steep slopes the soils are frequently shallow (< 1 m) and stony, with common to many coarse fragments throughout the profile.

Soil chemical properties

Nearly all surface (0–10 cm) soils have acidic pH (pH in water < 6.5), with most lying within the range 5.0–6.0. However, surface soils from one site located next to a cement factory were moderately alkaline (pH 7.8– 8.1) due to contamination from alkaline dust. Results of total carbon (C), total nitrogen (N), total phosphorus (P), available P, P retention and free iron are given in Table 1. Most samples are from red soils with only two from yellow soils. Levels of total C and N are either low (< 2.0% C, < 0.1% N) or medium (2.0–5.0% C, 0.1–0.2% N), reflecting relatively low content of organic matter in the surface layers of the soil. Although total P is high (> 250 mg/kg) or medium (100–250 mg/kg), available P is gen-

erally low. Most red soils have medium (30–60%) phosphate retention whereas yellow soils have low values.

Water-stable soil aggregates

Results of wet-sieving tests carried out on surface and subsurface layers for a range of red soils from Yunnan are presented in Table 2. They show that the proportion of water-stable aggregates > 0.25 mm range from 50% to 90%. For soils that are freely drained and permeable with few coarse fragments, erodibility is assessed as low where water-stable aggregates exceed 70% in all layers, and as moderate where the proportion of aggregates occurs within the range 30–70% in any layer (Laffan et al. 1996). The proportion of water-stable aggregates appears to be closely related to soil texture; profiles with sandy loams in surface and/or subsurface layers have water-stable aggregates between 50–70%, whereas clay loams and/or clays have water-stable aggregates > 70%.

Soil classification

Red soils have been previously classified in China as Red earths, Lateritic red soils and Latosols depending on the content of iron and aluminium oxides. According to the new Chinese Soil Taxonomy, red soils classify as Ferrosols and yellow soils as Argosols. Under the Australian soil classification, the red soils include Red Ferrosols, Red Dermosols and Red Kandosols. Dermosols have

Table 1. Concentrations of total carbon, nitrogen and phosphorus, available phosphorus and phosphate retention (PR) in surface soil layers (0–10 cm), free iron in subsoils (60–90 cm) and substrate type, for a range of red and yellow soils from southern China.

Location[a]	Substrate	Total C (%)	Total N (%)	Total P (mg kg^{-1})	Available P (mg kg^{-1})	PR (%)	Free iron (%)
Yunnan, Fumin	sandstone	1.3	0.11	313	4.5	27	–
Yunnan, Fumin	sandstone	1.0	0.10	353	3.05	32	–
Yunnan, Fumin	sandstone	1.8	0.15	470	7.86	31	5.3
Yunnan, Fumin	limestone	1.5	0.11	320	1.4	47	5.1
Yunnan, Chuxiong	siltstone	0.9	0.08	140	4.98	18	1.5
Hunan, Yongzhou	sandstone	0.45	0.08	383	2.32	41	4.8
Hunan, Chenzhou	siltstone	1.4	0.16	155	3.77	21	4.8
Guangxi, Guilin	limestone	1.8	0.15	266	9.41	28	–
Guangxi, Leizhou[b]	sandstone	1.9	0.15	173	6.0	19	2.0
Fujian, Yongan[b]	limestone	–	0.14	207	8.23	19	
Mean		1.5	0.12	278	5.2	28	

[a] The results given for each site are means of 3–4 samples. [b] Mainly yellow soils. Red soils occur at all other sites.

moderately to strongly structured subsoils, whereas Kandosols are characterised by weakly structured or massive subsoils. Both groups have < 5% free iron oxides in subsoils. Conversely, Ferrosols have > 5% free iron in the main subsoil layer and can have any degree of structural development. The yellow soils are classified as Yellow Dermosols according to the Australian system.

Table 2. Wet-sieving tests and ratings of erodibility for soils from Yunnan Province.

Location	Depth (cm)	Water-stable aggregates > 0.25mm (%)	Erodibility rating for profile
Fumin	0–20	90	Low
	20–40	84	
	120–140	90	
Fumin	0–20	86	Low
	20–40	80	
	120–140	81	
Fumin	0–20	94	Low
	20–40	89	
	120–140	90	
Fumin	0–20	80	Moderate
	20–40	50	
	140–160	66	
YAF arboretum	0–20	85	Low
	20–40	70	
	120–140	70	
Chuxiong	0–20	64	Moderate
	20–40	66	
	100–120	82	

Site Suitability for Plantations

Determining the suitability of land for plantations involves: 1) assessment of site productivity (or site quality), and 2) assessment of plantation management factors and land degradation hazards. Site productivity is dependent on various soil and climatic factors including; temperature regime, moisture availability, soil drainage characteristics, tree-rooting conditions and nutrient availability. Other factors such as salinity are not considered to be relevant in the areas proposed for afforestation in southern China.

Factors affecting site productivity

Temperature has a marked impact on the survival and rate of growth of trees. With increasing elevation, mean temperature and length of the growing season decrease and the incidence of frost increases. The frequency and severity of frost also increases with distance inland from the coast. Although mean temperatures are generally favourable for the fast growth of plantations, heavy frosts and/or snowfalls in some winters result in poor survival and severe stem damage in eucalypt plantations.

Moisture availability is the capacity of the soil to provide plant available moisture throughout the growing season. It is determined largely by mean annual rainfall, and soil depth and texture. At most sites, the soils are deep (> 1.5 m) and have loamy surface layers overlying clay loams or clays with adequate water-holding capacity. Mean annual rainfall (MAR) appears to be sufficient for good growth in most regions, although in central and eastern Yunnan where MAR is about 850 mm, shallow and moderately deep soils are likely to experience soil moisture deficits that will limit tree growth. Areas of karst terrain comprising complexes of both deep and shallow soils in association with extensive rock outcrop are thought to be most at risk of low moisture availability.

Drainage refers to the depth and duration of soil saturation, and it reflects the degree of waterlogging of the soil and its aeration status. However, the soils proposed for afforestation are invariably well drained and permeable, and restricted drainage is not considered to be a limiting factor in the dominantly hilly terrain.

Tree-rooting conditions are determined by effective root depth and ease of root penetration. Effective root depth is the depth to a layer that physically impedes root development, such as bedrock, cemented or compacted hardpans, waterlogged layers, massive and slowly permeable clay, or very stony layers. Ease of root penetration is a measure of the suitability of the effective root depth as a medium for root penetration. It is largely determined by soil texture, size and degree of soil structural development, and stone content. Most soils inspected in southern China are deep, well-structured and/or porous, with negligible limitations affecting root depth or ease of root penetration. Exceptions are shallow soils over bedrock, and very stony soils that typically occur on steep land. Such soils would be expected to have moderate to severe limitations to effective root depth and/or root penetration.

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Nutrient availability is the capacity of the soil to supply nutrients, including the quantities and forms of nutrients present in the soil and any nutrient fixation properties of the soil that make them unavailable to trees. Nutrient fixation is a process whereby added nutrients (mainly phosphorus) are adsorbed by soil particles and made unavailable to plants, thus necessitating repeated applications of fertilisers. Nutrient availability is the soil factor most limiting site productivity in southern China. The results of laboratory analysis reported earlier show that N and P are likely to be deficient, but because phosphate retention in surface soils is only low or medium, P-fixation is unlikely to be a major problem. However, high values of phosphate retention are expected to occur in deeper layers of red soils, and P-fixation could be limiting if surface layers are removed or displaced by erosion or inappropriate site preparation before planting. Other nutrients variously observed to be limiting include potassium (K), boron (B) and copper (Cu).

Factors affecting land degradation

Land degradation includes a variety of hazards such as floods, erosion, landslides, salinity, acidification and soil structural decline. Erosion and, to a lesser extent, landsliding are thought to be the most relevant land-degradation factors in the areas proposed for afforestation.

Erosion causes not only decreased site productivity resulting from loss of nutrients in topsoils and exposure of less fertile subsoils, but also off-site problems of sedimentation and lowered water quality. Severe erosion can lead to almost total loss of productivity as well as limit or even prevent access to plantations. Erosion hazard is dependent on a variety of factors including rainfall intensity and duration (erosivity), slope angle, position and length of slope, inherent soil properties (erodibility), vegetation cover and land management. All the regions proposed for afforestation in southern China experience high-intensity rainfalls in spring–summer, and it is concluded that high rainfall erosivity together with poor land management has been responsible for much of the land degradation observed.

Landslide hazard refers to the risk of mass movement of slopes, including landslip, earthflows, debris avalanches, slumps etc. It is dependent on various factors, of which the more important ones are soil/geologic properties, slope angle and vegetative cover. Soil and geologic attributes considered to be most relevant to landslide risk in the region include thickness of the soil mantle and hardness of underlying bedrocks. On easy sloping land and on lower slopes of hilly and mountainous land, bedrocks have generally been strongly weathered to produce relatively soft, saprolitic substrates many metres deep. It is concluded that landslide risk is highest on strongly rolling and steep slopes underlain by deep soils and soft substrates, particularly when severely disturbed by operations such as road construction.

Management Requirements

Apart from rocky sites, the red and yellow soils of southern China have physical properties well suited to plantation growth; they are generally deep, well drained and easily penetrable by tree roots. However, because of the widespread occurrence of nutrient deficiencies, particularly in soils degraded by the loss of the nutrient-rich topsoils, fertiliser applications will invariably be required to achieve acceptable productivity.

In China, most forest practices are carried out manually and they generally result in low impacts on the environment. Even so, specific management practices are required to minimise the risk of both erosion and landslides, so as to ensure the sustainability and profitability of eucalypt plantations. A brief discussion of the main management requirements is given below.

Fertiliser applications

Application of manufactured fertilisers or organic manures will be required to ameliorate nutrient deficiencies. Because of low levels of available P and the low and medium levels of total N, it is expected that applications of fertilisers containing P and possibly N will be required at or near time of planting. Further trials need to be established across a wide range of soil types to quantify the various macro and micronutrients that may be deficient and to specify appropriate rates and types of fertilisers.

Management practices to minimise erosion risk

Because rainfall erosivity is always going to be high, manual forest practices that cause least disturbance to the soil surface must be used, so as to minimise the risk of soil erosion. Management practices

that have most impact on erosion risk are those concerning site preparation and harvesting.

Site preparation

Current site preparation involves either construction of small terraces or spot cultivation. Spot cultivation is the preferred method as it is much less costly and results in minimal surface soil erosion compared to terracing. Dimensions of spots vary according to slope steepness but range from about 1 m × 1 m on easy slopes, decreasing to about 0.6 m × 0.6 m on steep slopes and they are typically 40 cm deep. The cost of spot cultivation, including clearing slash from the site, is markedly less than that for construction of terraces. Spot cultivation must be used for soils with sandy loam textures because they are more erodible (moderate erodibility) compared with other soils with clay loams or clayey textures where erodibility is generally low.

Terracing along contours is used widely throughout Yunnan on both easy sloping and steep land, to facilitate ease of access for the collection of foliage for essential oil production. It was also observed in some sites in the other provinces. Typical dimensions are about 1–1.2 m wide by 0.4–1.5 m high depending on slope steepness. Unfortunately, their construction invariably causes severe disturbance to large areas of soil, results in the loss of the nutrient-rich upper soil layer and predisposes bare subsoils to accelerated run-off and erosion. Construction of terraces should be discouraged because it is accompanied by a higher risk of soil erosion than is spot cultivation.

Periodic harvesting of foliage for essential-oil production markedly decreases vegetative cover and protection of the soil surface from raindrop impact. On terraced land, this leads to exacerbated run-off and soil erosion. Establishment of a protective ground cover with vegetation such as grasses/clovers would help lower the risk of erosion on terraces where the production of eucalypt oil is a major activity.

Harvesting

Skid trails or chutes used to manually drag or gravity-feed harvested logs to landings generally cause gouging of the soil surface and invariably lead to surface erosion and occasionally gullying. Such sites could be protected by partially burying logs on the contour at various distances down slope to provide mechanical support to the soil surface. At the very least, spoon drains or grips should be constructed along skid trails after logging to divert run-off and trap entrained sediment. Protective measures must be used where topsoils are more erodible (sandy loams).

Management practices to minimise landslide hazard

Access tracks or roads constructed on side-slopes in hilly and steep terrain underlain by deep soils and soft substrates are highly susceptible to landslides. In such terrain, large-scale collapse of batters and side-cast materials can be expected during and after heavy rains. Natural slopes above these tracks/roads are also susceptible to mass movement once collapse of batters occurs. Even relatively low natural slopes undercut during construction of roads may cause severe collapse of batters and mass movement within higher slopes.

Construction of access tracks or roads must be confined to the crests of ridges or other sites where negligible under-cutting of slopes will occur. Run-off from track/road surfaces on these sites must be safely dispersed to ensure that it does not cause soil saturation and mass movement on lower hill slopes.

Management practices required to ameliorate nutrient deficiencies and to minimise erosion and landslide risks are outlined in Table 3.

Summary and Conclusions

Red and yellow soils proposed for development to eucalypt plantations in southern China cover nearly 50 million ha of mainly rolling and steep hills and mountain land. Much of the area has been adversely affected by severe sheet and gully erosion and, to a lesser extent, by landslides. The climate is generally conducive to good growth of eucalypts although survival and growth may be restricted in shallow and stony soils where mean annual rainfall is below 900 mm, and in areas affected by episodic spells of sub-zero temperatures and heavy snow. Most areas have peak rainfall in spring–summer, when high rainfall intensities can be expected, followed by a dry season in late summer–autumn.

Soils are typically deep, well drained, porous and easily penetrable by tree roots. However, soil depth and rockiness are variable, particularly on steep slopes underlain by weakly weathered substrates. Both red and yellow soils are limited by low levels of nutrients. Wet-sieving tests carried out on a limited range of soils from Yunnan province indicate that erodibility ranges from low to moderate.

Table 3. Summary of management practices required to ensure high productivity and sustainability of commercial eucalypt plantations in southern China.

Management objectives	Required management practices
Achieve high site productivity[a]	Apply appropriate fertiliser regimes to ameliorate nutrient deficiencies.
Minimise erosion risk	During site preparation use spot cultivation only.
	Establish protective vegetative ground cover on terraced slopes.
	Provide mechanical support and construct grips/drains on skid trails/chutes.
Minimise landslide risk	No access tracks/roads on side-slopes in hilly and steep terrain underlain by deep soils and soft substrates.
	Run-off from access tracks/roads constructed on ridge crests must be safely dispersed to prevent initiation of landslides on lower slopes.

[a] Note that rocky sites with shallow and stony soils will have lower productivity than deep soils with few stones. However, it is preferable that rocky sites are also planted so as to minimise the risk of erosion and landslides.

With the exception of rocky sites the red and yellow soils found throughout the region have good physical properties for plantation growth. However, because of the low levels of nutrients occurring in most soils, fertiliser applications will be required to ensure optimum growth of plantations. The sustainability of the plantations will also be dependent on specific management practices to minimise the risk of soil erosion and landslides. These include spot cultivation rather than terracing during site preparation, establishment of protective ground vegetation such as grasses and clovers on terraced lands, construction of grips or drains and mechanical support to skid trails/chutes used during forest harvesting, and the avoidance of access tracks/roads on side slopes in steep terrain underlain by deep soils and soft substrates. Particular attention must be given to sites with moderately erodible topsoils.

The soil and site information gathered during this study forms a useful reference base, but it is recommended that further site inspections be carried out so as to ensure that appropriate management practices can be specified according to soil characteristics. To achieve this outcome, more detailed assessments are required of both the properties of the soils and their spatial distribution in the areas proposed for afforestation.

Acknowledgments

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Correlating Eucalypt Growth and Nutrition and Soil Nutrient Availability in the Cooler Provinces of Southern China

T. Baker,[1] M. Laffan,[2] W. Neilsen,[3] R. Arnold,[4] Chen Shaoxiong,[5] Jiang Yundong,[6] Xiang Dongyun,[7] Lin Mojiu[8] and Lan Hesheng[9]

Abstract

In China, fertiliser application is essential to achieve economically successful establishment and growth of most eucalypt plantations, with N, P K, B and Cu deficiencies being relatively widespread. This paper describes an ongoing study of *Eucalyptus globulus, E. smithii, E. dunnii* and *E. camaldulensis* aiming to variously relate growth, growth response to fertiliser application, tree nutrient status and soil nutrient availability, and focuses on field trials in Yunnan, Guangxi, Hunan and Fujian. Generally, S, Ca, Mg, Fe, Mn and Zn nutrition of the trial plantations was adequate. However, N and, to a lesser extent, P nutrition were commonly marginal to deficient at age 1.5 years, and there were clear instances of B deficiency at some sites. Across the sites, N, P, Cu and B status are correlated, indicating generally overall poorer or better status of soil fertility rather than a separation of limiting nutrients among sites. Moreover, a relatively wide range of N and P availabilities occurs in soils, indicating that site-specific N and P fertiliser prescriptions could be developed.

In China, fertiliser application is essential to achieve economically successful establishment and growth of most eucalypt plantations, particularly those on degraded (e.g. eroded) or strongly leached (e.g. trop-ical) soils (e.g. Zhang et al. 1991; Xu et al. 2002). The potential for N, P K, B and Cu deficiencies is relatively widespread, and has been confirmed in establishment fertiliser response trials and from foliar analysis, e.g. Dell and Malajczuk (1994). Dell et al. (2002) have identified broad soil types on which specific nutrient deficiencies may be observed, and have described visual symptoms and defined foliar concentrations commensurate with these deficiencies. An ability to identify marginal levels of nutrition in eucalypts, where growth is reduced but visual symptoms of deficiency are not apparent, is required to achieve optimal management of plantations.

Eucalypt plantations in China are generally managed on relatively short rotations corresponding to the time of peak mean annual increment (5–10 years); the peak current annual increment (CAI) having occurred at age 2–3 years (Chen and Zhou 2002). Rapid decline in CAI is common (e.g. Baker

1   Forest Science Centre, Department of Sustainability and Environment, PO Box 137, Heidelburg, Victoria 3084, Australia. Email: <tom.baker@nre.vic.gov.au>.
2   Forestry Tasmania, 15960 Midland Highway, Perth, Tasmania 7300, Australia.
     Email: <michael.laffan@forestrytas.com.au>.
3   Forestry Tasmania, Hobart, Tasmania 7000, Australia
4   CSIRO Forestry and Forest Products, Canberra, ACT 2600, Australia.
5   China Eucalypt Research Centre, Zhanjiang, Guangdong, China.
6   Yunnan Academy of Forestry, Kunming, Yunnan, China.
7   Guangxi Forest Research Institute, Nanning, Guangxi, China.
8   Hunan Forestry Department, Changsha, Hunan, China.
9   Fujian Forestry Department, Fuzhou, Fujian, China.

et al. 2003), and in part attributable to declining nutrient availability from the initial fertiliser input. This is exacerbated for some eucalypt species by rapid foliage growth–death–regrowth (i.e. nutrient demand associated with rapid canopy turnover), or by management, e.g. intensive foliage harvesting for oil production in *Eucalyptus globulus* (Turnbull 1981). The nutrition and fertiliser requirements for eucalypt plantations in China that might be grown on longer rotations (10–20 years) for sawlog production (e.g. Zhang et al. 2003) have not been determined.

This paper describes an ongoing study for cooler-climate eucalypts aiming to: (1) assess growth and rate of change in nutrient status of young eucalypt plantations, and correlate these with indices of soil nutrient availability, and (2) determine whether post-establishment fertiliser responses can be related to soil nutrient availability indices. At this early stage, the collection of a significant database on soil descriptions (Laffan et al. 2003), soil analysis, and foliar nutrient concentrations and growth for different species, allow us to examine some relational differences. Systems for soil and nutrient management can then be defined.

Methods and Study Sites

The study currently focuses on field trials in four southern provinces (Yunnan, Guangxi, Hunan and Fujian): (1) a silvicultural trial incorporating nutrition treatments, and an establishment fertiliser trial, planted in 2000 and 2001, respectively; (2) six species/provenance comparison trials planted in 2001; and (3) six age 5–12 years post-establishment ± fertiliser comparison trials planted 1988–1995 (Table 1).

The sites vary widely in altitude (130–2000 m) and annual rainfall (830–1900 mm), but are characterised by a 4–6 month winter dry season. Annual average temperatures vary from 10 to 23°C, and while minimum temperatures in the coldest month are 2–9°C, absolute minimum daily temperatures of –5 to –8°C can occur.

In recently established trials, foliage samples (youngest fully expanded leaves from the upper one-third of the live canopy, YFEL) were taken in late autumn–winter, dried (80°C), ground, and analysed for total N (HTIF – Dumas), and S, P, K, Ca, Mg, Fe, Mn, Zn, Cu and B (nitric and perchloric acid digestion – ICP-AES).

Table 1. Eucalypt study sites and trials.

Province	Location	Site code	Trial type	Species	Planted
Yunnan	Fumin	YU FU	Thinning [a]	*E. maidenii*	1992
		YU FU	Family [a]	*E. smithii*	1995
		YU FU	Silviculture	*E. globulus, E. smithii*	2000
		YU FU	Spp./Prov.	*E. camaldulensis, E. dunnii, E. globulus, E. smithii*	2001
	Yipinglang	YU YI	Family [a]	*E. globulus*	1990
	Chuxiong	YU CH	Demo. [a]	*E. smithii*	1991
Guangxi	Guilin	GU GL	Family [a]	*E. dunnii*	1988
	Liuzhou	GU LZ	Family [a]	*E. dunnii*	1991
	Shatang	GU SH	Spp./Prov.	*E. camaldulensis, E. dunnii, E. globulus, E. smithii*	2001
	San Jiang	GU SJ	Demo.	*E. camaldulensis, E. dunnii, E. globulus*	2001
Hunan	Yongzhou	HU YZ	Spp./Prov.	*E. camaldulensis, E. dunnii, E. smithii*	2001
	Shoayang	HU SY	Spp./Prov.	*E. camaldulensis, E. dunnii, E. smithii*	2001
	Chengzhou	HU CZ	Fertiliser	*E. camaldulensis*	2001
Fujian	Yongan	FU YO	Spp./ Prov.	*E. camaldulensis, E. dunnii, E. globulus, E. smithii*	2001

[a] Incorporating post-establishment fertiliser treatments.

Soil profiles at all trials were conventionally described (texture, colour, structure), and samples (0–10, 10–20 cm depth) were collected (avoiding fertiliser effects), dried (< 40°C) and ground (< 2 mm). Samples were analysed for pH (1:5 soil:water), total-N (HTIF – Dumas), total-C (HTIF – IR), total-P (nitric and perchloric acid digestion), exchangeable-cations (Ca, Mg, Na, K, Al extraction with 1:10 soil:solution 0.1M $BaCl_2$ and 0.1M NH_4Cl), and indices of available-N (hot 2M KCl-extractable, 16 hours ($NH_4^+NO_3$)-N), available-P (1:10 soil:solution 0.03 M NH_4F and 0.01 M HCl, 10 minutes), and phosphate buffering capacity (phosphate retention after equilibration with a solution equivalent to 5000 mg kg^{-1} P in soil).

Results and Discussion

Sedimentary rocks including sandstone, siltstone and limestone dominate the soil substrates. The soils are well drained with mainly red gradational texture-pro-files characterised by clay loam surface layers overlying well-structured and permeable light clay subsoils. Some sites have been degraded by severe sheet erosion to expose the underlying reddish-coloured subsoil layers. Under the Australian Soil Classification (Isbell 1996), most soils are classified as Red Dermosols or Red Ferrosols depending on the content of free iron oxides (varying from 1 to 9% and averaging 4.4% in subsoils).

To date, foliage samples have been collected and analysed from all the younger trials at age 1.5 years, and from one trial at age 2.5 years (Tables 2 and 3). Using published and other diagnostic foliar nutrient concentrations for young *E. globulus* as a guide (Dell et al. 2002), concentrations of S, Ca, Mg, Fe, Mn and Zn were adequate. For the other nutrients, there are some consistent differences between species across sites (e.g. Cu and B concentrations in *E. camaldulensis* are generally greater), indicating (expectedly) that individual species or sets of species need to be calibrated separately for diagnostic concentrations.

Table 2. Concentrations of (total) N, P, K, Cu and B in foliage (youngest fully expanded leaves) from age 1.5 years *Eucalyptus camaldulensis, E. dunnii, E. globulus* and *E. smithii* trees at seven sites in southern China.

Province	Location	Species	Concentration				
			N (g kg^{-1})	P (mg kg^{-1})	K (mg kg^{-1})	Cu (mg kg^{-1})	B (mg kg^{-1})
Yunnan	Fumin	*E. camaldulensis*	22.3	1.03	9.5	7.4	16.2
		E. dunnii	19.2	1.02	8.7	5.5	20.4
		E. globulus	18.0	0.93	7.4	6.2	16.5
		E. smithii	18.0	1.00	6.9	4.0	12.5
Guangxi	Shatang	*E. camaldulensis*	22.7	1.57	7.8	11.2	26.7
	San Jiang	*E. dunnii*	18.3	1.14	9.2	4.5	18.1
		E. globulus	19.1	1.45	8.9	11.2	15.8
		E. smithii	21.7	1.47	11.5	7.2	12.4
		E. camaldulensis	15.2	0.83	7.4	3.8	10.3
		E. dunnii	10.6	0.80	9.1	2.3	9.5
		E. globulus	11.8	0.71	7.3	2.3	6.5
Hunan	Yongzhou	*E. camaldulensis*	19.3	1.22	9.8	7.4	14.4
	Shaoyang	*E. dunnii*	22.0	1.23	9.9	4.9	7.5
	Chengzhou	*E. smithii*	22.2	1.60	11.0	3.4	6.3
		E. camaldulensis	19.0	1.57	6.8	9.6	17.3
		E. dunnii	18.3	1.18	6.4	4.8	10.9
		E. smithii	18.2	1.32	8.2	4.8	7.3
		E. camaldulensis	23.2	1.77	9.9	9.9	25.8
Fujian	Yongan	*E. camaldulensis*	20.5	1.70	9.9	9.1	19.9
		E. dunnii	17.1	1.01	8.2	4.0	10.6
		E. globulus	15.7	1.37	11.2	4.6	9.7
		E. smithii	19.1	1.35	11.7	4.4	8.7

Other data from China support this conclusion (Dell and Malajczuk 1994). The weight of data suggests that, by age 1.5 years: (1) concentrations of N and to a lesser extent P were generally marginal to deficient, (2) there were clear instances of B deficiency (San Jiang, Yongzhou, Shaoyang, Yongan), and (3) Cu may be deficient at one site (San Jiang) (Table 2). Across the sites N, P, Cu and B are correlated, indicating generally overall poorer or better status of tree nutrition rather than a separation of limiting nutrients among sites.

Foliar concentrations in *E. globulus* and *E. smithii* sampled at age 1.3 and age 2.5 years in one trial at Fumin indicate better initial levels of nutrition, probably associated with the application of greater than routine amounts of establishment fertiliser (including B). However, they illustrate marked decline in concentrations over one year (Table 3). Declines in N, P and K concentrations over time, even where high nutrient inputs are maintained, have been widely observed in *E. globulus* in southern Australia. The present study aims to test whether the rate of decline is related to nutrient supplying capacity of the soil.

Results from soil analyses are variously presented in Table 4 and Figures 1 and 2. Except at Yongan, which has an alkaline surface soil, surface soils were acidic with exchangeable cations decreasing markedly and Al increasing markedly at lower pH. The Yongan site is atypical since it is next to a cement factory and has received considerable deposition of alkaline dust over several decades.

The mainly low and medium concentrations of total C and N reflect relatively low levels of organic matter and indicate poor reserves of soil nitrogen. However, C:N ratios were moderate (averaging 13), and available-N (broadly correlated with total-N) for most (10 of 14) sites exceeded 100 mg kg^{-1}, an indicative value in other studies (T. Baker, unpublished data) that N-fertiliser responses may not be expected. Available-P was (expectedly) not correlated with total-P (100–600 mg kg^{-1}) and declined markedly with phosphate retention (values up to 50%, equivalent to 2500 mg kg^{-1}) which was, except for one site having limestone as soil substrate, correlated with exchangeable-Al. Newly established trees on most of the sites would be likely to respond to P-fertiliser where available-P < 5 mg kg^{-1}. Available N concentrations were similar between surface depths sampled (0–10, 10–20 cm), whereas differences for P were relatively greater and often marked. The commonly observed exponential decline in C, N and P in undisturbed soils would be confounded where significant erosion of topsoil has occurred. A four-fold range in soil available-P and a ten-fold range in available-N were observed across the sites but these were not correlated across sites.

Concentrations of N and P in foliage of young trees (age 1.5 years) are expected to be highly influenced by initial rates (and forms) of these nutrients applied at-planting. A generally negative relationship between soil C (or soil N) with foliar N and with foliar P indicates that fertiliser applied at planting is having a larger influence on foliar levels at age 1.5 years than the native soil nutrient levels. Foliage samples taken at an older age or from plots without fertiliser application are more likely to reflect actual soil nutrient availability. However, of interest is, except for one site (San Jiang where B is clearly deficient and Cu may also be deficient), a positive correlation of foliar N (averaged for *E. camaldulensis* and *E. dunnii* which are common to 6 of 7 sites) with available-N in soil (Figure 3). There was no relationship between foliar P and soil available-P.

Table 3. Concentrations of (total) N, P, K, Cu and B in foliage (youngest fully expanded leaves) from *Eucalyptus globulus* and *E. smithii* trees age 1.3 and 2.5 years at Fumin.

Species	Age (years)	Leaf morphology	Concentration				
			N	P	K	Cu	B
			(g kg^{-1})		(mg kg^{-1})		
E. globulus	1.3	Juvenile	29.0	1.90	11.0	17.7	24
	2.5	Adult	14.4	1.01	9.5	8.4	15
E. smithii	1.3	Juvenile	30.1	1.89	10.8	13.5	41
	2.5	Adult	15.6	1.05	10.3	6.0	22

Table 4. Mean chemical and nutrient availability characteristics for surface soils (0–20 cm) from 14 study sites in southern China.

Province	Location	pH	Total C (%)	Total N (%)	Avail. N (mg kg^{-1})	Total P (mg kg^{-1})	Avail. P (mg kg^{-1})	Phosphate retention (%)	Exch. Ca+Mg+Na+K (cmol(+)kg^{-1})	Exch. Al (mg kg^{-1})
Yunnan	Fumin (thin.)	5.3	1.25	0.10	127	310	4.3	27	4.23	59
	Fumin (fam.)	5.4	1.50	0.11	143	325	1.3	48	6.94	44
	Fumin (silv.)	5.5	1.01	0.10	184	451	3.0	33	4.23	29
	Fumin (spp.)	5.4	1.47	0.12	127	493	6.6	32	4.03	36
	Yippinglang	5.0	1.39	0.09	20	318	5.1	32	1.83	215
	Chuxiong	5.7	0.85	0.07	134	153	4.1	19	2.38	27
Guangxi	Shatang	4.9	0.94	0.09	169	150	4.0	19	0.71	205
	San Jiang	5.0	2.72	0.22	284	193	4.6	32	1.02	248
	Guilin	5.0	1.58	0.14	211	248	5.5	28	0.77	143
	Luizhou	5.1	1.51	0.12	167	138	5.2	15	1.01	135
Hunan	Yongzhou	4.7	0.40	0.08	51	377	1.7	42	0.73	378
	Shaoyang	4.5	1.29	0.10	39	177	3.2	27	0.47	298
	Chengzhou	5.0	1.15	0.11	206	154	2.7	23	1.88	151
Fujian	Yongan	7.9	No data	0.11	32	200	5.5	18	nd	12
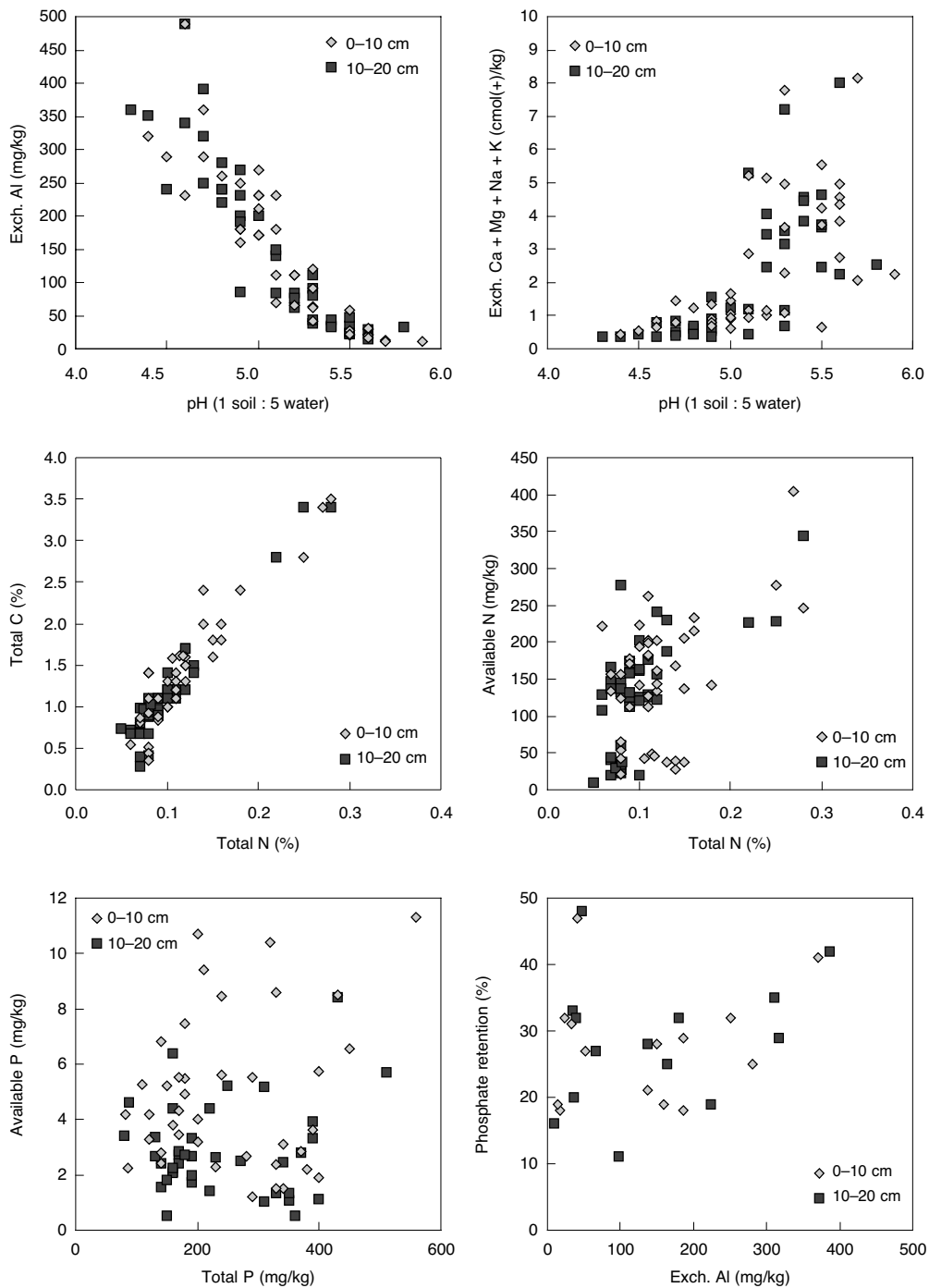
Figure 1. Chemical and nutrient availability characteristics for surface soils from 14 study sites in southern China.
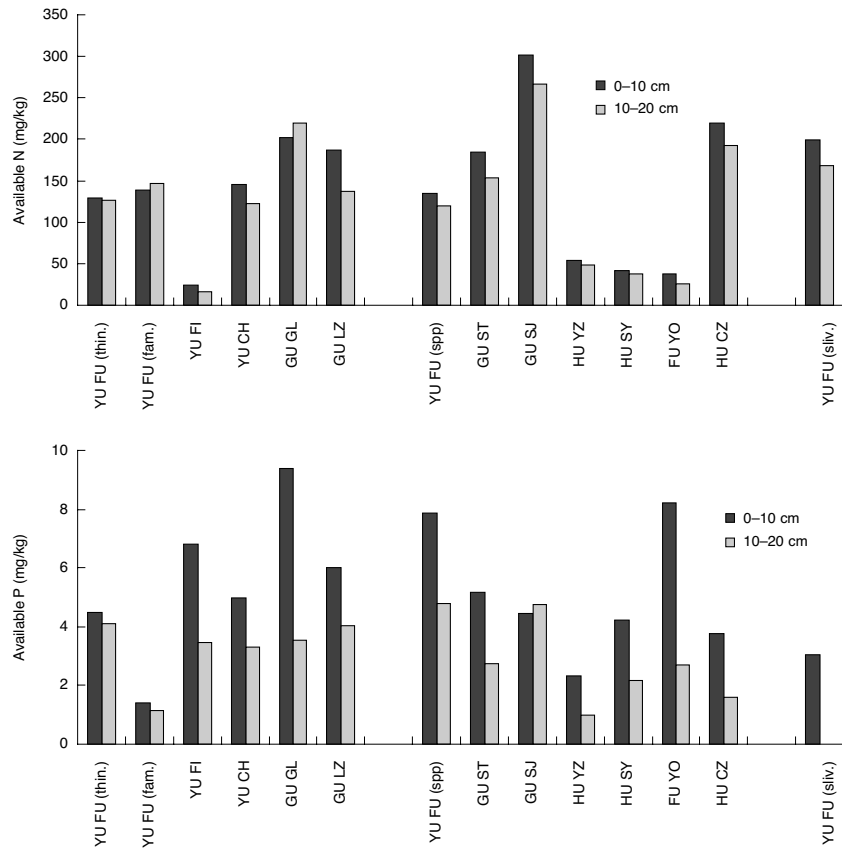
Figure 2. Available-N and -P in surface soils (0–10, 10–20 cm) from 14 study sites in southern China. See Table 1 for site coding. Sites/trials grouped according to purpose of study.
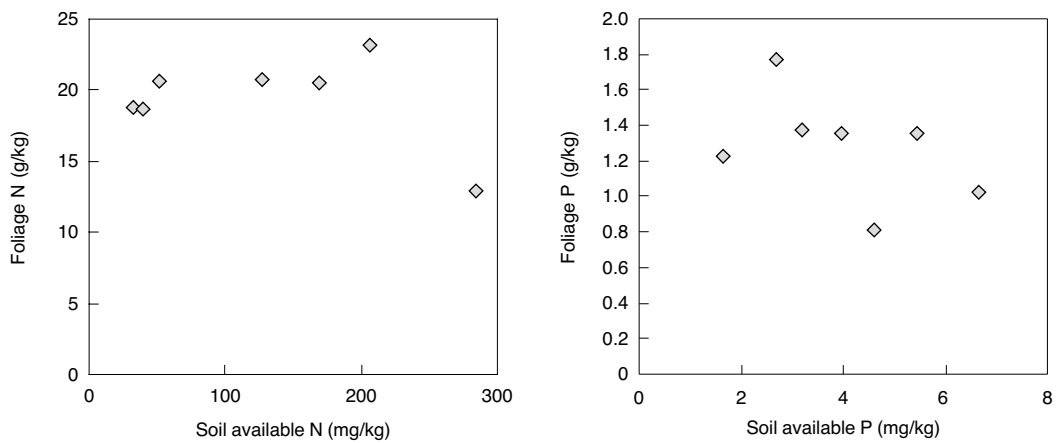
Figure 3. Mean concentrations of (total) N and P in eucalypt foliage (youngest fully expanded leaves) from age 1.5 years trees in relation to available N and P in soil at seven sites in southern China.

Conclusions

A relatively wide range of N and P availabilities occurs in soils used for farm forestry in southern China, indicating that site-specific N and P fertiliser prescriptions could be developed. While some P is generally required at planting, required application rates could be adjusted using knowledge of soil phosphate buffering capacity. The need for application of N at planting is less certain, and nitrogen fertiliser requirements at, say, age 1–2 years, may be best determined using both soil and foliage analysis. Because costs are relatively small, application of B might be undertaken routinely on those soils typically deficient in this nutrient.

The present study is providing basic site characterisation and soil nutrient availability data required for modelling early growth and fertiliser requirements and responses in eucalypts in China.

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Growth Responses to Thinning in Young *Eucalyptus* Plantations in China and Australia

Zhang Ronggui,[1] T. Baker[2] and W. Neilsen[3]

Abstract

Production of high-value sawlogs from eucalypt plantations requires silvicultural regimes incorporating early pruning and thinning. Three trials investigating responses to post canopy-closure (ages 6 to 8 years) thinning intensity in young *Eucalyptus maidenii*, *E. globulus* and *E. nitens* were established in Yunnan, China and in Victoria and Tasmania, Australia, respectively. Growth responses measured 2.5 to 4 years after thinning show that lighter thinnings did not substantially reduce total volume growth while concentrating growth on the dominant trees. Heavier thinning reduced total volume increment but further concentrated volume increment on the dominant trees (200 stems ha^{-1}) in each stand. Growth was increased significantly (up to 60%) with reduced density. In the longer term, the trials will provide data for accurate calculation of the economic trade-off between pulpwood and sawlog production from the same stand.

In Australia and China, the declining availability of hardwood sawlogs from natural forests juxtaposed with the rapid expansion of eucalypt plantations during the last decade (mostly for pulpwood production) (e.g. Chen and Zhou 2002; Ferguson et al. 2003) has prompted research and development into the silviculture of fast-growing eucalypt plantations for high-value timber production (Maree 1979; Schönau 1984; Gerrand et al. 1997; Stackpole et al. 2001). In Australia, this work has focused on optimising density (spacing) for yield and control of branch size (Neilsen and Gerrand 1999; Gerrand and Neilsen 2000; Pinkard and Neilsen 2003), pruning to achieve knot- and decay-free wood (Pinkard and Beadle 1998; Wardlaw and Neilsen 1999;

Mohammed et al. 2002), and early thinning to allow more rapid diameter growth of the retained trees to a sawlog size (Gerrand et al. 1997; Stackpole et al. 1999; Medhurst et al. 2001).

Silvicultural trials with *Eucalyptus nitens*, *E. globulus* and *E. grandis* have established that inter-tree competition occurs relatively early (from age 2 to 3 years) in fast-growing plantations, and that growth responses to non-commercial thinning around the time of maximum current annual increment (CAI) can occur. However, there are relatively few results available from trials where responses to commercial thinning (typically for pulpwood) after the maximum CAI, say around the time of maximum mean annual increment (MAI), have been investigated.

Financial optimisation of the trade-off between pulpwood and sawlog production from the same plantation requires thorough growth and growth response data across a range of sites (e.g. Candy and Gerrand 1997). This paper presents early growth response results from three thinning studies in *E. maidenii, E. globulus* and *E. nitens* plantations in

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[1] Yunnan Academy of Forestry, Heilongtan, Kunming, Yunnan 650204, China.

[2] Forest Science Centre, Department of Sustainability and Environment, PO Box 137, Heidelburg, Victoria 3084, Australia. Corresponding author:
Email: <tom.baker@nre.vic.gov.au>.

[3] Forestry Tasmania, GPO Box 207B, Hobart, Tasmania 7001, Australia.

Yunnan, China and in Victoria and Tasmania, Australia. These species are in the group 'Viminales'.

Sites and Methods

Thinning intensity trials were installed in three existing stands (Table 1). The Fumin stand was established on a degraded (eroded) gradational-textured soil formed on sandstone (Midgley and Arnold 2000), the Tostaree stand on a texture-contrast soil formed on marine sediments and previously used for agriculture (Feikema et al. 1999), and the Goulds Country stand on a texture-contrast soil formed on adamellite granite and previously used as *E. regnans* native forest (Gerrand et al. 1997).

Two levels of thinning intensity from below were applied in each trial, but the absolute residual densities following thinning varied between trials (Table 2). Unthinned reference treatments were incorporated into the trials. Tostaree and Fumin trials also incorporated plus or minus N and P fertiliser treatments, but early responses were relatively minor compared with the thinning treatments, so results are not presented here.

Trees were measured for height and diameter breast height over bark (dbh) immediately before and after thinning, and then 3 years (Fumin), 2.5 years (Tostaree) and 4 years (Goulds) later. Volume increments on all trees and on a subset of dominant trees (largest diameter 200 stems ha^{-1}) were calculated. Measurements of individual-tree live crown length (and crown width at Fumin) were made on these dominant trees to assist in interpretation of growth responses.

Results and Discussion

Stand parameters immediately before thinning varied widely between sites (Table 2). Growth was greatest on the relatively fertile site at Tostaree. On the Goulds

site, weed competition and lack of cultivation may have slowed growth and caused early mortality. Despite the almost three-fold higher planting density, growth at Fumin was relatively poor, in part because of low nutrient availability in the degraded soil and a history of intensive foliage harvesting (for eucalypt oil production). At the time of trial establishment, tree density at Fumin was only half that at planting, mostly because of an earlier, undocumented thinning.

Table 2. Average parameters for eucalypt stands immediately before and immediately after thinning treatments.

	Sites		
	Fumin	Tostaree	Goulds
Pre-thinning			
Density (stems ha^{-1})	1666	967	829
Height (m)	13.6[a]	18.8[b]	13.7[b]
Basal area (m^2 ha^{-1})	13.3	18.6	11.7
Volume (m^3 ha^{-1}).	60.5[c]	129[d]	52.6[d]
Post-thinning treatment 1			
Density (stems ha^{-1})	996	446	400
Height (m)	15.3[b]	19.3[b]	12.3[b]
Basal area (m^2 ha^{-1})	11.2	10.4	7.2
Volume (m^3 ha^{-1}).	57.5[c]	75.8[d]	38.5[d]
Post-thinning treatment 2			
Density (stems ha^{-1})	600	247	200
Height (m)	16.9[a]	19.0[b]	14.3[b]
Basal area (m^2 ha^{-1})	8.1	6.4	4.1
Volume (m^3 ha^{-1}).	45.9[c]	46.8[d]	21.8[d]

[a] Average height, [b] Dominant height, [c] Volume index, [d] Volume underbark.

At Fumin, total volume increment over 3 years varied only slightly with the residual density following thinning, but the dominant trees (largest diameter 200 stems ha^{-1}) showed a relatively greater

Table 1. Eucalypt thinning trails in China and Australia; site and trial details.

|	China Fumin, Yunnan	Australia Tostaree, Victoria	Australia Goulds Country, Tasmania
Latitude	25.37°N	37.78°S	41.08°S
Longitude	103.02°E	148.19°E	148.12°E
Altitude (m)	2040	40	120
Annual rainfall (mm)	1000	820	1000
Species	*E. maidenii*	*E. globulus*	*E. nitens*
Year planted	1992	1991	1984
Density (stems ha^{-1})	3333	1333	1143
Age thinned (years)	7.5	8	6.4

response to the thinning treatments (Figure 1). Thinning did not affect height increment, and there was no difference in live crown length or live crown volume (calculated from measurements of width and length) between the thinning treatments. However, the crown data may have been confounded by continued pruning of lower branches for oil production during the study.

At Tostaree, total volume increment over 2.5 years was proportional to residual density, but the components of the increase varied amongst the thinning treatments (Figure 1). Particularly, mortality in the unthinned treatment was significant, and it is clear that, in order to maximise yield from such stands, thinning is necessary to avoid these losses. The additional volume grown on the dominant trees to age 10.5 years (9–13 m^3 ha^{-1}) in the thinned treatments compared with unthinned corresponds to an increase in average dbh from 22.0 cm (unthinned) to 23.4 cm (450 stems ha^{-1}) and 23.9 cm (250 stems ha^{-1}). The average live-crown length (11 m) of the dominants did not vary between thinning treatments but it is noteworthy that it was twice that at Fumin (5.4 m) despite the trees being of similar height.

At Goulds, total volume increment was, likewise, proportional to residual density (Figure 1). Response to thinning was significant in the dominant trees within the first year, and continued for at least 4 years. At age 10 years, average diameter of the dominant trees was 25.2 cm (200 stems ha^{-1}), 22.7 cm (400 stems ha^{-1}) compared with 21.6 cm for the dominants in the unthinned stand. The average live-crown length of the dominant trees at age 10 years varied significantly amongst the thinning treatments: 200 stems ha^{-1} (11.8 m), 400 stems ha^{-1} (11.0 m) and unthinned (9.6 m); on average, comparable with those at Tostaree.

The lighter thinning at Fumin, to 1000 stems ha^{-1}, did not reduce total stand growth and thinning to 600 stems ha^{-1} only marginally reduced growth. This latter thinning did, however, concentrate growth on the dominant trees in the stand. Thinning to 450 stems ha^{-1} at Tostaree did not reduce total growth (live trees) but, at Goulds Country, thinning to 400 stems ha^{-1} reduced growth by about 23%. These thinnings were relatively heavier than at Fumin. In thinning to 450 stems ha^{-1} at Tostaree and 400 stems ha^{-1} at Goulds Country, about two-thirds of the total growth was concentrated on the 200 dominant stems ha^{-1} (Figure 1). This concentration of growth on the dominant trees in the stand will result in logs suitable for veneer and sawlog being produced in a relatively
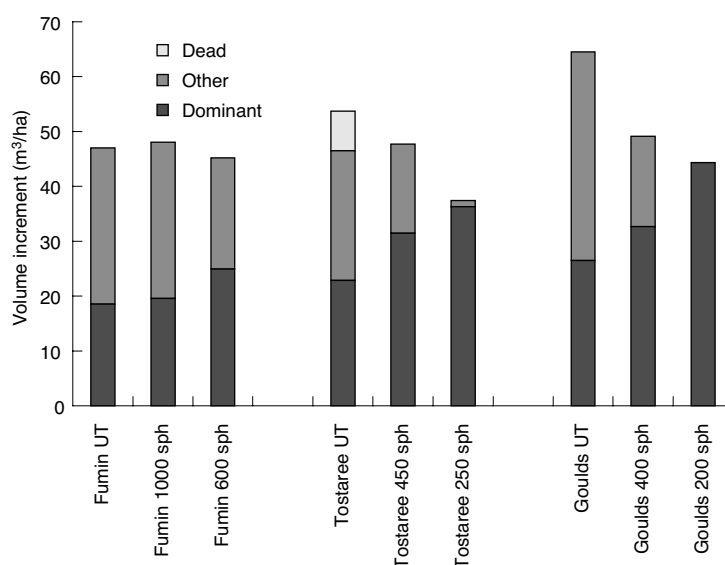
Figure 1. Volume increments of stand components. (Dominant trees = 200 stems ha^{-1}, Other trees, Mortality) following thinning at Fumin (age 7.5 to 10.5 years), Tostaree (age 8 to 10.5 years) and Goulds Country (age 6.4 to 10 years). UT = Unthinned, sph = stems ha^{-1}.

short time. As these results can be achieved with only a small impact on total growth, silvicultural thinning to these levels is warranted. Heavier thinning concentrates even more growth on the dominant stems, but with a more substantial reduction in total growth. The economics of thinning to these lower stocking levels will be determined by the relative value of solid wood products compared with total fibre.

Conclusions

Results presented here are relatively soon after thinning in relation to the expected rotation lengths required for the production of sawlogs, and the continuation and magnitude of longer-term responses have yet to be established. Nonetheless, it is shown that post canopy-closure thinning responses could be the rule for the species group Viminales. Furthermore, it is shown that it is essential to consider the components of the stand (dominants, other trees, mortality) to describe and understand the responses as a basis for economic evaluation of alternative silvicultural regimes. Simple measurement of crown dimensions (as surrogates of leaf area) can be useful for explaining growth and growth responses, but the accuracy and precision of rapid field methodologies require development. The trials described in this study should continue to generate useful results over the next decade.

Acknowledgments

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Tree and Stand Growth and Biomass Relationships for *Eucalyptus urophylla* and *E*. 12ABL on the Leizhou Peninsula, Guangdong Province, China

T. Baker,[1] J. Morris,[1] M. Duncan,[1] Zhang Ningnan,[2] Yang Zengjiang,[2] Huang Zhihong[3] and Chu Guowei[3]

Abstract

Results are presented of growth and biomass measurements from eucalypt pulpwood plantations grown in the western central Leizhou Peninsula of Guangdong province, China. Eighteen permanent monitoring plots were located in established stands of *Eucalyptus urophylla*, *E. urophylla* Clone U6, and *E*. 12 ABL (*E. tereticornis*) Clone W5 and measured at approximately 6-month intervals. Forty-eight trees were sampled and the biomass of above-ground components measured. Stands at a typical harvest age of 5 years achieved a mean height of 14 m, a mean diameter of 10 cm, a basal area of 20 m^2 ha^{-1}, a volume of 120 m^3 ha^{-1} and an above-ground biomass of 75 tonnes ha^{-1}. There was little difference in volume and total biomass growth of *E. urophylla* and *E. tereticornis*. Mean annual (volume) increment (MAI) peaked (30 m^3 ha^{-1}) at age 3–4 years. Periodic annual increment (PAI) between successive 6-monthly measurements peaked (50–60 m^3 ha^{-1}) by age 3 years and by indication in some stands as early as age 2 years. Rapid decline in PAI from age 2 years to 5 years corresponded to a rapid decline in leaf area index (from approx. 6 to 2). The relatively high early productivity of these eucalypt plantations is achieved in part through high initial planting densities (2500–3000 stems ha^{-1}).

More than 200,000 ha of *Eucalyptus* plantations have been established on the Leizhou Peninsula of southern China, predominantly as a source of woodchips for export or as input to a developing domestic pulp and paper industry. Indications of productivity decline over successive rotations (e.g. Yu et al. 1999a,b) resulting from intensive site preparation and harvesting, and of concerns for depletion of groundwater resources resulting from significant afforestation have prompted studies into the sustainability of plantation-management practices.

This paper presents results from growth measurements in permanent plots, and biomass sampling, primarily undertaken to support the parameterisation and validation of the 3PG forest growth model (Landsberg and Waring 1997) and its further development (Morris and Baker 2003). However, these data also provide immediately useful descriptions of tree and stand growth using conventional parameters (e.g. height, volume, basal area), and dimensional relationships for individual trees (e.g. volume or biomass with diameter).

Site Details and Methods

Two study sites were located within the Jijia (and the immediately adjacent Tangjia) (20°54'N, 109°52'E) and Hetou (21°05'N, 109°54'E) forest farms in the western central Leizhou Peninsula of Guangdong

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[1] Forest Science Centre, Department of Sustainability and Environment, PO Box 137, Heidelburg, Victoria 3084, Australia. Email: <tom.baker@nre.vic.gov.au>.

[2] Research Institute for Tropical Forestry, Guangzhou, Guangdong 510520, China.

[3] South China Institute of Botany, Guangzhou, Guangdong 510650, China.

province. The sites have an altitude of 70 m (Jijia) and 25 m (Hetou), and the topography is flat to undulating.

Annual rainfall averages 1470 mm, with approximately 80% (1200 mm) falling from April to October, and with monthly rainfall in the remaining 5 months averaging approximately 50 mm. Monthly averages of daily minimum and maximum temperatures are respectively 12°C and 21°C in January, and 23°C and 33°C in July.

Both Jijia and Hetou have deeply weathered red soils, but the parent materials — basalt at Jijia, sandstone at Hetou — result in markedly differing texture profiles. Consequently, maximum plant-available soil water in the upper 4 m of the profile at Jijia (450 mm) is more than twice that at Hetou (200 mm).

Plantations at the forest farms are typically established using machine soil cultivation, and manual weed control and fertiliser application, with planting month varying from June through December. Initial planting densities are approximately 2500–3000 stems ha^{-1} at an espacement of 2.5+ m between rows by 1+ m within rows.

Eighteen permanent monitoring plots were located in established stands of *E. urophylla* (= Eu), *E urophylla* Clone U6 (= U6), and *E.* 12ABL (*E. tereticornis*) Clone W5 (= W5) at Jijia (17 plots) and Hetou (1 plot) (Table 1). One plot at Jijia and the single plot at Hetou, both in Eu, were primarily established for tree water-use studies (Yin et al. 2003; J. Morris et al., unpublished data) and were 0.16 ha in area. All remaining plots averaged approximately 0.025 ha in area.

In each plot, all trees were measured for diameter over bark at 1.3 m height (dob1.3) and a varying subset of trees representing the diameter range were measured for total height (ht) at approximately 6-monthly intervals between September 1999 and September 2002 (Table 1). The measurement data for the oldest stands corresponded to ages 6–7 years after planting, which is beyond the usual rotation age for these stands (Chen and Zhou 2002). Individual tree measurements, together with dimensional relationships developed for individual trees, were used to calculate stand average diameter, average height, dominant height (average height of the largest-diameter 200 stems ha^{-1}), basal area, stem volume and biomass.

At Jijia, the above-ground biomass of five stands (including three of these stands at two ages) was measured by harvesting six trees per stand (Table 1). Sample trees were selected to represent the diameter frequency distribution of the stand. The oven-dry (80°C) mass of each of the above-ground biomass components (leaves, live branches, dead branches, stembark and stemwood) of each tree was determined by a sub-sampling procedure. A sample of 100 leaves per tree was used to measure specific leaf area (area measured by scanning and image analysis) hence used to calculate total tree leaf area. Sectional underbark stem diameter measurements on sample trees were used to calculate stem volume using Smalian's formula. Sample trees were used to develop conventional tree volume functions, and allometric relations between tree variables (diameter, height), and applied to estimate stand volume and above-ground biomass using the diameter measurements made in the permanent monitoring plots.

Table 1. Schedule of measurements and biomass sampling for eucalypt stands at Jijia (and adjacent Tangjia) and Hetou forest farm study sites.

| Species	Stand code[a]	Plots	Density[b] (stems ha^{-1})	Age (months) at measurement date						
				Sep. 1999	Mar. 2000	Aug. 2000	Mar. 2001	Sep. 2001	May 2002	May 2002
E. urophylla	Eu-0696	4	2124	39 [c]	45-B	50	57-B	63	71	75
	Eu-0696-H	1	1350	39	45	50	57	63	F	–
E. urophylla	U6-0699	1	3149	21	27-B	32	21-B	27	35	39
Clone U6	U6-1297	3	2100				39-B	45	53	57
E. 12ABL	W5-1296	1	2882	33	39	44	51	F	–	–
Clone W5	W5-0697	3	2710	27[d]	33-B	38	45	F	–	–
	W5-1297	5	2544	21	27-B	32	39-B	45	53	57

[a] Indicates month & year of planting (mmyy). H = Hetou study site. [b] At first measurement. [c] Three plots only. [d] Two plots only.
B = Biomass sampling. F = Felled.

Results and Discussion

Tree dimensional relationships

Tree ht–dob1.3 relationships differed between U6 and W5 (each a clone of different species), but also differed between Eu and U6 (respectively, seedlings and a clone of the same species) across the range of diameters measured (Figure 1). It was not possible to distinguish in the data any effects of stand age on these relationships, although more generally these would be expected to occur. The relationships, here fitted simply as power functions that are adequate given the observed diameter range, were used to estimate heights for all trees in plots, to provide the basis for calculation of stand mean height, dominant height and volume.
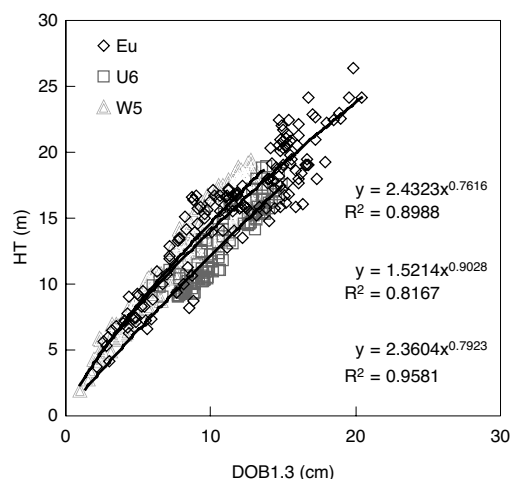
Figure 1. Tree height–diameter relationships for Eu, U6 and W5.

A single, simple, individual tree total stem volume (underbark) function was adequate for all species and ages of trees sampled (Figure 2):

$$\text{Volume (m}^3) = 0.00003156 \times [\text{dob1.3 (cm)}]^2 \times \text{ht (m)} \quad (1)$$

Relationships between tree volume and dob1.3 only, showed some divergence amongst Eu, U6 and W5 that is attributable to their differing ht–dob1.3 relationships. While more sophisticated volume functions could be developed (e.g. incorporating age and upper stem diameters), the simple use of the combined independent variable $(\text{dob1.3})^2 \times \text{ht}$ has

also proven adequate for young, gum-barked eucalypts (< age 20 years) across a wider diameter range (to 50 cm) in southern Australia.
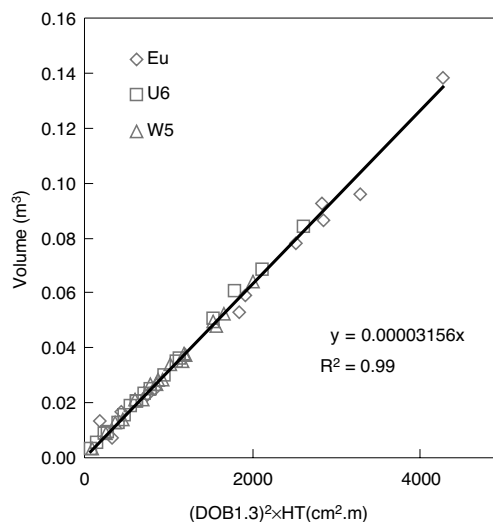
Figure 2. Combined individual-tree total stemwood volume function for Eu, U6 and W5.

It is worth noting that stand volume estimates made using the individual tree volume function were 10% greater than those made using the commonly adopted approximate relationship with stand mean diameter (d, cm), dominant height (h, m) and density (n, stems ha^{-1}):

$$\text{Volume (m}^3/\text{ha}) = 1/3 \times [\Pi \times d^2 \times h \times n/40000] \quad (2)$$

Tree biomass (either total or component) – diameter relationships are commonly fitted as allometric (power) functions:

$$\text{Biomass} = a \times [\text{dob1.3}]^b \quad (3)$$

Modern statistical software allows for fitting of the parameters (a, b) using iterative least squares methods (with or without weighting), avoiding the problems of fitting and use of the function as the logarithmic transformation. While equally good fits of tree biomass–diameter relationships can be obtained using other functions (for example, in the present study in a similar way to that for volume), allometric relationships provide an elegant mathematical solution to biomass partitioning in the 3PG growth model.
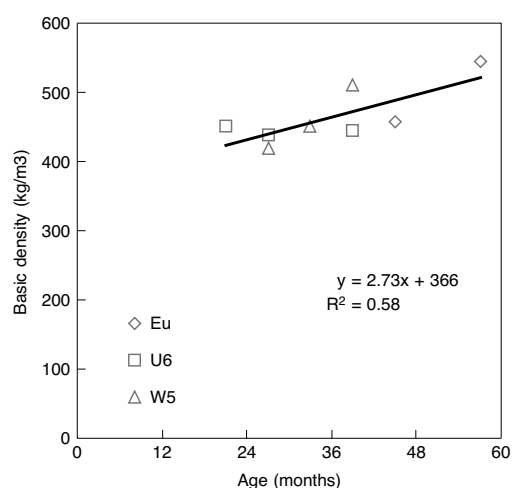
The allometric relationships for total aboveground biomass were indistinguishable amongst the species and ages sampled (Figure 3). While this may

be surprising given that stems were the major component of above-ground biomass (average 75%) and that the stem volume–diameter relationships differed (see earlier), the net effects of differing proportions of biomass components between species and ages, and differences in wood basic density with age (Figure 4) were such as to produce the one relationship:

Total above-ground biomass (kg) = 0.1000
$\times$ [dob1.3 (cm)]$^{2.4419}$ (4)
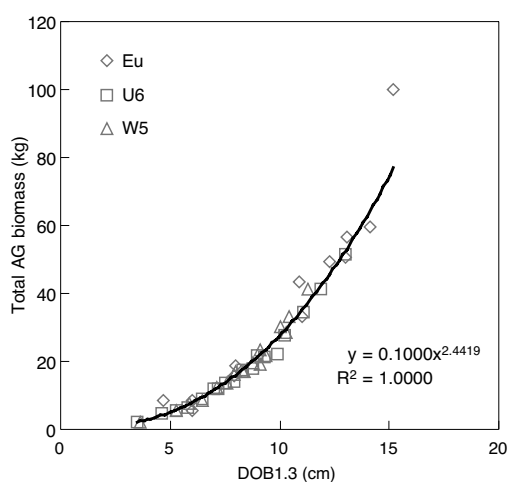
Figure 3. Combined individual-tree total AG biomass function for Eu, U6 and W5.

Figure 4. Relationship between stemwood basic density and plantation age for Eu, U6 and W5.

However, the corresponding allometric relationships for stemwood biomass differed marginally between species (see later).

Stand growth

Measures of stand growth (average height, dominant height, average diameter, basal area, volume and total above-ground biomass) to age 72 months are presented in Figure 5. The data represent gross production, i.e. including any mortality that occurred after the first measurement observation, although generally this was not significant. Interpretation of the differences in measured growth between species and sites should be made with some caution since observations have not been made in randomised and replicated experiments, there is only one plot in some stands, and seasonal and silvicultural differences may have been important.

Volume and biomass growth of Eu at Hetou was approximately 75% of that at Jijia at age 63 months, largely because of lower density (1350 compared to 2124 stems ha^{-1}) and therefore basal area. However, height and diameter growth was similar at both sites.

On average, the stands at Jijia at age 60 months (a typical harvest age) achieved a mean height of 14 m, a mean dob1.3 of 10 cm, a basal area of 20 m^2 ha^{-1}, a volume of 120 m^3 ha^{-1} and an above-ground biomass of 75 tonnes ha^{-1}. Placing the greatest weight on the data from stands with more than one measurement plot, there was little difference in volume and total above-ground biomass growth of Eu, U6 and W5, despite there apparently being larger relative differences in height and diameter. The greater dominant height growth of Eu compared to U6 and W5 can be attributed to wider between-tree variability arising in seedling-originated rather than clonal-originated stands.

Mean annual (volume) increment (MAI) at Jijia peaked for all stands at age 3–4 years, but was later at the lower-density Hetou stand (Figure 6a). Periodic annual increment (PAI) between successive measurements (Figure 6b) peaked at all sites by age 3 years, and by indication in some stands as early as age 2 years. An apparent zigzag pattern in PAI for some stands suggests dry- and wet-season effects on growth, but measurement accuracy, varying measurement increment period (4 to 8 months), and disturbance by typhoons confound such analysis.

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Figure 5. Growth (a) average height, (c) dominant height, (c) average diameter, (d) basal area, (e) total stem volume underbark, and (f) total AG biomass of Eu, U6 and W5 stands at Jijia and Hetou.
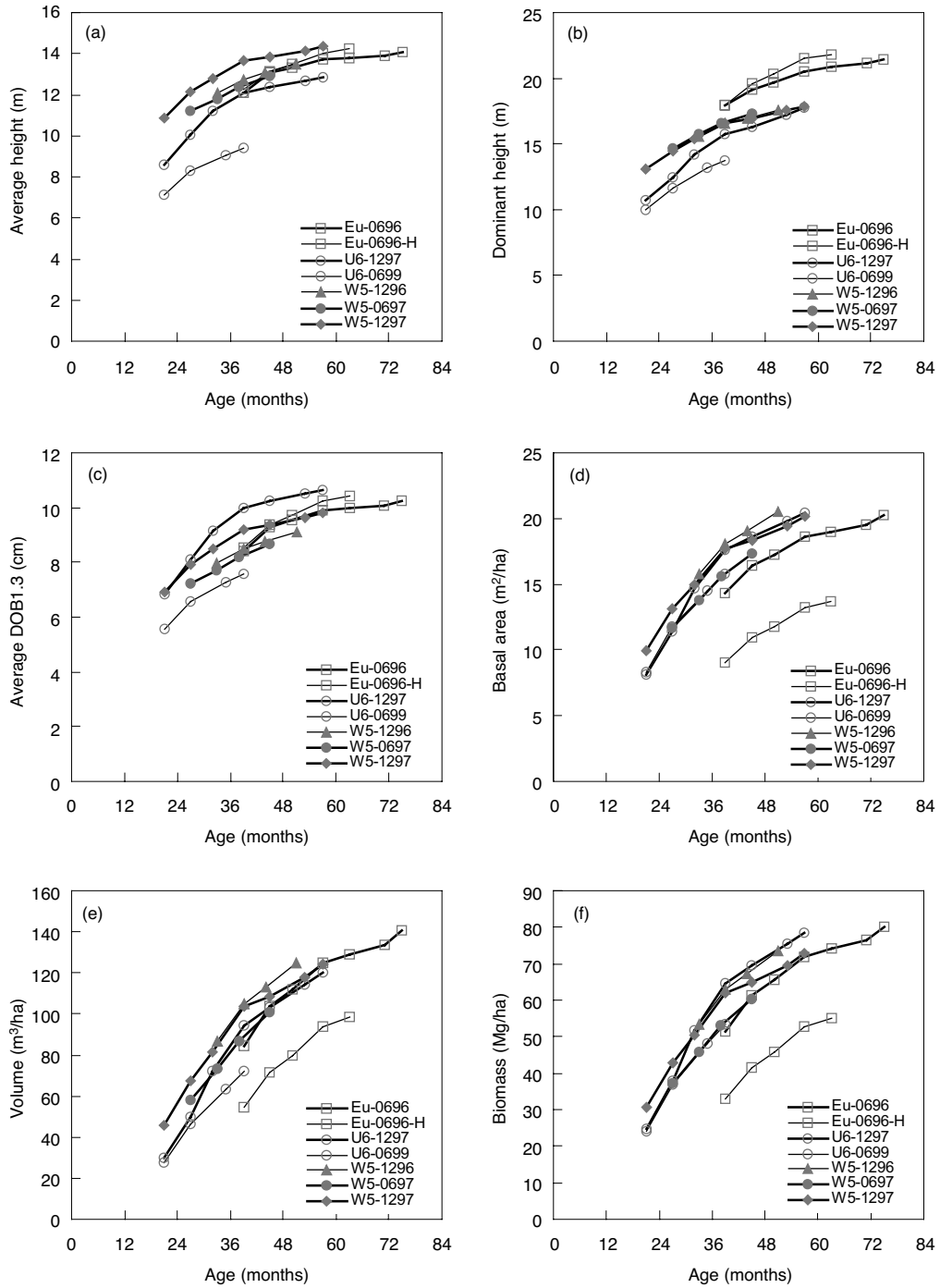
The comparable growth between seedling (Eu) and clonal (U6) *E. urophylla* suggests that apparent gains in volume growth from clonal selection as typically measured in single-tree-plot clone-comparison trials may not be as great in practice, particularly at relatively high planting densities and therefore rapid site occupancy. Maximum growth in the present study (above-ground biomass approx. 85 tonnes ha^{-1} at age 72 months, Figure 5f) was similar to that of clonal *E. grandis* × *urophylla* (89 tonnes ha^{-1} at age 75 months (Xu et al. 2002)), and indeed of *Acacia mangium* (77 tonnes ha^{-1} at age 72 months (Xu et al. 1999)) in Guangdong, indicating an upper limit of plantation productivity in the region.

Biomass and leaf area index

Allometric relationships for individual above-ground biomass components (leaves, live branches, dead branches, stemwood, stembark) were examined but not used in the present study to estimate areal component biomass either for the sampled stands, or for extrapolation to all stands for all measurements in the permanent monitoring plots. For components such as leaves, these relationships, as expected, varied with age (or declining stand nutritional status) but did not always progress predictably (Figure 7a,b). For some components such as dead branches, the assumption of an allometric model may not be justified, particularly given wide variability amongst sample trees (Figure 7c). For some components such as stemwood, apparent marginal differences with species or age (Figure 7d) may well be real but only demonstrable with more

intense sampling. The use of many specifically fitted functions is tedious, has a high risk of inconsistency if based on too few trees and, moreover, there is the problem of additivity of component estimates not equalling that estimated using a relationship developed for the total. A broader approach simultaneously allowing for relationship change with age and additivity is required but is beyond the scope of the present study.

Areal component biomass and LAI estimates for each of the eight samplings from five stands are detailed in this paper (Table 2) because such data for eucalypts in China are relatively rare and are valuable for growth and water-use modelling and nutrient accumulation and cycling studies. These estimates are based on average biomass of the components for the sample trees in each stand and the stand density. This method is not the 'mean-tree' approach (e.g. sampling a tree of mean diameter or basal area), and it should be remembered that the sample trees were selected to represent the frequency distribution of the diameter, not simply the range of diameters, and therefore the biomass estimates should be unbiased. Indeed, except for one sampling there was a good one-to-one correspondence (Figure 8) between total above-ground biomass estimated in this way and that by allometry (equation 4). The total above-ground biomass for the Eu-0696 stand at age 57 months may be overestimated by 14% (some 10 tonnes ha^{-1}), and the apparent increase of 24 tonnes ha^{-1} in this stand between ages 45 and 57 months should consequently be discounted.
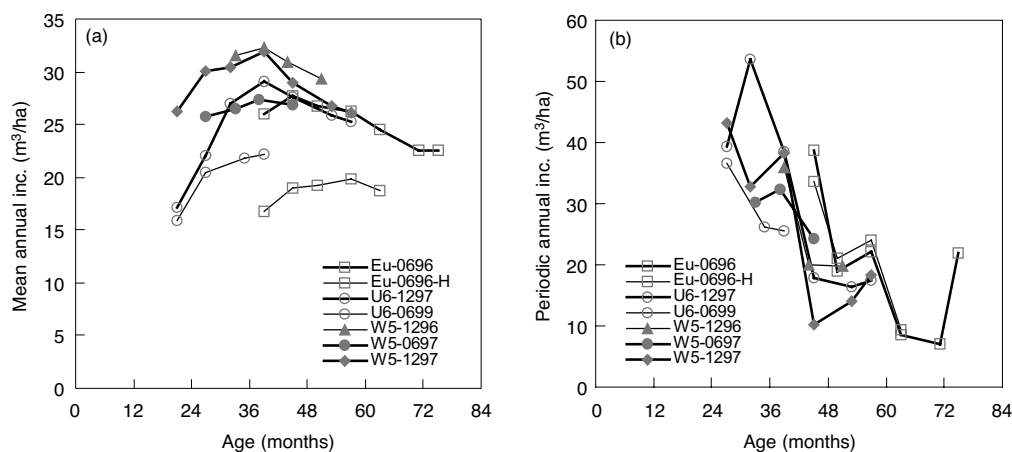
Figure 6. Total stemwood (a) mean annual increment and (b) periodic annual increment for Eu, U6 and W5 stands at Jijia and Hetou.
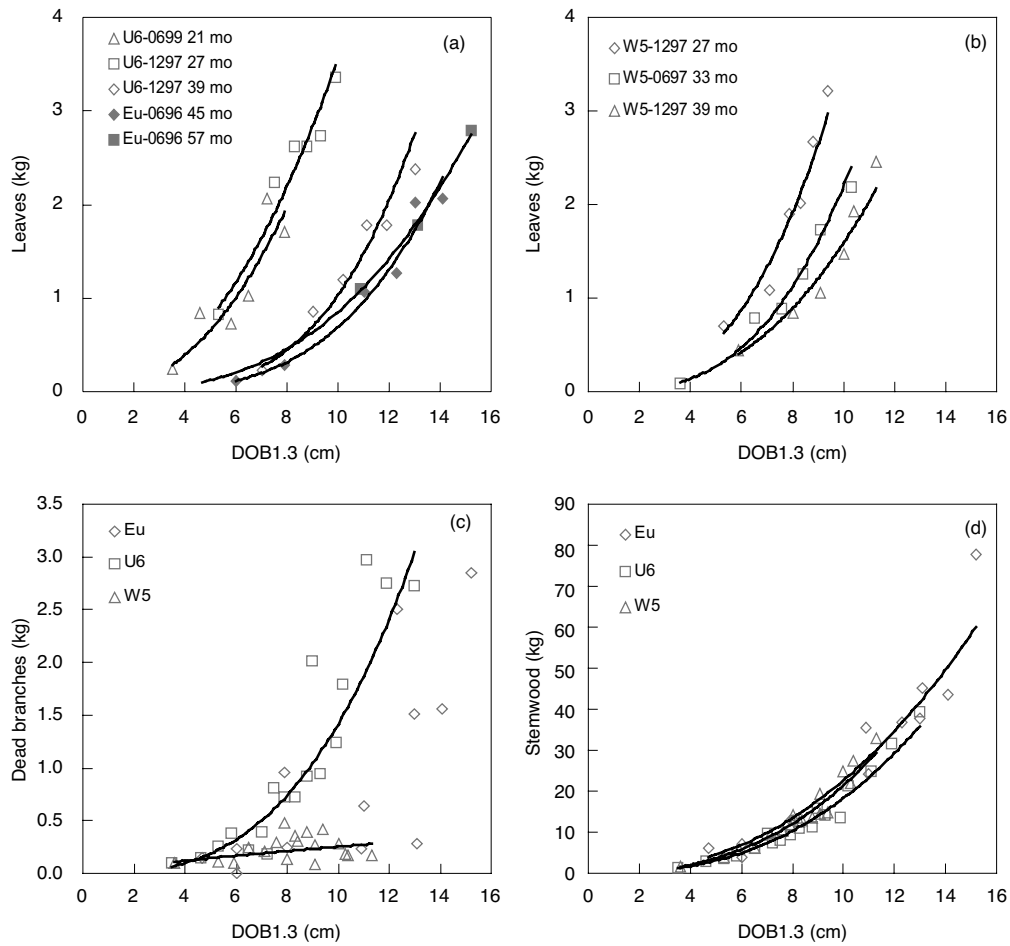
Figure 7. Allometric relationships between the mass of selected tree components and tree diameter: (a) Eu and U6 leaves, (b) W5 leaves, (c) Eu, U6 and W5 dead branches and (d) Eu, U6 and W5 stemwood.

Table 2. Above ground biomass and leaf area index (LAI) of five eucalypt stands at Jijia.

Stand	Age (month)	Density (stems ha^{-1})	Biomass (tonnes ha^{-1})						LAI
			Leaves	Branches (live)	Branches (dead)	Stem-bark	Stem-wood	Total	
Eu-0696	45	2124	1.76	4.86	0.85	5.99	43.6	58.3	2.1
Eu-0696	57	2124	2.37	5.98	1.33	8.15	64.1	81.9	3.2
U6-0699	21	3149	3.46	2.42	0.92	2.52	16.2	25.5	3.4
U6-1297	27	2100	5.04	2.63	1.71	3.50	21.6	34.4	5.6
U6-1297	39	2100	2.88	3.05	4.43	5.65	49.8	65.8	3.6
W5-1297	27	2544	4.91	1.90	0.84	3.52	28.0	39.2	3.6
W5-0697	33	2710	3.12	1.79	0.55	4.16	30.5	40.1	2.2
W5-1297	39	2544	3.47	1.87	0.47	6.11	52.7	64.7	2.4

The component biomass estimates allow some observations regarding growth and biomass relationships for the sampled stands, for example: (i) stemwood as a proportion of total above-ground biomass increased from approximately 60% at age 2 years to 80% at age 5 years; (ii) branches (live + dead) as a proportion of total above-ground biomass declined with age, but on average in Eu and U6 (12%) was twice that in W5 (6%); (iii) LAI peaked before age 3 years and as early as age 2 years (maximum LAI approached 6), corresponding to the peak PAI (see earlier) and declined to as little as 2 by age 5 years; and (iv) total AG biomass increment in the three stands sampled twice over 12 months was correlated with average LAI.
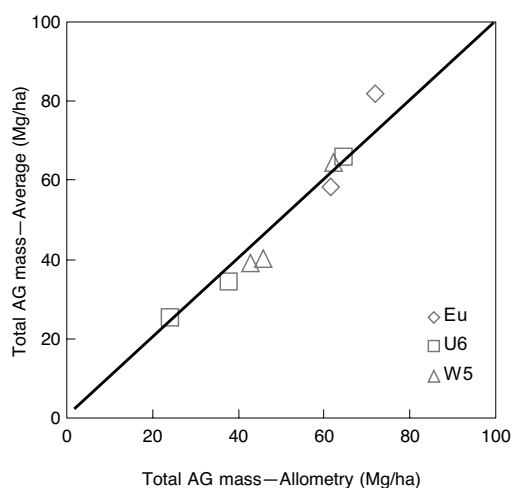
Figure 8. Comparison of total AG biomass estimates made using allometry and the average of sample trees for Eu, U6 and W5 stands.

Conclusions

On the Leizhou Peninsula, relatively high early productivity of eucalypt plantations (peak periodic annual increments (PAIs) of 50–60 m^3 ha^{-1} and peak mean annual increments of approximately 30 m^3 ha^{-1}) is achieved through high initial planting densities (2500–3000 stems ha^{-1}). However, rapid decline in PAIs from their peak, and typically short rotations (5 years), ultimately result in modest yields (120 m^3 ha^{-1}). In this study, productivity (volume, above-ground biomass) of clonal and seedling *Eucalyptus urophylla* and clonal *E. tereticornis* stands was generally similar.

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Insect Pests of Eucalypts in China

Pang Zhenghong[1]

Abstract

Eucalypt plantations in southern China are generally very healthy. Some 282 insect species, almost all endemic, were recorded in 2001 as compared with 206 species in 1991, and 53 species in 1981. The most serious pest groups are subterranean termites, geometrid defoliators, and leaf-roller and root-feeding scarab beetle larvae. Most insect damage has been to young trees, usually in the first year after planting, and to the nursery stock. By 2010, there will be 2 million ha of eucalypt plantations and 5–7% of them will be damaged by the pests. The estimated annual cost of the damage is US$1–2 million.

A total of 282 insect species in 10 orders and 59 families has been recorded on eucalypts in China. Of these, 30 species inflict severe damage resulting in economic loss, 60 species cause moderate damage and 192 species only light damage. The number of insect species feeding on eucalypts has greatly increased since 1981. The increase may be attributable to a combination of factors such as increasing adaptation over time of endemic Chinese insects to the exotic *Eucalyptus* as a food plant, expansion of the eucalypt plantation into new areas, and more intensive insect monitoring in plantations, in response to increasing incidence of pest damage.

Current Status of Different Types of Eucalypt Pests

Nursery pests

There are about 50 species of nursery pests, of which the more important include nymphs and adults of the ground cricket (*Brachytrupes portentosus* Lichtenstein) cutworm, termites, white grubs and leaf-rollers. The mole cricket (*Gryllotalpa africana* Palisot-Beauvois) also damages seedlings in nurseries, as do sap-sucking psyllids, a stem-boring longicorn beetle and caterpillars of geometrid moths. *Agrotis ypsilon* (Hufnagel) has caused 10–30% mortality in nursery stock at the Qinzhou Forest Research Institute.

Root-feeding pests

So far, termites are the most serious pests of eucalypts in the southern China, with 22 species recorded. Of these, 17 species cause moderate to serious damage. Losses of up to 30% have been recorded in some plots of *Eucalyptus grandis*. At Weidu Forest Farm, Guangxi, there have been losses of up to 80% of young trees due to attack by *Odontotermes formosanus* (Shiraki), *Macrotermes barneyi* Light and *Capritermes nitobei* Shiraki. At Qinfong Forest Farm, Tie Mao Shan Forest Farm and Dongmen Forest Farm in 1991 and 1994, *O. formosanus* and *M. annandalei* caused losses of up to 30–50% in young plantations.

Termite attack is usually concentrated on the tap root just below the collar region, and the damage leads to death of seedlings. In some cases, small trees are cut right through by termites. While the incidence of termite attack is highest in the first 6 months after planting, older trees are also susceptible. Termites can damage seedlings and young trees all year around, but the most serious damage occurs between April and July. *Eucalyptus grandis*, *E. exserta, E. globulus* and *E. camaldulensis* have been more seriously damaged than *Corymbia citriodora* (*E. citriodora*) and *E. robusta*.

White grubs

White grubs are the second most important eucalypt pests in China. They damage the roots of a wide range of eucalypts and cause death of seedlings. Most attacks occur in the first few months after planting. Thirty-one species damage eucalypts. *Lepidiota*

[1] Guangxi Forestry Department, Nanning, China 530022.

stigma F., *Anomala corpulenta* Motschulsky and *A. cupripes* Hope are the principal pests and they are common throughout southern China. At Qinlian Forest Farm, Beihai Forest Farm and Maijin Forest Farm, the most serious damage was caused by larvae of the large scarab, *L. stigma*, with losses of 50% of *E. exserta* in 1991.

Defoliators

There are 160 species that damage eucalypt leaves. They comprise more than half (57%) of the eucalypt pests in China. Seventy-five species belong to the order Coleoptera and 70 species are in the order Lepidoptera (families mainly Psychidae, Noctuidae, Lymantriidae and Geometridae). Most species are of only minor importance, but the case moth, *Chalia larminati* Heylaerts,and the tortricid leaf-roller, *Strepsicrates* sp., have caused moderately severe defoliation. *Strepsicrates* is widespread in southern China and occurs on several eucalypt species. It is mainly a pest of young trees and most damage has occurred in the first year after planting, usually in April to June. It rolls and skeletonises new leaves, and injury to the growing tip can result in multiple leaders. At Dongmen Forest Farm and Qinlian Forest Farm, 10–90% of seedlings were damaged by the moth. At Wujia branch of Qinlian Forest Farm, a 150 ha plantation was heavily infested by leaf-roller in 1991, with most trees damaged within 3 months of planting by 30–100 caterpillars per tree.

Among the beetle defoliators in the south are several species of the scarab genus *Anomala*. At Qinlian Forest Farm and Leizhou Forest Bureau, *A. cupripes* damage *C. citriodora* each year.

The ground cricket, *B. portentosus,* damages young plants in the field, cutting seedlings and low shoots and dragging them into its tunnel for food.

Sap-suckers

Sixty-seven species of sap-sucking insect have been recorded on eucalypts in China. They belong to the orders Hemiptera and Homoptera. They feed on the sap of leaves, shoots, twigs and stem, but there have been no reports of serious damage.

Wood-borers and bark-feeders

Eighteen species of wood-borers and bark-feeders have been recorded on eucalypts, 11 of them causing moderate damage. The most important are the longi-corn jewel beetle and carpenter bee. They bore into eucalypt stems or branches and most attacks have occurred in damaged or unthrifty trees or in dead crown wood.

Forecast for Insect Pest Damage to Eucalypts in China

It is estimated that there will be 330 species damaging eucalypts by 2010. The most serious losses will still be from termites, white grubs, geometrids and leaf-rollers. Sap-sucking and wood-boring insects will become increasingly important.

Pests caused an estimated loss of US$4.1 million in 2001. By 2010, there will be 2 million ha of eucalypt plantations in China and 5–7% of them will be damaged by pests. The estimated annual cost of the damage is US$10–20 million (60–140 million yuan).

Control measures

Strict quarantine

Several Australian pests have been introduced inadvertently into other eucalypt growing countries around the world and have become serious problems. Examples include the longicorn beetle (*Phoracantha semipunctata* (F.)), which has been reported from over 20 countries, and *Gonipterus* spp. (weevils) in Africa, Europe and South America. The likelihood of introduction into China of exotic eucalypt pests and the threat such insects would pose to the plantations is difficult to assess. A prohibition on the import of all *Eucalyptus* material, except for disinfested seeds, would substantially reduce the risk.

Periodic pest survey

Generally, pest attacks may be due to a combination of factors that include the pest species, population density, seasonal activity rhythm, air temperature, moisture conditions of the soil, physiological state of the plant, and age and species of plant. Greater knowledge of such factors would be a valuable aid in combating the problems. Periodic surveys in eucalypt plantations are necessary for early detection of developing pest problems.

Integrated control

Control of the most serious pest species, such as termites and white grubs in young seedling, requires integrated management measures. In general, cooperation between regions and countries is needed in addressing control of eucalypt pests.

Predicting the Environmental Interactions of Eucalypt Plantations Using a Process-Based Forest Model

J.D. Morris[1]

Abstract

Avoidance of possible negative impacts of eucalypt plantations on soil fertility, water resources, salinity and other environmental factors requires sound management based on a quantitative knowledge of the interactions of forest growth and environment. Process-based growth models may provide this knowledge in part, because to validly predict the influence of environmental factors on growth over a rotation, they must also predict the changes in those factors which result from the presence of the growing plantation. The 3-PG forest model provides a suitable basis for development of a management-oriented utility for predicting key environmental impacts of plantation establishment, silviculture and harvesting options. Functional extensions to 3-PG are described which allow an analysis of the interactions of eucalypt plantations with groundwater recharge, soil nutritional status and root zone salinity. Fitting 3-PG to plantation growth and biomass data from southern China reveals a need for modification of the model's response to fertility, and data sets from low rainfall areas of southeastern Australia suggest further enhancements to its ability to reflect species differences in drought tolerance. With these in place it is possible to draw conclusions about the rate of fertility decline in existing plantations, and potential growth rates and water consumption by trees if fertility decline is avoided. Within the limits of a simple root-zone hydrological and salt-balance model, it is also possible to predict the results of forest management options and salinisation or fertility decline on water output as stream flow and groundwater recharge from plantation catchments. 3-PG based modelling at the stand scale is suggested as a useful tool for forest planning, and could also form one component of a multi-part model for more comprehensive analysis of ecosystem or catchment-scale impacts.

Eucalyptus plantations are a highly productive source of raw materials for wood-using industries in many countries. Research and development in tree breeding, silviculture, disease control and other disciplines continues to improve yield and quality of plantation products. In spite of this successful development, the effects of eucalypt plantations on environmental factors have been a source of concern and conflict in a number of countries. Negative consequences attributed to eucalypts in different locations include soil fertility decline, salinity, erosion, biodiversity reduction, decreased stream flow, water quality and watertable depth, and increased fire hazard. In some cases these concerns have arisen from misconceptions, in others they have been a mask for underlying concern at social impacts of a plantation program, but in many cases they are real, are related to high productivity of the plantations, and can be overcome by appropriate management.

Faced with the need to avoid or minimise negative impacts of plantations, forest managers and land-use

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[1] Forest Science Centre, Department of Sustainability and Environment, PO Box 137, Heidelburg, Victoria 3084, Australia.
Email: <jim.morris@nre.vic.gov.au>.

planners would obviously benefit from a tool for predicting the short- and long-term environmental consequences of forest establishment, management and harvesting decisions. This is especially true in areas where plantations are a relatively new land use, so that experience-based knowledge of the interactions of forests and environment is lacking. Examples include plantation developments in southern China, where the area of exotic eucalypt plantations has increased significantly during the past 20 years, and Australia, where eucalypt plantations are being widely established on farmland as a replacement for timber harvesting from native forests.

The 'Eucalypts and water' project (ACIAR Project FST/1997/77) was initiated to investigate concerns related to perceptions of excessive water consumption, falling watertables and fertility decline in eucalypt plantations of western Guangdong province. Parallel research in southeastern Australia has focused on the sustainability of plantations in saline areas, and the impact on stream flow of land-use change from agriculture to plantation forestry. In both situations, there is a pressing need for simple but reliable modelling tools that can be applied at a management and planning level to quantify the environmental consequences of alternative plantation establishment and management strategies.

Process-based forest growth models have been widely discussed in the forest research literature in recent years, and have begun to be applied by some forest managers as a practical and valid tool for predicting growth and yield of tree plantations. The acceptance of such models in a management context as a more flexible alternative to the traditional regression-based empirical growth models is contingent upon: (i) simple data input requirements, (ii) useful output variables, and (iii) convenient user interfacing and documentation.

The respective values of these two contrasting approaches to growth prediction continue to be debated (Mäkelä and Sands 2002; Peng 2002). Because empirical models are inherently simple and can at least sometimes provide a better fit for a given set of data (Peng et al. 2002), they may be preferred for predicting future growth of familiar species with established management conditions within an existing forest estate. In the context of a plantation expansion program involving new, often non-forested planting locations and sometimes new or exotic genotypes, only a process-based model is suitable as a predictive tool.

The 3-PG forest model of Landsberg and Waring (1997) has been variously described as process-based, mechanistic, hybrid, and semi-empirical. This evidently uncertain classification is equally applicable to other, similar models; it arises from a disparity of scale between the models and the processes they attempt to represent. Key biophysical processes such as CO_2 absorption, evaporation through the stomata, cell division and expansion, root water uptake or ion exchange take place on very short temporal and spatial scales. In modelling these processes or their outcomes at more practical management scales (e.g. a monthly time step, stand scale model such as 3-PG), averaging and integration of variables in time and space hides the underlying relationships with physical constants that may be identified on smaller scales. The parameters that describe these processes on a large scale can then often be derived only empirically; nevertheless, the processes and their interdependencies remain defined within the model, with the result that the large-scale outputs are sensitive to the environmental factors that affect them. In spite of this embedded empiricism, such mechanistic models are clearly different from so-called empirical models, which use statistically derived coefficients to relate growth variables directly to tree age and selected environmental factors. In this difference lies the strength of mechanistic models for application where no forests have previously existed to allow derivation of a regression model and, more importantly in the present context, for predicting the effects of plantations on their environment.

Interactions between trees and environmental factors may operate in either one or both directions. Examples of the latter include canopy humidity and root-zone conditions such as moisture content, salt storage and nutrient concentrations, all of which both influence and are influenced by the growth of the trees. A mechanistic forest model that includes these variables as influences on tree growth must therefore also model the changes in external conditions that result, otherwise the natural feedbacks that control transpiration, soil moisture depletion, salt accumulation and fertility decline will not operate. The growth model then, of necessity, becomes capable of predicting impacts of the plantation on some key environmental variables. As discussed by Morris and Collopy (2001), valid prediction of any variable requires appropriate model structure and parameterisation, and it cannot be assumed that a validated growth model will also be valid for other outputs.

Furthermore, not all of the environmental effects of plantation growth are necessarily included as feedback factors affecting growth-related processes. Nevertheless, an appropriately defined and validated mechanistic growth model clearly may be capable of simultaneously predicting at least some key environmental impacts.

The purpose of this paper is to demonstrate an application of the 3-PG growth model with some functional extensions to predict the interactions of eucalypt plantations with groundwater recharge, soil nutritional status and root-zone salinity. Parameterisation of the model for *Eucalyptus urophylla* clone U6 was based on measurements of stand growth, climate and soil conditions from plantations managed by Leizhou Forest Bureau on the Leizhou Peninsula of western Guangdong province. Data for parameterisation of *E. globulus* were from similar measurements on saline and irrigated sites in north-central Victoria, Australia.

Modelling Stand Water Use, Soil Moisture and Deep Drainage

Soil moisture affects growth in 3-PG through a 0–1 modifier f_θ defined as a function of monthly available soil moisture, as a fraction of its maximum value. The form of the f_θ function depends only on two soil-texture parameters. The same modifier also influences canopy conductance and hence stand water use, calculated by a Penman–Monteith function. From the modelled monthly water use, monthly rainfall, maximum root-zone water storage and a rainfall effectiveness parameter (allowing for interception, surface evaporation and run-off), it is possible to estimate drainage out of the root zone (Figure 1). In situations of high soil hydraulic conductivity, shallow root-zone depth and high rainfall intensity, this monthly time-step model is likely to underestimate drainage, and on sloping sites with less conductive soils the drainage will be partitioned between surface and subsurface components. With recognition of these limitations, the simple root-zone hydrological submodel of 3-PG is potentially capable of making useful predictions of the impacts of forest growth and stand management options on stream flow and groundwater recharge.

This assumes that water use is correctly predicted by the model, and also that the f_θ function adequately describes the effects of declining available moisture on stand growth and canopy conductance. Morris and

Collopy (2001) reported investigations of plantations in southeastern Australia aimed at testing the validity of transpiration prediction by 3-PG. Modifications to the model suggested by that work have been implemented in an extended version of the model that will be referred to here as 3PG+. In addition, the model has been modified to allow for an enhanced rate of leaf senescence and litterfall when soil moisture falls below a critical threshold value, and to recognise that not all 'available' soil moisture in the root zone (depending only on bulk moisture content) is necessarily accessible to roots (depending on root biomass, hence carbon allocation and fine root turnover). The latter extension, which was suggested but not implemented by Landsberg and Waring (1997), provides scope for modelling differences in drought tolerance between different tree species, not possible when f_θ is wholly defined by soil factors. The 3PG+ model also estimates sapwood area and hence sap flux density (Figure 2), allowing comparison with tree-scale field observations as an aid to model validation.
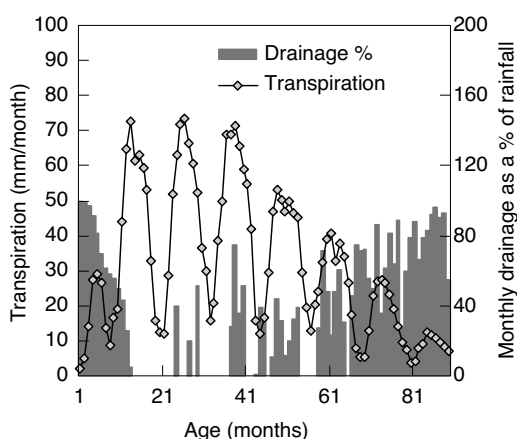

Figure 1. 3PG+ prediction of plantation water use and drainage from the root zone of *Eucalyptus urophylla* clone U6 in Jijia Forest Farm (Leizhou Peninsula, Guangdong province). Drainage is reduced to zero in the early years of stand development, but increases again as leaf area and water use decline in the ageing

## Modelling Fertility Decline

A striking feature of eucalypt plantations in tropical southern China is rapid early growth followed by the rapid decline of leaf area and hence growth rate, necessitating harvesting as early as 3 years after planting

(Figure 3). There is evidence that this is nutritionally induced, related to loss of nitrogen and possibly other key nutrients from the upper soil profile by physical and biological processes. Whatever the mechanism, in 3-PG terms this is evidently a decline in 'fertility', that is, an external site factor and not a physiological change in the trees. The sharp decline in leaf area with age leads to a strong shift in the relation between foliage mass and tree diameter, violating the 3-PG assumption of a constant relationship that is at the core of the model's carbon allocation and hence growth predictions. Morris and Baker (2002) showed that this change with age cannot be adequately explained as a result of litterfall, and suggested modelling the foliage mass–diameter relationship as an explicit function of age. However, if it is accepted that the change is external then it can be more usefully modelled as a function of fertility, with the important difference that fertility may or may not decline through time, depending on soil conditions and stand management (Figure 4). Early versions of 3-PG in fact included a fertility effect on nf, the power of the foliage mass–diameter relationship (Landsberg, pers. comm.), and in effect this has been restored in 3PG+.
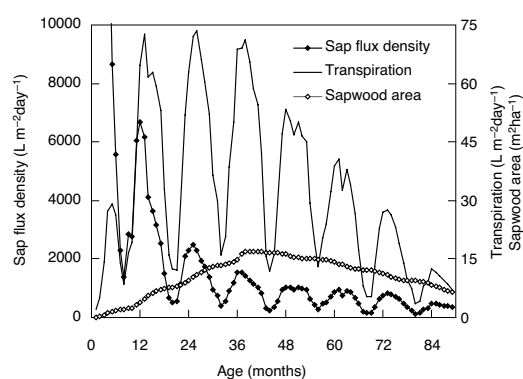
Figure 2. Sapwood area, sap flux density and stand water use of *Eucalyptus urophylla* clone U6 at Jijia Forest Farm (Leizhou Peninsula, Guangdong province). Rapid early growth and subsequent decline of these plantations are accompanied by large variation in water use with age.
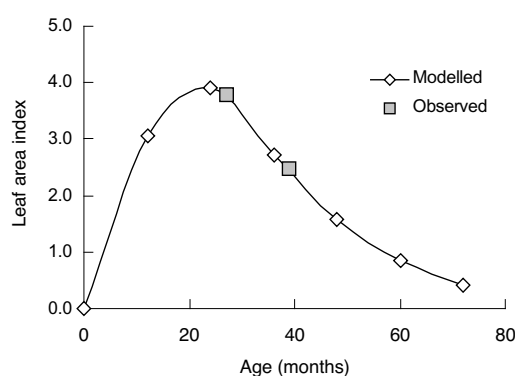
Figure 3. Modelled and observed (from biomass studies) leaf area index of *Eucalyptus urophylla* clone U6 at Jijia Forest Farm (Leizhou Peninsula, Guangdong province) over 7 years.
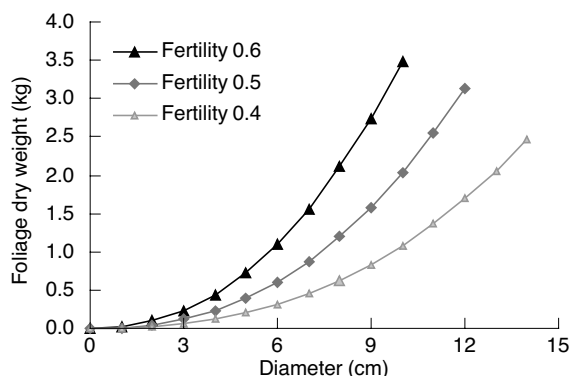
Figure 4. Relationship of foliage mass to mean tree diameter for differing levels of soil fertility, as calculated by 3PG+. In stands with rapidly declining fertility this effect leads to an apparent shift in the foliage mass–diameter curve with stand age.

The 3PG+ model is therefore sensitive to fertility in three respects: net photosynthesis, root allocation, and foliage-stem allocation. When combined with a capacity to impose a decline in fertility through time, this has allowed excellent results in fitting the model to sample plot growth data from plantations on the Leizhou Peninsula (Figure 5). At this stage, however, no attempt has been made to implement a feedback through which stand growth or litterfall may affect the rate or extent of fertility decline. As noted by Johnsen et al. (2001), soil and nutritional interactions remain the most difficult components for development of process-based forest growth models. Apart from the shortage of reliable data to construct such a link, a more compelling reason for maintaining fertility decline as an imposed change in the tree environment is the fact that it is likely to result to a large degree from other biological and physical factors outside the influence of the trees. Other models, such as TRIPLEX (Peng et al. 2002), do implement a feedback mechanism of litterfall and root decomposition influencing fertility through soil carbon and nitrogen pools.

Modelling Salt Accumulation in the Root Zone

Morris and Collopy (2001) described modifications to 3-PG for predicting growth in areas with saline soil conditions or saline irrigation. These include a modifier to reduce growth as a function of root-zone salt concentration, and a simple salt-balance model to predict monthly changes in salinity resulting from root water uptake, rainfall, irrigation, drainage and capillary rise from shallow groundwater. With these processes in place and acceptably parameterised, the feedback system relating stand water uptake and root-zone salinity is modelled, and 3PG+ is capable of predicting the monthly course of salt accumulation over the life of a plantation (Figure 6). The rudimentary hydrological functions of the model create a limitation to this application in soils of low hydraulic conductivity, where large changes in watertable depth (not modelled by 3-PG or 3PG+) may occur in response to groundwater uptake by trees.

Interactions of Environmental Factors

Environmental factors seldom vary independently of each other, and the response of a forest to one factor may well have an effect on others. Complex interactions are the result, and a useful application of a validated process-based model is to provide some help in exploring these or to alert forest managers to unexpected indirect effects of management actions. Effects of climate, nutrition, salinity and stand density on water uptake have implications for soil moisture availability, and may thereby exert an influence on stand growth to either reduce or reinforce their direct effects. Similarly, tree responses to fertility and salinity provide a link through which either of these site factors can affect the other.
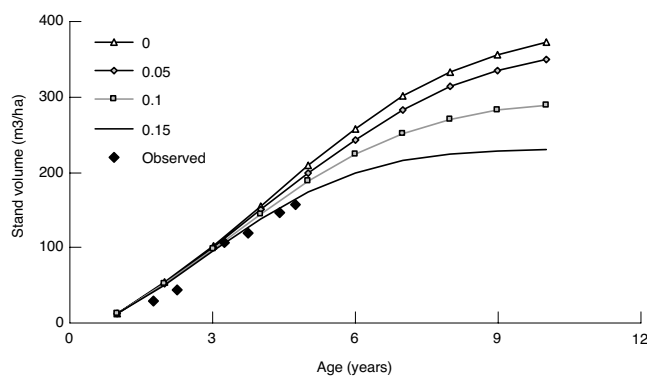

Figure 5. Observed volume growth of *Eucalyptus urophylla* clone U6 at Jijia Forest Farm (Leizhou Peninsula, Guangdong province) and predicted growth for three levels of fertility decline.

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Climate is a profoundly important factor influencing both growth and water use, but these responses are not directly related. As a result, the water-use efficiency (stand growth per unit of transpired water) of a plantation varies with climatic conditions (Figure 7). Stand water use typically reaches a maximum in the early years of development, along with leaf area index. The subsequent decline in annual water use is accentuated by fertility decline on sites where this is significant (Table 1). A result of this variation in water use with stand age is that the mean water use of a plantation estate containing approximately equal areas of all age classes up to rotation age will be less than the maximum observed in young stands, and the mean water use for the estate will tend to decrease as rotation length is increased (Figure 8).

Nutritional factors may interact to some extent with tree salinity tolerance in controlling growth rates, but this physiological effect is not modelled in 3-PG or 3PG+. The rate of accumulation of salt in the root zone of trees using saline water is for the most part determined by stand water use, which in turn is strongly governed by soil and climate conditions. As a result, the effects of salt accumulation on growth are not greatly affected by differing fertility or rate of fertility decline over a wide range. However, the growth of irrigated stands in saline conditions is subject to an interaction between the volume and salinity of applied water, which is further influenced
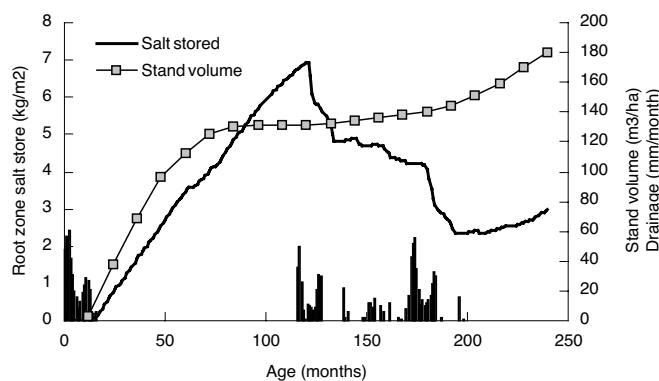
Figure 6. Root-zone salt storage versus time for a *Eucalyptus* plantation using saline groundwater in southeastern Australia.
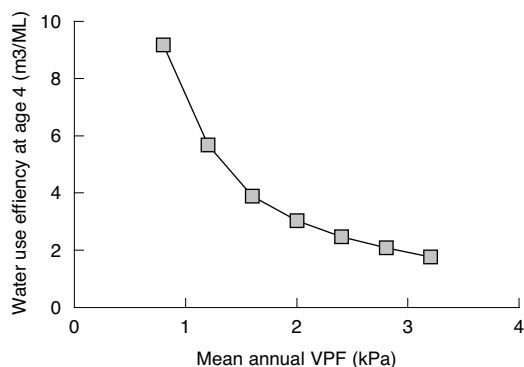
Figure 7. Water use efficiency at age 4 years for clone U6 in the soil and climate conditions of Jijia Forest Farm but with increased vapour pressure deficit to explore the effect of a less humid climate.
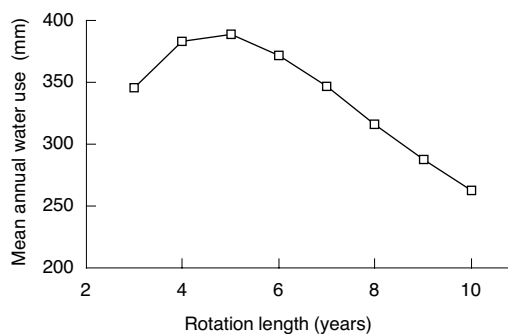
Figure 8. Effect of rotation length on plantation water use as an average over the full range of age classes in a plantation estate.

by soil texture and hydraulic conductivity. As water salinity increases, the volume of irrigation required to maintain growth rate increases steeply (Figure 9), but limitations of supply, application or infiltration rate usually preclude such a strategy. Even at relatively low water salinity, the best growth rate may be achieved by restricting the volume of applied water (e.g. to around 300 mm in the conditions of Figure 9).
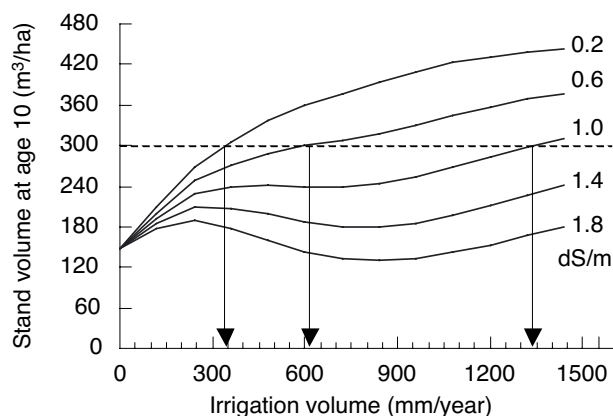
Conclusion

As a means of modelling the sustainability of forest ecosystems, the tree-focused approach described here may not be adequate in all situations. Some notable limitations include the absence of an understorey or multi-layer canopy; the imposition of a non-varying rainfall effectiveness factor to describe surface evaporation and run-off losses; and the rudimentary modelling of fertility dynamics, without a nutritional feedback from tree uptake or litter decomposition. All of these could be added to a further developed version of 3-PG if required, but possibly the more appropriate course for modelling at ecosystem or catchment scales is to apply 3-PG as one component of an integrated multi-component model (e.g. Liu et al. 2002; Peng et al. 2002). The purpose of the present paper is simply to demonstrate that, at a more modest stand scale, the interactions and feedbacks inherent in a soundly parameterised mechanistic growth model may allow a useful analysis of the implications of management decisions for environmental variables. Hence, an indication of the con-

Table 1. Fertility and stand water use: average annual water use of *Eucalyptus urophylla* clone U6 over a 10-year rotation, for sites with differing rates of fertility decline.

3PG+ fertility decline factor	Mean annual increment at age 5 years (m^3 ha^{-1})	Mean annual water use over 10 years (mm)	Annual water use at age 5 years (mm)
0	41.9	484	587
0.05	40.0	456	580
0.1	37.6	360	532
0.15	34.8	289	416

Figure 9. Trade off of irrigation volume and water quality as determinants of eucalypt plantation growth in southeastern Australia. Mean annual volume growth of 30 m^3 ha^{-1} can be achieved with 3.4 ML ha^{-1} of good quality water, but requires 6.2 ML ha^{-1} at water salinity of 0.5 dS m^{-1} and over 13 ML ha^{-1} at 1 dS m^{-1}.

sequences for plantation sustainability may be derived at the same time as forest growth and yield outcomes are predicted.

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Eucalypt Planting on Salt-Affected and Waterlogged Soils in Pakistan

K.M. Subhani, M.R. Chaudhry and M. Iqbal[1]

Abstract

Eucalypts have become popular in Pakistan in the past two decades. They are grown in small compact blocks, or single or multiple linear rows along the field boundaries or watercourses. Estimates of standing volumes and area of eucalypts vary but include a total volume grown on farm lands of about 0.36 million m^3 and of 245,000 ha of plantations in 2000. These figures will now have increased. Most wood produced in Pakistan is used as fuel, but 25% of *Eucalyptus* production is used for industry. Growing eucalypts on salt-affected and waterlogged abandoned lands has not been tested in a scientific and systematic way, but using these wastelands could generate income for farmers. This paper reports results of planting eucalypts on saline and waterlogged land with variables including different plant spacing, timing and planting techniques. The trees were irrigated with brackish groundwater. The unreplicated experiment cum demonstration area covered 29 ha in the Fordwah Eastern Sadqia South region of Punjab. Highest survival (78%) was achieved with September planting, while maximum growth was in trees planted in March. Trees spaced at 2.25 ✕ 2.25 m had the best growth. Planting eucalypts in the middle and bottom of the ridge was quite encouraging under saline and waterlogged land and gave a survival rate of 96%. It was concluded that eucalypts can be fairly successful under degraded soil and water resources with post-monsoon planting superior to spring planting. The trees lowered the water table and served as effective an bio-drainage intervention in waterlogged areas.

Agriculture plays a pivotal role in the economy of Pakistan but is confronted with problems of waterlogging and salinity, which result in reduced agricultural production. It is estimated that over 6.3 million ha of prime land has been taken out of production since the current extensive irrigation system was introduced, due to this menace. Much of this land lies barren or produces very little for farmers. Bio-saline technology shows that by growing salt-tolerant trees such as *Eucalyptus camaldulensis*, and crops and grasses, this poor quality land can produce good income for farmers (see e.g. Marcar and Khanna

(1997)). Perhaps more importantly, it can also help to protect their good agricultural land from such problems in the future. Planting of trees, especially eucalypts, can play a positive role in the improvement of socioeconomic conditions of the farming community. The current forest resources of Pakistan as compared with Asia and world are shown in Table 1.

The Status of Eucalypts in Pakistan

Eucalypts are planted on farmlands in social and farm forestry programs and as the promising tree species for afforestation and reclamation of waterlogged and saline areas in the plains of Punjab and Sindh provinces. They are grown either in the form of small compact blocks, or single or multiple linear rows along field boundaries.

[1] International Waterlogging and Salinity Research Institute (IWASRI), WAPDA, Muhammadpura Village, PO Thokar Niaz Baig, Lahore, Pakistan.
Email: <iwasri@brain.net.pk>.

According to the Forestry Sector Master Plan, the total volume of eucalypts grown on farmlands is 0.36 million m^3 (FSMP 1992). Another estimate was 0.57 and 0.16 million m^3 in Punjab and North West Frontier Province, respectively (Amjad 1991). This volume has since increased due to growth and planting programs. Eucalypts are exotic in Pakistan with few known uses. Farmers find eucalypts difficult to market because of strong competition from traditional farm trees with established uses. A marketing survey in the districts of Attock, Gujrat, Jhelum, Sargodha and D.I. Khan confirmed that most eucalypt tree farmers suffer from marketing constraints (Suleman and Shah 1995) and this is influencing farm resource management decisions in these areas. It was projected that, in 2000, there would be 245,000 ha of eucalypts in Pakistan, with 10% in the public sector and the balance in the private sector (Pandey 1998).

Farmers could be assisted and even motivated to plant more eucalypts if industrial uses of these species could be developed within Pakistan, or there was an export market. The present industrial base in the country is not strong enough to absorb expected supplies. In view of the scattered plantings, a feasible alternative could be to produce, on-farm with mobile chippers, eucalypt chips for export.

Projected forest planting areas, including *Eucalyptus*, in Pakistan at year 2000 are shown in Table 2.

About 90% of Pakistan's wood production is used as fuel, and almost 80% of households use wood for cooking. Most industrial roundwood is used for sawn timber. Imported wood pulp is mixed with local non-wood fibre pulp to produce paper. Pakistan also imports small quantities of logs, sawn timber, panels and paper. It is estimated that 207,000 t of short-fibre pulp (equivalent to 675,000 m^3 of *Eucalyptus*) and 130,400 t of long-fibre wood pulp would be required annually to produce all paper and paperboard products consumed in Pakistan (Ayaz and Qureshi 2000). Consumption of all grades of paper and paperboard is estimated to increase by 2.9% a year from 1998 to 2018. These estimates are based on 1997 trade data (FAO 2000) and conversions factors in Haynes (1990). Thus, the maximum potential use of *Eucalyptus* for pulp production would increase from 675,000 m^3 in 1998 to 1.9 million m^3 in 2018. A plantation area of 40,000 ha would be required to sustain production of 675,000 m^3, assuming an average yield of 17 m^3 $ha^{-1}yr^{-1}$. However, organisation of buying and collecting are crucial factors for a pulp industry, especially since the eucalypts are grown on so many individual farms.

Table 1. Forest resources of Pakistan, Asia and the world.

	Land area	Forest cover 2000	Forest cover change 1990–2000		Distribution of land cover/use (1990)		
					Forest	Other wooded land	Other land
	('000 ha)	('000 ha)	('000 ha yr^{-1})	(% yr^{-1})	(%)	(%)	(%)
Pakistan	77,088	2,361	39	1.84	3.1	1.4	95.8
Asia	3.084,124	547,791	−287	−0.05	17.8	4.6	78.3
World	13,139,618	3,869,453	−9319	−0.24	29.4	11.2	58.6

Source: <http://www.fao.org/forestry/fo/country> Forestry information system (FIRS) country profile.

Table 2. Projected plantation areas in Pakistan by genera in 2000.

Generic groups	Area		Industrial	Non-industrial
	(000 ha)	(%)	(%)	(%)
Acacia spp.	196	20	75	100
Dalbergia sp.	196	20	25	25
Eucalyptus spp.	245	25	10	75
Other broadleaved spp.	249	30		90

Source: Pandey (1998).

Pakistan could be a potential source of woodchips for export to East Asian countries. The main economic factor in the export of *Eucalyptus* woodchips from Pakistan is the cost of chip production and the marketing margin. Suleman and Ayaz (1995) discussed the economic feasibility of *Eucalyptus* chip exports. They noted the need to: 1) create a market demand for the *Eucalyptus* grown on farmlands in Pakistan; 2) improve socioeconomic conditions in the eucalypt growing area through better returns on the wood; and 3) provide motivation to the farmers to practise agroforestry and social forestry for the increased production of timber for fuels, industry and environmental improvement. Cost–benefit analysis suggests the negative marketing margin for manufacture of export *Eucalyptus* chips in Pakistan is due to higher transportation costs, lack of integration in the utilisation of eucalypts and absence of economies of scale in chip production. These three elements significantly hamper Pakistan's international competitiveness in *Eucalyptus* chip exports.

Growing eucalypts on salt-affected and waterlogged abandoned lands has not been tested in a scientific and systematic way, but using these wastelands could generate income for farmers. With this aim, *E. camaldulensis* was planted on saline and waterlogged land in Pakistan from 1998–99 to 2001–2002.

Research Methods

Variables tested included different plant spacings, timings and planting techniques. The trees were irrigated with brackish groundwater. An unreplicated experiment cum demonstration with an area of about 29 ha was laid out in Fordwah Eastern Sadiqia South region of Punjab. Data recorded were baseline soil analysis for texture and salinity/sodicity. Periodic water quality analysis and monitoring of soil salinity/sodicity, tree survival, girth and height, rainfall and water table fluctuation were carried out.

Planting months were February, March and April (spring) and August, September and October (post-monsoon). Spacings were 2×2 m, 2.25×2.25 m, 2.5×2.5 m, and 2.75×2.75 m giving plant densities of 2500 ha^{-1}, 1975 ha^{-1}, 1600 ha^{-1}, and 1322 ha^{-1}. Planting techniques included planting on top of the ridge, in the middle of the ridge, on the bottom of the ridge and in flat/basin soil (conventional).

The soil is a light textured, freely draining, loam to sandy loam. Chemical analysis in the 0–30 cm profile showed the soil profile was highly saline–sodic. Soil reaction was invariably alkaline (pH 8.5–8.9) with sodium adsorption ration in the range of 55–100 $(mmol_c\ L^{-1})^{0.5}$ and electrical conductivity (EC_e) 48–71 dS m^{-1}. Drainage water used for irrigation had SAR in the range of 14.0–16.4 $(mmol_c\ L^{-1})^{0.5}$ and EC_e 5.1–6.7 dS m^{-1}.

Results and Discussion

Tree survival

The data presented in Table 3 show impact of planting time on survival percentage in June 2002. September planting had 78% survival, which was significantly higher than other planting times. March and April planting survival was inferior to September but superior to February, August and October planting survival.

Table 3. Impact of planting time on tree survival.

Planting month	No. of trees planted	Percent survival
February	7457	23
March	7469	66
April	7755	57
August	4716	40
September	7507	78
October	7949	45

Survival at different spacings was in the range 49–58% but this may not be significant and may be due to variations in the site's soil salinity and sodicity.

Tree growth

Planting time had some influence on increase in tree height and girth (Table 4). Maximum mean tree height of 5.81 m was observed in March, with a mean of 5.60 m in April plantings. Trees planted in August had the minimum tree height of 3.79 m. In the case of February plantings, perhaps it was not just the time of planting that determined tree height: soil salinity/sodicity may have been more important. Examination of soil analysis data gives maximum salinity/sodicity values in February -planted fields.

The ranking of mean tree girth corresponded to the rankings for height growth. Mean maximum plant girth was in the March and April plantings: 8.11 cm and 7.95 cm, respectively. The smallest stem girth

growth was in August and February plantings: 4.96 cm and 5.24 cm, respectively.

Trees planted at 2.25 × 2.25 m spacings had the greatest height growth (4.79 m) and those planted at 2.00 × 2.00 m were the shortest (4.31 m) (Table 5). It is difficult to say if this difference is significant or due to site differences. Like height growth, maximum mean girth was in spacing 2.25 × 2.25 m, followed by S_4S_3 and S_1 (Table 5).

Effect of different planting techniques on tree survival

Survival of the 224 seedlings in each of the four treatments was: (i) top of ridge, 85%; (ii) middle of ridge, 96%; (iii) bottom of ridge, 96%; and (iv) flat/basin soil, 92%. Survival of plants on the top of the ridge appeared marginally poorer than in the other positions.

Effect of trees on the water table

Land occupied by the plantation had a relatively deeper watertable in its interior than at its perimeter or the outer peripheral area, due to intensive extraction of groundwater and evapotranspiration by trees.

Conclusions

The area under *Eucalyptus* in Pakistan is increasing and currently comprises 25% of plantation area. There will be more planting if the various uses of eucalypt wood are popularised. There is also the potential to save foreign exchange by producing paper pulp from eucalypts. Plantations on salt-affected wasteland are an option to provide economic returns to farmers. The following conclusions were drawn from this trial.

1. *Eucalyptus camaldulensis* grew fairly successfully on salt-affected abandoned land when irrigated with drainage water.
2. Extremely hot and dry weather, coupled with shortage of irrigation water, may result in significant plant failure. Post-monsoon planting (September) appeared to result in better tree survival than spring planting, while there was little effect of tree spacing on survival.

Table 4. Impact of planting time on tree height and girth.

Planting month	Tree height		Tree girth	
	Mean height (m)	Increase over August planting (%)	Mean girth (cm)	Increase over August planting (%)
August	3.37	–	4.96	–
September	4.25	+26	5.60	+13
October	4.39	+30	6.29	+27
February	3.79	+12	5.24	+6
March	5.81	+72	8.11	+64
April	5.60	+66	7.95	+60

Table 5. Impact of initial spacing on tree growth.

Spacing	Tree height		Tree girth	
	Mean (m)	Percent increase over (S_1)	Mean (cm)	Percent increase over (S_1)
2.00 × 2.00 m (S_1)	4.31	–	5.84	–
2.25 × 2.25 m (S_2)	4.97	15	7.21	23
2.50 × 2.50 m (S_3)	4.40	2	6.15	5
2.75 × 2.75 m (S_4)	4.46	3	6.40	10

3. Tree growth, and therefore wood production, after 4 years was considerably higher in pre-monsoon planting (March–April).

4. Land occupied by the plantation had a relatively deeper watertable in the interior than the perimeter or the outer peripheral area due to intensive extraction of groundwater and eva-potranspiration by trees.

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Water Use of *Eucalyptus camaldulensis* on Highly Saline and Non-Saline Soils in Yang Talad, Kalasin Province, Thailand

J. Luangjame[1] and R. Lertsirivorakul[2]

Abstract

A heat-pulse-velocity technique was used to monitor water use by *Eucalyptus camaldulensis* trees from Petford, Queensland, Australia. The trees were planted on recharge (non-saline soil) and discharge (highly saline soil) areas for ecological studies in Yang Talad, Kalasin province, Thailand. Watertables were over at 7.6 m depth on non-saline and 1.5 m on highly saline soil areas during 1998. Water use was studied for 14 months to investigate and assess the technique to improve saline soils in northeastern Thailand. Water use was 12.25 L tree^{-1} day^{-1} or 2.17 mm day^{-1} on highly saline soil, on which trees had a mean diameter at breast height (dbh) of 9.37 cm and a sapwood area of 35.69 cm^2. Water use was 15.51 L tree^{-1} day^{-1} or 3.48 mm day^{-1} on non-saline soil for trees with 11.09 cm dbh and sapwood area 51.10 cm^2. Water use of *E. camaldulensis* was 800 and 1322 mm yr^{-1} on the highly saline soil and non-saline soil areas, respectively.

Water use by vegetation is a very important tool to manage soil improvement in northeastern Thailand where there are soil salinity problems. Salinity affects the environment, land use, agricultural planting and water consumption in this area. It also contributes to the poverty of local people. Therefore, a strategy for soil improvement and prevention of soil salinity is necessary. Tree planting is the best means of long-term salinity prevention because it keeps the water balance both above ground and below ground, and stops saline dispersion. Tree roots hold the soil, prevent erosion and enable rainwater to infiltrate into the soil. Trees can prevent saline groundwater moving to the soil surface by capillary pressure through the soil pores and evaporation.

However, only salt-tolerant species will survive on saline soils, and *Eucalyptus camaldulensis* is an economic tree species that is recommended for such areas in Thailand. This drought- and waterlogging-tolerant Australian eucalypt survives and grows very well in northeastern Thailand (Luangjame et al. 1995). Therefore, studies of the ecophysiology of *E. camaldulensis* on soils with high, moderate and no salinity, to compare its ecophysiological characteristics of water use, are very relevant to land reclamation efforts on saline soils in this area.

The objectives of this study were to compare the water use of *E. camaldulensis* on highly saline and non-saline soils and its relationship to climate and watertable conditions.

Materials and Methods

The provenance of *E. camaldulensis* used for the study was from Petford, Queensland (CSIRO seedlot 16720). Seedlings were planted in 1992 on saline soil at Ban Dong Bang and non-saline soil at Ban Phonsim

[1] National Park, Wildlife, and Plant Conservation Department, Silvicultural Research Division, 61 Phaholyothin Road, Bangkok 10900, Thailand. Email: <jesada@mozart.inet.co.th>.

[2] Khon Kaen University, Faculty of Technology, Geotechnological Division, Khon Kaen 40000, Thailand. Email: <rungr_le@kku.ac.th>.

in Yang Talad district, Kalasin province (latitude 16°23'08"N, longitude 103°15'41"E, altitude 170 m asl (Luangjame et al. 1996). The highly saline soil area at Ban Dong Bang is in a discharge area, while the non-saline soil area at Ban Phonsim is in a recharge area. Annual rainfall in 1998–99 was 1170 mm and the rainy season was from May to October. Tree spacing was 2 m × 2 m on an area of 1.6 ha at each site. At each site in 1998–99, 30 representative trees at age 6 years were monitored, using 2 trees per month. Heat pulse velocities (HPVs) were measured using Greenspan Technology (Swanson and Whitfield 1981; Greenspan Technology 1993; Luangjame et al. 1998).

Results and Discussion

Water use and sapwood area

Water use was power-function related to sapwood area on highly saline soil and linearly on non-saline soil. Water use increased as sapwood area increased. Sapwood areas were 18.8–53.9 cm^2 and water use was 2.89–20.70 L $tree^{-1}$ day^{-1} (Table 1) on highly saline soil and 23.0–90.3 cm^2 and 6.64–30.37 L $tree^{-1}$ day^{-1} on non-saline soil (Table 1). Lertsirivorakul (1994) found that water use was 11–140 L $tree^{-1}$ day^{-1} in *E. camaldulensis* at 14 years old on a non-saline recharge area. The trees were of 7–31 cm dbh and sapwood areas of 35–180 cm^2. The main factors for water use are sapwood area, weather (precipitation. cloudy or sunny, temperature), and soil moisture.

Sapwood and diameter

Sapwood area was power-function related to stem diameter on highly saline soil and linearly on non-saline soils. Sapwood area and dbh were much greater on non-saline soil than on highly saline soil.

Water use and diameter

Water use was power-function related to stem diameter in both areas (highly and non-saline soils). Average water use was 15.51 L $tree^{-1}$ day^{-1} on non-saline soil and 12.25 L $tree^{-1}$ day^{-1} on highly saline soil. Olbrich (1991) found that water use by *E. grandis* was 3–11 L hr^{-1} at 10.00–14.00 hr at stem diameters of 12.1–15.5 cm and sapwood areas of 62.7–97.1 cm^2 at age 3 years. Water use was 35.45 L hr^{-1} at dbh 41.27 cm with sapwood area 37.1 cm^2 at age 16 years.

Dye et al. (1992) studied on *Eucalyptus grandis* at 11 and 18 cm dbh and sapwood areas 71.4 and 216.1 cm^2 at age 1.5 and 4 years by HPV and deuterium tracer comparison. They found that sapflows were 90 and 101 L day^{-1} by HPV and 67 and 94 L day^{-1} by deuterium tracer, respectively.

Diurnal water use

Water use of *E. camaldulensis* peaked at 10.00–14.00 hr on both non-saline and highly saline soils because this is a favourable time for photosynthesis (Luangjame 1990, 1992). It declined in the late afternoon, due to high temperature and water stress.

Water use of the eucalypt plantation

Water use of the *E. camaldulensis* plantation was 2.17 mm day^{-1} on highly saline soil and 3.48 mm day^{-1} on non-saline soil (Table 1), or 800 and 1322 mm yr^{-1} (Table 2). Water use was lower on highly saline soil than non-saline soil, because the growth was poorer and sapwood area was lower due to the soil conditions and lower survival rates. These results were similar to *E. camaldulensis* (CSIRO seedlot 15319) which had a water use of 272 and 1229 mm yr^{-1} on highly saline and moderate saline soils, respectively (Luangjame et al. 1998). However, the water use was much different on highly saline soil (800 mm yr^{-1} compared with 272 mm yr^{-1}), probably because it was a different provenance and year of measurement.

On non-saline soil, soil conditions were better, so the numbers of leaves and sizes of trees were much greater than on highly saline soils. This resulted in greater water use. The ECs were 48.5 and 92.0 dS m^{-1} on the surface of highly saline soils (Table 3). Roots of the eucalypts reached the watertable, which was salty because they were discharge areas (Figure 1). The roots were also shorter than those on non-saline recharge area Therefore, water use of *E. camaldulensis* was higher on non-saline than highly saline soils because of salt and waterlogging. Season and amount of precipitation also affected the depth of salinity levels. In the experiments, soil salinity was as high as 20 cm soil depth in the dry season, but after a period of rain salinity was moved progressively to depths of 60, 100 and 150 cm (Table 4). Salama et al. (1994) found that *E. camaldulensis* plantations could stabilise the watertable which did not fluctuate as it did under a cleared plantation. Clearing also caused salinity fluctuations and erosion.

Table 1. Water use of *E. camaldulensis* on non-saline and highly saline soils in 1998–99.

Measurement period	Days	Tree no.	Non-saline soil Diameter over bark (cm)	Sapwood area (cm^2)	Water use (L day^{-1})	Sap flux density (L m^{-2} day^{-1})	Standard water use (mm day^{-1})	Tree ID	Highly saline soil Diameter over bark (cm)	Sapwood area (cm^2)	Water use (L day^{-1})	Sap flux density (L m^{-2} day^{-1})	Standard water use (mm day^{-1})
18–18/2–3/98	27	N1	14.40	73.30	16.77	2287	2.56	S1	11.00	51.10	11.61	2271.28	1.69
18–21/3–4/98	33	N2	9.70	44.00	10.63	2416	2.70	S2	12.20	38.70	12.72	3263.05	2.43
21–22/4–5/98	30	N3	13.43	64.05	12.46	2833	3.17	S3	7.03	26.80	4.75	1740.43	1.30
22–16/5–6/98	25	N4	14.00	66.70	17.71	2655	2.96	S4	8.72	33.80	6.56	1957.64	1.46
17–22/6–7/98	34	N5	10.10	42.20	11.56	2739	3.07	S5	9.20	33.60	17.54	5220.58	3.89
22–17/7–8/98	26	N6	9.40	35.70	14.10	3949	4.42	S6	9.80	38.60	15.50	4070.89	3.04
18–22/8–9/98	35	N7	7.20	23.00	6.64	2847	3.19	S7	11.60	53.90	18.40	3581.76	2.67
23–19/9–10/98	26	N8	7.20	23.00	7.52	3267	3.66	S8	11.60	53.90	20.70	3841.30	2.87
20–15/10–11/98	26	N9	8.90	33.90	17.05	5079	5.68	S9	6.50	18.80	7.30	3761.93	2.81
16–16/11–12/98	30	N10	8.90	33.90	14.55	4292	4.80	S10	6.50	18.80	2.89	1542.63	1.15
17–24/12–1/98–99	39	N11	15.60	90.30	31.08	3441	3.85	S11	9.55	32.45	11.01	1920.38	1.43
25–22/1–2/99	28	N12	15.60	90.30	30.37	3363	3.76	S12	9.55	32.45	11.15	1862.31	1.39
23–16/2–3/99	21	N13	9.70	44.00	11.14	1234	1.38	S13	8.50	31.05	19.11	2865.59	2.14
Average	29.23		11.09	51.10	15.51	3108	3.48		9.37	35.69	12.25	2915.37	2.17

Table 2. Monthly water use of *E. camaldulensis* seedlot no. 16720 on non-saline and highly saline soils in Yang Talad district, Kalasin province.

Month	Non-saline soil (mm)	Highly saline soil (mm)	Month	Non-saline soil (mm)	Highly saline soil (mm)
February	29	19	September	95	80
March	84	68	October	142	90
April	85	55	November	154	59
May	98	43	December	135	39
June	85	75	January	120	44
July	120	121	February	90	43
August	119	87	Year 1998[a]	1322	801

[a] One year total (18 Feb. 1998–17 Feb. 1999).

Conclusions

1. Water use of *E. camaldulensis* depended on sapwood area, which is related to stem diameter.
2. Water use was higher on non-saline than on highly saline soils.
3. Factors that affected the water use of *E. camaldulensis* were (i) sapwood areas and diameter; (ii) climate (temperature, wind flow, humidity, cloud, and precipitation); (iii) leaf area; and (iv) levels of soil salinity.
4. *Eucalyptus camaldulensis* is a pioneer species for soil improvement on saline soils, e.g. grasses emerged when the land acquired humus from the litterfall. They were followed by other species, and finally plants sensitive to salinity (glycophytes) could grow.

Recommendation

Reforestation for saline soil improvement by lowering the watertable should be on both recharge and discharge areas and on non-saline and saline soils.

Table 3. Salinity levels and pH of soil samples collected 21 June 1998.

Sites	Soil depth (cm)	pH	EC (dS m^{-1})
Non-saline soil	0–20	4.86	0.071
	20–40	5.12	0.060
Moderate saline soil	0–20	4.63	0.043
	20–40	4.82	0.056
Highly saline soil	Surface soil	8.85	48.500
	0–20	6.56	5.245
	20–40	5.44	3.515
Highly saline soil at data logger	Surface soil	6.97	92.000
	20	6.23	1.479
	40	6.53	0.201
	60	6.50	0.831
	100	7.01	1.087

Table 4. Weather and soil data on site by data logger in 1998.

Month	Precipitation		Light intensity	Temperature		EC (dS m^{-1})
	(mm)	(days)	(MJ m^{-2})	(Max.)	(Min.)	Soil depth (mm)
January	151.4	12	20.73	34.4	18.7	9.3
February	27.2	4	18.64	35.6	20.6	50.1
March	90.2	5	21.05	38.3	23.6	35.5
April	93.0	7	22.64	37.9	23.7	8.8
May	122.6	12	23.50	37.7	24.1	1.0
June	111.4	13	23.49	36.8	22.9	1.1
July	90.8	8	22.63	35.0	23.8	0.8
August	108.2	16	21.43	35.1	23.7	0.9
September	158.8	12	19.35	33.2	23.3	0.5
October	43.2	8	20.90	34.1	21.6	1.7
November	23.2	3	18.39	32.6	19.4	7.9
December	0.2	1	17.88	30.7	17.3	12.1
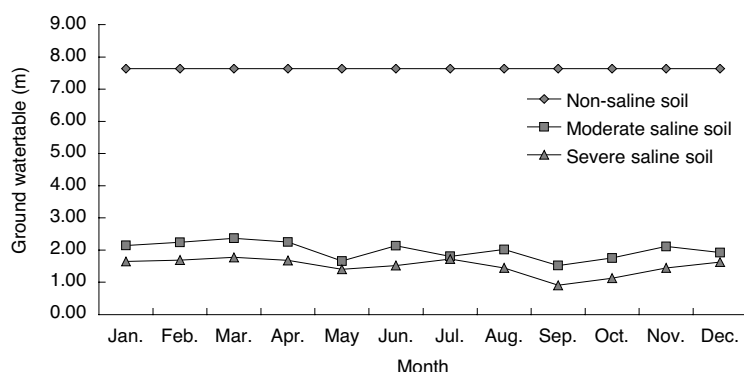
Figure 1. Watertable depths on non-saline, moderate, and severe saline soils in 1998.

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Water Quality as an Environmental Indicator for the Long-Term Sustainable Management of Forested Catchments

P. Hopmans[1] and L.J. Bren[2]

Abstract

The Cropper Creek Hydrology Project was established in 1976 to study the hydrology of three small catchments of native eucalypt forest. In 1980, one catchment was cleared for the establishment of a *Pinus radiata* plantation, but a 30 m wide buffer zone of undisturbed eucalypt forest was left along the stream. This change in land use increased annual water yield by 3.5 ML ha^{-1} during the first 6 years, but only minor changes in water quality were observed. In 1997, the long-term changes in hydrology and water quality of the 17-year-old plantation, compared with historic data for the original eucalypt forest before conversion, were evaluated. Median values for water quality including turbidity, suspended solids, salinity, and selected nutrients (P, Ca and S) were in close agreement with historic values. It was shown that physical parameters such as turbidity were strongly affected by stream flow, indicating the need for event sampling. In contrast, changes in nutrient concentrations with stream flow were comparatively small and monitoring can therefore be conducted at regular intervals. The plantation was thinned and treated with phosphate fertiliser to stimulate growth in 1998, but the buffer zone was left untreated. Intensive monitoring of phosphate levels in stream water across a wide range of flow conditions showed a slight increase in dissolved phosphate for 6 months before returning to pre-treatment levels. The study showed little change in long-term water quality associated with conversion of a native forest catchment to intensively managed, fast-growing plantation. Water quality remained within the range of historic variation, indicating that thinning and fertiliser treatment of the plantation had no detrimental impact on water from this catchment. The study also demonstrated the importance of maintaining an undisturbed vegetated buffer along the stream for the protection of water quality.

Industrial plantations have been established in Australia since the 1960s as part of a long-term strategy to expand wood resources. Initially, plantations replaced native eucalypt forest but, since the 1980s, they have been established mainly on cleared agricultural land. Associated with this conversion of catchments to intensively managed, fast-growing plantations, are changes in hydrology, and potential effects on both water yield and water quality. Water is an important resource in Australia and protection of water quality is of critical importance for the long-term maintenance of water resources and aquatic ecosystems. A national water-quality-management strategy has been formulated, and guidelines have been adopted for the protection of water resources (ANZECC 2000). In addition, Australia has adopted the Montreal Process of socioeconomic and environmental criteria and indicators for the sustainable management of forests (DPIE 1998). Maintenance of water quality within the range of historic variation is one of the environmental indicators included in this process.

[1] Forest Science Centre, Department of Sustainability and Environment, PO Box 137, Heidelburg, Victoria 3084, Australia. Email: <peter.hopmans@nre.vic.gov.au>.

[2] Department of Forestry, University of Melbourne, Creswick, Victoria 3363, Australia.

In the mid 1970s, the Cropper Creek Hydrology Project was established to study the hydrology of three small catchments of mixed-species eucalypt forest. In 1980, during Phase I of the project, one catchment was cleared for the establishment of a plantation of radiata pine, except for a 30-m wide riparian zone. In the short term, this change in land use increased annual water yield by 3.5 ML ha^{-1}, but yield gradually fell to pre-treatment values with time after clearing (Bren and Papworth 1991). Only minor changes in water quality were observed, but export of suspended solids and nutrients in stream water increased because of higher water yield in response to clearing (Hopmans et al. 1987).

In 1997, the project was resumed (Phase II) to evaluate the long-term changes in hydrology and water quality of the 17-year-old plantation compared with historic data for the original eucalypt forest before conversion. One year later, the plantation was thinned and treated with fertiliser to correct a phosphate deficiency and to stimulate growth, but the buffer zone of native eucalypt forest was left untreated. The long-term changes in water quality of the plantation catchment and the impact of phosphate fertiliser are reported in this paper.

Methods

The three forested catchments of the Cropper Creek Hydrology project are located at the Black Range in northeastern Victoria. Catchments range in size from 46 ha for the radiata pine plantation, to 44 ha and 113 ha for the two eucalypt forests. Average annual rainfall is 1300 mm, and soils are gradational clay loams derived from sandstone and slate. Details of the physiography of the catchments, climate, geology, native vegetation, instrumentation of the weirs, collection of streamflow data and monitoring of water quality are given by Bren et al. (1979). Stream water quality of the catchments during Phase I, and the impact of clearing native forest to establish a plantation, were reported by Hopmans et al. (1987).

Phase II of the Cropper Creek Hydrology project commenced in 1997. Weirs and gauging equipment for monitoring rainfall and stream height were reinstated and the original Leopold-Stevens chart recorders were fitted with shaft encoders for electronic logging of stream height. Regular collection of stream water for analysis commenced in May 1997. Samples were collected at weekly intervals from a fixed location above the weirs. Additional samples were collected more frequently (1–4 hours) during several storm events, using Sigma automatic water sample collectors.

Turbidity, salinity (EC), and total suspended solids (TSS) in stream water were measured using standard procedures (APHA 1995) and generally within 48 hours of collection. In addition, concentrations of P, S, and Ca in filtrate were determined by ICPAES (APHA 1995).

In 1998, the plantation was thinned to a stocking of approximately 600 stems ha^{-1}. Foliage diagnostic testing indicated that the plantation was deficient in phosphorus, and phosphate fertiliser (P:S:Ca, 18:9:14) was applied a rate 570 kg ha^{-1} in April 1998. Fertiliser was applied to the plantation area only; the 30 m wide buffer zone along the stream remained untreated.

Results

Median rather than mean values were calculated for all water quality parameters, because of the skewness of the distributions of the water quality data. The median absolute deviation (MAD) for each parameter therefore provides a measure of variability. In addition to minimum and maximum values, the 80th percentile values provide the level recommended by ANZECC (2000) as the low-risk stress indicator for water quality of undisturbed aquatic ecosystems.

Water quality (turbidity, TSS and EC) based on weekly sampling and excluding data from major rainfall events is summarised in Table 1 and compared with historic values for the same parameters during Phase I.

Median values for turbidity were slightly higher, and values for TSS were lower during Phase II (Table 1). In contrast, EC in stream water remained essentially the same, indicating little, if any, real change in total ionic strength or soluble salts in the streams. The changes in physical parameters of water quality were small, and median values have remained within the 80th percentile values for Phase I conditions. Therefore, the change in land use from eucalypt forest to radiata pine plantation appears to have had little if any long-term impact on these physical parameters of water quality.

Median values for calcium (Ca) during Phase I and II were in close agreement, but results indicated generally lower values of phosphorus (P) in stream water during Phase II for both the undisturbed native forest and the plantation catchment (Table 2). Concentra-

tions of P in stream water during Phase II were similar for the native forest and the plantation catchments. Measurements of sulfur (S) only began during Phase II, because of improved analytical methodology. This provided the opportunity to determine changes in sulfur in stream water following treatment of the pine catchment with phosphate fertiliser also containing sulfur (9.5% S).

There was little evidence of increased levels of P, S or Ca in stream water during Phase II following treatment of the radiata pine catchment with phosphate fertiliser in April 1998. The impact of this treatment on nutrient levels in stream water was examined in detail for 6-monthly periods following the application of fertiliser.

Median levels of P increased approximately five-fold from 0.002 to 0.010 mg L^{-1}, while levels of S increased only marginally during the 6 months immediately after treatment (Table 3). Peak values for P and S, 0.025 mg L^{-1} and 0.19 mg L^{-1} respectively, were measured during this period. The change in P levels was small and within the range of values in stream water during Phase I (Table 2). Concentrations of P returned to antecedent levels soon after treatment. Levels of Ca were not affected by the application of fertiliser.

Table 1. Turbidity, TSS and EC in stream water from Clem catchment before (Phase I) and after (Phase II) conversion to radiata pine, and for water from the adjacent undisturbed eucalypt catchment (Ella) for the same periods.

Water quality	Catchment	Phase	Median	MAD[a]	Min.	Max.	80th percentile
Turbidity (NTU)	Clem – Euc	I	2.0	1.5	0.2	17.0	4.0
	Clem – Pine	II	3.3	1.2	0.6	26.1	5.3
	Ella – Euc	I	2.0	1.0	0.1	11.0	3.0
	Ella – Euc	II	0.9	0.4	0.3	20.3	1.4
TSS (mg L^{-1})	Clem – Euc	I	5.0	3.0	0.5	75.0	9.0
	Clem – Pine	II	4.4	2.0	0.2	60.8	7.2
	Ella – Euc	I	2.5	1.5	0.5	25.0	6.0
	Ella – Euc	II	0.8	0.7	0.1	24.4	2.4
EC (μS cm^{-1})	Clem – Euc	I	29.5	2.4	16.2	35.2	31.9
	Clem – Pine	II	28.8	2.7	21.0	41.0	32.3
	Ella – Euc	I	25.0	1.9	17.7	40.5	27.0
	Ella – Euc	II	23.1	1.8	17.0	31.0	25.0

[a] MAD, median absolute deviation.

Table 2. Nutrients in stream water from Clem catchment before (Phase I) and after (Phase II) conversion to radiata pine, and for water from the undisturbed eucalypt catchment (Ella) for the same periods.

Nutrient	Catchment	Phase	Median	MAD[a]	Min.	Max.	80th percentile
P (mg L^{-1})	Clem – Euc	I	0.009	0.004	0.001	0.044	0.015
	Clem – Pine	II	0.004	0.003	0.001	0.025	0.008
	Ella – Euc	I	0.007	0.004	0.001	0.025	0.012
	Ella – Euc	II	0.003	0.002	0.001	0.021	0.006
S (mg L^{-1})	Clem – Pine	II	0.093	0.009	0.055	0.15	0.10
	Ella – Euc	II	0.089	0.009	0.055	0.14	0.10
Ca (mg L^{-1})	Clem – Euc	I	0.87	0.150	0.28	2.20	0.96
	Clem – Pine	II	0.79	0.076	0.55	1.21	0.88
	Ella – Euc	I	0.44	0.060	0.25	0.84	0.51
	Ella – Euc	II	0.39	0.031	0.33	0.73	0.44

[a] MAD, median absolute deviation.

During the same period, levels of P and S also increased in stream water from the adjacent undisturbed eucalypt catchment (Table 3). This catchment was not treated with fertiliser and it is suggested that these changes were due mainly to the resumption of stream flow during July 1998 after a prolonged dry period.

Physical parameters of water quality (turbidity and TSS) were significantly affected by stream flow (Hopmans and Bren 1999). Therefore, results for weekly sampling of stream water were compared with results from high intensity sampling carried out during rainfall events with contrasting peak flows in July and September 1998 and August 1999 (Table 4). This showed a substantial increase in median levels of TSS during periods of high flows, especially in the steeper radiata pine catchment. While higher flows were observed in the undisturbed eucalypt catchment, the effect on TSS levels in water was considerably smaller (Table 4). These results clearly demonstrate the need for event sampling to determine the impacts of forest management on turbidity and TSS.

A comparison of weekly sampling and more intensive event sampling for P, S and Ca applied in phosphate fertiliser showed that concentrations in stream water were only slightly affected by flow conditions (Table 4). Higher levels of P and S were observed in stream water from the radiata pine catchment during the first main rainfall event after fertiliser was applied, but levels returned to pre-treatment values soon thereafter. Compared with physical water quality parameters, concentrations of nutrients remained relatively constant, even during the major rainfall event in September 1998.

Likewise, some variation in median values of nutrients was observed for weekly and event sampling of stream water from the eucalypt catchment. This is assumed to be a reflection of seasonal variation and the more intermittent stream flow in this catchment compared with the radiata pine catchment.

Discussion

During the first phase of the Cropper Creek Hydrologic project it was shown that conversion of Clem catchment from native eucalypt forest to radiata pine in 1980 had little impact on water quality (Hopmans et al. 1987). However, exports of suspended solids and nutrients increased due to higher water yield after clearing the catchment. During the second phase of

Table 3. Levels of P, S and Ca in stream water before treatment of radiata pine with phosphate fertiliser in April 1998 and for 6-monthly periods thereafter.

Period	P (mg L^{-1}) median	MAD[a]	S (mg L^{-1}) median	MAD	Ca (mg L^{-1}) median	MAD
Radiata pine catchment						
Pre-treatment						
May '97–April '98	0.002	0.001	0.090	0.007	0.84	0.07
Post-treatment						
0–6 months	0.010	0.006	0.108	0.014	0.74	0.09
7–12 months	0.005	0.004	0.096	0.008	0.74	0.06
13–18 months	0.006	0.003	0.088	0.010	0.73	0.03
19–24 months	0.002	0.001	0.093	0.013	0.84	0.07
Eucalypt catchment						
May '97–April '98	0.002	0.001	0.087	0.004	0.42	0.03
Periods						
0–6 months	0.005	0.004	0.111	0.016	0.40	0.03
7–12 months	0.003	0.002	0.087	0.012	0.36	0.01
13–18 months	0.001	0.001	0.094	0.010	0.43	0.06
19–24 months	0.002	0.001	0.084	0.006	0.38	0.01

[a] MAD, median absolute deviation.

the project (May 1997 to April 2000), the radiata pine plantation of Clem catchment was thinned and treated with phosphate fertiliser in April 1998.

Water quality (turbidity, TSS, and EC) during Phase II remained largely within the original range of values characteristic for this catchment before disturbance. Median levels for these parameters during Phase II remained below the 80th percentile values considered to be indicative of low stress for undisturbed natural ecosystems (ANZECC, 2000).

Concentrations of Ca in stream water were similar during Phase I and II. In contrast, levels of P in streams were lower during Phase II, but were similar in the streams from the native forest and the radiata pine catchment. Likewise, levels of S in stream water from these two catchments were in close agreement. Therefore, there was little evidence to indicate any long-term change in P, S and Ca in stream water due to the change in land use from native eucalypt forest to radiata pine plantation. Furthermore, treatment of the plantation catchment with phosphate fertiliser also containing Ca and S had little impact on the levels of these nutrients in stream water.

Intensive sampling during major rainfall events showed considerable increases in turbidity and suspended solids in stream water as instantaneous flow increased to 400 L s^{-1}. Monitoring of the effects of forest management on these physical water-quality parameters requires sampling strategies that are closely linked with stream flow. In contrast, the change in concentrations of nutrients (P, S, and Ca) in water across a range of flow conditions was minor

and covered a comparatively small range. Therefore, weekly sampling is appropriate for monitoring nutrient levels in streams of these forested catchments.

Application of phosphate fertiliser (100 kg P ha^{-1}) to radiata pine, excluding the 30 m buffer zone along the stream channel, increased median levels of P in water from 0.002 mg L^{-1} before treatment to 0.010 mg L^{-1} (maximum value 0.025 mg L^{-1}) during the 6 months immediately after treatment. The impact of fertiliser was transient and levels returned to antecedent values after 6 months. The levels of P in stream water from the plantation catchment remained below 0.040 mg L^{-1}, the low risk trigger value for slightly disturbed ecosystems adopted in the National Water Quality Management Strategy for Australia (ANZECC 2000).

In New Zealand, application of phosphate fertiliser to radiata pine at low rates (36 kg P ha^{-1}), and excluding stream channels, increased P levels to a maximum of 0.08 mg L^{-1}, but peak values of 1.7 mg L^{-1} were observed when the entire catchment was treated (Neary and Leonard 1978). Higher rates of fertiliser (P at 112 kg ha^{-1}) applied across entire catchments increased peak levels in streams to 16 and 52 mg L^{-1} immediately after treatment. These studies also showed that changes in P levels were temporary, levels returning to antecedent values within a few months of treatment. Likewise, aerial treatment of loblolly pine plantations in the southern USA at low rates (24 and 40 kg P ha^{-1}), and excluding stream channels, resulted in peak values of 0.05 mg L^{-1}

Table 4. Median values for concentrations of TSS, P, S and Ca in stream water, based on sampling at weekly intervals and during contrasting short-term peak flow events.

Period	Peak flow (L s^{-1})	TSS (mg L^{-1})	P (mg L^{-1})	S (mg L^{-1})	Ca (mg L^{-1})
Radiata pine catchment					
Weekly '97–00	74	4.4	0.004	0.093	0.79
SF1 Jul '98	33	6.8	0.015	0.120	0.62
SF2 Sept '98	251	127	0.005	0.099	0.60
SF4 Aug '99	57	15.4	0.007	0.090	0.72
Eucalypt catchment					
Weekly '97–00	82	0.8	0.003	0.089	0.39
SF1 Jul '98	56	1.6	0.011	0.150	0.50
SF2 Sept '98	382	12.0	0.016	0.112	0.49
SF4 Aug '99	95	2.2	0.009	0.099	0.41

(Binkley et al. 1999), but levels increased to 1.1 mg L^{-1} when the entire catchment was treated.

Conclusions

1. Stream water quality, including turbidity, suspended solids, EC, and nutrients (P, S, and Ca), in a radiata pine plantation catchment has remained within the historic range of values of the original undisturbed eucalypt forest.
2. There was no evidence to indicate that water quality was adversely affected by the change in land use to a more intensively managed radiata pine plantation.
3. Turbidity and suspended solids were strongly affected by flow conditions, and monitoring of these indicators of sustainable forest management needs to be linked to stream flow.
4. In contrast, levels of nutrients (P, S and Ca) in stream water were only slightly affected by flow, and monitoring of these water quality indicators can be based on fixed time intervals.
5. Application of phosphate fertiliser to the plantation catchment increased median P levels in stream water during 6 months following treatment before returning to antecedent values. The levels of P in stream water did not exceed the low risk trigger value for slightly disturbed ecosystems adopted as part of the National Water Quality Management Strategy in Australia.

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Relating Sap Flow to Environment in Two *Eucalyptus urophylla* Plantations in Southeastern China

Yin Guangcai,[1] J. Morris,[2] Zhou Guoyi,[1] Wang Xu,[1] Huang Zhihong[1] and Zhang Ningnan[3]

Abstract

Sap flux density (SFD) of two eucalypt (*Eucalyptus urophylla* S.T. Blake) plantations was measured by the heat-pulse method between September 1999 and September 2000 on Leizhou Peninsula, southeastern China. Diurnal and seasonal dynamics of SFD, as well as the relationship between SFD and environmental factors, are discussed in this paper. Diurnal fluctuations of SFD were studied on 4 days in summer (25–28 October 1999) when soil moisture had been replenished by recent rainfall. SFD began to increase at about 7:00 am, peaked after 12:00, and fell gradually towards a minimum value soon after sundown. The mean maximum hourly rates for these days were 44.2 mL cm^{-2} h^{-1} for the Hetou plantation, and 29.2 ml cm^{-2} h^{-1} for the Jijia plantation. Seasonal patterns of hourly SFD were similar at both sites, higher during the rainy season from May to October and falling to a yearly minimum in February–March. Average daily SFD at Hetou (2436 L m^{-2} d^{-1}) was greater than that at Jijia (1703 L m^{-2} d^{-1}). Daily maximum SFD varied greatly on both seasonal and shorter time scales. Multiple regression and correlation analysis showed that the average daily SFD at Hetou and Jijia was strongly related to atmospheric vapour pressure deficit, solar radiation and soil volumetric water content. Differences in soil conditions at the two sites led to differences in the profile depths where moisture content was most strongly related to SFD. Empirical models were developed to estimate daily SFD from environmental factors at both sites.

Many studies in China and other countries have examined the ecological effects of eucalypt plantations (Liao et al. 1994; Kan et al. 1995; Liao et al. 2001a,b; Li et al. 2002; Zhou et al. 2002a). Uncertainty and unresolved questions remain for some key issues, including whether eucalypts make excessive demands for water and nutrient elements (Lin 2001).

A widely held concern that high water use by *Eucalyptus* plantations may have negative impacts on water resources and catchment values has been the stimulus for water-use studies in several countries (Calder 1992; Kallarackal 1992; Roberts et al. 1992; Calder et al. 1997; Kallarackal and Somen 1997; Soares et al. 1997), but further study is still needed on the influence of environmental and physiological factors that control plantation evapotranspiration (Hatton et al. 1998; Lane et al. 2003).

Substantial research attention has been given to developing methods for measurement of tree and stand water use. The theoretical bases of a number of methods were reviewed by Smith and Allen (1996)

[1] South China Institute of Botany, Guangzhou 510650, China. Email: <gcyin@scib.ac.cn>.
[2] Forest Science Centre, Department of Sustainability and Environment, PO Box 137, Heidelburg, Victoria 3084, Australia. Email: <jim.morris@dse.vic.gov.au>.
[3] Research Institute of Tropical Forestry, Guangzhou 510520, China. Email: <ewater@pub.guangzhou.gd.cn>.

who drew attention to associated practical considerations which might affect the choice of method. Sap flow methods including the heat pulse method and heat balance method have been widely use to measure sap flux density (SFD) of trees (Liu et al. 1997); canopy transpiration is equal to SFD multiplied by sapwood area. For this study, the heat pulse method, which is relatively easily operated and not influenced by environmental conditions, canopy structure or root characteristics, was chosen as the most appropriate technique for monitoring SFD and water use of individual trees and stands.

Morris et al. (in press) have recently described a study of the diurnal dynamics of SFD of two eucalyptus plantations (*Eucalyptus urophylla* S.T. Blake) on the Leizhou Peninsula of southeastern China. Lane et al. (2003) reported that the total evapotranspiration was 63 to 73% of precipitation in the same plantations, and Zhou et al. (2002b) derived an empirical formula for the variation in SFD with depth below the cambium at both sites. This paper reports the results of a further study on the diurnal and seasonal variation in SFD and its relationship to environmental factors.

Materials and Methods

Site description

The plantations are located within forest farms near the towns of Hetou and Jijia in the Nandu River catchment in central Leizhou Peninsula, Guangdong province, China. The Hetou site (21°05'N, 109°54'E) is on a coarse-textured soil of sedimentary origin, while Jijia (20°54'N, 109°52'E) has a basalt-derived clay soil. The climate is tropical, with long-term monthly mean temperatures of around 28ºC in July and 16ºC in January. Annual rainfall ranges from 1300 mm in the south to 2500 mm in the north of the peninsula but shows high variation from year to year. Over 80% of the rain falls in the wet summer between April and September. Typhoons occur two to three times per year on average during this season, bringing high intensity rainfall and strong winds. At the study sites, the monitored plantations were *E. urophylla* planted in mid-1996 (3 m × 2 m spacing at Hetou, 2 m × 1.5 m spacing at Jijia). A 40 m × 40 m plot was established at each site in September 1999, and a representative set of trees within each plot was selected for water-use monitoring.

Plantation water use

The measurement of water use by *E. urophylla* at Hetou and Jijia has been described in detail by Morris et al. (in press). Briefly, selected trees at both sites were monitored singly or in pairs for periods of 3 to 4 weeks to record sap flux at 30-minute intervals using heat pulse equipment from Edwards Industries (Otaki, New Zealand). Measurements of SFD at four points in the sapwood of each tree were integrated to whole tree values using either a second degree polynomial or area-weighted mean to account for variation in SFD with depth below the cambium. Half-hourly observations were summed to determine daily SFD.

Environmental monitoring

Instruments for measuring air temperature, relative humidity, solar radiation and wind speed were installed at both sites in September 1999. Micro-power data loggers (Tain Electronics, Box Hill, Australia) were used to collect data every half hour. Rainfall was measured by tipping-bucket rain gauges at 7.5 m above ground in an open area at each site. Soil moisture content at four depths (50, 150, 250 and 350 cm) in the soil profile was measured at two locations in each site using buried soil moisture sensors (MP-406 from Agri-Tech Instruments, Beijing).

Statistical analysis

Statistical software, SPSS 11.0, SAS 6.1 and Microsoft Excel, was used for correlation analysis and multivariate stepwise linear regression to examine the relationship between SFD and environmental factors. The Pearson product moment correlation coefficient (R) was calculated as

$$R = \frac{N\sum XY - \sum X \sum Y}{\sqrt{N\sum X^2 - \left(\sum X\right)^2} \cdot \sqrt{N\sum Y^2 - \left(\sum Y\right)^2}} \qquad (1)$$

The multivariate regression analysis assumed that SFD and environmental factors were linearly related as follows:

$$y = b_0 + b_1 x_1 + \ldots + b_k x_k \qquad (2)$$

where

$$b_0 = \bar{y} - b_1\bar{x}_1 - b_2\bar{x}_2 - \ldots - b_k\bar{x}_k \qquad (3)$$

and $b_1, b_2, \ldots, b_k$ are partial regression coefficients.

Results and Analysis

Diurnal dynamics of SFD

Figure 1 shows the diurnal variation in SFD at both sites over 4 days, from October 25 to 28, during which the maximum air temperatures were 29.2–32.3°C and 27.8–31.6°C, minimum air temperatures were 20.3–21.3°C and 20.8–21.8°C, and mean daytime vapour pressure deficits (VPDs) were 0.73–1.15 kPa and 0.73–1.09 kPa for Hetou and Jijia, respectively. The second and fourth days of the study period were slightly warmer and clearer than days 1 and 3; no rain fell at either site during this period. The sapwood areas of the selected trees were 46.4 cm^2 at Hetou and 30.5 cm^2 at Jijia. The higher SFD recorded at Hetou than at Jijia on these 4 days is typical of observations at the two sites throughout the year.

SFD began to increase between 0730 and 0930h each morning and rose rapidly to reach a peak value by 1400h. Water use during the middle part of each day was variable, related to varying cloud cover typical of the Leizhou Peninsula through much of the year. By 1500h each day, SFD was falling and a daily minimum was reached by around midnight, although the rate of sap flow after sundown was low compared with daytime rates. These observations are in accordance with the results of water-use studies in *Populus* spp. reported by Gao et al. (2001), confirming that transfer of water from the root system to the tree canopy occurs predominantly during daylight hours. On the four selected days, the maximum recorded SFD values were 51.8, 69.9, 45.3 and 60.4 mL cm^{-2} h^{-1} at Hetou and 29.4, 36.7, 22.5 and 35.5 mL cm^{-2} h^{-1} at Jijia.

Seasonal dynamics of SFD

The daily and seasonal pattern of variation in SFD was similar at the two sites, but the diurnal dynamics of SFD differed between seasons. Figure 2 shows diurnal patterns of SFD for representative trees in spring (21 March 2000), summer (21–22 June 2000), autumn (22 September 1999) and winter (21 December 1999) at both sites. The maximum SFD values on these four dates were 37.9 (1530h), 66.4 (1400h), 74.1 (1330h) and 30.3 mL cm^{-2} h^{-1} (14h) at Hetou; and 22.5 (1530h), 41.4 (1330h), 34.4 (1500h) and 22.6 Macon^{-2} h^{-1} (1530h) at Jijia. During the dry winter and spring seasons, maximum daily SFD was lower, but sap flow also commenced later, peaked later and declined earlier than in the wet season, contributing to the significant reduction in plantation water use recorded during the dry season (Morris et al. in press).

Seasonal variation in daily mean SFD is shown in Figure 3, displaying a relatively higher value during the rainy season and relatively lower during the dry season at both sites. The maximum and minimum daily SFD values at Hetou were 4900 and 439 L m^{-2} d^{-1} (mean SFD 2436 L m^{-2} d^{-1} with standard deviation of 1193). At Jijia, the corresponding values were 3789 and 362 L m^{-2} d^{-1} (mean SFD 1703 L m^{-2} d^{-1} with standard deviation of 825). For the two sites combined, estimated water use was 241 mm in October–March and 317 mm in April–September. Factors contributing to this difference are likely to include both increased evaporative demand during the warmer months of the wet season, and diminishing soil water availability during the dry season.
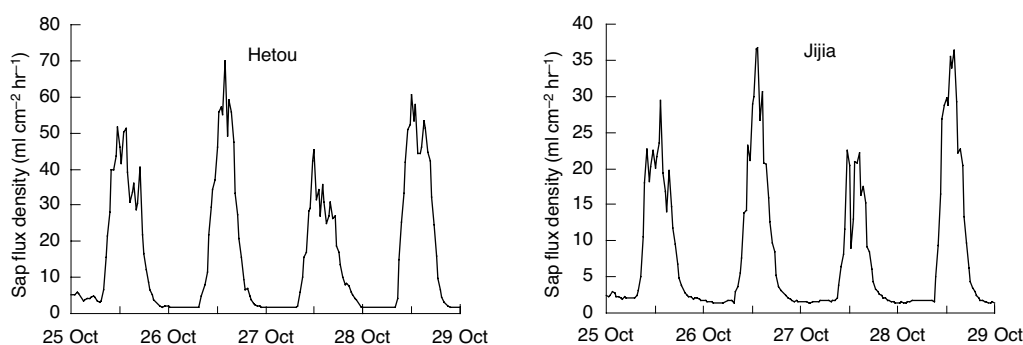
Figure 1. Diurnal sap flux density of *Eucalyptus urophylla* plantations at Hetou and Jijia between 25 October and 28 October, 1999.

Correlations among environmental factors

Pearson correlations relating daily solar radiation, rainfall, mean temperature, daytime mean VPD and soil moisture content at 50, 150, 250 and 350 cm depth at Jijia and Hetou are listed in Table 1. As expected, daily radiation was strongly correlated with temperature and VPD, while daily rainfall was negatively correlated with radiation and VPD but not temperature. Radiation, temperature and VPD were each also correlated with soil moisture, but this is presumably a result of parallel seasonal variation rather than any daily time scale relationship; that is, radiation, temperature and VPD are highest in the summer when soil moisture is increased by wet season rainfall. This seasonal relationship is not observed in the data for soil moisture at 50 cm depth at Jijia, where large variations in moisture content were common on a time scale of days to weeks. Daily

rainfall was correlated with soil moisture at 50 cm, suggesting that the rate of infiltration of water into the soil at both sites exceeds 50 cm day^{-1}. Higher correlation coefficients for both 50 and 150 cm at Jijia compared with Hetou probably reflect greater hydraulic conductivity and hence more rapid infiltration at Jijia as suggested by Lane et al. (2003). Among the soil moisture data, correlations were usually strongest between each layer and the layer immediately below it.

Relationship between SFD and environmental factors

SFD showed a strong positive correlation with radiation and VPD at both sites, as expected from its direct association with transpiration and the physics of evaporation from a vegetation canopy (Monteith 1965). Significant correlation with temperature was also evident, possibly due to the association of tem-
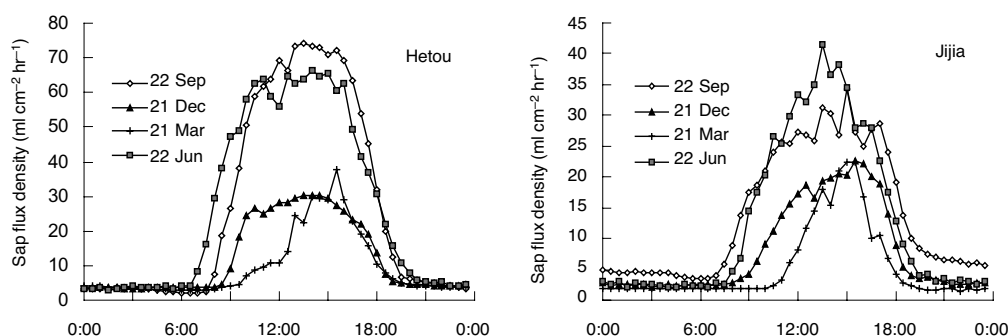
Figure 2. Diurnal patterns of sap flux density in *Eucalyptus urophylla* on selected days representative of spring, summer, autumn and winter conditions at Hetou and Jijia.
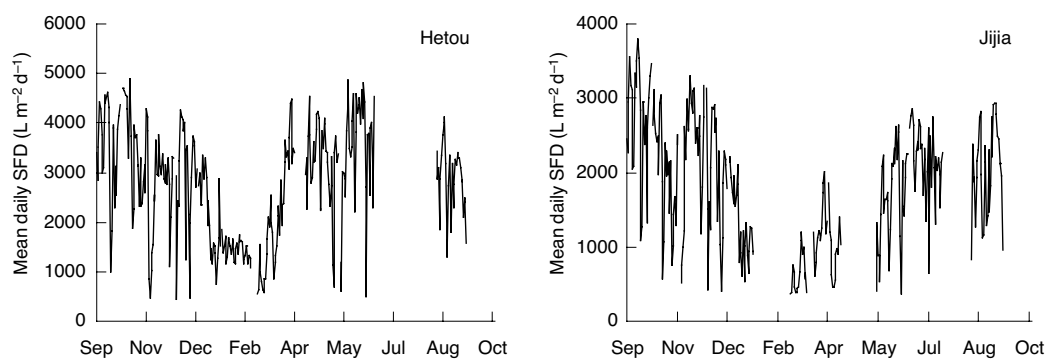
Figure 3. Seasonal variation in sap flux density in *Eucalyptus urophylla* at Hetou and Jijia, 1999–2000. Periods of missing data reflect failure of one or more instruments due to lightning or other causes.

perature with radiation and VPD, rather than a direct relationship. Similarly, the negative correlation between SFD and daily rainfall is almost certainly a result of low rainfall and low VPD on wet days, and should not be interpreted as evidence that water use is reduced by high rainfall on longer time scales. While the correlations between SFD and daily climate variables were generally similar at the two sites, those between SFD and soil moisture differed significantly. At Jijia, correlations with soil moisture at 250 and 350 cm were stronger than at shallower depth, but the reverse was true at Hetou.

Multivariate regression analysis showed that the relationships between daily SFD and environmental factors at the two sites could be expressed as follows:

$$SFD_{Hetou} = -10952 + 47739 \times SM50 + 83169 \times SM150 + 52661 \times SM250 - 111701 \times SM350 + 971.56 \times VPD - 19.71 \times P + 14.64 \times T + 33.61 \_ RAD \text{ (adjusted } R^2 = 0.78) \quad (4)$$

$$SFD_{Jijia} = -6871 + 5232 \times SM50 - 4534 \times SM150 + 8734 \times SM250 + 7696 \times SM350 + 925.75 \times VPD - 4.12 \times P -- 30.65 \times T + 47.31 \times RAD \text{ (adjusted } R^2 = 0.86) \quad (5)$$

where SFD is in L m^{-2} d^{-1}, SM50, SM150, SM250 and SM350 are volumetric soil water content at 50 cm, 150 cm, 250 cm, and 350 cm depth, respectively, VPD is daytime vapour pressure deficit (kPa), P is daily precipitation (mm d^{-1}), T is daily mean air temperature (°C) and RAD is daily solar radiation (MJ m^{-2} d^{-1}).

Optimal equations derived by stepwise regression analysis for prediction of daily SFD at Hetou and Jijia from climate and soil variables were:

$$SFD_{Hetou} = -18271 + 60644 \times SM50 + 95843 \times SM150 - 43195 \times SM350 + 1201.96 \times VPD - 19.44 \times P \text{ (adjusted } R^2 = 0.78) \quad (6)$$

$$SFD_{Jijia} = -4739 + 2415 \times SM50 + 9985 \times SM350 + 943.58 \times VPD - 34.84 \times T + 47.24 \times RAD \text{ (adjusted } R^2 = 0.85) \quad (7)$$

Table 1. Pearson correlation coefficients relating environmental factors and mean daily SFD at Jijia and Hetou.

	RAD	P	VPD	T	SM50	SM150	SM250	SM350
Jijia								
RAD	1.00							
P	−0.23	1.00						
VPD	0.92	−0.26	1.00					
T	0.61	−0.00	0.55	1.00				
SM50	0.09	0.35	−0.03	0.20	1.00			
SM150	0.45	0.13	0.35	0.50	0.66	1.00		
SM250	0.46	−0.04	0.43	0.38	0.15	0.51	1.00	
SM350	0.33	0.05	0.27	0.26	0.21	0.41	0.83	1.00
SFD	0.84	−0.23	0.85	0.39	0.12	0.39	0.59	0.51
Hetou								
RAD	1.00							
P	−0.23	1.00						
VPD	0.90	−0.32	1.00					
T	0.63	0.02	0.58	1.00				
SM50	0.52	0.19	0.43	0.74	1.00			
SM150	0.33	−0.05	0.32	0.32	0.45	1.00		
SM250	0.29	−0.07	0.29	0.33	0.43	0.66	1.00	
SM350	0.32	−0.07	0.32	0.38	0.47	0.61	0.997	1.00
SFD	0.79	−0.28	0.83	0.57	0.50	0.45	0.22	0.23

Notes: SM50, SM150, SM250, SM350 are soil moisture at 50, 150, 250 and 350 cm depth;
VPD is mean daytime vapour pressure deficit; P is daily rainfall; T is daily mean air temperature; RAD is daily solar radiation.
Correlations with absolute magnitude greater than 0.169 at Jijia (n = 230) or 0.164 at Hetou (n = 244) are significant at the 1% level.

Coefficients of climate variables in (4) and (5) are generally similar between sites, with the exception of temperature, while differences in the magnitudes and signs of soil moisture coefficients reflect the difference in correlation of SFD with moisture content at differing depths as noted above. The inclusion of T and RAD as positively correlated variables with coefficients of opposite sign serves to improve the precision of (7) as a predictive function, but does not imply a physical effect of temperature as a limiting factor for plantation water use at Jijia. A similar comment applies to the inclusion of both SM150 and SM350 at Hetou in (6), where rainfall replaces radiation and temperature as a climate variable. The similarities between (6) and (7) are perhaps more important than their differences: both include VPD and soil moisture at multiple depths, reflecting the importance of both supply and demand as determinants of plantation water use. The equations could be used to estimate SFD on sites where the input data are available, but it is emphasised that these are daily functions that are not suitable for application on longer time scales.

Discussion

The interpretation of SFD measured in single trees as representative of plantation means for comparisons of seasons and sites in this study assumes that variation in mean SFD among trees in even–aged plantations such as at Jijia and Hetou is negligible. This has been commonly observed in plantation water use studies (e.g. Khanzada et al. 1998; Morris et al. 1998; Benyon et al. 2001) and is implied by the findings of Hatton et al. (1998) for even-aged stands in which sapwood area at a given age is proportional to leaf area. The observation that transpiration per unit of leaf area or sapwood area (i.e. SFD) is approximately constant across trees of differing size, and in some cases differing species, at a given time and location suggests that SFD is predominantly determined by environmental factors. The assumption of uniform SFD among trees in a stand clearly can apply only to trees that experience similar soil and microclimatic conditions, and hence may be violated by the largest and smallest trees whose canopy and root environments may not be typical of the whole stand. Hence, sap flux measurements from two small trees (diameter 6.2 and 7.3 cm over bark at 1.3 m) overtopped by the plantation canopy at Hetou were rejected from analysis because their calculated SFD was anomalously lower others measured simultaneously or immediately before and after them.

Compared with other studies of tree water use, the annual range of observed daily SFD at Hetou and Jijia of approximately 400 to 5000 L m^{-2} d^{-1} was not extreme. Daily SFD values of *Quercus phellos, Liquidambar styraciflua* and *Pinus taeda* in North Carolina, USA were 2313, 2493 and 3194 L m^{-2} d^{-1} over 18 days in June (Pataki et al. 1998), while Liu et al. (1993) reported values of 3529–5916 L m^{-2} d^{-1} for 2-year-old trees and 5020–8588 L m^{-2} d^{-1} for 6-year-old trees of *Populus deltoides* in Beijing during September. In Shandong province of northeastern China, Li and Chen (1998) recorded daily SFD of 1580 L m^{-2} d^{-1} for *Betula dahurica* and 2130 L m^{-2} d^{-1} for *Acer mono* in July–August. Mahmood et al. (2001) reported an annual range of 1000 to over 10,000 L m^{-2} d^{-1} for young irrigated *Eucalyptus* plantations in a hot, dry area of Pakistan.

The factors that determine SFD are of three types: tree factors including leaf area and sapwood area, which influence the conductance of the transport pathway from soil to air; soil factors including available soil moisture as a source of supply; and climatic factors, which determine the demand for evaporation from the tree canopy (Sun et al. 2000). Morris et al. (in press) have discussed the importance of differing sapwood area between Jijia and Hetou (7.7 and 4.6 m^2 ha^{-1}, respectively, in September 1999) as a cause of the observed difference in SFD, and demonstrated that annual water use at the two sites was very similar. The contrasting soil environments of the two sites, highlighted by the correlation and regression analysis reported here, may also contribute to differing SFD. The influence of soil moisture supply on SFD would be most likely to become apparent in the dry season, when lower moisture-holding capacity of the Hetou soil is likely to lead to greater tree moisture stress and a requirement for roots to draw water from deeper in the profile compared with the Jijia plantation.

The close relationship of SFD to solar radiation and VPD based on both evaporation theory and empirical statistical analysis suggests that seasonal climatic variation must lead to corresponding variation in SFD and hence stand water uptake. In a dry winter climate such as at Leizhou, this pattern is likely to be reinforced by declining soil moisture availability during the dry season, and the regression and correlation analysis reported here suggests that this is the case at both Hetou and Jijia. The difference

between sites in the relative degree of correlation of upper and lower profile moisture content is of interest. At both locations, the seasonal trend of declining soil moisture through the dry season and replenishment early in the wet season was present at all four sampling depths, and the seasonal pattern of SFD was also similar at both. Higher correlation with the upper profile moisture content at Hetou might suggest that SFD was more limited by soil moisture content at this site, while at Jijia the upper profile moisture content seldom became limiting due to greater moisture storage capacity of the clay soil. Higher correlation with lower profile moisture content at Jijia might relate to a shorter lag time there for moisture content to be restored by rain events. However, the statistical relationships derived here should not be assumed to imply mechanistic causal relationships between the environmental factors and SFD.

Acknowledgments

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Water Balance of *Eucalyptus urophylla* Plantations in South China

P. Lane,[1] J. Morris,[1] Zhang Ningnan,[2] Zhou Guangyi,[2] Zhou Gouyi[3] and Xu Daping[2]

Abstract

Monthly, seasonal and annual water balances of *Eucalyptus urophylla* plantations on Leizhou Peninsula, Guangdong province, China have been estimated at two sites with contrasting soil types. The Jijia site is on basalt-derived clay-rich soils, while the Hetou site is characterised by coarse-textured soils formed on Quaternary sediments. Observations of evaporative processes (overstorey canopy interception and transpiration, and soil evaporation), soil moisture dynamics, and climate variables were collected at both sites over 2 years. Annual rainfall was 1525 mm and 1918 mm at Jijia, and 1555 mm and 2226 mm at Hetou. Total annual evapotranspiration (ET) was measured as 1079 mm and estimated as 1037 mm at Jijia, and measured as 1033 mm and estimated as 1104 mm at Hetou during years 1 and 2, respectively, despite 20–30% higher rainfall in year 2. ET at Jijia comprised 548 mm and 518 mm transpiration (T), 285 mm and 208 mm soil evaporation (Es), and 247 mm and 311 mm canopy interception (I) for years 1 and 2, respectively. At Hetou, T was 546 mm and 498 mm, Es was 177 mm and 169 mm, and I was 306 mm and 437 mm. Surface and sub-surface drainage was 396 mm and 1007 mm at Jijia, and 538 mm and 1090 mm at Hetou. The higher rainfall in year 2 was estimated to increase drainage rather than tree water use. Dry season water balances showed ET approached or exceeded rainfall, indicating water use from deep soil storages following shallower soil water depletion. However, storages were replenished by high wet-season drainage. The water use of the eucalypts does not appear to be deleterious for water supply in this area. Differences in soil properties between the sites resulted in a three-fold greater soil water store at Jijia that provided a supply for Es, and the sandier Hetou soils with poor water-holding capacity had greater wet season drainage and higher dry season abstraction from deep storages.

Concerns over excessive water use by exotic *Eucalyptus* species have been raised in several countries where commercial plantations have been established. Although there has been a number of robust scientific studies undertaken on eucalypt water use (see reviews by Calder (1992, 1999)), variation of species

and environments means generalised conclusions cannot yet be drawn. For example, eucalypts in India have been observed to transpire 3–8 mm d^{-1} in tropical conditions (Kallarackal 1992; Kallarackal and Somen 1997), and up to 6 mm d^{-1} post-monsoon and < 1 mm d^{-1} pre-monsoon in drier conditions at Karnataka (Roberts et al. 1992).

Calder et al. (1993) summarised the findings of the Karnataka experiments at four sites as demonstrating eucalypts could use 100% of rainfall, did not use more water than indigenous forest but more than crops, and that one site appeared to 'mine' 3400 mm of water from deep soil storages. Soares et al. (1997) reported 8 mm d^{-1} transpiration in Brazil when water

[1] Forest Science Centre, Department of Sustainability and Environment, PO Box 137, Heidelburg, Victoria 3084, Australia. Email: <pat.lane@dse.vic.gov.au>.

[2] Research Institute of Tropical Forestry, Longdong, Guangzhou 510520 China. Email: <ewater@pub.guangzhou.gd.cn>.

[3] South China Institute of Botany, Guangzhou 510650, China. Email: <gyzhou@scib.ac.cn>.

was not limited and almost zero transpiration in dry periods.

Replacement of grassland with trees results in a change in the water balance, principally through increased transpiration and interception (e.g. Van Lill et al. 1980; Fahey and Jackson 1997; Scott and Smith 1997; Samra et al. 2001). However, the impact of plantation establishment on the hydrology of multiple land-use catchments that include native tree or shrub species and tall crops such as sugarcane is, in many environments, still unknown. Over 200,000 ha of *Eucalyptus* plantations have been established in Guangdong province on Leizhou Peninsula of southern China, a subset of the more than 1 million ha of eucalypts planted in China. Species with high growth rates are favoured (e.g. *Eucalyptus globulus, E. grandis* and *E. urophylla*), with *E. urophylla* the most widely planted species in tropical areas.

In the Leizhou area, eucalypt plantations, rice, sugarcane, pineapples and other crops compete for the limited supply of surface and ground water. Surface water resources may be insufficient to meet these requirements during the dry season. With eucalypts replacing more traditional crops, there is an understandable fear that plantations may exacerbate water shortages. There are no data on the water use of eucalypts in the Leizhou area. To quantify eucalypt plantation water use in this environment, an experimental program was carried out to quantify the water balance of two 3 to 5-year-old plantations on the Leizhou Peninsula as part of ACIAR Project FST 97/77 'Eucalypts and water: managing forest plantations in China and Australia for sustained productivity and environmental benefits'.

Study Sites

The plantations are located at two sites in the Nandu River catchment. The Jijia site is on a basalt-derived clay soil within the Jijia demonstration catchment area (20°54'N, 109°52'E), while the other is approximately 40 km north near Hetou (21°05'N, 109°54'E) on a sandy soil of sedimentary origin. Both sites are on flat to undulating terrain typical of the peninsular lowlands. The climate is tropical, with monthly mean temperatures of around 28°C in July and 16°C in January. Annual rainfall varies from 1300 mm in the south to 1800 mm in the north of the peninsula and annual variation is high. Over 80% of rain falls between April and September, up to half of this in typhoons which occur two to three times a year on average. The monitored plantations at both sites were *E. urophylla* planted in mid-1996 (3 m × 2.5 m spacing at Hetou, 3.3 m × 1.5 m spacing at Jijia).

Methods

A monthly water balance was estimated according to the well-known equation:

$$P = ET + RO + \Delta S + D \qquad (1)$$

where P is rainfall, ET is total evapotranspiration, RO is surface run-off, ΔS is the change in soil water storage and D is deep drainage. The latter may also be regarded as recharge to ground water, often defined as drainage below the root zone. ET is composed of canopy interception (I), transpiration (T) and soil evaporation (Es). Interception can be calculated as gross rainfall less throughfall and stemflow. The components of (1) were measured or estimated as follows.

Rainfall was measured by tipping-bucket rain gauges. Interception was estimated by measuring throughfall (TF) and stemflow (SF) for a wide range of rainfalls up to 60 mm d^{-1} at Jijia and 86 mm d^{-1} at Hetou for 84 and 96 rain days, respectively. The relationship between rainfall intensity and TF could then be used to estimate TF and SF for all events.

Transpiration for year 1 was calculated from heat-pulse measurements as described fully by Morris et al. (in press). In year 2, when the heat-pulse program had concluded, monthly T was estimated by means of a multiple regression on P and PET (potential evapotranspiration), which returned an r^2 of 0.62 for Jijia and 0.90 for Hetou. PET was estimated by the Penman equation. Soil evaporation was measured by micro-lysimetry for 6 hours 1 day a month at 6–10 locations at each site. Daily Es was estimated by the following method: the Penman–Monteith combination equation (Monteith 1965) was applied to calculate mean hourly surface evaporation for each period of lysimeter measurement, using net radiation and vapour pressure deficit data estimated from half hourly meteorological observations at each site and assuming a boundary layer conductance of 0.2 m sec^{-1}. The surface conductance was adjusted to make the calculated rate of evaporation equal to the rate derived from lysimeter weight loss. The surface conductances for all measurements were inverted to obtain surface resistance (r_s), and a linear regression against soil matric potential at 50 cm depth (ψ_{50}) was calculated ($r_s = -0.6019 \, \psi_{50} + 106.9$, r^2 = 0.86). This relationship was applied to

calculate daily soil surface resistance for each day, estimating ψ_{50} from moisture content and the fitted moisture characteristic curve for each site. Daily Es could then be estimated by applying the combination equation to on-site meteorological data with these surface resistance values and boundary layer conductance again assumed as 0.2 m sec^{-1}. It must be noted that the ET estimates do not include understorey transpiration. It is assumed that this quantity is a small fraction (< 5%) of the bulk ET, and in the analysis described here it was included in the drainage component. The radiation, wind, temperature and humidity parameters for estimating PET were obtained from an on-site weather station.

Soil-moisture sensors (MP-406 dielectric moisture probes from AgriTech Instruments, Beijing) were placed at four depths (50, 150, 250 and 350 cm) in the soil profile to obtain ΔS. The run-off term in equation (1) was included in the residual drainage term. At Jijia, this component is believed to be negligible, as there is no anecdotal or physical evidence of surface run-off or extensive ponding within the plantation, outside of extreme rainfall events, and there were no observations of this process by the permanently resident site-watcher over the duration of the study. At Hetou, surface run-off and evaporation of ponded surface water following rainfall may have been more significant, and the calculated drainage overestimates deep soil infiltration to this extent. It should be noted that rainfall associated with typhoons can generate high intensity surface run-off in non-forested areas of the Leizhou Peninsula and surrounding regions. The low gradients and high soil infiltration rates of the plantation sites mitigate against both the ready generation of overland flow, and production of shallow lateral subsurface flow. Calculation of drainage as the residual term in equation (1) is not ideal, as any errors in the other terms are collected there. However, there are good measurements of the other components of the water balance, particularly in year 1, and the lengthy periods of high soil moisture ensure short periods of missing or poor quality data do not impact heavily on the results. The term 'drainage' is preferred here to 'recharge', as the data indicate that there was some abstraction of drained water in dry periods. Soil particle size distribution was measured from samples taken every 30 cm to a depth of 4 m at two locations within each site, and cores for bulk density determination to 0.8 m were taken from four locations. Points on the moisture

characteristic curve were obtained using the filter paper method (Greacen et al. 1989).

Results

Soil properties

Table 1 gives the average soil particle size distributions, and shows clearly the contrast in texture between the sites. Soils at Jijia are clays grading to silty clay and silty clay loam, whereas the Hetou soils are sandy loams grading to sandy clay loams. This contrast is reflected in the moisture content–matric suction relationship (Figure 1). Although there is scatter, the data demonstrate the very different water holding and storage capacity of the soils. Saturation is at the volumetric moisture content of 0.38 cm^3 cm^{-3} at Hetou and 0.58 cm^3 cm^{-3} at Jijia. Mean bulk densities ranged from 1.7 to 1.5 g cm^{-3} at Hetou and 1.2 –1.0 g cm^{-3} at Jijia.

Table 1. Soil particle size distribution at the Jijia and Hetou water balance study sites.

Site	Soil depth (m)	Sand (%)	Silt (%)	Clay (%)
Jijia	0–2	11	25	63
	2–4	22	42	36
Hetou	0–2	74	4	22
	2–4	66	7	27
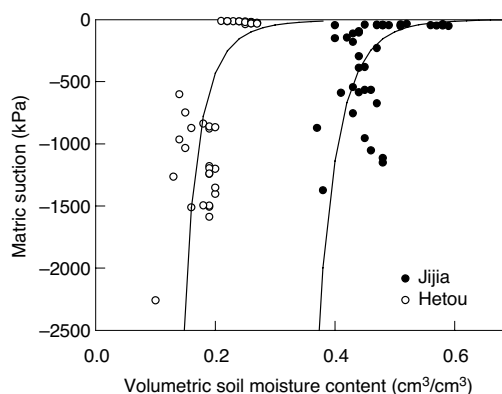
Figure 1. Volumetric soil moisture content at different matric suction for soil depths 0.5–4 m for Jijia and Hetou.

Water balance

Monthly and annual water balance values are given in Table 2 and depicted in Figure 2 for the two years October 1999–September 2000 (year 1) and October 2000–September 2001 (year 2), and expressed as percentages of annual and seasonal rainfall in Table 2.

Evapotranspiration

Total ET was very similar at both sites in both years despite a 20–30% difference in rainfall. Total ET comprised 70% of rainfall in year 1 at Jijia, and 54% in year 2. At Hetou, the values were 66% and 50%. Dry season values exceeded rainfall at Jijia and Hetou in both years (Table 2), while wet season ET was 52% and 43% of rainfall at Jijia, and 52% and 41% at Hetou. The components of ET are shown in Figure 3. Transpiration is the largest constituent of ET for most months, but is very close to, or slightly exceeded by, the sum of I and Es during wet seasons at Jijia. At Hetou, T is exceeded by this I + Es during the year 1 wet season, and by I alone in the year 2 wet season. T rarely rose above 2 mm d^{-1}, with a mean

Table 2. Water balance expressed as a percentage of rainfall on an annual and wet/dry season basis at Jijia and Hetou.

Period	P (mm)	I (%)	Es (%)	T (%)	ΔS (%)	D (%)
Jijia						
Oct 99–Sept 00	1525	16	19	36	3	26
Oct 99–March 00	243	16	30	100	–70	24
April 00–Sept 00	1282	16	18	21	17	27
Oct 00–Sept 01	1918	16	11	27	–7	52
Oct 00–March 01	346	16	22	66	–77	73
April 01–Sept 01	1571	16	8	19	9	48
Hetou						
Oct 99–Sept 00	1555	20	11	35	–1	35
Oct 99–March 00	221	20	30	103	–29	–24
April 00–Sept 00	1335	20	8	24	4	44
Oct 00–Sept 01	2226	20	8	22	1	49
Oct 00–March 01	373	20	16	57	–6	12
April 01–Sept 01	1853	20	6	15	3	56

Note: P is rainfall. Total evapotranspiration is composed of canopy interception (I), soil evaporation (Es) and transpiration (T). DS is the change in soil water storage. D is deep drainage.
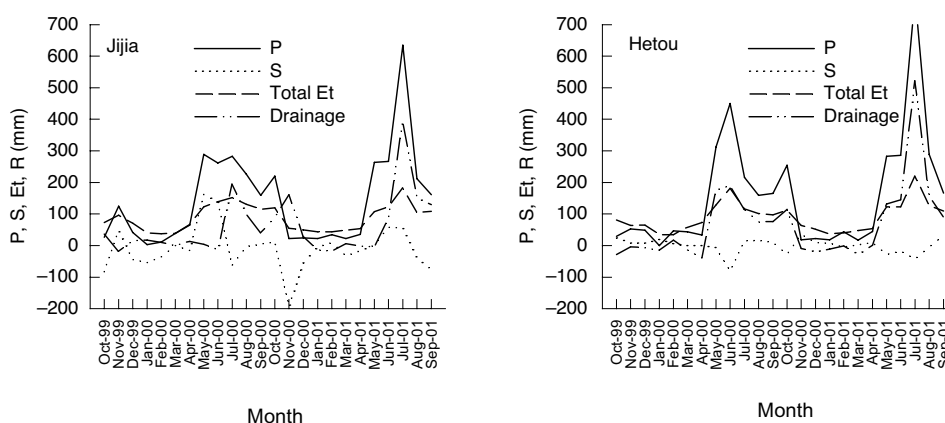
Figure 2. Monthly water balance for Jijia and Hetou.

daily value of 1.49 mm at Jijia and 1.53 mm at Hetou for the period of direct measurements (year 1) (Morris et al. in press). The high monthly values from Jijia in May and July 2001 may reflect errors in the estimation. A comparison of Figures 2 and 3 shows the high values of T relative to rainfall and ΔS during the dry seasons, indicating trees were accessing water from depths lower than 3.5 m.

The interception value is constant for both catchments, 16.2% of rainfall at Jijia and 19.9% at Hetou. TF and SF were 82.5% and 1.3%, and 77.6% and 2.5% at Jijia and Hetou, respectively. The relationship between daily rainfall and TF was strongly linear (r^2 = 0.94 and 0.84 for Jijia and Hetou), and a linear relationship was also satisfactory for SF (r^2 = 0.91 and 0.75). Soil evaporation was clearly an important component of total ET, particularly at Jijia, where it reached 49 mm per month in July 2000, and was 19% and 11% of annual rainfall, and 26% and 16% of ET in 1999–2000, for Jijia and Hetou, respectively. Thirty percent of the year 1 wet season ET was from Es at Jijia. The maximum daily rate was 2.77 mm at Jijia and 1.37 mm at Hetou. Es explains the difference in year 1 ET between the sites. Mean soil conductance was five times higher at Jijia (0.0084 to 0.0016 m s^{-1}). The greater ET at Hetou in year 2 is a function of the higher interception.

Soil water storage

Figure 4 shows the total soil moisture storage to 4 m at both sites for the duration of the study. There is a very large difference between the sites, both in terms of depth of water stored and the amplitude of responses to rainfall. The water-holding capacities of the soils are substantially different, as evidenced by Figure 1. The seasonal changes can be best seen at Jijia, where deficits of up to 200 mm are recorded during the dry seasons. Daily losses at Jijia during the wetter months can be 10–20 mm, with generally < 3 mm evaporated or transpired. At Hetou, the small changes in daily storage suggest either rapid drainage of infiltrated water or significant losses by surface run-off and evaporation of ponded water.

Drainage

Drainage at Jijia was estimated to be 26% of rainfall for year 1, and 53% in year 2, with 35% and 49% at Hetou. There are several months in the wet seasons in which drainage becomes the major loss term in the water balance at both sites (Figure 2). Importantly, there is a significant proportional increase in drainage at both sites with higher rainfall in year 2. The majority of drainage occurred in the wet seasons when there was far more rainfall than could be stored or evaporated. The opposite was estimated in dry months, when negative drainage values denote water accessed by trees from storages beneath the deepest soil-moisture sensors. These values were 32 and 39 mm from Jijia in years 1 and 2, respectively, and 92 and 71 mm at Hetou. The relatively high drainage estimated at Jijia for the year 2 dry season is a product of high rainfall in late October 2001, filling soil water storages which then drained over the subsequent month.
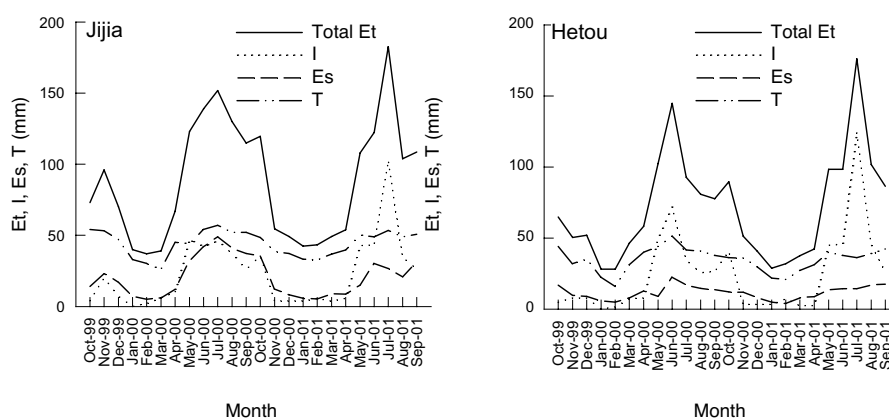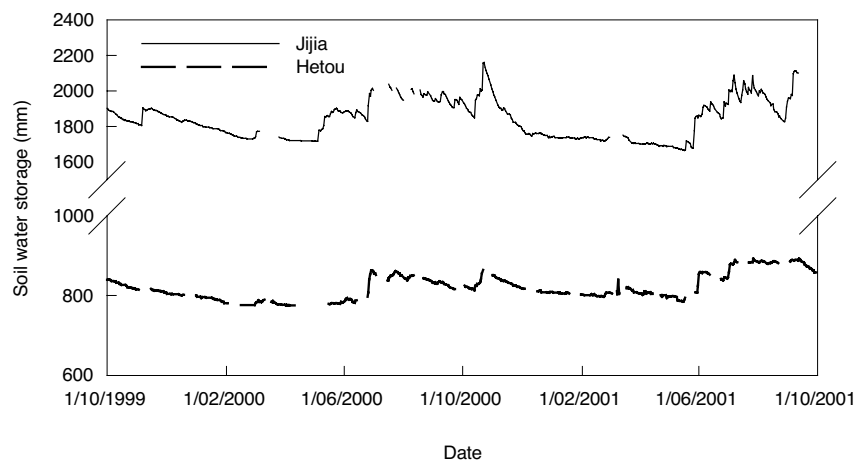

Figure 3. Monthly values of evapotranspiration (Et) components, Es, T, and I for Jijia and Hetou.

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Figure 4. Soil water storage to 4 m for Jijia and Hetou.

Discussion

There are several notable findings in this study. In terms of generalising results for the Leizhou environment, the most salient point is that transpiration appears to be capped at around 2 mm d^{-1}. Morris et al (in press) fully explore the reasons for the T limit, but they can be summarised as a combination of low leaf area, low vapour pressure deficits, and dry season water deficiency. It is unlikely Es would increase significantly above the observed and estimated daily wet season rates other than during short periods while the upper profile remained saturated after rain. The corollary to the limited transpiration rates is that, as rainfall increases, the only component of ET that will increase markedly in an absolute sense is interception. As this has been shown to be a constant proportion of rainfall over a range of daily rainfall up to 86 mm day^{-1}, it follows that a water balance can be estimated for an annual rainfall of 1500 mm or greater, with ET of around 1100 mm at Jijia and 1000 mm at Hetou. Excess water will become surface and sub-surface drainage. This presumes a reasonably similar distribution of rainfall and other climatic factors.

The rates of non-transpired ΔS at Jijia during the wet seasons demonstrate that large volumes of water can drain through these well-structured soils of high aggregate stability even with the relatively high clay content. At the observed maximum rate of 15–20 mm d^{-1}, monthly deep drainage could reach 450–600 mm if the supply existed. The negative drainage estimates suggest prolonged dry seasons would see mining of deeper soil or ground-water stores. The extent to which this would be a problem for storages would clearly depend on the wet season drainage. On the experimental evidence, abstraction of water from deep in the profile does not appear to be on the scale of that observed by Calder et al. (1993), and may indicate that an unsaturated soil moisture store is being accessed rather than an aquifer.

Soil properties appear to control the differences in some water-balance components between the two sites. The greater water-holding capacity at Jijia provides a store for soil evaporation which was almost three times higher than at Hetou, and accounted for the higher total ET rates. There was a 300 mm difference in maximum change in storage between the sites from dry season deficits. The lesser available water at Hetou contributed to a higher number of negative drainage months in the dry seasons.

Caveats must be applied to two aspects of the water-balance estimation, both concerned with error propagation. Firstly, the transpiration estimates for year 2 were not measured, and the regression for P and PET versus T exhibited considerable scatter for the Jijia data. However, the data presented by Morris et al. (in press) strongly suggest that the transpiration rates would be unlikely to increase in year 2. Secondly, the residual term, drainage, cannot be viewed as 'measured'. Errors in the other terms may collect as drainage. However, we believe the water balance does reflect the biophysical processes at the study sites, and estimation errors would not fundamentally change our results.

What are the implications of these results for assessing the impact of eucalypt plantations on water resources? It is difficult to answer this question without an accurate knowledge of the comparative water use of other vegetation or land uses in the area. There are no comparable studies in the Leizhou area. The ET rates are at the lower end of the spectrum tabulated by Bruijnzeel (1990) for tropical lowland forests, and can also be compared with the relationship between mean annual rainfall and ET for forests estimated by Zhang et al. (2001) from 250 catchments worldwide. These data indicate that ET at Hetou is significantly lower than that expected for the recorded rainfalls, and for year 1 Jijia conforms to the Zhang et al. (2001) model, but is on the lower bounds of the model for year 2. The implication is that the eucalypts do not use more water than other forest species, and that, at Hetou, with increasing rainfall, ET rates are lower than may be expected. Estimates of sugarcane water use have been made in several countries, all with differing environmental conditions and experimental or analytical methods. Published ET rates for non-water limited conditions are equal to or greater than those found in this study (Thompson 1976; Inman-Bamber and de Jager 1988; Wallace et al. 1991; Yang et al. 1997; Jalota and Arora 2002), but may not be from environments with comparable atmospheric demand. Certainly leaf areas quoted are higher than the Leizhou eucalypt plantations, but rooting depths are likely to be far shallower. The far shorter and variable crop rotations within a mixed agricultural system would also heavily influence water balances. Experimental data for a range of crops has shown Es/ET for the same LAI to be around twice that estimated here for Jijia (Villalobos and Fereres 1990; Wallace et al. 1991; Leuning et al. 1994) which could compensate for reduced extraction of water at depths. The interplay of these factors makes predictions of crop water balances difficult. The experimental evidence indicates that eucalypt water use in Leizhou is limited by environmental factors, but they can contribute to dry season soil moisture deficits. Irrigation is frequently required for establishing crops in the area at the end of the dry season. The evaporative demand far outweighs the dry season rainfalls recorded during this project, suggesting a net deficit would occur under most vegetation. Relatively small abstraction from deep storages could be viewed as self-irrigation.

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Solid-Wood Properties of Plantation-Grown *Eucalyptus globulus*: Their Variation, Effect and Evaluation

Jun-Li Yang,[1] D. Fife,[2] G. Waugh,[3] J. Ilic,[1] R. Evans,[1] G.Downes[4] and P. Blackwell[3]

Abstract

This paper reports the main findings of a comprehensive study of solid-wood properties of plantation-grown *Eucalyptus globulus*. Fifty-nine 10-year-old trees were sampled from three provenances grown at two separate sites in South Australia. The butt logs were back-sawn to produce $40 \times 100 \times 3600$ mm boards. One full-diameter billet was removed from each tree and small clear specimens prepared. Several. key solid-wood properties were measured including growth strain, shrinkages, collapse, density, microfibril angle (MFA) and cellulose crystallite width (W_{cryst}). Between-site and between-provenance differences in these properties were investigated and their interrelationships examined. Knots and pith were primary grade-limiting defects, mainly because the trees were grown as pulp logs and harvested at 10 years of age. There were significant differences in mean growth strain between sites and provenances and among individual trees. King Island provenance had the lowest growth strain (710×10^{-6}) and the least between-site and among-tree variation. Average growth strain and tree diameter at breast height in combination accounted for 42% of the variation in the percentage of excessively distorted boards. Highly significant between-site differences in density, radial and tangential collapse, and total tangential shrinkage were observed. However, between-provenance differences in these four properties were insignificant. Total tangential shrinkage was found to be the best single predictor for tangential collapse ($R^2 = 0.896$) and for total cross-sectional shrinkage ($R^2 = 0.924$) in wood blocks. These strong relationships hold for individual measurements as well as for tree means, and are not affected by positions along the radius. MFA and W_{cryst} were significantly correlated with several shrinkage properties. Density, MFA and W_{cryst} accounted for only small to modest amount of variation in shrinkage and collapse in either radial or tangential direction. Tangential collapse in wood blocks showed a high potential for identifying trees that developed internal checks during drying.

As with many other regions of Australia, there has been a considerable expansion in recent years of plantations of Tasmanian blue gum (*Eucalyptus globulus* Labill.) in the Green Triangle Region of South Australia and southwestern Victoria with the area increasing from about 4000 ha in 1995 to approximately 100,000 ha in 2001 (Fife et al. 2001). Currently, the sole market for timber from these stands is as woodchips, either to the local market or to Southeast Asian markets. Development of alternative higher value uses for this timber could be of economic benefit both to individual farmers and to the rural community as a whole by increasing income and providing additional employment in this region.

[1] CSIRO Forestry and Forest Products, Private Bag 10, Clayton South, Victoria 3169, Australia.
[2] CSIRO Forestry and Forest Products, Airport Rd, Mt Gambier, South Australia 5290, Australia.
[3] Institute of Land and Food Resources, The University of Melbourne, Creswick, Victoria 3363, Australia.
[4] CSIRO Forestry and Forest Products, GPO Box 252-12, Hobart, Tasmania 7001, Australia.

It would also help ease future pressure on domestic hardwood sawlog supply, as increasing areas of Australia's native hardwood forests become unavailable for commercial logging. At present, there is little knowledge of sawlog potential from existing plantations in these regions, genetic variation in wood quality, site impact and suitable management regimes of plantations for sawlog production over short–medium rotation length.

Sawlog potential is determined by volume and grade yield. Volume yield of sawlogs is normally affected by log size and log external quality (stem shape and external defects), whereas grade yield is affected by log internal quality (presence of defects and quality of clear wood). Sawing trials are arguably most reliable in evaluating sawlog potential but are costly. It would be ideal if sawlog potential could be predicted from log external characteristics and key wood properties that can be fast and non-destructively measured on small specimens such as increment cores.

High growth stresses and internal checking associated with cell collapse are the two features that distinguish eucalypt species from many other hardwoods and may present severe problems to the recovery of higher-value sawn timber. The release of growth stresses upon tree felling and log conversion may cause log end spitting, sawn board distortion and thickness inaccuracy, and reduced productivity (Jacobs 1938; Kubler 1987; Malan 1995, 1997; Muneri et al. 1999; Waugh 2000; Yang and Waugh 2001). Internal checking is common in many pale-coloured eucalypt species (Tiemann 1941; Kauman 1964; Chafe 1985; Ilic and Hillis 1986; Wilkes 1988; Thomson 1989; Bekele 1995; Innes 1995; Yang and Waugh 1996a,b), and its severity generally increases with collapse (Innes 1995; Ilic 1999). Internal checking and surface checking severely affect the recovery of high-value sawn timber products and are the most serious forms of drying degrade for the Australian hardwood timber industry. Internal checking is often associated with cell collapse during drying and is common in many eucalypt species. While there have been numerous studies on growth stress and shrinkage characteristics of many eucalypts as in the studies cited above, systematic information on those properties of *E. globulus*, including collapse and the effect of site and provenance, hardly exists.

A comprehensive study on 10-year-old plantation-grown *E. globulus* was completed recently at CSIRO Forestry and Forest Products. The objectives were:

- to determine major wood properties including growth strain, shrinkage properties, microfibril angle (MFA) and cellulose crystallite width (W_{cryst})
- to investigate the between-site and between-provenance variation in these properties, their interrelationships and impact on sawn timber quality, and search for potential non-destructive methods to predict sawlog quality.

Some key results have or will soon be published (Yang and Fife 2000, 2003; Yang et al. 2001, 2002a,b, 2003). This paper provides an overview of the project and selected key results. In the paper, growth strain or growth stress refers solely to the longitudinal growth strain or longitudinal growth stress except where specified, and 'shrinkage property' is used as a general term that can refer to any shrinkage property in radial or tangential directions.

Material and Methods

Fifty-nine trees were sampled from three provenances (Jeeralang, King Island, and southeastern Tasmania) of 10-year-old *E. globulus* plantations grown at two sites (Heath Block and Johnstons Block) in the Mount Gambier region of South Australia. These two sites were established in 1988 before the rapid expansion of blue gum plantations in the Green Triangle from the late 1990s onward. When clear-felled, the two sites yielded woodchips at rates corresponding to a mean annual increment (MAI) of 25–30 m^3 ha^{-1}, with Johnstons being less productive than the Heath site. Thus, the sites were of medium-to-high productivity in current industry terms. Detailed description of the two sites and the study trees can be found in Yang et al. (2001). As there was no replicate at each site, we considered it more appropriate to use Heath Block and Johnstons Block to refer to these two sites in later text.

Growth strain was measured (Nicholson 1971; Yang et al. 2001) at breast height in the standing trees at three circumferential positions. After the trees were felled, one 6.2 m bushlog was removed, commencing about 1.2 m from the butt of each tree stem. The bushlogs were debarked and the end-splits on both ends recorded. Growth strain was measured on the bushlog surface at three heights, equivalent to 2.5 m, 4.3 m and 6.1 m above the ground on the tree before harvest. At each height, growth strain was measured at the same three directional positions as those measured on the tree before harvest. One 1.2 m

billet was removed from the large end of each bushlog, followed by the 3.6 m sawlog.

The logs were back-sawn. The sawyer aimed at the maximum grade recovery using a sawing strategy implemented at the sawmill, and to cut as many 40×100 mm boards as possible along the pre-specified diametrical directions. All the boards were graded using the CSIRO in-house grading rules for appearance-grade sawn products (Waugh and Yang 1993). Only the boards that were back-sawn along the pre-specified diametrical directions were used in further experiments. They were air-dried under weight, reconditioned and, followed by final kiln drying, dressed to 35×90 mm in cross-section and re-graded using the same CSIRO in-house grading rules. Bow and spring were measured before and after drying. The boards with bow or spring that exceeded the limits specified in AS2796.1 (1999) when in green condition were identified as excessively distorted, the percentage for each log calculated and used as a measure of the impact of growth stresses. One 10 mm thick cross-section was removed at 400 mm away from the small-log-end of the seasoned sawn boards and inspected for internal checking. Yang et al. (2002b) provide additional details.

From each 1.2 m billet, two end-matched pith-to-bark strips were removed (20×90 mm, tangential $\times$ longitudinal). As many $20 \times 20 \times 90$ mm specimens as possible were cut from one strip. One set went through various experimental procedures to enable measurements of moisture content, density at 12% moisture content (m.c.), and shrinkage properties (normal shrinkage, collapse and total shrinkage, in radial and tangential directions; total cross-sectional shrinkage). Details of the measurements and calculation of the shrinkage properties are given in Yang et al. (2002a).

One pith-to-cambium SilviScan® specimen, in final dimensions of 2×6 mm (tangential $\times$ longitudinal) at 12% m.c., was prepared along the full length of the other strip. Each specimen was scanned using SilviScan®, and microfibril angle (MFA) and cellulose crystallite width (W_{cryst}) determined simultaneously in one run. Evans (1999) and Evans et al. (1999) provide details on the acquisition of MFA using SilviScan®. The first four MFA data points corresponding to the 20 mm radial segment of the specimen were arithmetically averaged to represent the MFA of the $20 \times 20 \times 90$ mm shrinkage specimen located next to the pith. The average of the next four MFA data points represented the MFA of the

shrinkage specimen second from the pith, and so forth. This same averaging process was also carried out for W_{cryst} (Yang et al. 2003).

Analysis of variance on growth strain and shrinkage properties was carried out to test the significance of differences between sites, provenances and the interaction. Relationships between wood properties were examined using simple correlation, multiple regression, or PATH analysis. Relationships of growth strain to tree characteristics and the effect of growth strain on grade yield of sawn boards were examined. The association between wood properties and the incidence of internal checks was investigated on a tree basis.

Abbreviations are used in this paper to designate six groups of trees: HJ, HK and HT refer to, respectively, Jeeralang, King Island and southeastern Tasmania (SE Tasmania) provenances at Heath Block; JJ, JK and JT refer to, respectively, Jeeralang, King Island and SE Tasmania provenances at Johnstons Block.

Results and Discussion

Site and tree characteristics

Growth, measured as diameter at breast height over bark (dbhob), differed considerably between the three provenances in the study areas (Table 1), and the ranking of growth between provenances was different at each site. Productivity per hectare was influenced by markedly different survival rates from the initial planting of 1040 seedlings ha^{-1}, and the most vigorous provenance at each site had a MAI approaching the maximum of 45.6 m^3 ha^{-1} reported by Hingston et al. (1998) for the area with higher rainfall.

None of the trees in the two sites had a 'perfect' shape. All trees had various amounts of localised sweep and elliptical stems. At only 10 years of age, the trees had not over-grown stem 'imperfections'. Butt sweep was commonplace in almost all the trees at Heath Block, as a result of the site having little protection from wind. Butt sweep was less obvious in the trees at Johnstons Block. Wandering pith of varying severity was frequently observed in a number of the sawlogs.

Frequency and diameter of branches varied considerably and did not appear to be solely related to the proximity of the trees to the edge of the plantations. A number of trees appeared to have 'spiral bark', but

such characteristic was found to be an unreliable indicator of spiral grain in the wood immediately adjacent. A similar finding was made earlier on Tasmania-grown *E. globulus* plantations (Yang and Waugh 1996a).

Growth strain — variation, relationship and effect

The average growth strain was in the range of 694 to 1313×10^{-6} between tree groups (Figure 1). There were significant between-site differences and highly significant between-provenance differences. There was no significant difference between Jeeralang and SE Tasmania provenances, but both provenances had significantly higher growth strain than the King Island provenance (Figure 1) (post hoc comparison of means, Scheffé test). The Jeeralang provenance may have had higher growth strain, followed by SE Tasmania, then King Island provenances, if the stocking had been similar at both sites. Data in Table 1 and Figure 1 suggest wider spacing seemed to be associated with higher growth strain.

Growth strain varied between trees. At each Block, the King Island provenance had the least between-tree variation. The SE Tasmania provenance at Johnstons Block had the highest between-tree variation. Smaller between-tree variation tends to suggest more uniform behaviour of logs during processing. The amount of between-tree variation of all six tree groups lies in a range approximately similar to that observed in young plantation-grown *E. nitens* (Chafe 1985) and regrowth *E. regnans* and *E. obliqua* (Nicholson 1973). The highly significant differences between individual trees indicate that genetic differences within provenances, or environmental differences related to planting position, are important in determining growth strain. In this ANOVA analysis, the error term was caused by circumferential locations of growth strain measurements around the stems.
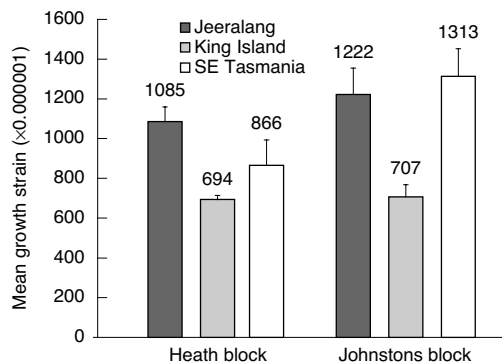
Figure 1. Mean growth strain of six *Eucalyptus globulus* tree groups averaged from measurements at four heights and three circumferential locations at each height.

There were no significant differences in mean growth strain between heights. Quantitatively however, mean growth strain of each tree group reduced with height. Growth strains at breast height were significantly correlated with those at other heights ($r \approx 0.45$), and with the mean growth strain of over four heights ($r \approx 0.70$). If mean growth strain does decrease with height, it would have significant

Table 1. Growth characteristics of *Eucalyptus globulus* trees within the measurement plot of each provenance at each site.

Tree properties	Heath Block			Johnstons Block		
	Jeeralang	King Island	Southeastern Tasmania	Jeeralang	King Island	Southeastern Tasmania
Stocking (stems ha^{-1})	833	1042	917	958	875	458
Mean dbhob[a] (mm)	175	217	182	232	216	257
Standard deviation of Dbhob (mm)	86	50	81	52	70	67
Basal area (m^2 ha^{-1})	24.6	40.6	28.3	42.3	35.2	25.2
Mean annual increment (m^3 ha^{-1})	21	41	23	37	27	21

[a] Diameter at breast height over bark

implications for growth strain sampling. Firstly, the measurement of strain at several heights in the forest is impractical. Secondly, if ground-level strain is used as a predictor of sawn board distortion, the amount of distortion is unlikely to be underestimated. Future work is needed to investigate the full-stem growth strain distribution with height in trees of various ages.

Dbhob and the ratio of tree height to dbhob were more consistently, although not significantly ($r \approx -0.40$ and $r \approx 0.40$, respectively), correlated with mean growth strain at breast height than other tree characteristics such as tree height, height of low crown, vertical length of crown and stem taper.

The study trees had not been grown for sawlogs and were only 10 years old when harvested. Knots and pith in this circumstance became the two top defects that downgraded most sawn boards. A combination of genetic selection and silvicultural management can effectively control the type, size, and frequency of knots, and reduce the knotty core. Harvesting at larger diameters also reduces the relative contribution of the knotty core and pith. However, the economic feasibility of the above measures to improve grade recovery is a separate matter and must be examined carefully.

Severe bow (up to 71 mm) and spring (up to 58 mm) were observed. The percentage of excessively distorted boards varied between tree groups (Table 2), which was relatively consistent with growth strain variation between tree groups (Figure 1). Distortion alone can cause a rejection of sawn boards as feedstock at up to 40% (Table 2). A PATH analysis showed that mean growth strain in logs and log diameter together explained 42% of the variation in the percentage of excessively distorted boards. This supports previous studies showing sawn timber distortion increases with increasing growth stresses and decreasing log diameter (Jacobs 1938; Boyd 1950; Kubler 1959; Malan 1997; Waugh 2000). PATH analysis is a special use of multiple regression to help analyse the direct and indirect causal effects of independent variables and find the best regression model by elimination of variables that contribute little to the equation.

The PATH analysis also showed that density had no direct effect on the distortion grading result, but had indirect effect through its significant correlation with growth strain. If density and growth strain are genetically correlated, selection for growth strain can be achieved through selection for density. Positive correlation between these two properties suggests that breeding for lower-growth-stress trees could result in lower density wood and probably also affect other desirable wood properties. Caution, therefore, may be advised.

Table 2. Percentage of excessively distorted boards from *Eucalyptus globulus* graded for distortion only in green condition as feedstock of 40 × 100 × 3600 mm against AS2796.1.

Statistics	Tree groups					
	Heath Block			Johnstons Block		
	HJ[a]	HK	HT	JJ	JK	JT
Average	34.5	24.1	25.8	40.2	25.0	31.6
Standard deviation	19.5	9.7	22.0	15.1	19.3	29.7

[a] J = Jeeralang provenance; K = King Island provenance; T = southeastern Tasmania provenance.

Shrinkage properties — variation, relationships and prediction

When averaged over the combined data, the mean radial and tangential shrinkage were, respectively, 2.48% and 5.73%, and the mean radial and tangential recoverable collapse were, respectively, 0.96% and 4.69%. The standard variation was under 5% for the radial properties but approximately 10% for the tangential properties. They were well below the equivalent mean values for 17 to 23-year-old *E. globulus* trees grown in Tasmania (Kingston and Risdon 1961). The within-tree radial location of the samples presented in Kingston and Risdon (1961) is unknown.

Site had a highly significant effect on most shrinkage properties, including radial and tangential collapse (Table 3). The approximate between-site difference was 130% for radial collapse, 100% for tangential collapse (Figure 2), and 44% for total tangential shrinkage.

There were no significant between-provenance differences in any shrinkage property.

Despite non-significant differences between provenances, Jeeralang provenance consistently had the highest mean value for every shrinkage property in both radial and tangential directions (except for radial shrinkage), followed by King Island then SE Tasmania provenances (Table 3).

Table 3. Summary of ANOVA results and mean values of *Eucalyptus globulus* wood properties for each block and provenance.

Properties	Significance of differences			Mean values for each site			Mean values for each provenance	
	Between sites	Between provenances	Interaction	Heath Block	Johnstons Block	Jeeralang	King Island	Southeastern Tasmania
Number of trees				29	30	20	19	20
Radial shrinkage (green to 12% m.c.) (%)	n.s.	n.s.	n.s.	2.56	2.40	2.48	2.44	2.51
Tangential shrinkage (green to 12% m.c.) (%)	*	n.s.	n.s.	5.42	6.03	5.95	5.76	5.49
Radial collapse (green to 12% m.c.) (%)	***	n.s.	***	0.57	1.35	1.43	0.80	0.65
Tangential collapse (green to 12% m.c.) (%)	***	n.s.	*	3.10	6.22	5.49	4.70	3.86
Total radial shrinkage (green to 12% m.c.) (%)	*	n.s.	*	3.13	3.75	3.91	3.25	3.17
Total tangential shrinkage (green to 12% m.c.) (%)	***	n.s.	*	8.52	12.25	11.44	10.47	9.35
Cross-sectional shrinkage after reconditioning (green to 12% m.c.) (%)	n.s.	n.s.	n.s.	7.59	8.89	8.95	8.23	7.58
Moisture content (%)	n.s.	*	n.s.	118	112	104	122	118
Weighted density at 12% m.c. (kg m^{-3})	**	n.s.	n.s.	600	649	681	578	613

Note: n.s. for $p > 0.05$; * for $p < 0.05$; ** for $p < 0.01$; *** for $p < 0.001$.

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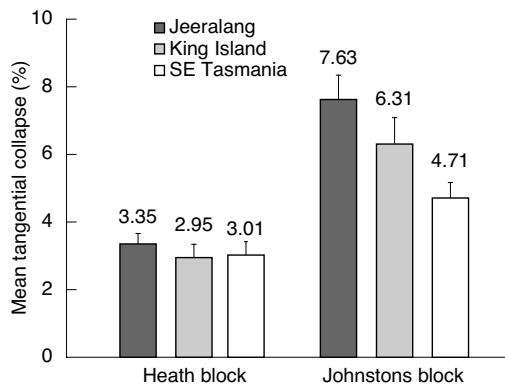
Figure 2. Mean values of tangential collapse (green to 12% m.c.) for each provenance of *Eucalyptus globulus* at each block.

The two sites differed in their stocking (Table 1) and rainfall (680 mm for Heath site and 860 mm for Johnstons site). We are not certain of the magnitude of actual differences in soil nutrients and water-holding capacity between the two sites and their impact on tree growth and wood properties. Site difference resulted in differences between Heath and Johnstons Blocks in many shrinkage properties. The small between-provenance differences at Heath Block and relatively large differences at Johnstons Block (Figure 2) cannot be readily explained by stocking and dbhob (Table 1). Although Johnstons site is suspected to be less uniform, again we do not have enough information to identify the reasons. The effect of growth conditions (site quality and silviculture) on shrinkage properties of *E. globulus* requires detailed examination in future studies.
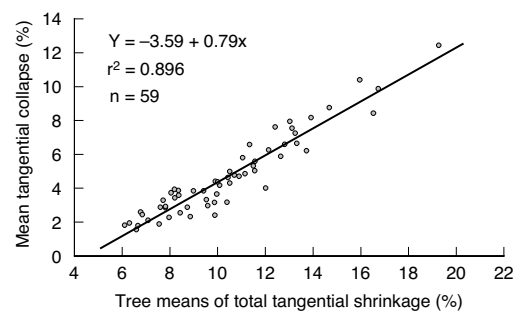
Most correlations among shrinkage properties, between shrinkage properties and MFA and W_{cryst} were highly significant (p<0.001). However, many of the correlation coefficients were well below 0.7. Strong correlations were found only among tangential collapse, total tangential shrinkage and total cross-sectional shrinkage. Their correlation coefficients were greater than 0.9.

Closeness of the relationship between tangential collapse and total tangential shrinkage was independent of data composition. The r^2 was 0.896 whether the data were measurements on individual specimens (Figure 3) or tree means (Figure 4), or whether the specimens were inner-wood only (the first three shrinkage specimens from the pith) or outer-wood only, or whether tension wood was

present or not (wide bands of several millimetres of severe tension wood may be an exception). This is in line with the results on *E. regnans* by Chafe (1985) and Ilic (1999) who observed collapse was highly correlated ($r > 0.90$) with volumetric shrinkage and total cross-sectional shrinkage, respectively. Total tangential shrinkage therefore is the single property that can most reliably predict tangential collapse. The practical significance of this result is that total tangential shrinkage is much quicker and easier to determine than tangential collapse. The tangential collapse profile along the tree radius is an important wood quality indicator because it reveals the susceptibility of internal checking that is associated with collapse across tree stems. It should be easy to predict through a series of measurements of total tangential shrinkage on trimmed increment cores.
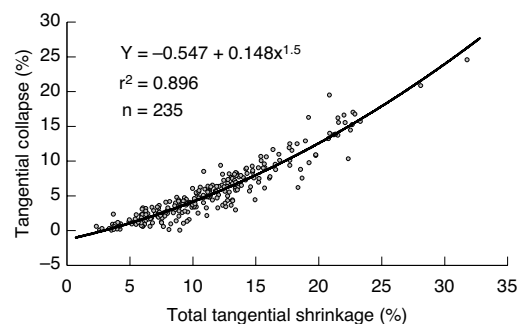
Figure 3. Relationship between total tangential shrinkage and tangential collapse of individual shrinkage specimens of 10-year-old *Eucalyptus globulus* ($p < 0.001$).

Figure 4. Relationship between tree means of total tangential shrinkage and tangential collapse in *Eucalyptus globulus* ($p < 0.001$).

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MFA and W_{cryst} were significantly correlated with several shrinkage properties, but overall these relationships were moderate to weak. They were less able, either singly or jointly, to predict shrinkage properties, in particular tangential collapse and total cross-sectional shrinkage. It appeared that reliable assessment of collapse and shrinkage properties requires direct measurement, based on findings in this study. On the other hand, since the radial variability of wood properties in these specimens was high, the size of the specimens might have affected the strengths of the relationships when average values of MFA and W_{cryst} were used in the data analysis. However, such effects could not be estimated from the data in this study. Further studies of different experimental plans are needed to discover factors that likely affect the possibility of using density, MFA and W_{cryst} to predict shrinkage properties. In the meantime, direct measurement of tangential shrinkage offers rapid and accurate assessment of important shrinkage properties of trees and boards for both wood processing and tree selection.

Twelve of the 176 study boards showed internal checks, mostly as hairline cracks, following examination using an in-house procedure (R. Northway, pers. comm.). These check-present boards were from nine trees grown at the Johnstons Block, about one board per tree. All three provenances were affected. Interestingly, not all the boards from these nine trees showed internal checking. Internal checking was almost entirely absent in small specimens ($20 \times 20 \times 90$ mm) that were dried from green to 12% m.c.

Predicting susceptibility to internal checking

The potential of using wood properties to identify trees with internal-check sawn boards was investigated by examining the relationship of the magnitude of a wood property with the check-present trees. This was done by ranking the tree means of all the wood properties determined in this project in ascending or descending order and inspecting where check-present trees were located in the ranking.

There was a conspicuous and definite pattern when tangential collapse was used to rank the 59 trees — the 9 check-present trees were all located within the top 50% of the rank (Figure 5). The highest-ranked check-present tree had the highest mean tangential collapse of 12.43%; the lowest-ranked check-present tree was ranked 21st and had a tangential collapse of 4.99% (Figure 5). Trees that had internal-check boards apparently had higher tangential collapse although not all trees showing higher tangential collapse had internal-check boards. Total tangential shrinkage and total cross-sectional shrinkage demonstrated a slightly less sensitive potential in this aspect (Figure 5).

The check-present trees were scattered within the entire range of the rank and showed no distinct 'regional' concentration when other wood properties such as density, moisture content, growth strains,
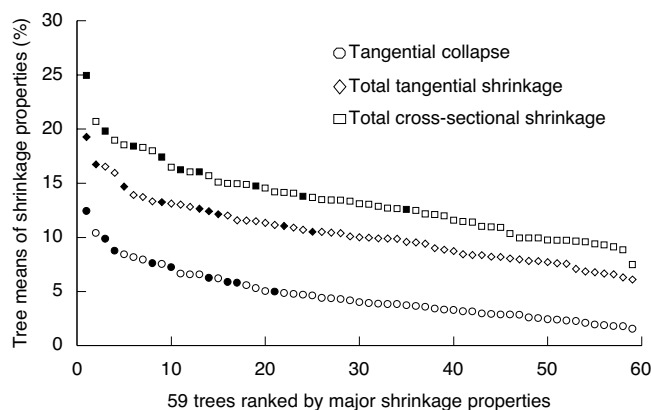
Figure 5. Ranking of 59 *Eucalyptus globulus* trees by tree means of tangential collapse, total tangential shrinkage and total cross-sectional shrinkage respectively. The solid data points represent check-present trees.

MFA, W_{cryst} and the rest of the shrinkage properties were used to rank the 59 trees.

Tangential collapse showed better potential than any of the other wood properties in terms of accuracy, in identifying trees that had internal-check boards. The second and third best indicators were total tangential shrinkage and total cross-sectional shrinkage. Density, moisture content, growth strain, MFA, W_{cryst} and other shrinkage properties showed little prospect in this regard. No similar work has been reported before.

It is considered, from the user convenience point of view, that total tangential shrinkage was a more suitable property than tangential collapse for this predictive purpose. Total tangential shrinkage was not only a good identifier by itself but also can be easily measured on trimmed increment cores at low cost (the cores can be dried under room temperature and a calliper is sufficient for measuring tangential dimensions) and is easier to measure than tangential collapse, since no re-conditioning is required.

Acknowledgments

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Growth Strain in Eight Species of Plantation-Grown Eucalypts in Southern China

Jiang Xiaomei, Yin Yafang, Lu Jianxiong and Zhao Youke[1]

Abstract

Growth strain was measured in standing trees and fallen trees of *Eucalyptus exserta*, *E. urophylla* × *E. grandis*, *E. grandis*, *E. urophylla*, *E. cloeziana*, *E. pellita*, *E. tereticornis* and *Corymbia citriodora* (*E. citriodora*) grown in southern China. There were highly significant differences in the mean growth strain averaged from circumferential measurements of standing trees among different species. *Corymbia citriodora* and *E. exserta* (37 and 27 years old, respectively), two species currently used for solid wood utilisation, had low growth strain. *Eucalyptus grandis*, now widely planted in China, also had low growth strain. *Eucalyptus cloeziana*, a new planting species, had the lowest growth strain in four new species evaluated for solid wood products uses, while *E. urophylla* had the highest growth strain of the species tested. No significant differences were found both between different circumferential measurement locations and among three clones of *E. urophylla* × *E. grandis*. There were no significant differences in growth strain of north measurements between standing trees and felled trees in different species, or between tree heights, although the data indicated mean growth strain increased with tree height in most species.

Eucalypts occur naturally in Australia, with a few species also found in Indonesia, East Timor, Papua New Guinea and the Philippines. As a fast-growing hardwood, eucalypts have been introduced into many tropical countries in the past 20 years. The total eucalypt plantation area in tropical and subtropical regions is more than 14 million ha, including 10 million ha for industrial purposes (Yin et al. 2001a). The first introduction of eucalypts into China was in 1894. The present area of eucalypt plantation has reached about 1.55 million ha, in more than 600 counties in southern China. Growing stock volume is about 60 million m^3 (Yin et al. 2001b). Current use of plantation-grown eucalypt wood is mainly for woodchips for export.

In China, there is a growing interest in manufacturing high-value-added products from eucalypt plantations, to give better economic returns, due to a fall in woodchip prices and greater demand as a result of protecting natural forests. However, there are few applications of plantation wood for high-value-added solid wood products, such as joinery products, furniture and building products (Yin et al. 2001b). High growth strain differential, due to high growth stress in eucalypts, is a determining factor in end splitting of logs during harvesting and in considerable distortion during sawing. High growth stress is therefore a major problem in processing eucalypt timber. The problem appears more serious in utilisation of young trees of small diameter. Growth stress evaluation could be beneficial to the more efficient use of eucalypt plantation wood.

Growth stress can be calculated from growth strain and modulus of elasticity (MOE), both of which can be measured. High growth stress causes end splitting

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which reduces sawing recovery rate. Australian experience suggests that sawn products distortion become acceptable only when growth strain in logs is below 8×10^{-4} (Waugh 2000). Early studies have indicated that levels of longitudinal growth stress vary not only between and within species, but also between provenances (Kubler 1987; Wahyudi et al. 1999; Hu et al. 2000; Raymond et al. 2002; Yang et al. 2002). Therefore, tree growth stress evaluated by growth strain may become an important indicator for tree breeding and selection. Information on the size and distribution of growth stress would be helpful in determining appropriate management practices to reduce growth stress.

This paper reports only growth strain results. Growth stress data will be discussed in a subsequent report when the MOE testing of small, clear samples is completed.

Materials and Methods

Site information

The experimental forest was situated in Dongmen Forestry Centre, Fusui County, Guangxi (latitude 22°17'–22°30'N, longitude 107°14'–180°00'E, altitude 100–300 m). Mean annual temperature was 21.2˚C (12.5–41˚C). Mean annual rainfall was 1100–3000 mm. The terrain was infertile red soil of pH 4.5–6.0, organic matter content 1.3–3.7%, total N 0.1%, total P 0.097% and total K 0.183%. The experimental plots of eight eucalypts were planted with 1-year-old seedlings at 3 m × 2 m spacing in random regions. The species were *Eucalyptus exserta*, *E. urophylla* × *E. grandis*, *E. grandis*, *E. urophylla*, *E. cloeziana*, *E.*

pellita, *E. tereticornis* and *Corymbia citriodora*. The former vegetation included *Rhodomyrtus tomentosa*, *Vitex negundo*, *Evodia lepta*, *Hierochloe* sp., *Dicranopteris linearis*, *Rhus chinensis*, and *Heteropogon contortus*.

Selection and measurement of sampling trees

Sixty-eight trees, 5–10 of each species, without obvious tension wood, were selected in the experimental forests (Table 1). Longitudinal growth strains were measured on the surface at four circumferential locations (East, West, South and North) at breast height (Table 1). After felling the sample trees, we measured growth strains at the north side, log diameters at 0.3 m, 1.3 m, 3.3 m, 5.3 m and 7.3 m heights above ground and clean length of each tree. For *E. grandis*, grain strain tests were conducted only on standing trees. Felled sample trees were sawn into four logs at the abovementioned heights, and one disc with a thickness of 2 cm was cut immediately from the top end of each log for measuring green moisture content. After coating the two ends of marked logs with asphaltum to preventing end splitting, these logs were transported to the Chinese Academy of Forestry for sawing, drying, assessment of wood properties and finger jointing tests.

Growth stress measurement methods

Growth strain was measured using the CIRAD-Forêt strain gauge developed by the Tropical Forestry Research Centre (CTFT). At first, four circumferential locations were labelled from east, west, south and north directions at breast height of standing trees. The bark (about 200 mm height and 100 mm

Table 1. Growth characteristics and number of sample trees.

Species	Age (years)	Number	Height (m) $\bar{x}$	Height (m) δ_n	Clean length (m) $\bar{x}$	Clean length (m) δ_n	Dbh (cm) $\bar{x}$	Dbh (cm) $\bar{x}\delta$
Corymbia citriodora (N)	37	10	30.67	1.2455	16.57	3.1816	28.68	1.9395
Eucalyptus exserta (L)	27	10	19.96	1.6548	10.76	2.1925	26.05	1.4401
E. urophylla × *E. grandis* (W)	14	10	31.08	0.8929	20.26	3.9376	24.77	2.0122
E. grandis (J)	13	10	27.49	2.5049	12.04	4.6198	24.6	5.5987
E. urophylla (Y)	13	5	28.3	1.5443	15.1	3.6654	25.4	1.2410
E. cloeziana (D)	16	5	30.9	1.8493	16.8	4.0577	25.9	1.8748
E. pellita (C)	13	9	22.03	2.4090	9.27	1.9732	19.93	2.6949
E. tereticornis (A)	15	9	26.53	0.2887	11.77	0.2887	21.34	4.8583

width) was peeled and two pins were nailed into the wood 45 mm apart. The strain gauge was then hung over the upper pin and with the sensor touching the lower pin. A hole (about 20 mm deep) was drilled by hand in the centre of the two pins. The digital gauge recorded the growth strain. The following formulas for calculating growth strain and growth stress were deduced by CTFT:

$$\alpha_L - \Phi\delta$$
$$\sigma_L - E_L\alpha_L$$

where: α_L = growth strain

Φ = species coefficient (m^{-1})
δ = measurement value (m)
E_L = module of elasticity (Pa)
σ_L = growth stress (Pa).

Other studies (Nicholson 1971; Wahyudi et al. 1999; Hu et al. 2000) have shown mean growth strain values can be used to compare the surface growth strain between logs. Longitudinal growth strain results were therefore adopted and analysed in this paper.

Results and Analysis

Comparison of growth strain from standing trees among eight eucalypt species

Mean growth strains averaged from circumferential measurements of standing trees are shown in Table 2. There were highly significant differences among different species. Overall, mean growth strain of *E. urophylla* (Y) was the highest in all eight species followed by *E. tereticornis* (A), *E. pellita* (C) and *E. urophylla × E. grandis* (W), then *E. cloeziana* (D), *E. grandis* (J) and *E. exserta* (L). The mean

growth strain of *C. citriodora* (N) was the lowest (Figure 3). It was clearly showed that the mean growth strain of *E. urophylla* (Y) was more than twice as high as that of *E. citriodora* (N) (Figure 1).
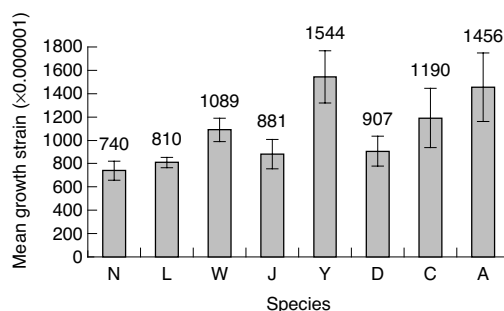
Figure 1. Mean growth strain of eight eucalyptus species averaged from measurements at four circumferential locations of standing trees. Error bars represent the standard error.

Some studies have suggested larger growth strain is associated with juvenile wood and that old trees have low growth stress (e.g. Archer 1986; Fournier et al. 1990). Our results also indicate *C. citriodora* (N) and *E. exserta* (L) have low growth strain that may be related to their age (37 and 27 years old, respectively). However, the other six species had similar ages (13–16 years old) and there were highly significant differences among their mean growth strains. *Eucalyptus grandis* (J) and *E. cloeziana* (D) had low growth strain in the same age range. The high strain level of *E. urophylla* (Y) may be related to its growth rate (Table 1). Yang et al. (2002) and Raymond et al. (2002) found significant provenance differences for

Table 2. Mean tree growth strain averaged from circumferential measurements.

Species	Growth strain ($\times 10^{-6}$)								
	Basic density (g cm^{-3})	East		West		South		North	
		$\bar{x}$	δ_n	$\bar{x}$	δ_n	$\bar{x}$	δ_n	$\bar{x}$	δ_n
Corymbia citriodora (N)	0.785	636	384.5	731	256.3	763	291.6	829	352.1
Eucalyptus exserta (L)	0.681	746	283.0	824	422.5	838	184.1	830	320.6
E. urophylla × E. grandis (W)	0.561	1050	148.8	971	249.3	1196	428.2	1139	180.3
E. grandis (J)	0.587	887	245.6	852	328.2	743	234.7	1043	344.1
E. urophylla (Y)	0.590	1610	384.4	1512	490.4	1260	432.0	1795	949.6
E. cloeziana (D)	0.717	770	201.6	878	402.4	1080	590.7	898	232.8
E. pellita (C)	0.665	1512	129.8	1232	69.3	900	391.1	1116	292.4
E. tereticornis (A)	0.651	1572	890.6	1784	120.1	1376	525.9	1092	659.1

eucalypt growth strain, but the ranking of the provenances was very different between the two studies, and Hu et al. (2000) also reported that variance of growth strain was significant among different species and in different ages within a species, although the variance trend was different. These results and our study suggest growth strain of standing trees may be genetically controlled and considered as an indicator for the selection of low growth strain species.

Hu et al. (2000) have also reported no significant differences among growth strain measurements from different circumferential locations at the same tree height. Similarly, our study also showed no significant variance among measurements from four directions in the eight species.

Comparison of growth strain between standing trees and fallen tree

Mean growth strain of fallen trees was a little lower than that of standing trees, except for *E. urophylla × E. grandis* (W) and *E. urophylla* (Y) (Table 3). Data in Table 3 also illustrate that there were no significant variances in growth strain of north measurements between standing trees and felled trees.

It is generally agreed that continuous formation of growth stress during tree growth with cambium differentiation, results in an uneven and continuous variation distribution of stress across whole tree stems. Boyd (1950) and Kubler (1959, 1987) proposed some classical models of growth strain distribution in standing trees. When a tree is cross-cut, the balance of longitudinal growth stress at the cut end may be broken immediately with partial stress release and residual stress in logs redistributed. It should affect the measurements of longitudinal growth strain. However, the effect of tree felling on growth strain was negligible among seven eucalypt species in the current study. This result is consistent with the report of Kubler and Wilhemy (1973).

Comparison of growth strain among three *E. urophylla × E. grandis* clones of standing trees

Mean growth strain values of three *E. urophylla × E. grandis* clones averaged from four circumferential measurements of standing trees are shown in Table 4. Clone DH30 had the lowest growth strain (Figure 2) but the analysis of variance indicated no significant differences between different circumferential measurement locations or the different hybrid clones.

Comparison of growth strain at different height in different species

Mean growth strain measured at different heights for seven species (except *E. grandis*) is shown in Figure 5. There were no significant differences in growth strain between heights. Similar to the result with standing trees (Figure 1), the mean growth strain, averaged from five different heights, of felled *E. urophylla* (Y) trees was the highest of the species tested (Figure 4), and the highest growth strain was at 1.3 m (Figure 3). For all individual trees, some sample trees had an increasing trend of growth strain with height, whereas some had a decreasing or irregular pattern. Overall, mean growth strain values of each species increased with tree height, although it appeared to decrease a little at 7.5 m height after reaching the highest value at 5.3 m. There was also a large amount of variation around the means at each height. Only *E. urophylla* (Y) and *E. cloeziana* (D) did not entirely fit into this pattern (Figure 5).

The current study showed mean strain level of these four species at 5.3 m was greater than at other heights. A few trees in these six species had quite high growth strain at 5.3 m height, which inflated the mean growth strain of the six species at that height. High growth strain appeared to relate closely to tree

Table 3. Growth strain of standing trees and felled trees at 1.3 m height.

Species	Growth strain ($\times 10^{-6}$)		*F* value
	Standing trees	Fallen trees	
Corymbia citriodora (N)	829	760	0.0932 n.s.
Eucalyptus exserta (L)	830	754	0.2431 n.s.
E. urophylla × E. grandis (W)	1139	1265	1.0324 n.s.
E. urophylla (Y)	1795	1932	0.0543 n.s.
E. cloeziana (D)	897	840	0.2089 n.s.
E. pellita (C)	1116	1084	0.1775 n.s.
E. tereticornis (A)	1160	1128	0.0035 n.s.

growth features, such as stem straightness, length of the crown, tree height, stem diameter at breast height and stem taper. Chafe (1981) reported mean growth strain increased with tree height over a 7.5 m span in 39-year-old regrowth *E. regnans*, but there was a significant negative relationship between growth strain and height of measurement over a 15 m span in an 8-year-old *E. nitens* plantation (Chafe 1985). For *E. globulus* plantations in Australia, Yang et al. (2002) found a tendency for growth strain levels to decline along the bottom log in 10-year-old trees, while this contrasted with results of Raymond et al. (2002), who found a tendency for growth strain to increase with increasing tree height within the bottom log in 20-year-old trees. Nevertheless, both studies suggested a strong relationship between the mean of multiple strain measurement made at 1.3 m and the mean of measures tested along the bottom log.

Table 4. Growth strain of three clones *E. urophylla* × *E. grandis* (W) from measurements of standing trees.

Clones	Growth strain ($\times 10^{-6}$)							
	East		West		South		North	
	x	δ_n	x	δ_n	x	δ_n	x	δ_n
DH33	992	36.66	1220	182.1	1112	498.3	1248	181.2
DH32	1071	209.5	819	99.13	1425	461.2	1152	216.7
DH30	1080	158.7	924	298.6	976	263.5	1012	24.97
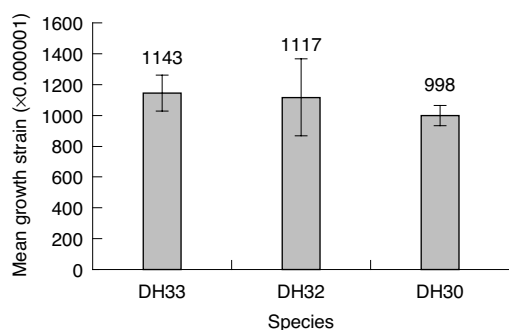
Figure 2. Mean growth strain in standing trees of three *E. urophylla* × *E. grandis* clones
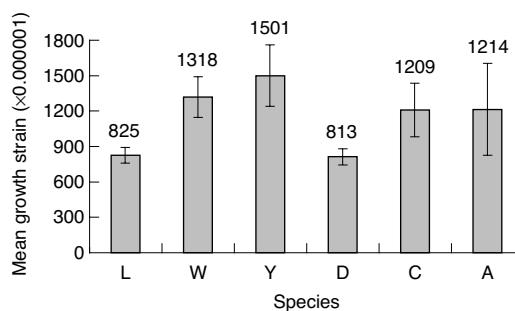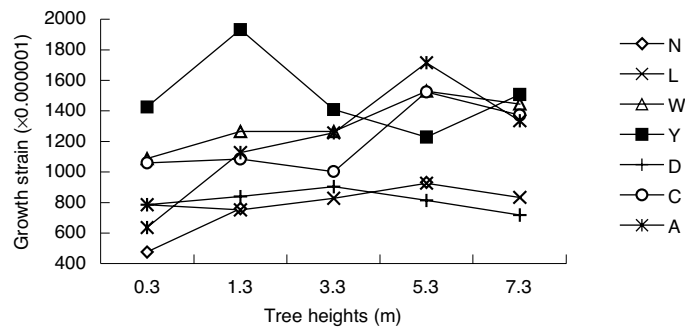

Figure 4. Mean growth strains of six eucalypt species averaged from measurements at five heights.
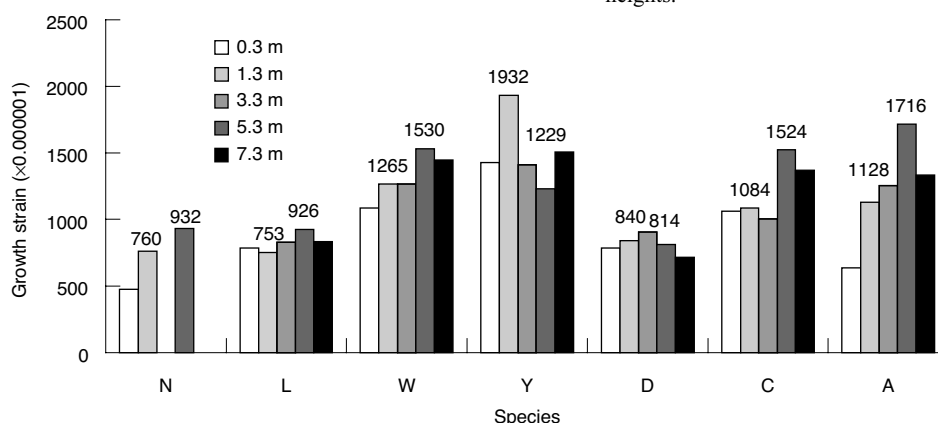
Figure 3. Mean growth strain at different heights for seven eucalypt species.

Figure 5. Variation of mean growth strains at different heights for seven eucalypt species.

Note that not only was there a different growth strain trend with height between different species, but also a different trend between the same species at different ages. Chafe (1985) and Yang et al. (2002) suggest these differing results can be interpreted in terms of different stages in tree maturity along the stem.

Conclusions

The CIRAD-Forêt strain gauge not only realised repeatable measurement of longitudinal growth strain, but was also less damaging than other non-destructive testing methods for growth strain, such as the Nicholson technique (Nicholson 1971). This kind of strain measure is convenient to use both on standing trees and on fallen trees of different species. The results are summarised as follows:

1. There were highly significant differences in the mean growth strain averaged from circumferential measurements of standing trees among different species.
2. *Corymbia citriodora* and *E. exserta* (37 and 27 years old) with low growth strain are two species currently in plantations in China that can be considered for solid wood utilisation. *Eucalyptus grandis*, which has been widely planted in China recently, also had low growth strain.
3. *Eucalyptus cloeziana*, a new species in plantations, had the lowest growth strain in four new species evaluated for solid wood products uses, but *E. urophylla* was the highest of all eight species tested.

4. There were no significant variances in growth strain of north measurements between standing trees and felled trees in different species.
5. There were no significant differences between different circumferential measurement locations or between three clones of *E. urophylla* × *E. grandis*.
6. There were no significant differences in growth strain between tree heights. Nevertheless, the data indicated that mean growth strain increased with tree height in most species.

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SHORT COMMUNICATIONS

Eucalypt Breeding in Sri Lanka: a Review of Progress and Future Breeding Strategies

B. Kangane[1] and P. Kanowski[2]

Eucalypts comprise 20% of major reforestation planting in Sri Lanka, principally for timber and fuelwood, but their uses also include protection and essential oils. Sri Lanka's Forestry Department plans to establish 400–500 ha of eucalypts annually, with additional plantings by tea estates and for farm forestry. The main eucalypt-growing areas of Sri Lanka are the wet highlands and dry lowlands.

Although eucalypts were introduced into the country in the late 18th century, plantation establishment with eucalypts did not begin until the early 1930s. The first extensive species and provenance evaluations began in the early 1970s, and indicated *Eucalyptus grandis* and *E. microcorys* are the most suitable for the wet and intermediate highlands of the country, and *E. tereticornis* and *E. camaldulensis* for the dry lowlands. On highland sites, *E. grandis* had a higher growth rate than *E. microcorys,* with mean annual increments of 24–36 m^3 ha^{-1} on fertile sites over longer rotations (25–30 years). Studies on lowland sites confirmed that tree form, self-pruning ability and the commercial wood production of *E. tereticornis* were superior to *E. camaldulensis*. Further, results of provenance trials of *E. grandis* and *E. tereticornis* showed most northern Queensland, Australia provenances performed better than other natural provenances and local landraces tested.

Detailed breeding plans were formulated in the early 1990s for *E. grandis* for the highlands and for *E. tereticornis* for the lowlands, and were initiated in 1995 and 2002, respectively. Key components of the plans were to establish provenance–family trials, using families from a broad range of provenances from Australia.

Early results of the *E. grandis* provenance–family trial show significant differences between provenances and between families within provenances ($p < 0.05$) for growth and wood basic density at age 6 years. Two provenances — S18138 (Windsor Tableland) and S16583 (Atherton) — from high altitudes of northern Queensland, Australia were outstanding for wood volume production (0.32 and 0.29 m^3 $tree^{-1}$, respectively) at age 6 years. Further, these two fastest-growing provenances also had some of the highest wood basic densities (492.4 and 495.4 kg m^{-3}, respectively). The within-provenance individual tree heritability (h^2) estimates for growth traits and wood basic-density are moderately high: h^2 estimates for height, diameter at breast height (dbh), volume and wood basic density were estimated as 0.43±0.14, 0.20±0.1, 0.28±0.11 and 0.35±0.24, respectively. Genetic correlations among growth traits are very strong, and the genetic correlations between growth traits (dbh, height and volume) and wood basic density are neutral or negligibly adverse (–0.04, –0.27 and –0.17, respectively, with standard errors of similar magnitude). The magnitude of heritability estimates indicates that seeds from the selected population would provide considerable genetic gain in the next generation, and genetic correlations between growth traits and wood density suggest they could be improved simultaneously.

Heavily thinned provenance–family trials of *E. grandis* and *E. tereticornis* will be converted to seedling seed orchards, and their performance is to be tested in genetic gain trials in the respective ecological zones. Furthermore, first generation *E. grandis* trial results suggest that incorporation of more families from the best-performing provenances would improve the genetic base of *E. grandis* breeding population.

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[1] Forest Department, Rajamalwatta Road, Battaramulla, Sri Lanka. Present address: Forestry Program, School of Resources, Environment and Society, The Australian National University, Canberra ACT 2600. Email: <Bandara.Kangane@anu.edu.au>.

[2] Forestry Program, School of Resources, Environment and Society, The Australian National University, Canberra ACT 2600.

Potential of *Eucalyptus dunnii* at the Northern Limit of Eucalypt Introduction in China

Liu Youquan, Li Zhihui and Ou Yanglei[1]

Eucalypts, which are a major source of short-rotation, industrial timber, have developed quickly in the southern subtropics of China. Lying in the mid-subtropics, Hunan province has introduced 62 *Eucalyptus* species and over 130 provenances, has developed 53 ha of field trials, and plantations cover 13,000 ha. After the species provenance trials, we found *E. camaldulensis, E. dunnii, E. grandis* and *E. grandis* × *E. urophylla* grew well.

Eucalyptus dunnii has a limited distribution in Australia in northeastern New South Wales and southeastern Queensland (latitude 28°45'–30°09'S, longitude 152°20'–152 °54'E). It is a fast-growing species that, in places, can have an annual height growth increment over 5 m. In Central and South America it is planted commercially and regarded as a cold-resistant species. In South Africa, it is more cold resistant than *E. grandis*, and it tolerates a dry season of 6 months in Zimbabwe where 5-year-old trees in a trial averaged 21 m in height and 18 cm diameter at breast height (dbh).

Introduction trials in Hunan, Fujian, Guizhou, Guangxi, Jiangxi etc., showed *E. dunnii* to be fast growing and cold tolerant, so it is now planted widely. It has tolerated lower temperatures than the – 5°C absolute lowest temperature in its natural stands in Australia. Its wood density is high (0.55 g cm^{-3}), cellulose content 45.3% (4-year-old material) and fibre length is 805–809 μm. *Eucalyptus dunnii* is suitable for making pulp, and large diameter trees can provide construction and furniture timber. Its development and utilisation deserve more attention.

Eucalyptus dunnii planted in Zhuzhou, Hunan in June 1987 was exposed to a temperature of –7.9°C in January 1990. In the following year, on 29 December 1991, these trees experienced –11.5°C for 72 hours, the lowest temperature for 40 years, and freezing

conditions for 7 days. Before this cold exposure, the 4.5-year-old trees averaged 8.1 m in height and 10.2 cm dbh. After these cold events we observed 1-, 3-, 4- and 6-year-old *E. dunnii*. The upper parts of most eucalypts were nearly frozen to death, except in *E. rubida.* In spite of this, the stumps coppiced well after several years. In the following spring, 40 days after bole cutting, 89% of *E. camaldulensis* coppiced

Table 1. Rate of coppicing at 40 days after cutting and coppice growth 8 months after cutting in four *Eucalyptus* species damaged by frost.

Species	Coppice % at 40 days	Height (m) at 8 months	Ground diameter (cm) at 8 months
E. camaldulensis	89	2.59	2.6
E. grandis	88	3.44	3.2
E. grandis × *E. urophylla*	96	3.46	3.0
E. dunnii	100	3.14	3.3

It is evident that *E. dunnii* has some cold resistance and that it grows well in different areas. At Liuzhou, for example, 11-year-old *E. dunnii* had an average height of 19.3 m, and dbh of 20.1 cm. Ten-year-old *E. dunnii* in Hehua village, Zhuzhou, Hunan, averaged 15.6 m in height and 19.5 cm dbh, greater than *Pinus massoniana* planted in the same place. Also, in 1992, among the *E. dunnii* planted in the garden of central South Forestry University are two plus trees with heights 25.6 m and 27.0 m and dbh 40.6 cm and 37.3 cm, respectively. Based on these performances, *E. dunnii* has good prospects in afforestation projects.

Seed supply from natural stands is limited because of relatively poor seed crops and the limited area of the stands. The seed is expensive to import, with prices as high as A$2000 kg^{-1}. So far it has not been possible to produce *E. dunnii* seed in China. There

[1] Central South Forestry University, Zhuzhou, Hunan 412006, China

has been much effort for develop clonal techniques for *E. camaldulensis, E. grandis, E. grandis × E urophylla* etc. The rooting rate of cuttings of *E. camaldulensis* is up to 90%, but for species such as *E. viminalis* the rate is very low. If the planting of *E. dunnii* for commercial purposes is to expand then it is desirable to develop rapid asexual propagation methods.

It is possible to root cuttings of *E. dunnii* from seedlings. In the climatic conditions of Zhuzhou, we sow seeds in the last 10 days of October, then we transplant seedlings in farmland where we take shoot cuttings the following March–April. With selected rooting media and hormones, the rooting rate can be 80%. Also, the Botanical Garden of Hunan province has applied for a patent for a method of tissue culture for *E. camaldulensis* and *E. dunnii*.

In two lake areas of Hunan and Jiangxi provinces, episodic low temperatures are the main obstacles to increasing cultivation of *Eucalyptus.* After introducing good, cold-resistant *Eucalyptus* species and provenances, we need to solve the problem of producing good quality nursery stock if we are to extend their planting. While *E. dunnii* is cold-resistant and fast-growing, the introductions into Zhuzhou and Liuzhou have not yet flowered even though they more than 10 years old. If we are to produce seed, we need to promote earlier flowering and so must undertake research to understand the factors that influence the physiology of its flowering and seeding. We need to conduct research on tissue differentiation, to understand of the conditions for root initiation and development in cuttings, so we can increase the rooting rate and make propagation by cuttings a feasible option.

Flowering and Seed Production in Tropical *Eucalyptus* Seed Orchards

K. Pinyopusarerk* and C. Harwood[1]

During the 1990s, seedling seed orchards and unpedigreed seed production areas of several eucalypt species were planted in a number of Asian countries. The objectives were to mass produce genetically improved seed for plantations, and establish base populations for breeding programs. Orchards were planted at close initial spacing, and developed via two or more selective thinnings, to achieve an orchard stocking of around 200 stems ha^{-1} for seed production.

Over the period 2000–2002, a systematic survey of the performance of the seed orchards was conducted, focusing on site conditions, management inputs, flowering and seed production. Individual orchards were surveyed at ages ranging from 4 to 10 years after planting. Fifty or more trees per orchard were surveyed to determine the percentage of trees flowering.

Results

The percentages of trees flowering, plotted against orchard age, are shown for each species in Figure 1. In the majority of orchards, 50% or more of the trees had flowered by age 5 years or older. However, *Eucalyptus tereticornis* and *E. urophylla* had lower percentages of trees flowering at this age. From the survey and other information, the following climatic ranges were identified as suitable for good flowering and orchard performance for the different species (Table 1).

Orchards on shallow, infertile soils had inferior flowering relative to those of the same species on fertile, deep clay-loam soils. Moderate to heavy seed yields, ranging from 1 to 10 kg ha^{-1} yr^{-1}, were obtained from the majority of the orchards from age 5–6 years onwards.

To avoid inbreeding, our provisional recommendation is to collect seed only from crops resulting from a flowering of at least 50% of the trees in an orchard. Out-crossing rates in the seed crops from the orchards are currently being determined by allozyme analysis.

[1] CSIRO Forestry and Forest Products, PO Box E4008, Kingston, ACT 2604, Australia.
Corresponding author, K. Pinyopusarerk;
email: <khongsak.pinyopusarerk@csiro.au>.

Table 1. Range of climates suitable for seed orchards of the species surveyed.

Species	Mean annual rainfall (mm)	Dry season (consecutive months with <40 mm rainfall)	Mean annual temperature (°C)	Age for 50% of trees to flower, given suitable climate, soil type and management (years)
Eucalyptus camaldulensis[a]	800–1800	3–6	>21	5–6
E. grandis	>1200	2–5	15–23	5
E. pellita	>1400	2–5	>21	4
E. tereticornis[a]	1000–2000	2–6	>21	7
E. urophylla	>1200	2–5	>21	5–6

[a] Tropical provenances
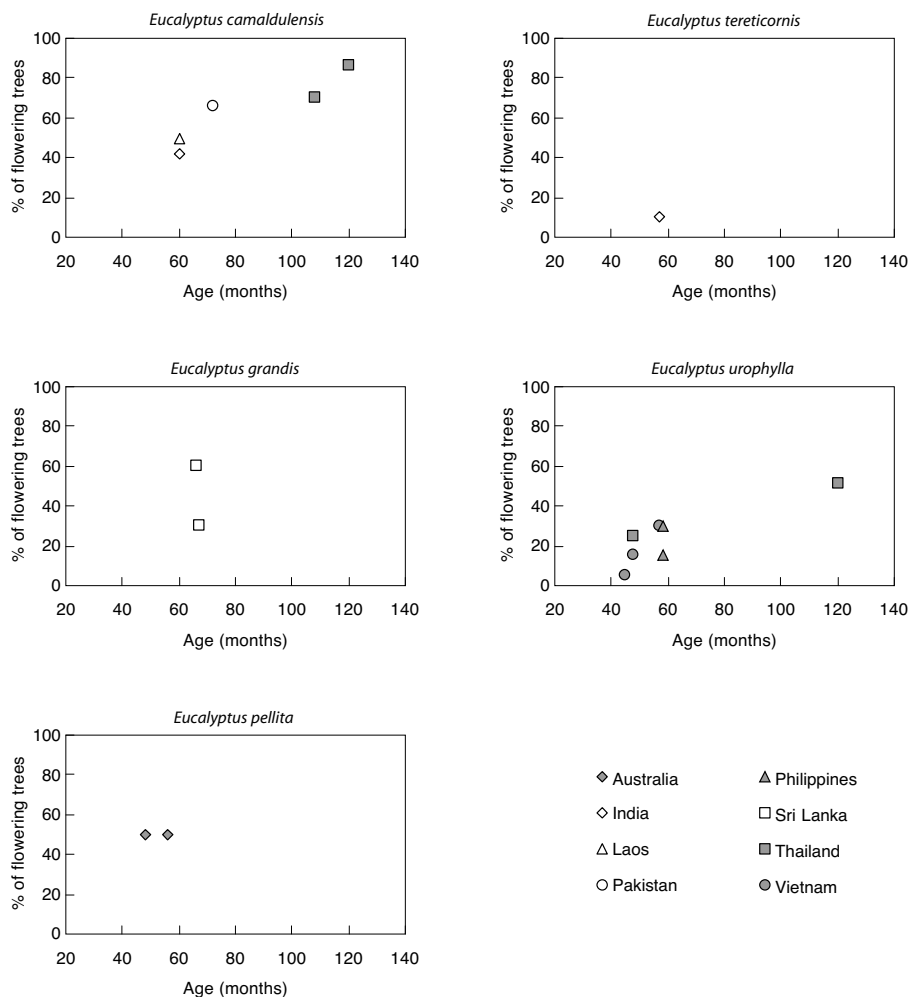
Figure 1. Percentage of trees flowering in eucalypt seed orchards at different ages in several countries.

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Developing a Seedling Seed Orchard of *Eucalyptus smithii*

Zhang Ronggui, Jiang Yundong and Li Siguang[1]

A *Eucalyptus smithii* seedling seed orchard has been established in Fumin County, Yunnan province at an altitude of 1894 m. Annual average temperature is 15.8°C, while the average temperature in January (the coldest month) is 8.2°C and the average temperature in June (the hottest month) is 21.2°C. The annual accumulated temperature is 6271°C (≥10°C). The extreme maximum temperature is 33.4°C, the lowest temperature –7°C and the mean annual rainfall 855 mm. The soil is a mountainous red soil developed from limestone and has a pH of 5.5.

Material and Methods

Seven provenances, including 100 families, of *E. smithii* were introduced and 88 families tested in 1995 (Table 1, next page). The spacing was 2×3 m, and base fertiliser and additional fertiliser were applied twice. In 1999, the provenance/family tests were converted to a seed orchard, and an experiment carried out to promote flowering and bearing.

A randomised block design was used with five trees per block and five replications. There was an untreated control and two treatments were applied to promote flowering and seed bearing:

- control (the first replication of family test)
- addition of the growth-retardant chemical paclobutrazol and fertiliser (the second and third replications of family test)
- fertiliser only applied (the fourth replication of family test). The fifth replication was not tested.

In 1999, the first fertiliser application was of urea 500 kg ha^{-1}, superphosphate 48 kg ha^{-1}, borax 32 kg ha^{-1}, and zinc sulphate. In 2000, there was a second application of 0.5 kg urea to each tree and, at the same time, the trees were treated with paclobutrazol. In 2001, a third application of 1 kg compound fertiliser was applied to each tree. Thinning took place at the end of 1999 and 2000, respectively. Phenological observation was made in 2000 and 2001. Flowering and seed bearing were investigated in December of 2001 and December of 2002.

Three inferior families were eliminated, reducing the number of the families from 88 to 85. Thinning intensity was 77.5%, reducing the number of individuals from 1471 to 331 (345 trees ha^{-1}).

Results and Discussion

Flower buds formed in January–March and flowering occurred in December and in January of the next year. Fruits matured from January–March of the third year. Results in Table 2 indicate that fertiliser and paclobutrazol in combination promoted earlier flowering of trees in the seed orchard and can play an important role in increasing the level of flowering and fruiting.

The average flowering and seed-bearing percentage of 7.5-year-old trees was 24.6% compared with 21.3% for 6.5-year-old trees. There are flowering families in all provenances, among which provenances of 18676 and 18688 have the most, and 18682 the least.

Some 65% of the 20 superior families are flowering compared with 28.6% of families of all flowering families. This result suggests superior families have the characteristic of earlier flowering.

[1] Yunnan Academy of Forestry, Kunming 650204, China.

Table 1. Provenances and families of *Eucalyptus smithii*.

Provenance code[a]	Family no.[b]	State of origin in Australia	Latitude (°S)	Longitude (°E)	Altitude (m)
18676	0–11	New South Wales	34°44'	150°10'	300
18682	12–21	Victoria	36°54'	149°43'	370
18681	22–32	New South Wales	37°04'	149°45'	900
18688	35–45	New South Wales	35°08'	149°49'	650
18284	46–64	New South Wales	35°26'	149°36'	300
17131	65–92	New South Wales	36°12'	150°04'	400
16916	94–99	New South Wales	37°34'	148°29'	400

[a] Seedlot number of the CSIRO Australian Tree Seed Centre.
[b] Families 8, 17, 25, 29, 33, 34, 49, 79, 80, 83, 93, 96 were not included in the test.

Table 2. Flowering and seed bearing families of *E. smithii* with different treatments at 7.5 years old and 3.5 years after thinning.

Treatments	Number of families	Flowering and seed bearing families		Flower buds		Flowers		Fruits	
		No.	%	No.	%	No.	%	No.	%
Control	71	11	15.7	3	4.3	1	1.4	7	10
Fertiliser + paclobutrazol	138	64	46.4	48	34.8	1	0.7	15	10.9
Fertiliser	76	18	23.7	16	21.3	0		2	2.6
Average			28.6						

Research Advances with Eucalypts by Leizhou Forestry Bureau, Guangdong Province

Mo Xiaoyong[1]

Leizhou Forestry Bureau is located in Zhanjiang City, Guangdong province (20°45' 21°40'N, 109°45' 110°30'E). The climate is tropical, with a mean annual temperature 23.7°C and a mean annual rainfall of 1788 mm. There is a rainy season from March to September. Mean annual evaporation is 1711 mm and relative humidity 80%. Each year there are one or two severe tropical cyclones. Soils in the area are latosols.

There are 30,000 ha of eucalypt plantation in Leizhou Forestry Bureau. Total growing stock is 1.68 million m^3 and the total annual increment 550,000 m^3 Mean annual increment is up to 22.5 m^3 ha^{-1}.

Eucalypt Research Priorities

Eucalypt research priorities at Leizhou Forestry Bureau are:

- selection of high-quality material for tree breeding
- clonal multiplication
- clones assignment and mid-term tests
- cultivation technologies for high yields
- prevention and control of diseases and pests
- wood processing and utilisation.

Selection of high-quality material for tree breeding

Introductions

We have introduced 95 eucalypt species since 1966 including *Eucalyptus urophylla, E. camaldulensis, E. grandis, E. robusta, E. cloeziana, E. alba, E. gummifera,* and *E. saligna* among others. Those principally used for afforestation are *E. urophylla, E. grandis, E. tereticornis, E.* Leizhou No 1, *E.* 12ABL and *E. camaldulensis*.

[1] Leizhou Forestry Bureau, China State Forest Farm Co. Ltd, Chengyue, Suixi County, Guangdong, China 524348. Email: <mxyyxh@21cn.com>.

Provenance/family trials

Since 1984, we have introduced several provenances of *Corymbia citriodora* (9), *E. exserta* (8), *E. camaldulensis* (10) and *E. saligna* (9). Overall, 36 species were tested. Systematic trials of provenance/ families began from 1990. We have successively introduced 13 provenances (201 families) of *E. wetarensis* (*E. urophylla*) and 14 provenances (244 families) of *E. pellita*, There are also many provenances and families of *E. tereticornis, E. camaldulensis* and *E. urophylla* in the trials.

Selection of superior trees

Superior trees (plus trees) are selected using the 'five dominant trees pairing' method. Our research group has selected 8800 individuals including: 4680 *E.* Leizhou No 1, 2300 *E. urophylla*, 390 *E. camaldulensis*, 100 *E. tereticornis*, 96 *C. citriodora* and 1234 eucalypt hybrids.

Hybridisation breeding

Since 1970, we have made more 100 crosses using *E.* Leizhou No. 1 × *E. exserta, E. pellita* × *E. urophylla*, and *E. urophylla* × *E. camaldulensis*. We have also selected a set of excellent F_1 families and individuals. Two key technologies have assisted the crossbreeding: pollen storage and controlling the size of seed trees used for hybridisation.

Breeding resistant clones

We have selected a set of clones with superior wind resistance that have been deployed in production plantations, i.e. W5, U6, SH1, LH1, DH201-2, and M1. We found a positive correlation between wind resistance and the ratio of tree height and stem diameter, but more research is needed on other characteristics, such as tree crown form, lateral branch angle, wood density, and root distribution.

In selecting disease-resistant trees, we cooperated with Guangxi Academy of Forestry in 1997–2000 and joined the National Forestry Key Project with Science and Technology on *Eucalyptus* 'Research on control techniques for bacterial wilts'. Eight clones

with disease resistance were identified and used in production plantations.

Clonal multiplication

Tissue culture

In 1978, tissue culture laboratories were built. Leizhou Institute of Forestry initially produced 1000 plants from No. 50 clone of *E*. Leizhou No. 1, but the young plants were very variable. In 1990, our Forestry Institute cooperated with Guangdong Forestry Institute and developed a short-propagation technique for culture in vitro with bud organs. This made tissue culture effective and we have cultivated 200 clones of 11 eucalypts. Our Forestry Institute's tissue culture facility has an annual capacity 1 million clonal *Eucalyptus* plants.

Cutting propagation

In 1989, we cooperated with Guangdong Forestry Institute, and from 1990 with South China Agricultural University, to research clone rooting problems. Now we have prepared 'No. L1 rootone' which can increase the rooting percentage of cuttings.

Clonal tests

There is a rolling project to expand the number of clones in Leizhou Forestry Bureau.

From 1990 to 2002, we have tested more than 200 clones to select superior clones which have been included in mid-term tests. Up to 20 clones have been deployed in plantations including: M 1, LH 1, SH 111, DH201-2, DH 184-1 and DH32-22.

Site preparation and maintenance

Site preparation

Complete cultivation and deep ripping were investigated. A technique for removing roots was developed.

Density trials

Since 1980 we have researched the optimum density of trees per hectare for different clones. Main densities are based on the following spacings: 1.33×2.67 m, 1.67×3.0 m, 1.67×2.67 m, 1.33×3 m, 1.0×3.0 m.

Fertilising

We cooperated with South China Agriculture University and Guangdong Ecology and Soil Institute to research how to maintain appropriate nutrient levels in the soil. We obtained good experience on how to fix nitrogen with symbiotic micro-organisms and maintain soil productivity by cultivating understorey cover crops, such as grass and green soybeans. Mixed plantations of *Eucalyptus* spp. and *Acacia* spp. were also successful.

Wood processing and utilisation

Chips trade

Leizhou Forestry Bureau pioneered the export of eucalypt chips with its first shipment through the port of Zhanjiang in 1988. Chips to the value of US$190 million have been exported to Japan, France, Taiwan and elsewhere.

Large diameter trees

Corymbia citriodora, E. pellita, E. camaldulensis and other species are grown to large stem diameters and used as timber for shipbuilding, furniture, and flooring among other things.

Comprehensive utilisation

Apart from timber and pulp, the eucalypts are used to produce essential oils (from leaves); tannin extract (from bark); EF accelerating foams (from branches and leaves); and charcoal (from roots).

Managing Diseases of Eucalypts in Southeast Asia

K.M. Old[1] and C. Mohammed[2]

Widespread planting of eucalypts in Asia has been associated with the appearance of significant foliar and stem diseases. The most damaging of these are caused by leaf and shoot blight pathogens, especially *Cylindrocladium reteaudii* (*C. quinqueseptatum),* *Phaeophleospora destructans* and *Cryptosporiopsis eucalypti*. These fungi are favoured by warm, humid climates, cause defoliation and shoot death, and have the potential to greatly reduce the growth, yield and product quality of plantations. Most widely grown eucalypt species are susceptible to attack. Severe defoliation may be followed by outbreaks of stem canker disease, caused *by Lasiodiplodia theobromae* and related fungi, which rapidly spreads through the main stem of stressed trees and causes death.

Experience in Vietnam, Thailand and Indonesia has shown that, provided reliable, diagnoses are made of the pathogens present in replicated clonal trials and well-designed provenance and progeny trials, resistance to these shoot blight pathogens can be readily identified at the individual tree or clone, family, provenance and species levels. Resistant selections can then be propagated as clonal plantations or established as clonal seed orchards to provide seed for planting in disease-prone environments. Although present in Indonesia, Thailand and Vietnam, the well-known canker pathogen *Cryphonectria cubensis* has not been a major problem in Southeast Asia, due possibly to the relative resistance of widely planted species such as *Eucalyptus uro-* *phylla, E. tereticornis* and *E. camaldulensis.* This situation could change if susceptible clones are planted in the future.

Another pathogen of note is *Ralstonia solanacearum,* the cause of bacterial wilt of eucalypts and other species. This disease has been known in southern China for many years and has recently been found in Vietnam and Thailand on clonal plantings of *E. urophylla* and *E. camaldulensis*, respectively. This disease has been found to cause up to 30% tree deaths during the first year or two after planting, after which little further damage occurs. Australian scientists from CSIRO Forestry and Forest Products have worked on aspects of the above diseases in Southeast Asia for the past decade. Additional pathogen threats are associated with fungi exotic to the region that may be accidentally introduced through unsafe movement of germplasm. The rust, *Puccinia psidii,* is of particular concern and a three-year program of research has screened a wide range of eucalypts for their resistance to this disease and. also developed a highly efficient PCR-based detection system. A forthcoming 'Manual of diseases of *Eucalyptus* in South-East Asia', to be published jointly by CSIRO, the Australian Centre for International Agricultural Research and the Center for International Forestry Research, will give plantation managers and forest health specialists an up-to-date picture of the status of these pathogens and how to manage them.

[1] CSIRO Forestry and Forest Products, PO Box E4008, Kingston, ACT 2604, Australia.
   Email: <kmold@webone.com.au>.
[2] CSIRO Forestry and Forest Products, GPO Box 252-12, Hobart, Tasmania 7001, Australia.

Effect on Growth of *Eucalyptus urophylla* Seedlings by Inoculation with Ectomycorrhiza and Associative Nitrogen-Fixing Bacteria

Ma Haibin, Kang Lihua, Jiang Yegen and Wan Lu[1]

The potential for using mycorrhizal associations to increase the productivity in eucalypt plantations has recently been the focus of major research (Chen et al. 1998; Gong et al. 2000). Artificial inoculation of eucalypts with associative nitrogen-fixing bacteria can reduce the use of chemical fertiliser and relieve the corresponding problems (Kang 2002), but there are few literature reports of dual inoculation of eucalypts with a mycorrhizal fungus and associative nitrogen-fixing bacteria. This paper reports the results of dual inoculation with *Hebeloma westaustralianese* and *Klebsiella oxytoca* NG13/pMC73A on *E. urophylla* seedlings.

Materials and Methods

Hebeloma westaustralianese, an ectomycorrhizal fungus (ECM) from Australia, and an associative nitrogen-fixing bacterium (ANFB), *Klebsiella oxytoca* NG13/pMC73A with Ap^r and Km^r plasmid, provided by Guangdong Microbiology Institute, were used. Both were cultured by shaking for 5 days.

Eucalyptus urophylla seedlings were used. The trial had a fully randomised block design with four replicates. Each treatment (T1–T4) included three seedlings. Seedlings roots were dipped into the inoculant for 3–5 minutes before transplanting. Seedlings were further inoculated by placing inoculant near the roots in pots 1 month after transplanting. All seedlings were grown in a greenhouse. The treatments were:

T1– inoculated with *Klebsiella oxytoca* only

T2– inoculated with *Hebeloma westaustralianese* only

T3– inoculated with both *Klebsiella oxytoca* and *Hebeloma westaustralianese*

T4– uninoculated (control).

Mycorrhizal infection in the root system was investigated 3 months after inoculation. The seedlings were harvested 2 months after the second inoculation. The roots and shoots were dried and weighed. Dry weights of roots, shoots and total seedling were analysed statistically using SAS software (Version 6.12, SAS Inc.).

Results

The mycorrhizal infection rate of seedlings inoculated with ECM only was 87%, while the mycorrhizal infection rate of seedlings inoculated with both ECM and ANFB was 80%. There were significant differences of seedling heights and biomass within the different treatments ($p < 0.05$). The average height of seedlings inoculated with both ECM and ANFB was increased by 103%, while seedlings inoculated with ECM or ANFB were, respectively, 72% and 65% taller than uninoculated seedlings. Total dry weights of seedlings inoculated with both ECM and ANFB, ECM alone, and ANFB alone were greater than the control by 363%, 146% and 114%, respectively. Similar effects of dual inoculations have been reported in other plants (Zheng et al. 2000; He et al. 2001).

The effect of dual inoculation with *Hebeloma westaustralianese* and *Klebsiella oxytoca* NG13/pMC73A on seedling growth of *E. urophylla* was significantly greater than for ECM and ANFB alone. This suggests that artificial inoculation with a combination of ECM and ANFB is a promising approach to improving growth of eucalypt seedlings.

[1] Research Institute of Tropical Forestry, Chinese Academy of Forestry, Longdong, Guangzhou 510520, China.

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A Comparative Study on Understorey Vegetation Diversity in *Eucalyptus* Plantations in Hainan Island

Yu Xuebiao and Yang Zaihong[1]

Eucalypts are widely planted in southern China, but stands have a simple structure and poor diversity of understorey vegetation. Understorey vegetation is an important component of the artificial plantation ecosystem, playing a role in maintaining soil fertility (Maohe Yao et al. 1991; Yu Xuebiao 1999). Growing volume and biomass of 4.5-year-old eucalypt plantations decreased with successive rotations (Yu Xuebiao 1999). Biodiversity also decreases with continuous planting, and understorey vegetation is a component and technical link in management and sustainable development of forest plantations.

This short communication summarises research to identify critical factors that influence understorey vegetation diversity on the basis of comparative analysis of the flora component species and the diversity of understorey vegetation. The research aimed to provide a basis for developing understorey vegetation in eucalypt plantations and a theoretical basis for their sustainable management. Research was conducted in 14 counties as well as Haikou city, Qiongzhong, Baisha, Tongzha, and Baoting County of Hainan Island (latitude $10°09'$–$20°10'$N, longitude $108°03'$–$110°03'$E). *Eucalyptus* plantations investigated in 14 counties covered 3000 ha. The climate of the area is monsoonal, with the annual sunshine of about 2500 hours, annual mean temperature 23–26°C, and annual mean rainfall 1000–2500 mm. The soils are lateritic.

Results and Discussion

Composition of understorey vegetation

There were 224 vascular plant species recorded in understorey vegetation, belonging to 65 families and 53 genera, of which 88 were woody plants (39.3%) and 136 herbaceous plants (60.7%). Thus, the under-

storey vegetation in the *Eucalyptus* plantation sampled was simple in structure and relatively low in plant species. The most common woody plants, in order decreasing frequency were: *Rhodomyrtus tomentosa* (Ait.) Hassk, *Urena lobota*, *Aporosa chinensis*, *Urena lobota* Linn., *Helicteres angustifolia*, *Breynia fruticosa* (Linn.) Hook f., *Melastosa candidum* D.Don, *Clerodendrum cyrtophyllum* Turcz. *Zanthoxylum avicennae* (Lam.) DC, and *Helicteres hirsute.* The most common herbaceous plants, in order decreasing frequency were: *Eupatorium odoratum*, *Borreria articularis*, *Imperata* sp., *Sebastiania chamaelea*, *Paspalum commersonii*, *Sacciolepis indica* (Linn.) A. Chase, *Desmodium triflorum* (Linn.) DC, *Mimosa pudica* and *Eragrostis hainanensis*. The composition of the understorey at a particular site varied with rainfall, temperature and soil conditions, type of *Eucalyptus* species, age structure and pattern of management.

Biodiversity of understorey vegetation

The species richness index (S), Shannon–Wiener index (H') and Simpson index (D) of woody plant were highest in Datong, Tunchang: 25, 1.3567 and 0.9557, respectively. The three indexes were lowest in stands on the coastal platform, with corresponding values were 1 (S), 1(H'), 0(D). The highest index values of herbaceous plants in understorey vegetation were in mixed *E. exserta* plantation: their corresponding values were 18(S), 1.1538(H) and 0.9201(D). Generally, H' and D values in woody plants increased S values, but the opposite occurred with herbaceous plants. It was easy to form a single dominant species community in the herbaceous layer in a young stand of eucalypts, but this was not observed in the woody plants of the understorey.

Comparative analysis of biodiversity

Diversity indexes H' and D of woody plants had a significant relationship with rainfall and soil mois-

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[1] Research Institute of Wood Industry, Chinese Academy of Forestry, Beijing, China 100091

ture content, but this relationship was weaker for herbaceous plants. The growth and distribution of woody plants were strongly affected by hydrolytic N and available P in the soil.

The diversity index of both shrubs or the herbaceous layer of understorey vegetation in mixed *E. exserta* and *Pinus caribaea* plantation was the highest in a comparative study of diversity under different types of management, but the highest diversity index was not an indication that understorey vegetation could improve productivity of *Eucalyptus* plantations. More research will be needed to determine an understorey vegetation for sustainable *Eucalyptus* plantation management, but inter-planting and continuous-planting rotations are an obstacle to increased diversity in woody plants and herbage in understorey vegetation.

In *Eucalyptus* plantations there was a significant relationship between the diversity in understorey woody plants and rainfall, soil nutrients and soil moisture content, but the relationship was not significant for herbaceous plants. Principal component analysis of diversity, indicated that rainfall was the key factor among factors affecting diversity of woody plants in the understorey vegetation of *Eucalyptus* plantations. The second factor was soil moisture content and the third was the amount of rapidly available N in the soil. The results suggest that districts having a mean annual rainfall below 1000 mm are suitable for ecological public forest plantations, while districts above 1000 mm rainfall are suitable for industrial wood plantations of *Eucalyptus*. Rainfall in the coastal platform–sandy zone was low and these areas are suited to protective forest. Rolling hill and mountain areas, where rainfall is above 1000 mm, are suited to all kinds of forest, including plantations for pulpwood or other industrial wood.

Biomass of understorey vegetation

Above ground total biomass was measured at six sites. The results indicated that the biomass of herbaceous plants of understorey vegetation was greater than that of woody plants, especially in young *Eucalyptus* plantations before crown closure, but that the difference decreased with age of the stand. The biomass of understorey vegetation was the highest in young *Eucalyptus* plantations, but there was a tendency for biomass to increase with age of stand. Correlation analysis indicated no significant relationships between biomass of understorey vegetation (herbaceous, woody, and total biomass) and rainfall, soil moisture content, and soil nutrient content (hydrolytic N, available P, rapidly available K). This means that biomass of understorey vegetation in *Eucalyptus* plantations has no relationship with rainfall, soil moisture content, and rapidly available nutrient content of soil.

Conclusion

From the view point of understorey diversity, coastal-platform–sandy-zone districts having mean annual rainfall below 1000 mm are suitable for ecological public forest plantations (protection forests), while rolling hill and mountain districts with above 1000 mm rainfall are suitable for industrial wood plantations of *Eucalyptus*.

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Effects of Microwaving, Freezing and Soaking Pre-Treatments on Drying and Shrinkage of Eucalypt Wood

Jiang Zehui, Fei Benhua, Wang Ximing, Zhao Rongjun and Liu Junliang[1]

During general drying, wood defects such as surface checking, end splitting and collapse, easily occur, especially with juvenile wood, and greatly limit utilisation of eucalypt wood. Some countries, such as Australia and South Africa, have good results in drying eucalypt wood by adopting combined air and kiln-drying technology, and special methods, such as solar-energy, high frequency and microwave drying. This paper summarises the results of an experiment on the effects of microwave, freezing and soaking pre-treatments on drying and shrinkage of eucalypt wood.

Materials and Methods

Timber of three trees from both *Eucalyptus urophylla* × *E. tereticornis* and *E. cloeziana* came from plantations at Dongmen Forest Farm, Guangxi. The hybrid trees were 6 years old and had a mean diameter at breast height of 22.9 cm and a mean height of 25.7 m. *Eucalyptus cloeziana* trees were 8 years old and had a mean diameter at breast height of 28.8 cm and a mean height of 27.4 m.

The timber was dipped in water until saturated at normal temperature, then 40 samples were taken. Of these, five were treated by microwave (MW), five by pre-freezing and the rest soaked. The MW treatment was for 1 minute 40 seconds. The MW treatment generates internal heating, which can change the wood structure and properties, enhancing permeability, decreasing density, lowering heat-conduct ratio, shrinkage and inflation, and accelerating drying speed. The pre-freezing was for 36 hours. After the pre-treatments the samples were dried according to a standard drying schedule for 124 hours in a temperature-controlled kiln.

[1] Research Institute of Tropical Forestry, Chinese Academy of Forestry, Longdong, Guangzhou 510520, China. Email: gzfsrd@pub.guangzhou.gd.cn

Results

Drying speed

Providing drying quality is assured, the faster the drying speed the better. In the experiment, drying speed of pre-freezing wood was the highest, followed by the MW-treated wood, and then the soaked wood. When the water content is over fibre-saturation point, the drying speed of MW-treated wood exceeded that of soaked wood by 17%, while the drying speed of pre-freezing wood was 4% faster than soaked wood (Table 1).

Moisture-content changes

It was clear that MW treatment accelerates the velocity by which free water in the wood moves. The velocity is 17.4% faster than in soaked wood and 13.3% faster than in pre-freezing wood. Nevertheless, below fibre-saturation point, the difference between the drying velocities of the three pre-treatments is very slight.

Shrinkage

In manufacturing, most boards are neither flat nor radial but are usually mixed. Thus, it is the shrinkage in thickness and width that should be investigated. The results show that, no matter the width or thickness, shrinkage of pre-freezing wood was much greater than MW and soaked wood, which were very similar. The differing shrinkage is a result of differences in the collapse of cells in the wood.

Layer water content

The drying velocity of MW wood at the primary earlier stage of drying is faster than that of the soaking wood and pre-freezing wood, because of the

Table 1. Drying time and drying velocity for the three pre-treatments.

Wood Pre-treatment	Initial moisture content (%)	Total drying time (hr)	Final moisture content (%)	Drying time (hr)		Drying velocity (% hr^{-1})_		
				>30%	<30%	>30%	<30%	Average velocity
Soaked	70.6	124	9.6	36	88	1.09	0.25	0.492
Microwave	70.6	124	6.6	36	88	1.13	0.26	0.516
Pre-freezing	69.7	124	7.9	30	94	1.28	0.25	0.498

Table 2. Effects of different pre-treatments on wood quality after drying.

Wood pre-treatment	Initial moisture content (%)	Final moisture content (%)	Stress index (%)		Depth of collapse (%)		Inner check (stripe)	Deviation of water content (%)	
			Before	After	Before	After		Before	After
Microwave	70.6	9.6	7.8	3.2	2.45	1.36	2	22.4	2.1
Soaked	69.7	7.9	7.5	1.8	2.22	1.43	0	22.0	1.6
Pre-freezing	70.6	6.6	6.2	1.8	1.88	0.33	0	17.9	1.4

strengthened filtering ability of wood resulting from MW treatment. Thus, in the earlier stage of drying, deviation of layer water content of MW wood is small, while at the later stage of drying it is larger than that of soaked wood and pre-freezing wood, hence the possibility of MW wood splitting is increased. For this reason, it is important to prolong the times of conditioning treatment and to measure stress index of board immediately. The deviation in water content in the earlier stages of drying for pre-freezing wood is comparatively larger, which enhances the chances of surface-checking.

Overall, the drying quality of pre-freezing wood is superior to that of the soaked wood and MW wood, which is reflected in small depth of collapse (0.33 mm), no inner check, small stress indication, and well-distributed water content (Table 2).

Conclusions

Eucalypt wood is difficult to dry. Routine drying can easily cause collapse and check, so a drying schedule that is not too fast is preferable. The temperature in the earlier stages of drying must be kept below 55°C. Equalisation treatment must be carried out in the later stages of drying, to relieve drying stress and reduce the moisture gradient. MW and pre-freezing treatments can improve the drying process as follows:

1. MW treatment accelerates drying velocity for eucalypt wood at the earlier stages of drying, while it has no obvious influence impact on drying velocity in the later stages.
2. Pre-freezing treatment accelerates drying velocity for eucalypt wood and at the same time greatly reduces collapse. It can also reduce the possibility of splitting, which ultimately improves drying quality.
3. Shrinkage of pre-freezing wood in thickness and width is greater than that of soaked wood and MW treated wood.

A Drying Strategy for 25 mm Thick *Eucalyptus* Lumber

Du Guoxing,[1] Gu Lianbai,[1] Zhong Zhendeng[1] and Liang Zhiqiang[2]

Since the *Eucalyptus* lumber is difficult to dry due to its high density, hardness and twisted grain, it has been largely used for paper and pulp. It is essential to develop a drying strategy for eucalypt lumber if it is to be used for more purposes.

Material and Methods

Green eucalypt lumber was supplied by a sawmill in Hanna province. The lumber was cut to 110×25 mm cross section and 425 mm length. It was block piled to minimise moisture loss and shipped to the research laboratory of Nanjing Forestry University. It remained covered until needed.

The main physical characteristics of the eucalypt wood are: basic density 0.61 g cm^{-3}, air dry density 0.81, radial shrinkage 0.211%, tangential shrinkage 0.294%, modulus of rupture 1026 kgf cm^{-2}, modulus of elasticity 613 kgf cm^{-2}.

Ends of eight test samples were coated with silicon to restrict moisture content movement in a longitudinal direction, and two other matched samples were not coated. Ten samples were tested in each run. Initial average moisture content was 30.4%, measured by the oven-dry weight method.

A mini timber-drying kiln with semiautomatic controller was used. Relative humidity was measured by the dry/wet bulb temperature method. A combination of electrical resistance meter and oven-dry weight method was used to determine the moisture content (m.c.) of samples during drying. Two runs were carried out.

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[1] Wood Drying Laboratory, College of Wood Science and Technology, Nanjing Forestry University, Long Pan Road, Nanjing, China 210037.
Email: <dugx@xinandrying.com>.
[2] Zhanjiang Sunwin Arts and Crafts Co. Ltd, 8 Baipeng Road, Zhanjiang, Guangdong, China 524018.

Drying Strategy

Drying schedule

Since eucalypts have high density, high hardness and twisted grain, a low temperature drying schedule was developed. A moisture-based drying schedule was used (Table 1).

Table 1. Drying schedule for 25 mm thickness eucalypt timber.

Moisture content (%)	Dry bulb temp. (°C)	Wet bulb temp. (°C)	Time (hr)
Pre-steaming	44	44	4
35–30	44	39	
30–25	49	41	
25–20	55	43	
Mid-steaming	55	50	4
20–15	60	40	
<15	71	43	
Equalising	71	58	
Conditioning	71	67	4

Preheating

To reduce the surface checking in early stages, preheating is very important for drying eucalypt wood. In the preheating step, the dry bulb/wet bulb temperatures (DBT/WBT) were set at 44/44°C and maintained for 5 hours. The severe growth stresses were relaxed partly due to the pre-steaming. After the preheating, a mild schedule with low temperature and high relative humidity was used in the first-drying stage, to prevent drying timber collapsing.

Equalisation

The target final moisture content demanded by customers was 9% (DBT 71°C, WBT 58°C). The kiln conditions at the end drying were reset to an give equilibrium moisture content of 7% for the driest

sample, until the moisture content of the wettest sample reached 9%. In this case, the equalisation time was about 17 hours.

Conditioning

Residual stresses, both tensile and compressive, must be relieved after equalisation. An equilibrium moisture content of 12% (DBT 1°C, WBT 67°C) was pre-set for stress relief. Around 5 hours conditioning time was needed in this case.

Results and Discussion

The drying curves are shown in Figure 1. Total drying time, including pre-steaming, equalisation and conditioning, was about 15 days. After drying, the final moisture content (oven-dry), warp, check and stresses of each sample board were measured. The final moisture content was 9.3%, standard devi-

ation 0.28. A small amount of end checking occurred at the early drying stage on the two control samples, but not on the end coated samples. At the late stage, the end checks disappeared. Twist, bow and crook did not occur, but small cupping occurred within two samples of load top, and residual stresses were about 0.73%.

Conclusions

High quality eucalypt timber, without collapse, twist, bow or crook, can be obtained by this drying schedule. Equalisation can significantly equalise final moisture content distribution among sample boards. Final conditioning can greatly reduce residual stresses. End checking can be avoided if ends are coated with silicon. The residual stresses were minor due to the mild drying and final conditioning. Total drying time can be reduced to 15 days from an initial moisture content of 30.4% to final moisture content of 9.3%.
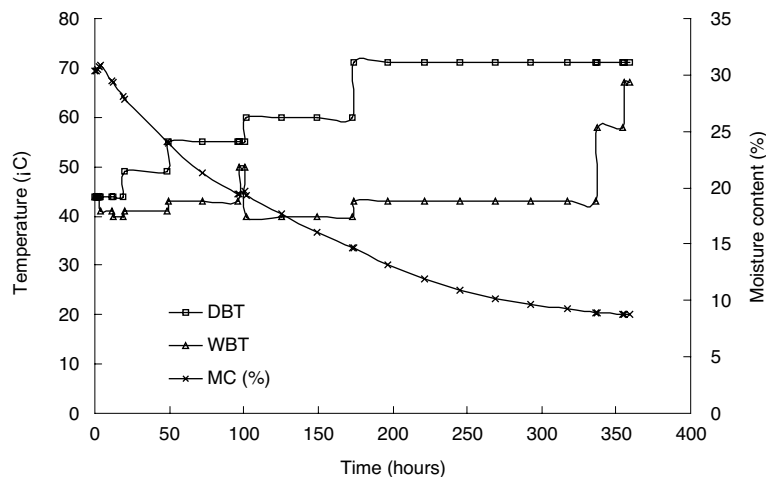

Figure 1. Drying curves for 25 mm thickness eucalypt lumber.

A Study on Eucalypt Wood Lightfastness

Jiang Zehui, Zhao Rongjun, Fei Benhua and Wang Ximing[1]

Surface colour and lightfastness of wood are the main features by which to decide if the wood is suitable for furniture-making and interior decoration, as well as mirroring its close relationship with the psychology, physiology and health of people. Wood pigmentation is generally induced by the xylem and the extractives deposited in wood cell cavities and cell wall. Different tree species show varying degrees of wood pigmentation.

Nobuya (1994) screened three attributes — hue, lightness and colour saturation — for tree species throughout the world, using the colour system index provided by A.H. Munsell. Using a photoelectric examiner, Youko (1987) collected the wood surface pigmentation parameters of commercial timbers belonging to 51 categories in the Japanese market, and the decorative veneers made from 32 tree species. In China, Liu Yixing and Li Jian (1995) made a systematic analysis of the physical quantity of wood surface pigmentation involving 110 tree species. Duan Xinfang et al. (1998) carried out studies on poplar and Chinese fir concerning their distinguishing features of wood colour and the changes in wood pigmentation following chitosan treatment.

There has been no report of studies of surface pigmentation and lightfastness of eucalypt wood from plantations. This short communication summarises results of preliminary research on wood lightfastness of eucalypts under xenon-simulated natural light irradiation of varying durations so as to provide some reference for the full utilisation of eucalypt wood.

Materials and Methods

The tree species selected for the study were: *Eucalyptus urophylla, E. urophylla × E. grandis, E. urophylla × E. tereticornis, E. urophylla × E. camaldulensis, E. cloeziana,* I-72 *Populus × euramericana* Guinier CI. 'San Martino' and *Cunninghamia lanceolata.* Samples of the eucalypts came from Dongmen Forest Farm, Guangxi, the poplar from Hanshou, Hunan Province, and the Chinese fir from Junshanpu, Hubei. Test samples were categorised as radial or tangential sections; sample dimensions were 100 mm × 60 mm × 1 mm.

A X25F xenon fade meter and a CR-300 chromatic aberration meter were used. Seven durations of xenon irradiation were applied: 1, 3, 5, 10, 25, 50 and 100 hours. The colour index of the wood surface was taken after each irradiation by measuring the test pieces in situ.

Results and Discussion

The degree of discoloration is generally the principal standard of wood lightfastness measurement, and is referred to as the reciprocal ratio of wood lightfastness. Wood of high lightfastness is applicable to furniture making and interior decoration. In the experiment, the degree of discoloration was higher as irradiation hours increased. Discoloration increased rapidly within 25 hours of xenon beam irradiation, but slowed beyond 25 hours of irradiation.

The lightness value of Chinese fir wood is lower than that of poplar wood, but higher than eucalypt wood. The experiments show that the lightness value of all eucalypt wood declined with the increase of irradiation hours, while the chromatic index of both red–green colour axis and yellow–blue axis and colour saturation show a gradual increase. Among the eucalypt species tested, wood lightfastness was best in *E. cloeziana* and worst in *E. urophylla × E. tereticornis* (Table 1).

It is concluded that the experimental data will provide a basis for considering the value of plantation-grown timber for architecture, furniture-making and interior decoration.

[1] Research Institute of Wood Industry, Chinese Academy of Forestry, Beijing, China 100091.

Table 1. Change of wood colour parameters[a] in eucalypts and other tree species after 100 hours irradiation.

Species	Radial section				Tangential section			
	L	a	b	c	L	a	b	c
E. urophylla	−14.53	2.34	3.06	3.79	−18.52	5.82	2.02	4.22
E. urophylla× E. grandis	−15.35	2.76	6.18	6.76	−8.4	3.57	6.92	7.72
E. urophylla × E. tereticornis	−16.32	6.25	9.54	11.08	−17.1	5.02	4.83	6.4
E. urophylla × E. camaldulensis	−13.26	3.14	6.93	7.61	−14.59	3.69	7.05	7.94
E. cloeziana	−8.92	2.77	8.41	8.85	−7.62	3.67	6.57	7.27
Populus sp.	−9.89	4.25	13.39	13.95	−11.14	4.54	10.46	11.18
Cunninghamia lanceolata	−10.79	3.51	13.52	13.96	−6.06	1.58	9.75	9.84

[a] L = lightness value; a and b = chroma indices; c = colour saturation.

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Development of Eucalypt Cement Flakeboard: a New Fire-Retardant Board

Feng Jin-Tao,[1] Ye Ying-Xiang,[2] Wu Zhen-Ji[3] and Wu Qlan-Ping[4]

Fire brings us light and heat, and promotes social development and progress. But fire can also be a risk. In the last 20–30 years, the application of macromolecular materials and their products in building construction has brought hidden fire problems. It is evident that heavy casualties and economic losses would be caused by fire in a multistorey building. Nowadays, for seeking a more comfortable lifestyle, as well as meeting personal physiological and psychological needs, householders like to decorate their rooms with wallpaper, wooden ceilings and floors etc. Doubtless these decorative materials pose a hidden fire risk. Serious effects from fire are induced by high temperatures, dense smoke and poisonous gases. Therefore, it is very important to conduct studies on burning and smoke-control of building materials.

Development of Fire-Retardant Cement Flakeboard

For a thousand years, brick has been the traditional construction material in China. To build residential and industrial buildings, we have to destroy large areas of land to make bricks. Development of highrise buildings in the past 50 years has stimulated development of light-weight, high-strength, fireretardant cement flakeboard (cement-bonded particle board, CBPB) It can be used not only as a construction material but also as indoor decorative and furniture material. CBPB is an inorganic wood-based panel made with cement as adhesive and timber fragments as strengthening material. It is made with selected chemicals and water, through a process of stirring, layering and pressing.

In the early 1960s, a CBPB factory of 20,000 m^2 annual output was set up in Japan. Now CBPB is mainly produced in Europe, Russia, Southeast Asia and Japan. At the beginning of the 1970s, Guangzhou Xicun timber factory produced some CBPB manually. In the 1980s, Beijing, Shanghai, and Fujian conducted CBPB product line tests, but fire-retardant CBPB has yet to be produced on a large scale in China.

CBPB has developed quickly and has been produced on a large scale in other countries. The German Schworerhaus Construction Company near Berlin was the first company to produce inorganic construction concrete structures using CBPB. It made largesize, weather-resistant, fire-retardant CBPB. This inorganic construction structure using CBPB is a large panel (12–38 × 6500 × 3000 mm, with a tolerance within 0.3–0.5 mm). There is no pollution in the production process, all waste can be recycled, and the cost is less than traditional construction material. It has similar properties to the marketed CBPB, because the company used fast-glue inorganic adhesive. This technique can make use of residues of bagasse, straw etc. and produce high quality CBPB.

Production and Utilisation of CBPB

CBPD manufacture can be separated into three processes: raw material preparation, shaping and quality control. The raw material can come from fastgrowing, small-diameter trees, harvesting residues, and sawmill waste. The wood is chipped and screened, then layered according to size and shape. Cement and additive are also required.

Tests show that the static bending strength changes with time. After 6 years indoors, with the hydration in the mineral material in cement, the cohesion improves significantly, and dimensional stability improves. Static bending strength increases by 10–12%, and flush tensile strength rises by 36–100%.

[1] Guangdong Forestry Department, Guangzhou, 510173, China.
[2] Guangzhou International Trust and Real Estate Development Corp., Guangzhou, 510045, China.
[3] Jinlianshan Forest Farm, Lianpian, Guangdong Province, 517100, China.
[4] Guangdong Forest Products Industry Company, Guangzhou, 510080, China.

Table 1. Strength properties of CBPB, gypsum particle board and synthetic resin particle board.

Panel	Density	Static bending strength	Elastic modulus	Flush tensile strength	Surface rupture of stretching	Swelling
	$(kg\ m^{-3})$	(Mpa)	(Mpa)	(Mpa)	(%)	(%)
CBPB	1100–1200	9–15	3000–6000	4–5	0.4–0.7	1
Gypsum particle board	1100–1200	6–10	2000–3500	2.5–4	0.3–0.6	1
Synthetic-resin particle board	650–750	12–24	2000–3500	7–10	0.5–1.0	8

CBPB has the properties of both cement and timber. It has high strength, fire retardance, water-proofing, resistance to fungi and termites, and good sound and heat insulation characteristics. It is also light in weight, and has high elasticity and good machining properties (Table 1). It can be nailed, drilled, notched and decorated with different materials on its surface.

CBPB is used widely in construction. One cubic metre of CBPB can make a 25–30 m^2 wall at a cost of about 70 RMB m^{-2} compared with 60 RMB m^{-2} for walls built with solid clay brick (SCB) (US\$1 = 8 RMB). However, because of its light weight, the costs of transportation and building foundations are reduced. Also, as the width of construction walls is small, room space is enlarged.

CBPB can be glued, coated directly, or decorated with ceramic tiles, mosaics etc. As interior and exterior walls, CBPB accepts a wide range of surface treatments. It can reduce the weight of the building, and because of its light weight and large dimensions can increase significantly the speed and efficiency of building construction.

Sound insulation of CBPB 12–100–12 mm composite hollow wall is 46.4 decibels, compared with 45 decibels for a 12 mm hollow brick wall, and 35 decibels for a two-side plate coated wall. CBPB's good sound insulation and quakeproof properties make it an ideal panel for wall partitions where there is a high noise level. Its fire retardance and waterproofing are better than other artificial panels. It is a relatively inexpensive material. The price of CBPB is about 2000 RMB m^{-3}, compared with 3200 RMB m^{-3} for medium density fibreboard (MDF) and an even higher price for plywood.

Research on Medium-Density Fibreboard at CSIRO

P. Collins, G. Freischmidt, S. Terrill and P. Warden[1]

Medium-density fibreboard (MDF) has found a growing range of applications in recent years, and production capacity in Australia, based mainly on *Pinus radiata*, now totals about 850,000 m^3 of board per annum. It is anticipated that production capacity will increase in future years to meet increased domestic demand and rapidly expanding export markets.

Future challenges facing the Australian MDF industry include the need to diversify the range of product types manufactured, in particular with respect to density, durability and machinability. In addition, it is likely that the industry will need to process a more diverse range of wood-based feed-stock, as increasing quantities of plantation hardwoods become available. In order to support the Australian industry in addressing these needs, CSIRO Forestry and Forest Products has recently installed a state-of-the-art MDF pilot plant, which will accurately simulate industry practice, ensuring that research findings have 'real world' relevance.

The pilot plant, which is based in Melbourne, consists of a pressurised TMP defibrator, blowline with resin and wax injection, flash dryer, off-line moisture content meter, mattress former and pre-press, and a computer controlled hot press with a 1 m × 1 m platen area. Supplementary equipment includes a chipper, automated chip sieving, belt sander for sanding panels and a comprehensive suite of analytical and mechanical testing equipment, including a density profilometer, for product-property evaluation. The plant has a throughput capacity of approximately 60 kg dry fibre per hour.

The pilot plant has already been used by Australian industry to investigate new wood-based feed-stocks and adhesive formulations. It is currently being used in two related projects to investigate the suitability of a diverse range of indigenous species of Australian hardwoods for MDF production. The main aim of the projects, named Search (funded by the Natural Heritage Trust) and Florasearch (funded by the Rural Industries Research and Development Corporation and the Murray–Darling Basin Commission through the Co-operative Research Centre for Plant-based Management of Dryland Salinity), is to identify woody perennials that could be grown to both ameliorate degraded land and provide feed-stocks for forest products industries. MDF is a key product of interest. While the work is ongoing, early results suggest that there is a range of previously ignored species which could potentially be grown as a future source of wood feed-stock for the Australian MDF industry.

Future planned research areas include the evaluation of other new sources of fibre (including non-wood plant fibres such as cereal straws), optimised approaches for the incorporation of insecticides, fungicides and fire retardants in MDF, and the development and evaluation of fast cure phenol formaldehyde adhesives.

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[1] CSIRO Forestry and Forest Products, Private Bag 10, Clayton South, Victoria 3169, Australia.
Corresponding author, Peter Warden;
email: <Peter.Warden@csiro.au>.

SilviScan — Revolutionary Technology for Rapid Evaluation of Wood Properties

R. Evans, G. Downes and Jun-Li Yang[1]

SilviScan is a fast and cost-effective instrument for measuring wood properties. It provides profiles of commercially important wood properties in both softwoods and hardwoods.

The SilviScan technology, developed in CSIRO, Australia's national science agency, heralds momentous change in how hardwood and softwood forests are managed, the precise matching of timber quality to end uses and the growing of superior strains of trees worldwide.

While the ability to analyse aspects of wood quality has been around for some years, it was laborious, time-consuming, expensive and usually involved felling trees. SilviScan tests for a dozen quality factors at up to 1000 times the speed — while the trees are still standing in the forest or plantation. SilviScan has made it possible to choose the most appropriate type of trees for future planting so that the next generation of trees will have a greater economic value. It will also soon enable forestry managers to map large areas of trees for quality and suitability for particular products, leading to potential savings of millions of dollars, high value 'designer' products — and more satisfied timber customers.

Measurements are generally made on a 12 mm core of wood taken from the living tree. The TrecorTm corer can be used to sample over 100 trees per day without the risks of overuse injuries associated with hand coring. The core sample is prepared using a twin edged saw to produce 2 mm sample which is sanded smooth before passing it through the SilviScan instrument. SilviScan combines X-ray densitometry, diffractometry and image analysis to measure a variety of properties in a single process, from a single sample.

SilviScan can measure: ring width, latewood proportion, ray angle, fibre diameter (radial, tangential), fibre orientation (indirect), wall thickness (indirect), microfibril angle (MFA), cellulose crystallite width, coarseness (indirect) and stiffness (indirect).

[1] CSIRO Forestry and Forest Products, Private Bag 10, Clayton South, Victoria 3169, Australia. Email: <rob.evans@csiro.au>; <geoff.downes@csiro.au>.