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Making Nature Pay: economics of plant germplasm collections in Papua New Guinea

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1. Introduction

Papua New Guinea has major germplasm collections in its major subsistence and semi-commercial food crops aibika, banana, cassava, sweet potato, taro and yams. PNG also has a collection of hybrid sugar canes for its own sugar cane industry. Except for sugar cane, nearly all the varieties in these collections were collected in PNG. PNG is also a major centre of genetic diversity for some of these plant kinds (e.g. plantain bananas, taro, some yams and sugar cane). Since varieties of these plants are heterozygous and cannot be stored as seed, all agricultural varieties of these plants are vegetatively propagated, and predominantly vegetatively maintained in germplasm collections in the field. Although the absolute costs of maintaining these collections are low, the costs are high relative to PNG's financial resources. Even if external funds could be obtained for this germplasm maintenance, economic issues still arise such as whether alternative techniques should be used to preserve existing plant germplasm resources, or whether funds should be targeted on different species.

Because use of plant material in one breeding program does not preclude its use in another program, plant germplasm is non-rival. Because of difficulties in establishing effective property rights in plant varieties used in breeding,[1] germplasm may often be non-excludable. Non-rivalry and non-excludability characterise public goods which are generally under-produced in market economies. Because germplasm conservation is a public good, sufficient conservation would probably not be undertaken if left solely to the private sector. Consequently, the collection of accessions for and the maintenance of plant germplasm collections have typically been undertaken in the public sector. Public goods are even more likely to be under-produced in developing countries because of high demands on government resources, and germplasm collection and maintenance are often undertaken internationally (cf. Kambuou 1995 on collecting expeditions to PNG). Because the use of plant germplasm is non-rival, there has developed a corresponding ethos of the free exchange of plant germplasm among plant breeders; this free exchange is probably an economically efficient system. However, the greater commercialisation of public breeding, and the higher profile of private breeders supported by plant breeders' rights, has increasingly highlighted the value of genetic material used in plant breeding (Godden 1984, 1991). Coupled with financial restrictions on germplasm conservation programs and current (and likely future) increased emphasis on the commercial value of germplasm collections, there is a need for a more systematic analysis of the optimal levels of funding, and the optimal economic organisation, of plant germplasm collections.

Maintenance of plant germplasm is an investment problem. Economic analysis of germplasm storage requires a comparison between the rate of return from investing in the conservation of germplasm and rates of return obtainable elsewhere. The principal difficulty in evaluating germplasm investment decisions lies in being able to assess the value of the germplasm. The production process for plant breeding may conceptually be modelled, linking germplasm to (i) an understanding of the constraints limiting plant production; (ii) the relaxation of those constraints to produce varieties providing higher yields and better quality characteristics; and (iii) contributions to maintenance research to offset declines in the resistance of commercial cultivars to scourges.[2] Such modelling would enable estimates to be made of the value of germplasm.

With the exception of bananas and sugar cane, there has been much less plant breeding in the above crops than in the comparable staples of developed countries. There is thus likely to be considerable potential for plant breeding to improve the yields and other product characteristics of these crops. Plant germplasm collections are likely to play a major role in crop improvement in these species. Thus the collections that PNG holds will be of major significance to future crop improvement for both PNG, and possibly also in other countries. Some of the historical and potential benefits of this material are international—for example, some 25 per cent of the genes of modern sugar cane hybrids are derived from the PNG canes *Saccharum officinarum*. However, PNG is bearing the full cost of maintaining its germplasm collections. There is likely to be under-investment in conservation of PNG's plant genetic resources (from the international viewpoint) unless mechanisms for paying PNG to maintain its genetic diversity can be established. Further, in a developing country like PNG, insufficient resources may be available for the conservation of plant germplasm even from a purely national perspective.

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[1] Even with intellectual property rights in commercial plant varieties (plant patents, plant breeders rights, plant variety protection, plant variety rights etc.) there may be difficulties in establishing effective property rights (cf. Godden 1982).

[2] i.e. pests, diseases and weeds.

The objective of the research is to assist PNG to assess whether or not it wants to maintain these germplasm collections and, if the collections are to be retained, what is the most efficient means of doing so. The general framework of the analysis will also be relevant to other developing—and developed—countries interested in examining the social returns to investment in plant germplasm collections. The initial focus will be on the costs of maintaining a restricted set of PNG's plant germplasm collections (in aibika, banana, sweet potato and taro). This analysis will enable policy makers to evaluate the effects of changing the sizes of collections and/or reallocating funding across different plant kinds and different methods of germplasm conservation. A general framework for analysing the contribution of germplasm to the plant breeding process which integrates cost data and estimates of the value of various classes of germplasm will also be developed. This general framework will be applied to the germplasm collections in PNG to assess the net contribution of these collections to PNG and world agriculture, and to guide decision-making about the future of these collections and related collections elsewhere.

2. PNG agriculture[3]

2.1 Background to PNG

New Guinea lies between 3.5 and 12 degrees south of the equator and is approximately 2,500 kilometres east to west, with an area of around 775,000 square kilometres. The eastern part of the island comprises the mainland of Papua New Guinea (PNG) which also includes the large islands of New Britain, New Ireland, Buka and Bougainville, and many smaller islands. Irian Jaya, a province of Indonesia, occupies the western half of the New Guinea island. The area of PNG is about 475,000 square kilometres and it has a population of around 4 million.

The centre of the main island of PNG consists of a series of mountain ranges rising to over 4,000 metres with populous upland valleys. The climate in coastal areas and larger islands is generally hot and humid, with temperatures ranging from 25 to 35 degrees Celsius. The valleys of the Highland region are usually hot in the daytime but cool to very cold at night. Rainfall varies from 1000mm per year in Port Moresby, to over 8000mm in some wetter areas of the country; about 80 per cent of the country receives over 2500mm. Some areas also have a pronounced dry season (McAlpine et al. 1983, chapter 4).

The vegetation of the country varies with elevation and rainfall. PNG flora has some similarities with those occurring in Indonesia, Malaysia, the other Pacific Island countries and the wetter parts of northern Australia. The tropical rainforest areas of the central and the north western parts of mainland PNG are rich store houses of genetic resources of flora and fauna much of which is unique.

2.2 Agriculture

Agriculture is the most important sector of PNG's economy. It provides a livelihood for about 85 per cent of the economically active population of PNG, and employment for 25 per cent of the workforce in the commercial sector of the economy. Agriculture creates about 25 per cent of Gross Domestic Product and contributes 14 per cent to foreign exchange earnings. The agricultural sector comprises subsistence, semi-subsistence and commercial sub-sectors. Smallholder farmers are the most prominent producers who produce 75 per cent of coffee production, 65 per cent of cocoa, 66 per cent of copra and 35 per cent of oil palm and almost all food crops (96 per cent of all agricultural produce). The employment structure of agriculture is 8.5 per cent purely subsistence, 87 per cent semi-subsistence or semi-commercial engaged in both subsistence and commercial activities, and 4.5 per cent purely commercial.

(a) Food Production and Consumption

Production of staple foods remains the most important economic activity for most of PNG's rural population. Semi-subsistence food production is based upon the traditional systems of shifting cultivation. Pressures of development and modernisation, such as urbanisation, rising population pressure in some areas, and the growing desire for cash among rural people are likely to cause a gradual change towards more sedentary systems of production.

Subsistence farmers in PNG grow a diversity of food crops in their gardens. A variety of crop species are planted in a mixed cropping manner, usually at very high densities. The succulent leafy vegetables

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[3] Based on Kambuou (1995, chapter 1).

are planted first, followed by root crops and then tree crops like bananas and fruits and nuts. Sweet potato (*Ipomoea batatas* L. Lam.) is the predominant crop in the Highland areas of the country. In the Lowlands, the cropping systems are more diverse and vary among areas. The dry coastal areas of the Central Province follow a yam-banana-cassava based system. Yams (*Dioscorea spp.*) are usually harvested first, followed by a number of harvests of banana (*Musa spp.*) and cassava (*Manihot esculenta* Crantz). Taro (*Colocasia esculenta* L. Schott) is predominant in the wet lowland areas of Morobe Province and the atoll environment of the North Solomon Island. Diploid bananas are widely cultivated in the Madang, New Britain, New Ireland, Morobe and the Sepik Provinces. Triploid and tetraploid bananas are more suitable to the drier areas of the Markham/Ramu valleys and the Central Province. Yam based cropping systems are practised in some inland areas of East Sepik, Madang and the Trobriand Islands of the Milne Bay Province. Sago (*Metroxylon spp.*) is predominant in low marshland areas throughout the country and is still harvested from the wild. People from the wetland areas of the Fly, Sepik, Ramu and Puerari deltas closely follow the sago based cropping system; root crops and leafy vegetables are grown on marginal arable land as a supplement to sago.

Despite periodic localised food shortages and a few pockets of severe malnutrition, food supplies and overall levels of nutrition appear adequate throughout PNG. Commercial production of food crops is limited by the size of the domestic market, while the marketing of traditional staple crops is adversely affected by their low value-for-weight ratio and perishability. Sugar is commercially produced in the country essentially for the domestic market and is currently completely protected by an import ban.

Domesticated pigs are the main animal used in the traditional systems, together with village fowls and chickens. The remaining livestock for food are hunted. Domesticated pigs play a significant role in the social life of the Highland areas. Pigs are regarded as a form of wealth and are used mainly in traditional marriage ceremonies and death feasts. Domesticated livestock are generally free ranging although supplements of sweet potato tubers and vines and split coconuts are occasionally fed to pigs. With contemporary changes in life style and greater emphasis on the monetary economy, farmers across PNG are expanding into livestock production, including cattle, sheep and goats, piggeries and poultry for both layers and broilers. These are intensive systems and farmers have to make changes to their subsistence way of life to cater for these changes.

The commercial livestock industry consists of a few intensive broiler chicken operations that also supply feed and chicks to out-growers, a few intensive piggeries and cattle ranches mainly in the Markham Valley. Since independence the poultry and pork industries have reached self-sufficiency levels with Government protection. The government is attempting to develop a small sheep industry in the Highlands to increase local production and consumption of meat.

The main river systems in the country include the Sepik, Fly, Ramu, Markham and Puerari river systems. The livelihood of PNG's coastal and river people revolves around the sea and the water ways. These people depend on harvests from the sea and the river systems. The coral reefs surrounding the islands and the coastal areas of PNG are rich in marine life including a diversity of fish, shells, lobsters, crabs, sea weeds and variety of other sea creatures. The waterways are also rich in fresh water fish, prawns, crabs and other river food.

People from the coast and the river systems also practise shifting cultivation for production of fresh vegetables and staple root crops to supplement their aquatic diets. Sago is the main staple food crop for the people living on the plains of the Sepik, Fly and Puerari deltas. It grows wild in the river plains and swampy areas throughout the country and is harvested whenever needed. Due to the shortage of arable land for cultivation, river people establish social contacts with mountain and inland people for barter purposes. Fish and other river food are exchanged for root crops and other vegetables.

(b) Export Crops

Crops contribute significantly to export earnings with an average of K260 million between 1985 and 1993.[4] Coffee is the important crop in terms of foreign exchange and employment with about 50 per cent of all rural households producing over 70 per cent of the crop annually. About 64,500 hectares (50,000 ha smallholdings and 14,500 ha plantations) are under coffee. Cocoa is the second most important crop with 22 per cent of the value of major agricultural exports. About 11 per cent of all rural

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[4] PNG's currency unit is the kina (K). In October 1995, the kina traded approximately 1:1 with the Australian dollar. In September 1994 there was a 25 per cent depreciation of the kina.

households produce 66 per cent of the crop and the balance from the plantations. Cocoa has an area of 116,600 hectares with 49,900 ha under estates and 66,700 ha as smallholdings. Oil palm is the third major crop with 14 per cent of the value of exports annually. It covers an area of about 58,000 hectares (33,000 ha estates and 25,000 ha smallholders involving about 7,000 families); estates produce 65 per cent of the output and the remaining 35 per cent is from smallholders.

In the coconut industry, copra and coconut oil account for 11 per cent of the value of major agricultural exports and the industry supports about 111,000 households cultivating an area of about 100,000 hectares. Rubber and tea are small in terms of production, acreage and foreign exchange earning. About 8,000 households grow rubber and the production in 1993 was 2,800 tonnes with an export value of K2.2 million. More than 83,000 households are engaged in the growing of spice crops and other alternative cash crops. The important individual crops are chillies, cardamom and pyrethrum. The export value of these crops in 1992 was K8.2 million.

3. PNG's food plant germplasm

The selection and/or development of new plant varieties still largely depends on traditional techniques of observing and recording superior plant material, inducing sexual reproduction using superior parent material, and selecting the elite offspring of these crosses. The continued development of superior new varieties depends on the continual search of the plant genepool for desirable characteristics that might be incorporated in new varieties. Conventional plant breeding is thus dependent on the maintenance of the existing genepool and its thorough evaluation as a source of suitable new genetic traits. The first of the genetic material derived from "genetic" engineering" is just beginning to become available but it, too, is currently dependent on the incorporation of known genetic traits into existing plant kinds. A typical example of such search for new varieties was the screening of taro varieties for resistance to taro leaf blight, and the incorporation of this characteristic into varieties by traditional sexual crossing of varieties in a PNG plant breeding programme.[5]

3.1 Background

Subsistence farmers in PNG traditionally maintain, multiply and distribute their own planting materials. Almost all the crops grown are vegetatively propagated, and planting materials of crops such as bananas, taro, cassava, aibika and other leafy vegetables are maintained in old garden sites until the new gardens are made. Seeds of amaranths and other vegetables are usually wrapped in leaves and stored above fire places for up to a month before planting. The good tubers of yams are selected and stored in specially built yam houses to allow the tubers to sprout before they are planted out. In the Trobriand Island of Milne Bay Province, yams are stored in yam houses for a longer period of time for eating as well as for planting.

New Guinea is a centre of genetic diversity for plantain bananas, taro, some yams and sugar cane (Kambuou 1995). Sweet potato and cassava are exotics but have been in Papua New Guinea for at least several centuries; the former flowers profusely in the Highlands and there is thus the opportunity for continued field evolution. The PNG germplasm collections of the food staples (i.e. excluding sugar cane) are of PNG origin, and little of this material has been relocated outside PNG.

Varieties of these plants are all heterozygous and are thus vegetatively propagated in agricultural use. These varieties can only be stored as vegetative material, although seeds of some plant kinds are viable (e.g. sweet potato, taro, sugar cane) and thus gene pools can be stored using seed. Varieties of these plant kinds have traditionally been maintained as field collections via frequent vegetative propagation. Aibika and the root crops are replanted at about 6-monthly intervals, while banana and sugar cane are replanted every few years.

There are major collections of germplasm in Papua New Guinea for the following crops (cf. Table 1):

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[5] As an example of the vlaue of conventional plant breeding, Brennan and Fox (1995, Table 17) estimated the present value of direct benefits of the incorporation into Australia's wheat varieties of the wheat "dwarfing" genes derived from the CIMMYT programme in Mexico as $2,640m in 1993-94 values.

Aibika (*Abelmoschus manihot*), banana (*Musa spp*), cassava (*Manihot esculenta*), sweet potato (*Ipomoea batatas*), taro (*Colocasia esculenta*), yams (*Dioscorea* spp)—at research stations of the Department of Agriculture and Livestock (DAL).

Sugar cane (*Saccharum* hybrids)—Ramu Sugar Company has an extensive collection of commercial cane hybrids; there are also the remnants of a collection of indigenous sugar canes at DAL's Bubia Agricultural Research Centre.

Some PNG material is also held in field collections outside PNG (e.g. bananas in the INIBAP regional collection in the Philippines, Queensland Department of Primary Industries' Maroochy Research Station, and at Montpellier in France). Tissue culture can be, and has been, used to maintain PNG germplasm for some of these crops—both within PNG (e.g. sweet potato at the Lowlands Agricultural Experiment Station, Keravat) and outside PNG (e.g. bananas at Maroochy and sweet potatoes in the PRAP project in Western Samoa). Some variation may occur in tissue culture (e.g. bananas).

The annual cost of maintaining the publicly-held germplasm collections in PNG is approximately K107,000, and the breeding programme in taro and variety evaluation programme in sweet potato directly associated with two of these collections also costs approximately K107,000 p.a. (Table 2). The cost of maintaining the Ramu Sugar Company's sugar cane collection is unknown. While this public expenditure appears small, for a country like PNG with major macroeconomic and government budgetary constraints, even relatively small expenditures are of considerable economic importance, especially when such expenditure must be incurred every year. Germplasm maintenance and crop improvement programs for the food staples together comprise about 24 per cent of DAL's research budget (Ghodake and Wayi 1994, p.93).

PNG's scarce resources in plant germplasm conservation are devoted to the relatively small number of plant kinds which are the major current food sources for the population. However, PNG has a rich source of plant genetic diversity (Kambuou 1995), some of which is currently used to obtain food, fibre and medicinal materials. Some of these plant materials may also provide significant future commercial opportunities. These potential future benefits may not be attained if the current emphasis on existing crops is maintained and existing diversity in other species is not protected and explored. Future benefits foregone from a failure to exploit other species are an opportunity cost of the current concentration of conservation efforts in a small range of plant kinds.

3.2 Genetic Diversity of Edible Plants[6]

(a) Root crops

Root crops constitute the main staple diet of PNG. Sweet potato (*Ipomoea batatas* L. Lam) is PNG's main root crop. It is widely cultivated in PNG from sea level up to 2700m with the main production sites in the Highland provinces. Sweet potato actively seeds and constantly undergoes cross-pollination in field conditions particularly in high altitudes. This has contributed to its great genetic diversity in the country. *I. tuba* is cultivated for its tuber in the Transfly area of Western Province. *Ipomoea aquatica* (locally known as kangkong) is an aquatic, floating herbaceous perennial cultivated for its young succulent terminal shoots and leaves which are used as spinach in the local diet. Several wild Ipomoea species are found in PNG (*I. digitata* L., *I hederifolia* L., *I. plebeia* R. Br. and *I. triloba* L).

Taro (*Colocasia esculenta* L. Schott) is the second most important root crop of PNG. It is one of the traditional indigenous food crops of PNG and is predominantly grown in lowland rainforest areas of moderate fertility from sea level up to 2700m. PNG has the world's largest genetic diversity of taro. A survey of wild taro by the team of taro scientists based at Bubia Agricultural Research Centre, Lae, PNG has shown that there is relatively low diversity within the wild taro population observed in 21 locations throughout the main taro growing areas. Other species of Araceae commonly grown in the country include chinese taro (*Xanthosoma sagittifolium* L. Schott), swamp taro (*Cyrtosperma chamissonis* Schott Merr.), giant taro (*Alocasia macrorrhiza* L. Schott) and elephant foot yam (*Amorphophallus campanulatus* Blume). Except for a few cultivars of chinese taro, the remaining species grow as natural stands in the wild. The polynesian arrowroot (*Tacca leontopetaloides* L. O. Kuntze) is commonly seen growing wild in the coastal areas up to 200m.

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[6] Based on Kambuou (1995, chapter 2).

The yams (*Dioscorea* species) are the third most important root crops of the country. Eleven of these species have edible tubers and six are found in PNG. The diversity of genetic materials is found in two commonly grown species, *Dioscorea alata* and *Dioscorea esculenta*. These species are widely cultivated throughout the country for food and are very important ceremonial crops in some areas. Other species not so commonly cultivated are aerial yam (*D. bulbifera* L.), five leaflet yam (*D. pentaphylla* L.), bitter yam (*D. hispida* Dennst.) and nummularia yam (*D. nummularia* Lam.). The genetic diversity of the less common species has not been fully explored. Most of this germplasm grows in natural forest habitats.

Cassava (*Manihot esculenta* Crantz.) is an important staple root crop in areas of poor soils and harsh conditions with a prolonged dry season. It is the main staple root crop in the dry coastal areas of the country. *Manihot esculenta* is not known in a wild state. There are a few cultivars grown as ornamentals and temporary shade in towns and villages but there is no information on the germplasm of the ornamental cassava.

Other minor edible root crops have been reported such as hangar (*Operculina turpethum* L. S Manso.), kudzu (*Pueraria lobata* Willd. Ohwi), yam bean (*Pachyrrhizus erosus* L. Urban) and winged bean (*Psophocarpus tetragonolobus* L.D.C.). Except for wing bean, very little is known about the genetic diversity of these minor root crops in PNG.

(b) Bananas (plantains)

Cooking bananas, including plantains, are the third most important staple food crop in PNG. The indigenous population consumes bananas more as a staple food than as an accompaniment or a dessert. Well over 500 accessions of diploid, triploid and tetraploid bananas have been collected throughout the country and assembled into a national ex situ field collection.

The original collection comprised cultivated *Musa acuminata* as diploid (AA, AB), triploid (AAB, ABB, AAA) and tetraploid (AAAB, AABB, ABBB) genomes, together with seven wild species (*Musa banksii*, *M. balbisiana*, *M. schizocarpa*, *M. peekelii* (*angustigema*), *M. maclayi*, *M. textiles* (Manila hemp), and *M. lolodesis*). The collection also had a plant of *Ensete glaucum* which has been lost. About 30 per cent of the total collection has been lost over the years due to problems of field maintenance. The current collection now holds 353 accessions mostly of edible genomes.

(c) Leafy Vegetables

There are well over 40 different species of green leaf vegetables eaten in PNG. The most popular species include aibika (*Abelmoschus manihot* L. medik), amaranthus spp., tulip (*Gnetum gnemon* L.), rungia (*Rungia klossii* S. Moore), water dropwort (*Oenanthe javanica* D.C.), blackberried nightshade (*Solanum nigrum* L.), kumu mosong (*Ficus copiosa* Steud. and *F. wassa* Roxb.) and other Ficus species, kangkong (*Ipomoea aquatica* Forskal), watercress (Nasturtium spp.), valanguar (Polyscias spp.), kumu gras *(Callipteris prolifera* Lam. Bory.) and other edible ferns, choko tips (*Sechium edule* Jacquin Swartz) and pumpkin tips (*Cucurbita moschata* Duch ex Lam). All these leafy vegetables are either cultivated in gardens or grown wild. Some of these crops have great intra-specific variation (cf. Kambuou 1995, chapter 2). Kambuou (1995, Appendix 1) listed other edible greens mainly harvested from the wild which have not identified nor recorded.

(d) Other Indigenous Vegetables

Over 60 species or kinds of vegetables have been reported as grown and eaten in PNG. Many of these species have been recently introduced in the country and are gaining popularity in village gardens and in the local diets. The few indigenous species include the Highlands pitpit (*Setaria palmifolia*, Koenig. Stapf), coastal pitpit (*Saccharum edule* Hasskarl), ginger (*Zingiber* spp.), choko (*Sechium edule* Jacq. Swartz), cucumber (*Cucumis sativus* L), pumpkin (*Cucurbita moschata* Duch ez Poir), wingbean (*Psophcarpus tetragonolobus* L. DC), arenga palm (*Arenga microcarpa* Becc.), small bamboo (*Bambusa forbesii* (Ridl. Holt.), bamboo (*B. vulgaris* Schrad and *Nastus elatus* Holttum), Job's tears (*Coix lachryma-jobi* L.), lotus (*Nelumbo nucifera* Gaetn.) and waterlilies (*Nymphaea pubescens* Willd.). Many other wild indigenous plant species are eaten by local people as minor vegetables (cf. Kambuou 1995, Appendix 2).

(e) Fruit Tree Species

A wide variety of tree fruits is utilised in PNG, and their uses may include both consumption of the fruit itself and other parts of the plant. Mangoes (*Mangifera* spp.) are common in the lowlands but their productivity is restricted mainly to areas with prolonged dry spells. There is one widely cultivated species and several edible wild species grown in forested areas. Bukubuk (*Burckella obovata* Forst. Pierre) is a native fruit to the atolls of PNG and is a highly preferred fruit in East New Britain, New Ireland and other small islands. Marita (*Pandanus conoideus* lamarck) grows throughout PNG from sea level to 1600m altitude. Taun (*Pometia pinnata* J.R. & G Forster) is a large tree with wild stands throughout the lowlands and the lower montane forests. Golden plum/apple (*Spondias cytherea* Sonnerat) grows up to 15m and occurs wild in the lowland rainforest areas; a wild species (*S. philippinensis* (Elmer)) occurs naturally in the Sepik area. The tree cucumber or bilimbi (*Averrhoa bilimbi* L.) grows wild in secondary forests in many coastal areas.

A number of *Citrus* spp is grown in the country, many of which may have been introduced a considerable time ago. The indigenous species of the country is *C. hystrix* (L.) D.C., occurring wild in most coastal areas. Other cultivated species include lime (*C. aurantifolia* Christm. Swing.), sour orange (*C. aurantium* L.), pomelo (*C. grandis* L. Ossbeck), lemon (*C. limon* L. Burm. F.), citron (*C. medica* L.), grapefruit (*C. paradisi* Macf.), mandarin (*C. reticulata* Blanco) and orange (*C. sinensis* L. Osbeck). *Clymenia polyandra* (Tanaka) Swingle is related to citrus and occurs only in PNG.

A native fruit of Manus Island is *Corynocarpus cribbianus* (F.M. Bail) L.S.Sm. Mabewa (*Baccaurea papuana* Bailey) occurs in several lowland areas from sea level up to 1600m altitude. The New Guinea walnut (*Dracontomelon dao* Blanco Merr. & Rolfe), known locally as mon, is a large tree up to 50m tall and occurs wild in the high rainforest areas of the country. There are several *Eugenia* species occurring in the country. Six species are reported as eaten (*E. aromatic* (L) Bill., *E. aquea* Burm.f., *E. jambos* L., *E. javanica* Lam., *E malaccensis* L. and *E. uniflora* L.) which occur mostly in coastal areas from sea level up 1600m altitude. Three *Flacourtia* species are reported eaten in the country (*F. inermis* Roxb. known locally as Lovi-lovi, *F. jangomas* (Lour.) known locally as raeusch or coffee plum, and *F. rukam* Zoll. & Mor. known locally as rukam. Four *Rubus* or Raspberry species are reported to be eaten in PNG and they occur mostly in the Highland areas (*R. fraxiniflius* Poir., *R. moluccanus* L., *R. rosifolius* Smith and *R. lasiocarpus* Sm.). The alpine strawberry (*Fragaria vesca* var. *semperflorens*) grows from 1600m to 3500m and mostly occurs around the Mt. Wilhelm area. Five species of *Passiflora* were introduced into PNG but the local wild species is *P. foetida* L. which grows abundantly in the lowland areas and fruits throughout the year. A fruit tree species *Parartocarpus venenosus* (Zoll. & Mor.) Becc grows wild in the humid rainforest areas in the country. Kambuou (1995, Appendix 3) listed othern minor indigenous fruit crop species.

(f) Nut Tree Species

Nut species utilised in PNG include betel nut (*Areca* spp., known locally as Buai), pandanus species, four edible *Canarium* species (the most popular of which is known locally as galip nut or canarium almonds (*Canarium indicum* L.) and the other species are *C. kaniense* Laut., *C. salomonense* B.L.Burtt and *C. schlechteri* Laut), five edible *Terminalia* species (the most common of which is *T. kaerrbachii* Warb known locally as okari nut and other species *T. catappa* L., *T. copelandii* Elm, *T. impediens* Coode and *T. megalocarpa* Exell), *Barringtonia novae-hebernae* Laut (locally known as Pao) and the related edible species *B. procera* (Miers) Knuth together with a non-edible wild species *B. asiatica* (L) Kurz used as a fish poison, the PNG oak or castanopsis chestnut (*Castanopsis acuminatissima* Bl.A.DC), the finschia nut (*Finschia* spp), the Tahitian chestnut (known locally as aila) is a tall tree occurring in lowland forest areas near rivers and swamps, candle nut (*Aleurites moluccana* L Willd), nipa palm (*Nipa fruticans* Wurmn.), pangi (*Pangium edule* Reinw., locally known as sis).

(g) Genetic Resources of Indigenous Sugarcane Plants

Sugarcane species of importance to the sugarcane industry are *Saccharum officinarum* L., *S. robustum* Brandes and Jeswiet ex Grassl, *S. spontaneum* L., *S. barberi* jesw. and *S. sinense* Roxb. Related genera which are also of interest to sugarcane breeders are *Erianthus*, *Miscanthus*, *Sclerostachva* and *Narenga*. Four species of Saccharum are found in PNG: *S. officinarum*, *S.robustum*, *S. spontaneum* and *S. eduli*. New Guinea is the centre of origin and centre of genetic diversity of *S. officinarum* or 'Noble cane', clones of which have been reported in New Guinea. The Noble canes are cultivated in subsistence gardens in a wide range of environments from the coast to the highland areas but cannot survive in the wild. Conversely, *S. robustum* and *S. spontaneum* are highly polymorphic species and do exist in the wild. *Saccharum edule* is cultivated for its inflorescence which is cooked and eaten as a vegetable.

Diverse forms of both *S. robustum* and *S. spontaneum* and their hybrids exist throughout the coastal regions and low lying inland areas of the country. *Saccharum robustum* prevails in the wetter areas near river systems, while *S. spontaneum* also exists in savanna type environments like parts of the Markham/Ramu plains. The related genera of *Erianthus* and *Miscanthus* are also found in PNG—*Miscanthus floridulus* (Labill.) Warb occurs in PNG and other parts of the Pacific region; *Erianthus arendinaceus* occurs in the country around the Fly River.

The cultivated genotypes of *S. officinarum* could be regarded as landraces or farmer cultivars. Most of these materials have been in cultivation through many generations. It is difficult to identify exactly which are traditional landraces and which are not.

(h) Genetic Resources of Spice Crops

Unlike in its Asian neighbours, little spice is used in traditional PNG cooking. Almost all spice crops commonly used in the country were introduced many years ago and only a few indigenous plants are used as herbs or flavourings in some local dishes. Ginger (or kawawar is used in flavouring food and the young shoots are also eaten. The common cultivated species is *Zingiber officinale* Rosc. Wild ginger (*Z. zerumbet* L. J.E.Sm) which occurs in the coastal forest areas is consumed and also used in medicine and magic. Three wild genera of ginger are also eaten in PNG: Alpinia (Golgol), *Amomum aculeatum* Roxb and *Horrstedtia scottiana* F.Muell K. Schum.

Begonia occurs wild in the rainforest areas in the highlands. Its stalks are eaten and the leaves are used for flavouring food; leaves of some genotypes are used as ointment on sores. The stems of *Coix gigantea* Koenig ex Roxb are used for making salt for food flavouring. Leaves of *Coleus scutellarioides* (L.) Bth are used as seasoning in food. *Euodia* species, most probably *E. hortensis* Forst, is a shrub whose leaves have a lemon flavour and has been recorded as being used in flavouring food in PNG. The fennel plant (*Foeniculum vulgare* Mill.) may have been introduced but also grows wild throughout the country in areas over 500m altitude.

(i) Medicinal plants

PNG has a rich knowledge of the use of traditional medicines derived from plants, developed over centuries by trial and error. Over 600 identified species of medicinal plants have been reported, with some 450 botanically described. Kambuou (1995, Appendix 4 and p.24) listed some 55 species used to treat injuries and common illnesses, and mentioned other common uses of indigenous plants.

(j) Pasture species

Research into possible pasture species for PNG is based on introduced species but little work has been carried out on PNG's potential indigenous pasture species. There has been little collection of indigenous pasture species in the past and, within PNG, they are currently only maintained in situ. There is a report of a substantial collection of one potential pasture species from PNG (Kambuou 1995, pp.24-25).

(k) Ornamentals

PNG is believed to contain extensive resources of as-yet undiscovered plant germplasm. PNG's National Botanical Gardens contains a collection of 500 described species of orchids with material of about 50 undescribed species. It is believed that 60 per cent of PNG's genetic resources of orchids are yet to be collected (Kambuou 1995, p.25). The National Botanical Gardens has described more than 15 species of ferns, but it is believed that 50 per cent of PNG's ferns and shrubs have yet to be collected. Similarly, the Gardens' collection of 39 species of palms is thought to represent at best only 40 per cent of those in PNG. Some of PNG's plant germplasm it at serious risk because of the effects of logging, especially clear felling, and expansion of agricultural activities (Kambuou 1995, pp.25-26).

3.3 Conserved Plant Genetic Resources of PNG[7]

3.3.1 In Situ Conservation

In situ conservation involves the conservation or maintenance of plant genetic resources in their natural states and in their own habitats, and in the form of wild relatives or progenitors of the crop species, forest tree species, medicinal plants and ornamental plant species. Continued genetic evolution and integrity of biodiversity requires germplasm to be maintained or conserved in such environments.

(a) Community Controlled Land[8]

Land in PNG is owned by the community, clan or the family. There is no individual ownership unless a person is sole heir to the land or it has been purchased through traditional or legal means. Because all land in PNG was owned prior to European colonisation there is no "unoccupied" land over which "the government"—either the former colonial governments or the government of independent PNG—could assert ownership unless this land had been purchased from its traditional owners. Under the old colonial system, some parcels of suitable agricultural land were leased to foreign owners for 99 years; almost all this land has now reverted to the local land owners.

(b) National Parks and Nature Reserves

There are three officially recognised National Parks in the country with numerous Nature Reserves. These areas are privately owned, but the Government through the Department of Wildlife and Conservation has negotiated with the landowners to maintain them as parks and reserves. The national parks are manned by park rangers who are based on site. Nature reserves are not manned, but officers from the Department of Wildlife and Conservation aim to ensure that these areas are kept free of agricultural or lumbering activities. There is no written record of the germplasm composition of these parks and reserves but, since they are heavily forested, they are likely to contain a great diversity of plant species as well as animals, birds and insects. These forested parks and reserves are ideal habitats for some of the unique germplasm of ornamental and useful plants of PNG such as orchids, ferns, palms, rattans and bamboos. Forest tree species, wild fruits and nut species, medicinal plants and wild progenitors of the food crops are also common features in these areas.

3.3.2 Ex situ collections of plant germplasm

(a) Food staple crops

The national lowlands collection of sweet potato is located at the Laloki Agricultural Research Station just outside Port Moresby. A total of 1044 accessions was collected as landraces, farmers' cultivars and common varieties. A small number of accessions has been identified as duplicates; and 67 per cent of the original accession have subsequently been lost from Laloki (Table 3). The national highlands collection of sweet potato is located at the Aiyura Agricultural Research Station; there have been 1453 accessions to this collection; 14 per cent of this collection was lost during relocation of the collection at Aiyura (Table 3). The sweet potato collection is also being duplicated *in vitro* (i.e. as "tissue culture") at the Lowlands Agricultural Experiment Station, Keravat (near Rabaul). A working collection of 1208 accessions of sweet potato at LAES Keravat, comprising varieties in trial and a small number of maintained varieties, duplicates the Aiyura and Laloki collections (Table 3).

The national taro collection is maintained at the Bubia Agricultural Research Centre near Lae. The original collection of about 600 accessions of mostly landraces and farmers' varieties has been reduced by nearly 30 per cent (Table 3). There is a small taro collection from PNG islands at LAES Keravat, and a small collection of taro varieties from the Sepik at Saramandi Research Station.

Of 423 accessions to the national yam collection at Laloki, 25 per cent have been lost (Table 3). Recent financial pressure has endangered up to half of the remaining collection (Kambuou 1995, p.30). There is a small collection of 39 accessions of three yam species at Saramandi Research Station.

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[7] Based on Kambuou (1995).

[8] cf. Donigi (1994).

There is a small collection of 79 landraces of cassava from PNG at Laloki, and 36 cassava accessions from the islands are maintained at LAES Keravat (Table 3). Both collections are based mainly on landraces and farmers' varieties.

A collection of over 500 banana accessions was maintained at Laloki, including indigenous diploids; as many as 30 per cent of these accessions may recently have been lost (Table 3). Some of these accessions are duplicated in a regional collection in the Philippines (INIBAP), although these accessions are not readily accessible to replace losses in the collection because PNG is free of bunchy top, a major banana disease endemic in the Philippines. There is also a small collection of island banana species at LAES Keravat.

A small collection of sago accessions is maintained at Saramandi Research Station (Table 3).

(b) Leafy vegetables

A collection of 142 aibika accessions of landraces and farmers' varieties was maintained at Laloki, with up to 40 per cent being lost in recent years (Table 3). Some 200 seedlings of aibika have been raised from the small proportion of aibika varieties which set seed. Some 67 islands varieties of aibika are maintained at LAES Keravat, and 23 Sepik varieties at Saramandi Research Station.

A collection of 48 accessions of other traditional leafy green vegetables of eight plant kinds (*Amaranthus* spp., *Ficus* spp., *Gnetum gnemon*, *Polyscias verticillata*, *Rungia klossii*, *Oenanthe javanica*, *Solanum nigrum* and *Setaria palmifolia*) is also held at LAES Keravat (Kambuou 1995, p.31).

(c) Other food species

There is a collection of 32 accessions of 17 various fruits and nuts of both indigenous and exotic origins maintained at LAES Keravat. Keravat also has a collection of 35 accessions in 14 types of herbs, spices and condiments (Kambuou 1995, p.31 and Appendixes 5 and 6).

(d) Commodity crops

The Coffee Research Institute currently maintains a collection of 70 exotic accessions of *Coffea arabica* and *C. robusta* in both field and *in vitro* ("tissue culture") forms. Most plant materials have been introduced from overseas in the form of micro-cuttings, and sometimes as bare root seedlings or seeds. New materials introduced as micro-cuttings are multiplied in the tissue culture laboratory prior to field establishment and evaluation.

The Cocoa and Coconut Research Institute maintains a small collection of cocoa based on introductions dating from early in the twentieth century, and is planning to commence collecting germplasm material from PNG locations (Kambuou 1995, p.32). The CCRI also has a collection of local coconut varieties at Madang.

The Oil Palm Research Association maintains an undocumented collection of genetic material for oil palm (Kambuou 1995, p.33).

Genetic materials for commercial tea production are maintained in the private sector. Privately-owned rubber estates maintain their own genetic material, while the Department of Agriculture and Livestock maintains genetic material for smallholder rubber producers. Pyrethrum plant material is maintained largely by its smallholder growers (Kambuou 1995, p.33).

(e) Sugar cane

The Ramu Sugar company has a "museum" collection of over 500 commercial hybrids near Lae (Kambuou 1995, p.33). Only hybrid varieties are held in this collection. The company's own recently commenced breeding program will soon add locally-developed varieties to this museum.

The earliest collecting expedition for sugarcane in New Guinea was made in 1875. Several collecting trips have been made since and the most recent was undertaken in 1977. Most of these expeditions were sponsored by organisations in USA and Australia, and the International Society of Sugar Cane Technologists. The germplasm collected was exported where some failed to survive; others were established in the World Collections run by USDA/ARS (USA), while the fate of others and in particular those collected in early expeditions are unknown. There are no documentary records to provide a realistic figure on genetic variation of *S. officinarum*, *S. robustum*, *S. spontaneum* or *S. edull* in PNG. Expeditions collecting sugar cane varieties could not have thoroughly collected throughout the entire country.

A total of 206 accessions were collected during the 1977 expedition. No proper records were kept of the composition of this collection. Part of the collection was established at Bubia Agricultural Research Centre outside Lae where the collection currently holds 32 accessions of *S. officinarum*, 28 of *S. eduli* and 12 accessions of *S. spontaneum*.

(f) Minor crops

Commercial seed material of a variety of other crops of introduced plant types—such as rice, maize, peanuts and beans—is multiplied, stored and distributed in PNG by both the Department of Agriculture and Livestock and the private sector.

3.3.3 Summary

While PNG has considerable ex situ conservation of its major crop staples, the degree of conservation relative to the food crops consumed by its population, and its own heritage of genetic diversity, is quite small. Thus, while PNG currently has an onerous financial burden in maintaining its current germplasm collections, there appears to be a much greater amount of plant germplasm conservation that could be undertaken. Kambuou (1995, chapter 4) outlined the uses that have been and are currently being, made of PNG's conserved plant germplasm.

Most food crops grown in PNG are based on farmer selected landraces, often distributed by the farmers themselves. Kambuou (1995, pp 23-24) reported variety trials and breeding programmes undertaken by PNG's Department of Agriculture and Livestock using indigenous materials. Accessions of sweet potato, taro, yams, bananas and aibika have been evaluated in variety trials at DAL research stations. A taro breeding programme has also been undertaken to incorporate resistance to taro leaf blight. Breeding has also been undertaken in coffee and cocoa by the public sector. Ramu Sugar is currently undertaking a breeding programme in sugar cane; this programme has recently received a stimulus from a breakdown in quarantine in Australia, from where materials were previously imported. Extensive investigations of currently minor exotic crops—e.g. balsa, cashew, Japanese mint, kava, nutmeg and vanilla have also been undertaken.

3.4 Conservation techniques

In Western agriculture, most food staples such as wheat are seed propagated.[9] Seed-propagated plant kinds may be stored as seed, and there has been considerable investment in such seed storage facilities. Varieties may be maintained untouched for many years, with occasional reproduction to ensure that stored seed maintains its viability. Seeds of non-seed propagated plants may also be stored as seed but, in general, such seeds come from plants which are highly heterozygous (i.e. do not breed true to type) and therefore an individual *variety* cannot be stored as seed, but rather a vast range of heterozygous individuals—many of which may have little or no agricultural value, and some of which may not even produce viable plants.

Many of PNG's staple food plants are vegetatively propagated. The existing varieties are highly heterozygous and do not breed true-to-type from seed, and are thus vegetatively propagated in subsistence or commercial production. Maintenance of the existing varieties of these plant kinds requires that they also be vegetatively propagated in germplasm collections. The conventional form of vegetative storage of plant varieties has been in the form of growing collections. A variety (perhaps in replication) is grown in a field location. Particularly where an individual plant has a long life—e.g. trees—field conservation can be relatively cheap, as the plant only requires reproduction every few decades. The principal difficulty of such collections is the large land areas they may occupy, especially where there are large numbers of varieties, and the operating costs (labour force and materials) required to maintain the physical health of the collection. However, where vegetatively-propagated plants have short lives,

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[9] Some "Western" crops are vegetatively propagated (e.g. sugar cane, potato, most fruit trees) and many crops of non-Western agriculture are seed propagated (e.g. rice, millet, sorghum).

frequent propagation may be required and this may be expensive in the form of field collections. In recent years, *in vitro* ("tissue culture") collections of vegetatively propagated materials have been established which eliminate the land and field labour costs of reproduction. However, where plant lives are short, even *in vitro* samples may require frequent reproduction, and this may require expensive laboratory facilities and highly trained laboratory technicians. Considerable effort has recently been devoted to develop techniques to retard development of *in vitro* plant samples, to extend generation times and thus reduce reproduction costs.

In PNG's case, only a few of its staple vegetatively propagated plant kinds produce seeds that may be stored; these seeds only store genetic material, not "varieties" (cf. above). Sugar cane and sweet potato seeds may be harvested and stored, and recent advances have been made within PNG to induce taro to set seed which can subsequently be stored. About 25 per cent of aibika varieties set seed which may be used for reproduction. In the case of sweet potato, its profuse sexual reproduction in the PNG Highlands provides a rich store of genetic diversity and continued field evolution. In those plant kinds which set seed, germplasm conservation may conceivably be based upon the natural seed bank of farmers' fields, or ex situ seed banks. Such seed banks would, of course, only store genetic diversity and not specific varieties; and the usefulness of this procedure would depend on the ability to efficiently recover genetic characteristics into field varieties. Where it was desirable to have ready access to specific varieties for distribution to farmers or for use in plant breeding, seed storage of heterozygous varieties would probably be highly inefficient.

Seed crops such as rice, maize, peanuts, beans and vegetables are introduced germplasm. Small quantities of these crops are multiplied and seeds are stored under short-medium term storage conditions on various Research Stations for distribution to small farmers on request. Seeds for distribution are maintained in air conditioned rooms, operating at 15-20 degrees Celsius while those for regeneration purposes are maintained under the normal household refrigerator conditions. The seed crops germplasm regeneration work is carried by each research station responsible for these crops. The regeneration programme is carried out every year to ensure continuity of viable seeds. Only "orthodox" seeds are maintained and stored under these conditions. Plants with "recalcitrant" seeds are maintained vegetatively in ex situ collections or in their own natural habitats as for the case of the indigenous timber tree species.

3.5 International collaboration[10]

The International Plant Genetic Resources Institute (IPGRI, formerly known as the International Board for Plant Genetic Resources, IBPGR) sponsored some of the previous major germplasm collecting expeditions in PNG. PNG joined the then IBPGR South East Asian Regional programme in 1978. Papua New Guinea is represented on the IBPGR Regional Committee for South East Asia (RECSEA), now known as the Regional Cooperation in South East Asia on Plant Genetic Resources (RECSEA-PGR). The main objective of this initiative is to promote and enhance the conservation and management of the region's rich and diverse plant genetic resources through collaborative activities that are of benefit to member countries. These initiatives enable member countries to exchange useful genetic materials and information on utilisation of plant genetic resources for the well-being of the people in the region. Through these initiatives the member countries believe that the sovereign rights and responsibility for indigenous plant genetic resources in situ and the prior informal consent for the exchange of plant genetic resources will be adhered to. This collaboration will result in a more effective use of available resources in the region.

Through financial and technical assistance from IPGRI and the other RECSEA member countries, PNG was able to collect and assemble the genetic diversity in traditional food crops throughout the country into *ex situ* collections. The national plant genetic resource collections for the traditional food crops are currently held at Laloki Agricultural Research Station, outside Port Moresby, with working collections located on other research stations throughout the country.

IPGRI and DAL co-sponsored two collecting trips on sweet potato and one on traditional food crops, particularly the green leafy vegetables of the country. The Japanese Government and IPGRI co-sponsored two collecting trips in PNG, again collecting traditional food crops, with special interest in taro and yams. Three major banana collecting expeditions were sponsored by IPGRI with technical assistance from Queensland Department of Primary Industry (DPI) and DAL. The main purpose of collecting banana germplasm was to obtain and identify genetic materials that have natural resistance to

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[10] Based on Kambuou (1995).

the sigatoka disease complex and those that show tolerance to the disease. These collected banana germplasm is held *in vitro* at Nambour Research Station, Queensland and the duplicates are at the national collection at Laloki. A small collection of this germplasm showing some tolerance to the sigatoka complex is held at Montpellier for the crop improvement programme.

More than twenty research personnel from PNG were sponsored by IPGRI on training courses on plant genetic resources most of which were conducted in member countries within the region. IPGRI also sponsored a research officer to undertake a masters degree programme in the United Kingdom. An 'internship' arrangement was made by DAL some years ago with IPGRI funding for an experienced PGR scientist who was responsible for the characterisation and documentation of the national sweet potato germplasm collection. IPGRI has sponsored a banana expert from Queensland DPI to assist in the identification, characterisation and documentation of banana germplasm in the PNG national collection. Some financial assistance was provided by IPGRI for the maintenance of seed crops germplasm and for the improvement of *in vitro* storage facilities.

Papua New Guinea collaborates with regional research centres including AVRDC in Taiwan, IITA in Nigeria, IRRI in the Philippines, ICRISAT in India, IPGRI Head Office in Rome and the Regional Office in Singapore, CIMMYT in Mexico, the International Network for the Improvement of Banana and Plantain (INIBAP) in Montpellier, France and the International Service for National Agricultural Research (ISNAR) in The Hague, Netherlands.

Under the IBPGR umbrella, a number of regional collections on plant genetic resources were established. The regional collection of banana was established at Davao, Philippines. Well over 100 accessions of PNG bananas are maintained at Davao.

Papua New Guinea also participates in the Pacific Agriculture Research Programme (PRAP) on sweet potato. The project funded the maintenance of a field genebank collection which holds over 1,000 accessions at the Lowlands Agriculture Experimental Station, Keravat. The project scientists evaluate and select superior or promising accessions which are sent to the tissue culture laboratory in Western Samoa where they are cleaned of diseases before distribution to other countries in the Pacific region. Over 20 accessions of sweet potatoes from the Highlands collection at Aiyura were sent to the international base collection at the Asian Vegetable Research and Development Centre (AVRDC) in Taiwan. These accessions are maintained as seeds in long-term storage conditions.

Through its research stations, DAL has previously introduced experimental lines of food legumes (pulses), coarse grain crops (sorghum and maize), rice and introduced vegetables from various genebanks throughout the world. The food legumes were introduced from CSIRO genebank in Brisbane, ICRISAT in India, and the peanut genetic materials from DPI Kingaroy, Queensland. The genetic materials of coarse grain crops were introduced from DPI Queensland and CIMMYT in Mexico. Some bilateral initiatives were undertaken by Bubia Agricultural Research Centre and IRRI in the Philippines for rice genetic materials. Improved breeding lines of rice bred for Asian conditions were introduced to PNG for performance testing.

3.6 Risk

The risks of plant germplasm conservation in a developing country are likely to be higher than in wealthy developed countries. Risks of maintaining whole plant conservation in the field in PNG include flood (Laloki 1994); volcanic eruption (Keravat, near Rabaul 1994); landowner disputes (at various times have affected all major research stations in PNG); accidental, careless, malicious or starvation-induced harvesting (Keravat 1994-95 in the case of the last); or inadequate resources leading to varietal losses through weed competition, inadequate irrigation, poor pest and disease control, and sub-optimal timing of relocation of collections (all stations from September 1994). The effects of these risks can be seen in Table 3 which documents recent considerable losses in PNG's food staple ex situ plant germplasm field collections (cf. Table 1). There are also risks with other forms of plant germplasm conservation; in tissue culture, for example, the maintenance of optimal conditions depends on sometimes uncertain infrastructure such as electricity supplies.

4. Economic analysis of germplasm conservation

Since maintenance of plant germplasm is an investment problem, the key element of an economic analysis of germplasm conservation is evaluation of the costs and benefits of this activity. Some of the technical and financial issues involved in the provision of germplasm storage have been documented (e.g. Plucknett *et al.* 1987) although, in PNG's case, analysis requires comparison of the costs of field and non-field forms of germplasm conservation. Such cost analysis requires careful definition of the appropriate costs but, in principle, this is not a difficult problem. Economic analysis of optimal investment in germplasm storage also requires estimates of the benefits of this storage. The value of germplasm collections depends on the future incorporation of the genetic material into commercial varieties via plant breeding, and estimation of this value is not a trivial problem. The principal difficulty in evaluating investment decisions relating to germplasm collections lies in being able to assess the value of germplasm.

Assessing the value of germplasm collections requires being able to relate existing conserved germplasm to future advances in plant breeding. Because, by definition, these advances occur in the future, a model is required to forecast the (approximate) future value of existing collections. There are at least two possible ways of deriving such estimates. One method is to use agronomists' or plant breeders' knowledge of current constraints on crop production to indicate the consequences of being able to relax these constraints by incorporating genetic traits from the germplasm resource. A second method would be to directly model the incorporation of genetic traits from the germplasm pool into commercial varieties.

Both these approaches require modelling the plant breeding process at different levels of sophistication. Plant breeding may be regarded as a production process (cf. Arnold 1987, p.63) and thus, conceptually at least, is suited to economic modelling. However, the form and parameters of research processes are much less well defined than for agricultural or industrial production processes. And, because plant breeding is an uncertain process, the value of germplasm in terms of future plant varieties that could be developed from it is similarly uncertain. Modelling the plant breeding research process is more formidable the further from commercial varieties and the closer to basic science the research is being conducted. Further, the value of conserved germplasm is not simply obtained from its direct use in plant breeding, but may also arise from its use in extending scientific knowledge, or acting as insurance against future needs. While it is not difficult to document the value of particular germplasm *ex post* (e.g. Evans 1987, Frey 1987) and even to estimate its value *ex post* (e.g. Brennan and Fox 1995), it is much more difficult to determine this value *ex ante*.

4.1 Germplasm conservation — a simple neoclassical model

The inputs in a plant germplasm conservation process are principally labour, and physical and human capital. In the case of in situ or field conservation of plant germplasm, land is also important. A simplified model of plant germplasm conservation is presented in Figure 1, in terms of labour, and physical and human capital. Consider options for maintaining a stock of plant germplasm varieties equal to N. Several technologies might be used to maintain this stock: at A, N varieties may be maintained in the field (in situ or field) using labour but relatively little capital; conversely, the same number of varieties may be maintained with relatively little labour, but considerable quantities of human and physical capital using techniques such as seed storage or tissue culture (e.g. at B in Figure 1).

In PNG's case, labour is relatively cheap compared to human and physical capital, and plant germplasm is generally maintained as field collections. There are some exceptions to this generalisation, but these exceptions involve the use of external aid funds to relax the capital constraint; thus, for example, the tissue culture collection at LAES Keravat is funded by PRAP. Tissue culture facilities are also available at the University of Technology at Lae, but these facilities are research and teaching facilities rather than for long-term storage. Some experimentation is currently proceeding to investigate the feasibility of lower-cost tissue culture storage—e.g. to develop an intermediate technology like C (Figure 1)—by extending the storage life of tissue culture specimens. There are also possible intermediate technologies available for labour-intensive germplasm conservation—for example, human capital in the form of the statistical design of field conservation may reduce the amount of labour involved while requiring higher levels of human capital.

When the economic problem is simply to choose between discrete technologies for conserving a given quantity of plant genetic material, empirical solutions to the problem can be obtained by directly comparing costs using standard budgeting. However, economic constraints in plant germplasm maintenance do not arise simply in the form of relative resource costs. The more interesting economic problem concerns how many varieties should be conserved. Consider the choice between the number of varieties to conserve in Figure 1: how should a choice be made between conserving N or N* varieties. In a conventional neoclassical problem, relative output:input prices determine the optimal level of output. Thus, the key issue is the "price" of the conserved germplasm. However, since there is at best a highly imperfect market for plant germplasm, there are no good market estimates of its value. Thus, the key problem is to estimate the value of germplasm.

Two approaches are possible. The first is to build on the cost budgeting approach noted above. Models could be constructed of the costs of conserving plant germplasm with the following variables:

- different plant kinds (e.g. aibika, banana, cassava, sweet potato, taro, yams in the case of PNG),

- different ways of conserving varieties (e.g. field conservation, tissue culture),

- different approaches to conserving germplasm (e.g. conserving varieties (e.g. in the field or tissue culture) or conserving genepools (e.g. seeds of heterozygous varieties)),

- different numbers of varieties,

- different numbers of replicates of each variety, different locations or numbers of locations for each plant kind or variety (both affect degree of risk of conservation)

These cost models could then be linked (e.g. by linear programming) to select a least cost way of achieving a given set of objectives for plant germplasm conservation. Parametric programming could then be used to investigate the consequences of varying any of the objectives or constraints. This analysis could be used to investigate the consequences of relaxing the budget constraint either by increasing the availability of domestic funding, or by the availability of aid funding in the case of developing countries like PNG. By experimenting with such a least cost model, administrators and researchers could investigate the cost consequences of different types of decisions, and intuitively compare the explicit costs of varying decisions with their subjective valuation of different types or levels of germplasm conservation.

An alternative approach is to attempt to directly estimate the benefits of plant germplasm conservation, and this approach is outlined in the remainder of this section.

4.2 Estimating Benefits of PGR Collections

4.2.1 Modelling output of selection and breeding

Plant breeding is a production process to develop superior new varieties of plants. Plant breeding may have a single objective—e.g. to breed a blue rose, or to insert the genes necessary to confer resistance to a specific disease. In general, however, plant breeding has multiple objectives: the value of a variety can be envisaged as the weighted value of that variety's characteristics. For example, if 'T' traits t_i are economically valued where t_{ij} is the expression of trait i in variety j, and the marginal value of trait i is a_i—where a_i may be a function of variables such as the price of final product—then the value of a particular variety j may be defined as V_j:

$$V_j = \Sigma_T \, a_i.t_{ij}$$

The degree of improvement of some new variety k over existing variety j is defined by the difference in value between varieties j and k:

$$V_k - V_j = \Sigma_T \, (a_i.t_{ik} - a_i.t_{ij}) = \Sigma_T \, a_i.(t_{ik} - t_{ij})$$

For simplicity, in the present case, only a single trait—yield—is considered as having economic value.

Determining the economic nature of the benefits from germplasm collections requires specification of a model of how germplasm contributes to the breeding process. Identification of the contribution of germplasm to the breeding process requires a model of the discovery or purposeful breeding of new varieties, and how plant germplasm contributes to that process. The production process for new plant varieties is somewhat different from a conventional neoclassical production function:

$$Y = f(X_j, \text{ for } j = 1, \ldots, J \text{ inputs})$$

Rather than there being a deterministic relationship between plant breeding inputs (land, labour, human capital, produced capital, plant germplasm), plant selection and breeding activities give rise to a distribution of new plant varieties (cf. Evenson and Kislev 1975). For example, from a simple cross of two heterozygous parents with 10 independent traits of interest to the breeder, a second generation resulting from the random mating of the first generation of offspring has $4^{10} = 1.05 \times 10^6$ offspring and, if a particular homozygous individual were sought, approximately 3 million plants would need to be grown to have a 90 per cent chance of finding it. It is likely that, in practice, plant breeders would be interested in a minimum of 10 traits (Simmonds 1981, chapter 4).

In Figure 2 are plotted the probability distributions of various populations of plant varieties. If varieties simply breed in the wild, a probability distribution can be envisaged of the off-spring of random crosses—e.g. pdf1. If the maximum subsistence yield—i.e. without fertilisers, chemicals, machinery etc.—is S, and the current subsistence yield is Xs, then some proportion of possible crosses will be varieties superior to existing varieties; this proportion of superior crosses is defined by the area under pdf1 and to the right of Xs. Time and skill are required to select from the population those varieties that do indeed have yields superior to Xs.

Out-pollinating varieties that breed in farmers' fields—e.g. sweet potato in the Highlands of PNG—might be conceived of as having an associated probability function pdf2 (Figure 2). These varieties have already had some selection pressure applied to them and so, when they breed, the proportion of varieties with yields less than existing varieties—i.e. lower than Xs—is reduced, and the proportion having yields above Xs—defined by the area under pdf2 to the right of Xs—is likely to be higher than if new varieties are randomly selected from the wild. Similarly, time and skill are required to select from the population those varieties that have yields superior to Xs.

Where specialist agronomic expertise is available to assist farmers to select from varieties that breed in their fields, a distribution function of the new varieties might look like pdf3 (Figure 2). Agronomists have resources that enable them to evaluate a greater number varieties from a wider range of sites than might be available to farmers, and so the distribution function may have more varieties concentrated towards the superior end. Additionally, agronomists have specialised knowledge that assists them to select those varieties having yields greater than Xs.

Systematic plant breeding adds a new dimension to the creation of new varieties. Instead of relying on wild plants to reproduce or a selection of improved varieties to breed in farmers' fields, plant breeding adds several new dimensions to the production process for new varieties. Reliance on selections from the wild or farmers' fields largely restricts varietal improvement to out-pollinating plant kinds, because varietal change in self-pollinated plant kinds is much slower. However, by intervening directly in pollination, the plant breeder expands varietal improvement to self-pollinating varieties. Further, even among open-pollinated varieties, the plant breeder may be able to induce crosses between plants that normally would not cross, and thus may add new classes of characteristics to a plant kind. Additionally, knowledge of the characteristics possessed by plant kinds enables the breeder to more purposefully breed for particular characteristics in the selected varieties. Thus, it might be expected that the probability distribution of new varieties with plant breeding might look like pdf4 (Figure 3); pdf3 is carried over from Figure 2. Since plant breeding can be used to control the numbers of off-spring, particularly of off-spring less likely to carry desirable traits, the plant breeder may be able to reduce the proportion of progeny actually bred that have yields less than Xs and increase the proportion of progeny with yields above Xs, and can thus make the search for desirable off-spring more efficient. Further, the breeder has technical tools that permit the better—and perhaps earlier—identification of progeny whose yield potential exceeds Xs. Finally, by being able to more closely control the pollination process, the breeder widens the genetic combinations that are possible, and thus relaxes the constraints of maximum yield in farmers' fields—which may increase from S to S1. In commercial agriculture, where more of the production constraints may be relaxed by additional inputs, the yield constraint may be further relaxed from Xs to C. Above the commercial yield C, there may be a current biological yield maximum M corresponding to the relaxation of all agronomic constraints of nutrition, water availability and scourges.

However, if the plant breeder searches widely for desirable traits among plant germplasm, it may be possible to expand the biological "maximum" M to some M1. Thus, for example, the discovery of the Rht1 and Rht2 "dwarfing" genes in wheat enabled a substantial change in the plant's partition between vegetative growth and grain yield, and thus enabled an increase in the corresponding commercial yield (cf. Brennan and Fox 1995). A corresponding distribution function for new varieties bred with the relaxed biological "maximum" M1 might be pdf5 (Figure 3). Thus, the benefit of maintaining or augmenting the basic genepool which may be used to develop new varieties is a shift in the distribution function of new varieties from that possible using existing varieties as a source of genetic variation (e.g. pdf4) to a distribution function in which a larger proportion of the whole known genepool is utilised in developing new varieties (e.g. pdf5 in Figure 3).

Finally, new plant breeding techniques—deriving from advances in molecular biology or "genetic engineering"—assist the breeder's search for improved varieties. These new techniques increase the range of genetic material that may be incorporated in new varieties—by bypassing sexual reproduction, it may be possible to easily include genetic material from outside the particular species. For example, new commercial cotton varieties will soon be released which have genetic material from the bacterium *Bacillus thuringiensis* which manufactures an insecticide. In the latter case, the new varieties shift a commercial yield constraint, but such possibilities may also shift the biological "maximum" yield (e.g. to M2), and create new distribution functions for varieties like pdf6. In this case, plant—and other kinds of—genetic resources become increasingly valuable as the range of plant kinds in which they may be used to develop improved varieties has dramatically increased. New biological techniques may also increase the efficiency of search for new varieties, in particular reducing the number of new varieties developed that have yields less than the existing yield Xs or to improve the efficiency of searching for superior varieties. Indeed, by avoiding sexual reproduction as a source of variation from which new varieties are selected, it may be possible to substantially avoid producing a vast array of new varieties in which a search is required to find superior varieties.

4.2.2 Static model of selection and breeding

The varietal distribution functions pdf_j in Figures 2 and 3 were drawn implicitly assuming a given quantity of resources used in the search for or development of a new superior variety. However, the resources used in the search for a new variety may clearly vary. In Figure 4, the models of Figures 2 and 3 are transformed into models which relate the benefits of breeding (vertical axis) to the quantity of resources (number of labour units, U) used in the search for superior varieties.

Let yield (X) be the sole characteristic of varieties, and let f(X) be the probability density function for the selection of superior varieties from a wild population. The skill in selecting new varieties is finding new varieties X: X>Xs, where this skill is denominated in activity units (U). Suppose the first unit of selection activity (U=1) buys a random selection of varieties $\{X^{\#}\}$from the range X>Xs. Then the expected value of the first unit of selection activity is E(U=1):[11]

$$E(U=1) = \int_{Xs}^{S} X.f(X).dX$$

and let E(U=1) be the marginal benefit of the first unit of selection activity. The selection of the set of varieties $\{X^{\#}\}$ is sampling without replacement from the distribution of X since, once a variety is selected, it will not be selected again.[12] Thus, after the first unit of plant breeding activity is undertaken, the distribution function for X is some function f1(X):

$$f1(X) \leq f(X) \text{ for } X > Xs$$

Now, like the first unit of selection activity buys $\{X^{\#}\}$, the second unit of selection (U=2) buys a selection of varieties $\{X^{\#\#}\}$ from the range X>Xs. Thus, when $\{X^{\#\#}\}$ is selected, the expected value of the selection is E(U=2):

$$E(U=2) = \int_{Xs}^{S} X.f1(X).dX \leq \int_{Xs}^{S} X.f(X).dX$$

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[11] The expected value of search for new varieties is denominated solely in terms of the yield of the new varieties; in economic terms, this physical value requires multiplication by the area that would be planted to the new variety (A), and the gross margin of output (py-c), where py is the price per unit of output and c is the average production cost per unit of output.

[12] Since yield was assumed to be the sole characteristic of a variety, knowing its yield uniquely identifies a particular variety.

because $f1(X) \leq f(X)$ and therefore $E(U=2) < E(U=1)$, and similarly, $E(U=n) < ... < E(U=2) < E(U=1)$.

Thus, the marginal benefit from plant selection or plant breeding will be a declining function of the level of breeding effort *ceteris paribus*. (The ceteris paribus infers that each additional unit of selection or breeding activity is homogeneous; if different types of breeding effort are added—for example, the first unit is conventional plant breeding and the second unit is a unit of germplasm facility—then clearly marginal benefit may increase because of interactions between the various kinds of breeding activity.) This result of the declining marginal benefit of additional *homogeneous* units of plant selection or plant breeding activity will also hold for selecting from farmers' fields, for plant breeding, and for plant breeding using molecular biology.

The expected value of employing U units of selection or breeding effort is g(U):

$$g(U) = \int_0^U \int_{Xs}^{S} X.f_u(X).dX\,du$$

where $f_u(X)$ is the probability density function of varietal yield associated with the u^{th} unit of effort.

Thus, for selection from the wild, the marginal benefit function is the first derivative $g'(U)$, represented as MBw in Figure 4. The marginal cost of this search is MCw in the same Figure. The optimal level of search for new varieties is Uw, and the aggregate value of the optimal level of search for new varieties is:

$$\int_0^{Uw} MBw.du$$

Because the distribution function for the search for new varieties in farmers' fields is likely to be above that for search in the wild (pdf2 compared to pdf1 in Figure 2), the marginal benefit of a unit of search for new varieties in farmers' fields is likely to be higher—i.e. MBf > MBw in Figure 4. If the marginal cost of search for new varieties is the same in the wild as in farmers' fields (MCw), then the optimal level of search for new varieties in farmers' fields is Uf.

Adding specialised agronomic labour to the search for new varieties may also improve the chances of finding new varieties (pdf3 cf. pdf2 in Figure 2); hence the marginal benefit curve for using agronomic specialists—collecting from the wild, evaluating material in farmers' fields, or conducting controlled experiments—is likely to be above that for farmers' search (MBa > MBf). However, the marginal cost of an agronomic labour unit is likely to be higher than that of a farmer (MCa > MCf). Whether or not the optimal level of search with agronomists (Ua) is higher than for farmers will depend on the relative shifts in MB and MC.

Similarly, adding plant breeders is similarly likely to increase the marginal benefit curve (MBb) and the marginal cost curve (MCb).[13] Maintaining a larger genetic pool from which breeders can select is similarly again likely to increase the marginal benefits and marginal costs of search (e.g. MBg > MBb, MCg > MCb). Similar shifts could also be expected to be observed in the marginal benefit and marginal cost curves with techniques of advanced molecular biology. The net benefit of the larger genepool at activity level Ug is:

$$\int_0^{Ug} (MBg—MBb).du$$

or area abcd in Figure 4.

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[13] For a model of breeding costs see, for example, Brennan's (1989a,b) model of a wheat breeding program, including the extent of progress to date in breeding in the particular species, expected time to produce a new variety, rate of yield decline in field and/or rapidity of variety breakdown (e.g. to disease). Firms' technical and financial constraints might include the number of breeders, funds, land, technical support (chemists, pathologists etc.). Firms' objectives might vary from public breeders (not-for-profit firms) to conventional private, profit maximising firms. In both cases, firms could be modelled as optimising firms subject to conventional production process, technical and financial constraints. In the case of not-for-profit plant breeding firms, objective functions might include maximising the number of cultivars or maximising the yield increase between commercial cultivars.

In Figure 4, the units of plant breeding effort (U) are defined in a common physical unit (e.g. labour time) but the productivity of units of labour time in different activities—e.g. farmers' selection in the wild or in their fields, agronomists' selection, plant breeders' selection—will not be identical. The productivity of different kinds of labour units will reflect the human capital embodied in each form of labour, and the physical capital with which labour units of different kinds are combined. Thus, for example, in Figure 4, just because the optimal level of plant breeding activity *in physical labour units* is Ub (< Uf for the optimal level of farmers' labour search for new varieties in their fields), this does not mean that plant breeders would produce fewer superior new varieties per period than farmers selecting varieties out of their own fields.

In this model, the benefits of maintaining a larger genepool for plant breeding or selection—i.e. having larger plant germplasm collections—is the increased benefit of new varieties being bred compared to the situation where a smaller genepool is used. Thus, the key relationship to be modelled is that between the size of the available genepool and the rate of yield advance in commercial varieties.

4.2.3 Dynamic Model of Selection and Breeding

(a) Formal model[14]

The intention of plant selection or plant breeding is to shift the achieved yield, in the case of subsistence farming, from the existing level (say Xs) to some new level (say Xs1) where Xs1>Xs. When a new variety has been selected then, if the distribution function for new plant varieties remains unchanged, probabilities associated with the new function will have the characteristic that:

$$pr(X>Xs1) < pr(X>Xs), \text{ because } Xs1>Xs$$

Thus, in a subsequent period when the achieved yield has increased to Xs1, the marginal benefit from the first unit of selection effort applied in the subsequent period $E(U=1_{t+1}|U_t)$ will be:

$$E(U=1_{t+1}|U_t) = {}_{Xs1}\int^{S} X.f_{1U_t}(X).dX < {}_{Xs}\int^{S} X.f(X).dX$$

and the effect of applying n units of selection/breeding activity in period t+1, following U units applied in period t is:

$$E(U=n_{t+1}|U_t) = {}_{Xs1}\int^{S} X.f_{nU_t}(X).dX < {}_{Xs1}\int^{S} X.f_{1U_t}(X).dX < {}_{Xs}\int^{S} X.f(X).dX$$

i.e. the marginal benefit of breeding effort declines over time as long as the maximum achievable yield remains unchanged (e.g. at S).

Thus the yield gain obtained from applying U_{t+1} selection/breeding units in period t=1 is:

$$g(U_{t+1}) = {}_0\int^{U_{t+1}} {}_{Xs1}\int^{S} X.f_{u_{t+1}U_t}(X).dX.du$$

and the yield gain obtained from selection/breeding over T periods is $G_T(u)$:

$$G_T(u) = {}_0\int^{T} e^{-s.t} {}_0\int^{U_t} {}_{Xs1}\int^{S} X.f_{u_tU_{t-1}}(X).dX.du.dt$$

where s is the continuous time discount rate. The function defining the benefit from selection/breeding is V_T:

$$V_T = A.(py-c).G_T(u) - {}_0\int^{T} e^{-s.t} C(u_t).dt$$

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[14] cf. Evenson and Kislev (1975).

where $C(u_t)$ is the cost of selection/breeding activity in period t.

For given T, S, $C(u_t)$ and $f_{u_{t+1}U_t}(X)$, the optimisation problem is to maximise V_T subject to any external constraints (e.g. limitations on funding of selection/breeding activities). Since the maximum value of V_T varies depending on the process for developing new plant varieties (corresponding to pdf1-pdf6 in figures 3 and 4), the problem is to optimise the *combination* of V_{iT} for the range of varietal techniques i which are available (i = selection from wild, selection from farmers' fields, selection including agronomic expertise, conventional breeding etc.).

However, T, S, $C(u_t)$ and $f_{u_{t+1}U_t}(X)$ are not necessarily "given". For example, T will vary depending upon the funding mechanisms and the decision horizons of individual selectors/breeders; and S, $C(u_t)$ and $f_{u_{t+1}U_t}(X)$ are functions of breeding effort (cf. Figure 4). This adds an extra dimension of complexity to the problem.

(b) Heuristic solution

Under the preceding assumptions about the distribution of available varieties, selecting or breeding is like exhausting a natural resource, where the natural resource here is the maximum available yield. Although plant material itself is a renewable resource, the theoretically attainable yield is non-renewable in the sense that, once it is attained, yield cannot be further increased. Thus plant breeding is like harvesting this resource—the exhaustion point of the natural resource of yield occurs where plant yield reaches (or, at least, asymptotes to) the theoretical maximum yield.[15]

Suppose the *permanent* yearly yield increment resulting from plant breeding is dy(t)/dt, where dy(t)/dt is a deterministic function of resources devoted to plant breeding and closeness to theoretical maximum and, for simplicity, is continuous in its arguments and has satisfies appropriate convexity conditions. The value of this yearly increment is:

$$dy(t)/dt.A.(py-c).(1/\{r.[1+r]^{t}\})$$

where A is the area sown to the plant kind, (py-c) is the long-run gross margin and the discount factor r sums the value of the increment of yield y(t) in all years succeeding year t. If the cost of yearly breeding is pb(t)—which is likely to be inversely related to the difference between existing yields and the theoretically attainable yield—then the expected time of terminating breeding can be determined by solving for t in:[16]

$$dy(t)/dt = pb(t)/\{A.(py-c).(1/\{r.[1+r]^{t}\})\}$$

The theoretically maximum yield in the preceding model may be modified via relaxing all existing genetic constraints in a plant kind—e.g. by finding genetic material conferring resistance to taro leaf blight etc. There is also an achievable maximum yield (less than the theoretically maximum yield) which may be shiftable (e.g. dwarfing genes in wheat and rice shifted the dry matter partition between foliage and grain) and a commercial theoretical maximum yield (less than the achievable maximum yield) which may be shifted by changed input/output prices, improved husbandry etc., including plant breeding to enable the optimal commercial yield to be attained. In this model, the value of germplasm is the value of relaxing the genetic constraints to theoretical, achievable or commercial yields. Expanding the framework adopted above, therefore, a plant breeding problem is analogous to an intertemporal problem with the achievable maximum yield as a non-renewable resource.

The plant breeding model outlined above is further complicated by the continual erosion of many varieties' resistance to scourges (plant diseases, pests etc.). In such cases, in any one year there is the

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[15] While the use of germplasm in plant breeding activities might be likened to permitting the full expression of the plants species' genetic potential to be realised, note Evans (1987) who noted that Austin's (1978) theoretical maximum for wheat had been exceeded by 1982.

[16] $\Sigma(1/(1+r)^{i}; i=t, \ldots = 1/\{r.[1+r]^{t}\})$.

probability of failure of a variety's resistance to scourge. For simplicity, this uncertainty may be replaced by a model of a continuous deterministic process; i.e. there is a yearly yield decrement dy^{*}/dt (due to scourges). Maintenance research denotes the breeding process to prevent or mitigate a reduction in yield due to scourges (cf. Blakeslee 1987), and might be represented by $dy^{**}(t)/dt$ (the prevention of yield reduction in year t due to maintenance research) which is a function of resources devoted to maintenance plant breeding, closeness to theoretical maximum, genetic complexity of scourge resistance, the extent of scourge resistance already utilised etc. If the cost of maintenance research is pd, then the optimal level of maintenance research is given by solving:

$$dy^{**}(t)/dt \; A \; (py-c) \; \{1/(r.[1+r]^{t})\} = pd.$$

Another expression of the value of plant germplasm is the degree to which it assists in raising the raising the value of maintenance research $dy^{**}(t)/dt$. In the preceding framework, the resource is both renewable in the sense that plant breeding increases the size of the plant genetic resource, but this resource also deteriorates in quality due to diseases etc. Thus, the complete problem is a complex intertemporal optimisation problem with significant uncertainty because of the unknown future biological value of germplasm.

4.2.4 Empirical Modelling

Apart from the data requirements, analysis of the future impact of plant genetic conservation on economic welfare requires a procedure by which the effect of the conservation programme can be related to breeding benefits. Clearly, it is not just the size of a germplasm collection that determines its impact on progress in plant breeding, but the effectiveness of the germplasm conservation programme in delivering benefits to practical plant breeding. Apart from the size/comprehensiveness of germplasm conservation, the degree to which plant breeding may be benefited by germplasm conservation will depend on the particular plant kind (K) and the ease of breeding in that plant kind (Ek), the degree to which the genepool has been explored (X), the level of previous breeding effort (and therefore closeness to a theoretical "maximum" yield) (ΣE), the level of the current breeding effort (E), whether the plant kind is destined for subsistence or commercial agriculture (CS), pressure of scourges and thus need for maintenance research (S). In the first instance it is proposed to explore empirical formulations of the following function as a means of predicting the potential benefits of plant germplasm conservation:

$$gy = f(K, Ek, X, \sum E, CS, S)$$

where gy is the rate of yield improvement.

5. Costs of ex situ germplasm conservation

Analysing the costs of maintaining plant germplasm collections has four related aspects:

1. Information may be collected on a range of *types of plant germplasm*. Plant types include the food staples of aibika, banana, sweet potato and taro which will be evaluated in the present study. For each of these plant kinds, cost information is required on the number of accessions, the number of individual plants or samples maintained per accession, and the cost per individual sample maintained.[17]

2. The *types of costs* on which data is required include the conventional Fixed Capital and Overheads, comprising facilities, human capital, land and new accessions. Land is somewhat difficult to value, since its most immediate alternative use is in other research projects. In PNG, the opportunity cost of land outside agricultural research varies from urban use (Bubia) to agricultural uses (most other stations). New accessions are a fixed cost in that either an expedition needs to be mounted, whose cost is independent of the number of new varieties ultimately collected, or new accessions are obtained from overseas, in which case the cost of obtaining and

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[17] There are many other important PNG crops that will not be evaluated in the present study but which must be considered in developing policies based on this research. These other crops are: other food staples (cassava, sago and yam); sugar; Institute crops (cocoa, coconut and coffee); indigenous alternative crops (food, fibre, timber and medicinal crops); and exotic alternative crops (also food, fibre, timber and medicinal crops.

quarantining the new material is an investment cost. The other conventional cost item is Variable Costs comprising cultivation, vegetative propagation, pest disease and weed control using labour and other purchased inputs.

3. The *types of activities* relating to germplasm maintenance for which data is required include activities relating to new accessions (collecting new accessions, passport documentation, preliminary description, preliminary evaluation, intermediate evaluation, replicated trials, full characterisation) and maintenance of accessions in the collection. The costs of maintenance will depend on the method by which accessions are maintained. Such methods include field conservation (currently used for all PNG plant kinds being investigated) of either the full, or a limited, range of the varieties of a plant kind and maintained using IPGRI protocols (at least 10 individuals per accession) or at lower levels of intensity (e.g. some sweet potato varieties are currently maintained as one individual per accession), or tissue culture (currently undertaken for sweet potato in PNG, and demonstrated as feasible for taro; demonstrated for bananas and sugar cane and used in other countries; not currently able to be used for yams because of internal bacteria). A possible alternative is to maintain, either as vegetative or seed collections, gene pools of plant kinds which flower and to select varieties from seed when required. Implicitly this last technique is currently being used for sweet potato, where germplasm maintenance, field evolution and selection currently occurs in farmers' fields in the Highlands.

4. Germplasm maintenance may occur in a *variety of locations*. These locations are, for field collections, research stations in PNG, research stations in Oceania or Southeast Asian, or international centres (either within the CGIAR group or outside). These research institutes may be either public or, as in the case of sugar cane in PNG, private. Seed or tissue culture collections may also be maintained at the preceding locations, or at other locations such as universities within or outside PNG.

6. Paying the piper—policy issues

If there is a positive net benefit to the world from maintaining PNG's crop germplasm collections—and especially if the net benefit to PNG of maintaining these collections is negative—then there is a need to investigate the appropriate institutional structure for sustaining these collections. This analysis requires, firstly, comprehensive documentation of the existence of market failures in germplasm conservation, such as the existence of property rights problems (e.g. non-rivalry in use of plant germplasm, difficulty of enforcing price exclusion), and the degree of uncertainty over the current and future value of germplasm and market failure in coping with this risk. Secondly, an assessment is required of the severity of any market failures that exist, particularly in the context of a developing country like PNG. This analysis also requires appreciation of recent international developments in intellectual property rights such as farmers' rights, the Biodiversity Convention and intellectual property regimes under the most recent GATT Agreement, and possible future changes particularly as they interact with further likely developments in molecular biology.

If there are net international benefits from maintaining PNG's plant germplasm collections and it can be demonstrated that there are serious market failure problems with respect to maintaining this germplasm, then a case needs to be documented to convince public donors to assist in maintaining the collections. The empirical economic analysis proposed to be undertaken in this study would provide a foundation for approaching potential donors. Alternatively, institutional changes to the way in which PNG collections are maintained might also be suggested as a way of devoting additional funds to plant germplasm conservation, or to economise on the existing allocation of funds.

7. Conclusion

In an ideal world, the conservation of PNG's plant germplasm resources—both its current food staples and other plant types—could be justified using the precautionary principle. In a less-than-ideal world, the PNG Government is having severe difficulties maintaining its existing collections, let alone being able to devote additional resources to plant germplasm conservation. In the absence of sufficient national resources to both maintain and expand plant germplasm collections, it may be desirable to seek international funding to preserve existing collections, and to add new accessions. Again, in this less-than-ideal world, potential donors are also likely to require evidence that the proposed expenditure on PNG germplasm is appropriate—and part of the decision-making appropriateness is likely to include the costs of collections, and the likely benefits from maintaining them. While a precise evaluation of the investment in germplasm maintenance and additional accessions is unlikely, sufficiently robust estimates are likely from an appropriately-constructed analysis.

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Table 1: Comparison of Major Crop Germplasm Collections in Papua New Guinea and Corresponding Collections in the Rest of the World, late 1980s-early 1990s

Plant type	PNG Collections		Other Collections		
	location(s)	accessions (no.)	collections (no.)	accessions (no.)	large collections@
Aibika	Laloki Agricultural Research Station	159	6	62	none
Banana	Laloki Agricultural Research Station	356	88	very large	none
Cassava	1. LAES, Keravat 2. HAES, Aiyura 3. Department of Agriculture, Unitech, Lae 4. Laloki Agricultural Research Station	125	91	large	6##
Sugar cane	Ramu Sugar Company, Morobe Province	297	20	small, except for big collections	5 **
Sweet Potato	1. LAES, Keravat 2. HAES, Aiyura 3. Laloki Agricultural Research Station	1425	81	large	2 ***
Taro	1. LAES, Keravat 2. HAES, Aiyura 3. Laloki Agricultural Research Station 4. Department of Agriculture, Unitech, Lae 5. Bubia Agricultural Research Centre, Lae	867	51	moderate	none
Yams	1. LAES, Keravat 2. HAES, Aiyura 3. Laloki Agricultural Research Station 4. Department of Agriculture, Unitech, Lae 5. Bubia Agricultural Research Centre, Lae	469	56	large	1 #

Source: data from FAO, Commission on Plant Genetic Resources; most of the PNG data is from 1987; see Table 2 for current data for PNG collections

Notes: @ exceeding 1000 accessions

** Brazil (4565), Cuba (1400), Dominican Republic (corporate) (1907), India (3979), USA(2038, plus second collection of 787)

*** Nigeria (IITA) (1000), Peru (CIP) (2867)

Nigeria (IITA) (2500)

Brazil (1259), Colombia (CIAT) (5035), India (1327), Nigeria (IITA) (1700), Philippines (5430), Uganda (1019)

LAES - Lowland Agricultural Research Station

HAES - Highlands Agricultural Research Station

Table 2: Cost of Maintaining Crop Germplasm Collections in Papua New Guinea

	Germplasm-related research		Particular studies	Annual Cost (kina)
	Main scientist	Specific topic		
Highlands Agricultural Experimental Station, Aiyura, Eastern Highlands	M. Kanua	Germplasm	Sweet potato germplasm & PRAP	10 794
	B. Bino	Germplasm	. variety evaluation	
	T. Nevenimo	Germplasm		
Bubia Agricultural Research Centre, Lae, Morobe	A. Ivancic	Crop breeding	Taro germplasm, characterisation and evaluation	19 996
	A. Ivancic	Germplasm	Taro improvement programme	51 077
			Screening of taro varieties for resistance to leaf blight	3 396
			. various variety evaluation	
Lowlands Agriculture Experimental Station, Keravat, East New Britain	G. Ling	Germplasm	Germplasm of foodcrops and vegetables	21 896
	M. Woruba	Germplasm	Germplasm source collection for plant derived pesticides	3 198
	P. Foerster	Germplasm	Sweet potato germplasm collection	6 189
	P. Van	Germplasm	Germplasm of alternative crops and spices	13 037
	W. Akus	Germplasm	PRAP sweet potato evaluation (x2)	52 362
			. various variety evaluation	
Laloki Agricultural Research Station, Port Moresby NCD	L. Kurika	Germplasm	Aibika germplasm collection	5 347
			Banana germplasm collection	10 236
			Cassava germplasm collection	4 228
			Yam germplasm collection	12 427
			. various variety evaluation	

Source: Ghodake and Wayi (1994)

Table 3: Status of Major Crop Germplasm Collections in Papua New Guinea, 1995

	Aibika	Banana	Cassava	Sugar cane	Sweet Potato	Taro	Yams	Sago
Highlands Agricultural Experimental Station, Aiyura			????		1453 (mx) 149 (du) 95 (ls) 1209 (mt) 1173 (ft)	????	????	
Bubia Agricultural Research Centre, Lae, Morobe Province	(wk)		(wk)	206 (mx) 134(ls) 72 (mt)		600 (mx) (du) (ls) 437 (mt) 360 (ft)[c]	(wk)	
Lowlands Agriculture Experimental Station, Keravat, East New Britain	67 (mt) (islands cultivars) 57 (ft)	17 (mt) (islands cultivars) 30 (ft)	36 (mt) (islands cultivars)		1208 (ft)[e] 19(du)	40 (mt) (islands cultivars) 93 (ft)[f]	32 (ft)	
Laloki Agricultural Research Station, Port Moresby NCD	142 (mx) 30 (ls) 112 (mt) 87 (ft)[b]	500 (mx) 479 (mt) 353 (ft)	79 (mt)		1044 (mx) 52 (du) 669 (ls) 375 (mt) 36 (ft)[a]	135 (islands cultivars)	432 (mx) (du) 108 (ls) 315 (mt)	
Saramandi Research Station, East Sepik	23 (mt)					21 (mt) (local cultivars)	27 (mt) (local cultivars) 12 (mt) (IITA)	13 (mt)
Ramu Sugar Company, Morobe Province				500+ (ft)[d]				
Department of Agriculture, PNG University of Technology, Lae			????			????	????	

Source: Kambuou (1995) supplemented by Godden (1995)
Notes: mx (maximum number of accessions); du (duplicates), ls (accessions lost), mt (accessions currently being maintained), wk (working collection), ft (information collected during field trip May 1995).

a - most of the sweet potato collection has since been moved to LAES Keravat.
b - 200 seedlings of aibika have been grown from some varieties which have seeded at Laloki
c - a large number of varieties from the taro breeding programme will soon be added to the collection
d - a large number of varieties from the sugar cane breeding programme will soon be added to the collection
e - 280 former Laloki varieties are maintained at Keravat
f - includes Colocasia, Xanthosoma, Alocasia and Swamp

Figure 1: Plant Germplasm Conservation Production Process

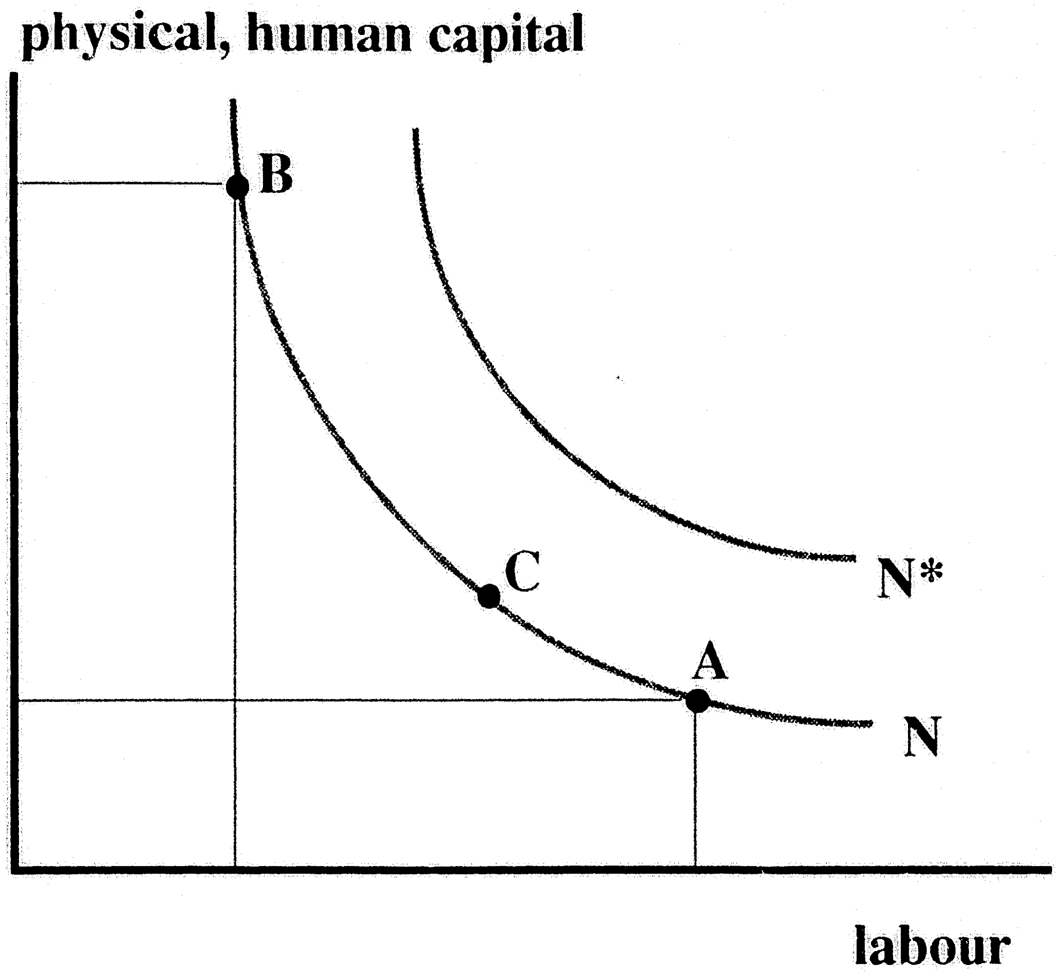


Figure 2: Distributions for Selecting Superior Plant Varieties

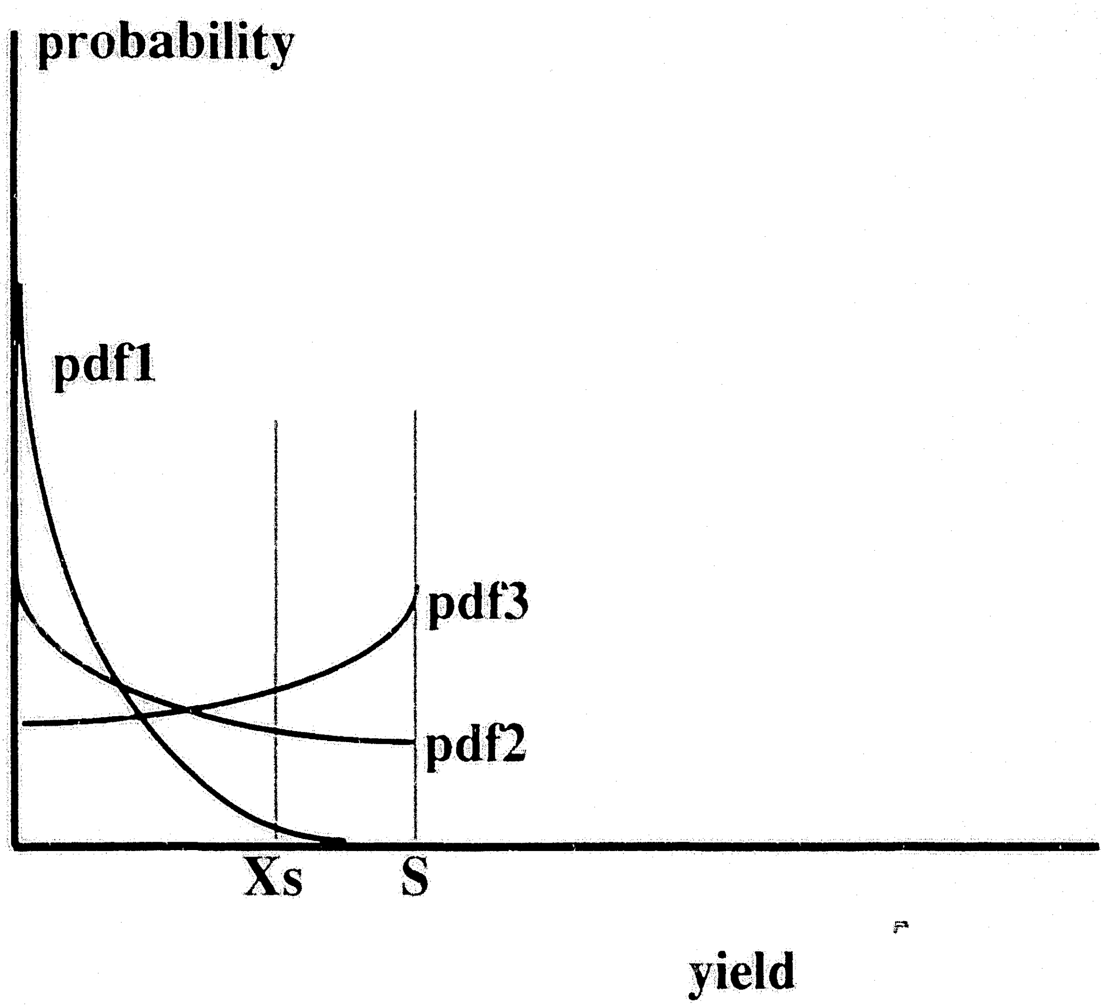


Figure 3: Illustrative Effect of Systematic Plant Breeding

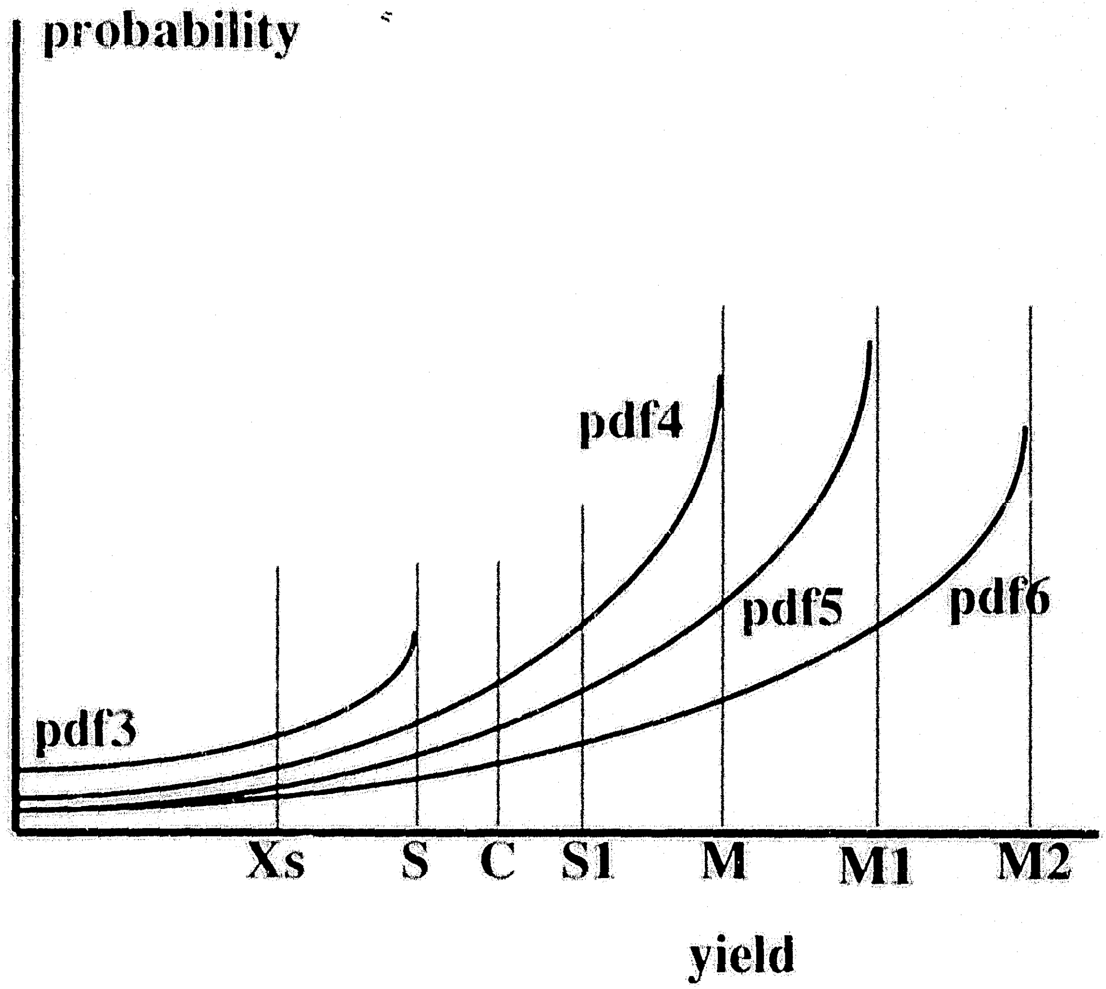
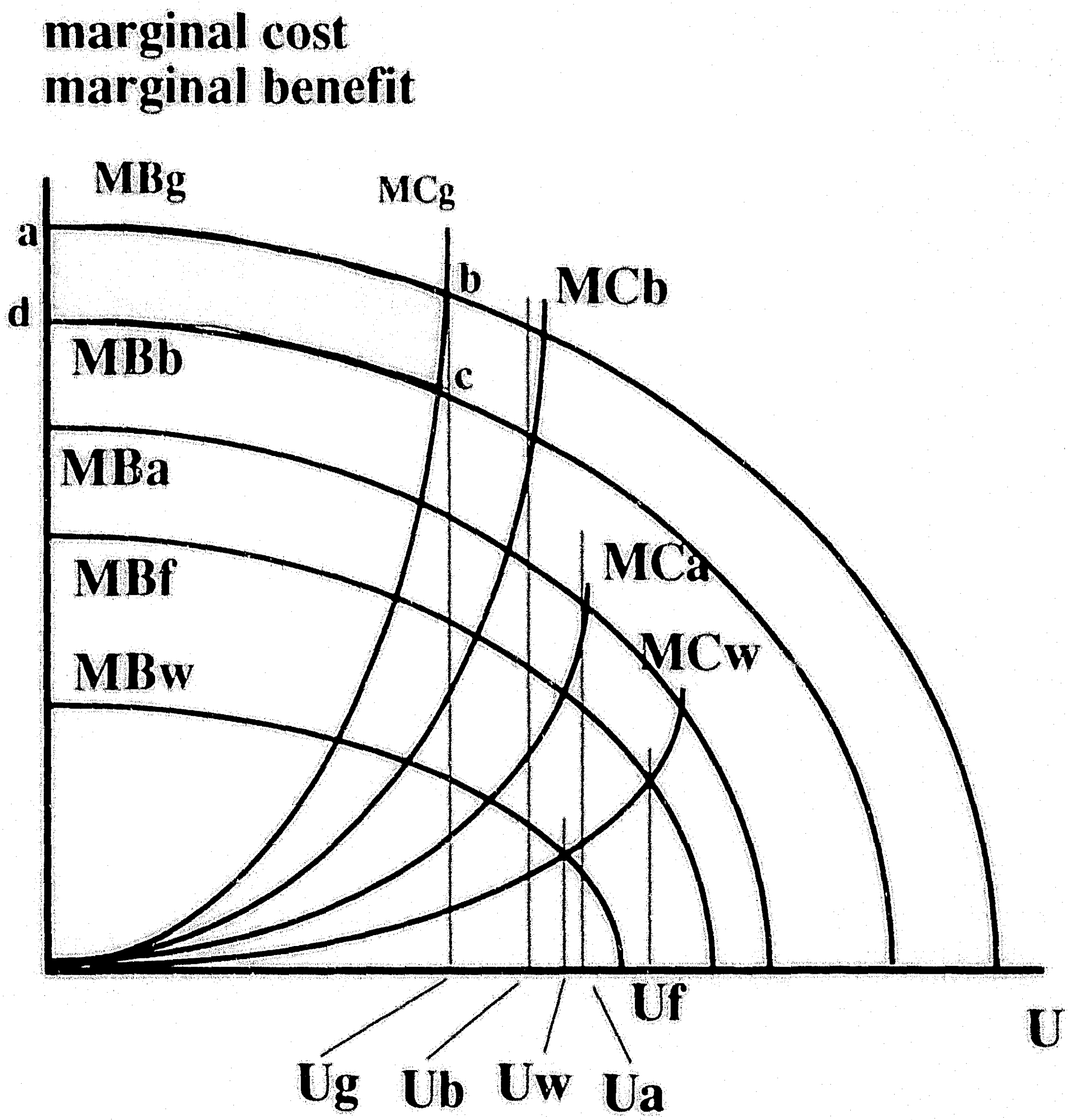


Figure 4: Marginal Benefit and Marginal Cost Curve for Selection and Breeding



Note: the shapes of the curves, either strictly convex upwards (MBj) or strictly convex dc (MCj) was dictated by the limitations on drawing curves in Word 5.1a.