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Greenhouse gas and groundwater recharge abatement benefits of tree crops in south-western Australian farming systems*

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The indirect benefits of a commercial tree crop for greenhouse gas and groundwater recharge abatement are analysed. Oil mallees are introduced into a whole-farm linear programming model as a source of income, an offset to greenhouse gas emissions from the mixed sheep and cropping enterprises and as a source of groundwater recharge abatement. The profitability of oil mallees is found to be very sensitive to the discount rate, yield and price assumptions and the relative profitability of other farm enterprises (especially the wool enterprise). Under standard assumptions where oil mallees are profitable, the trees significantly reduced greenhouse gas emissions and groundwater recharge and the farm remains profitable. If farm-level policies are introduced for greenhouse gas abatement, without tree crops or some other technological change, the current farming systems would fail and be replaced by alternative land uses.

1. Introduction

Many scientists claim that atmospheric concentrations of greenhouse gases have increased markedly due to human activity, such as the burning of fossil fuels, land clearing and agricultural production. These scientists argue that increases in atmospheric greenhouse gases are having a discernible impact on climatic conditions, especially global warming (Intergovernmental Panel for Climate Change 2001). Concern for the risks of human-induced climate change and the realisation that addressing the issue requires an international cooperative effort led to the establishment of the United Nations

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Framework Convention for Climate Change. One of the most significant initiatives of the parties to the Convention is the Kyoto Protocol, an agreement that requires ratifying countries to restrict emissions to a specified percentage of 1990 emissions (United Nations Framework Convention on Climate Change 1997). Australia is a signatory to, but has not ratified, the Protocol. If ratified, Australia will have to restrict emissions to 108% of 1990 levels in the first commitment period of 2008–2012. Most Australian emissions have their source in the burning of fossil fuels (53% in 1990, 55% in 1996); however, agriculture is the second biggest contributor (16% in 1990, 20% in 1996). Ruminant livestock are the greatest source of emissions in the agricultural sector, contributing 70% of agricultural emissions (although emissions from livestock decreased by 5.1% from 1990 to 1998 (NGGI 1998a), mostly due to the drop in sheep numbers associated with the drop in wool prices).

One question, then, is ‘what actions could farmers take to reduce greenhouse gas emissions if required to do so?’ This analysis specifically focuses on the Great Southern region of Western Australia, a region with relatively high rainfall compared with other agricultural regions in the state. Petersen *et al*. (2003) found that, in the absence of carbon sinks, there are few economically feasible management options for greenhouse gas abatement in the region, due to the dependence of the system on ruminant livestock production (typically 85% of the system is grazed). Any abatement policy would rapidly cause the present system to become unprofitable unless swift technological change provided alternative enterprises or reduced emission levels in current practices. Given current conditions, any abatement policy to decrease agricultural emissions in predominantly grazing systems is likely to be politically impossible. So, can farmers sequester some of the greenhouse gases emitted by flocks of sheep and still remain economically viable in the region?

The introduction of a commercial tree crop is considered to be an example of a technological change; however, the use of forests and other plantations as carbon sinks under the Kyoto Protocol is a contentious issue. This was demonstrated at the Sixth Conference of the Parties to the United Nations Framework Convention on Climate Change (COP6) at The Hague in November 2000, where no consensus was reached regarding the accreditation of forests as carbon sinks. The COP6 was resumed at Bonn in July 2001, where there was agreement to credit afforestation and reforestation activities as carbon sinks and this agreement was confirmed at COP7 at Marrakech in November 2001.

The properties of trees as a carbon sink are not yet well understood and are difficult to define and measure. Certain signatories to the Protocol resisted the inclusion of trees as sinks on the grounds that it allows parties to continue the burning of fossil fuels at a higher rate. Another criticism of using trees as a carbon sink is that the effect is only temporary. Carbon will be released into the atmosphere at harvest and with the oxidation of the harvested timber. However, defenders argue that tree crops could permanently contribute to reductions in atmospheric carbon levels if they are used to replace products that take a lot of energy to produce (i.e. replacing steel, aluminium and cement with wood products). Irrespective of the time period for which the carbon is sequestered, it is generally argued that accrediting tree crops as carbon sinks will 'buy time', so that new, less-polluting technologies (such as alternative energy sources) can be developed (Shea 1999).

Another indirect benefit of reforestation is the possible reduction in the extent of dryland salinity. Along with biodiversity loss, dryland salinity is one of the most important environmental problems facing Western Australia and has received much public attention (Government of Western Australian 1998, 2000; Frost *et al*. 2001). Campbell *et al*. (2000) argue that the Great Southern region has the potential for being the region with the highest proportion of land affected by salinity in the state. Secondary dryland salinity is directly linked to Australia's history of land clearing that started with European settlement. It is caused by the increase of recharge into the soil profile causing the water table to rise and eventually to intercept the soil surface, bringing salt with it (Wood 1925). The impact of reforestation on recharge abatement in the Great Southern region is also investigated in the present paper as an extra benefit derived from planting commercial trees.

The aim of the present paper is to contribute to the environmental policy debate by assessing the viability of a commercial tree crop, specifically oil mallees, for greenhouse gas and recharge abatement on mixed cropping enterprises in Western Australia. The paper proceeds as follows. In section 2, the methodology of the study is presented, giving a brief discussion of the tree crop species analysed (oil mallee) and the modelling techniques used. Results are presented with discussion in section 3, where the economic performance of the tree crops in the Great Southern region is presented, followed by an analysis of greenhouse and recharge abatement impacts of the commercial tree plantations. Some conclusions are drawn in the final section.

2. Methods

The instrument of analysis is a linear programming model of a steady state single-period representation of a farming system. Named MIDAS (Model of an Integrated Dryland Agricultural System), the model was originally developed for the Merredin region of Western Australia, but has since been calibrated for several other regions. MIDAS includes the relevant biological complexities and interactions between enterprises in a typical wool or wheat belt farming system by using a whole-farm modelling framework (Pannell 1996). MIDAS has been used to analyse issues concerning greenhouse gas abatement (Petersen *et al.* 2003), farm management (Schmidt and Pannell 1996), agricultural policy (Morrison and Young 1991), research (Pannell 1999) and the introduction of new technologies, such as new legume crops (Schilizzi and Kingwell 1999).

The objective of the model is to maximise farm profit where profit is defined to be net return to capital and management invested in the land. It equates to residual income from production receipts after depreciation, operating overheads and opportunity costs have been deducted (the latter associated with farm assets exclusive of land). Labour is costed as a yearly salary not dependent on the individual tasks he or she carries out. MIDAS is based solely on expected values (the first moment of the probability distribution) and, therefore, assumes risk-neutral decision making. Model output indicates optimal (i.e. profit-maximizing) land use, stock numbers, greenhouse gas emissions and groundwater recharge from each source associated with the optimal plan.

2.1 Some elements of the Great Southern MIDAS

The Great Southern region was chosen because, due to its soil-climate constraints, it supports a predominantly grazing farming system. Ruminant livestock contribute far more greenhouse gases than crops, especially non-irrigated crops. This region is approximately one million hectares in size, with approximately 1000 farms of an average of 1100 hectares (Australian Bureau of Statistics 1997). Readers are referred to Morrison and Young (1991) and Young (1995) for detailed expositions of the nature and structure of the Great Southern MIDAS model (GSM; which excludes accounting for greenhouse gas emissions). Petersen *et al.* (2003) present a detailed description of the developments made to the standard version of GSM to include greenhouse gas emissions. A brief description of GSM and the modelling of greenhouse gas emissions is presented in this section and a detailed discussion of the inclusion of the tree crop in GSM is documented in the following text.

The Great Southern region of Western Australia typically has a Mediterranean climate, with the majority of the annual rainfall (approximately 500–600 mm) falling between April and the beginning of November. The production enterprises included in GSM are livestock (sheep) and crops (cereals, lupins and canola), with an average of 15% of land cropped in

Table 1 Great Southern MIDAS model soil types

Soil class	Description	Area (ha)
LMU1	Shallow saline sands over heavy gleyed or mottled clay	100 (saline soils)
LMU2	Deep sands often water-logged over grey gleyed clay	150 (water-logged soils)
LMU3	Deep sands but not water-logged over mottled clay	50 (deep sands)
LMU4	Gravels and sandy gravels to 50 cm over clay or gravelly clay	500 (sandy gravels)
LMU5	Sandy loam, loamy sand over clay; rock outcropping in landscape	200 (sandy loams)
		Total = 1000

LMU, land management unit.

Table 2 Rotational options in the Great Southern MIDAS model

Rotations on all LMU	Rotation on LMU4 and 5 only (70% of area)
PC, PPC, 4PC, 8PC, 5PCC, 5PLC, 5PCCC, 5PCLC, PPPP, 5PS	5PNC

P, pasture; C, cereal; L, lupin; S, fodder crop; N, canola; 4PC, 4 years pasture followed by 1 year cereal rotation; LMU, land management unit.

both the benchmark solution and observed field data. The model farm is family owned and run and is highly mechanized, which represents the nature of the Great Southern farming systems.

2.1.1 Soil types

The soil types are modelled in five land management units (LMU; see table 1). The LMU display a range of fertility. The saline (LMU1) and water-logged (LMU2) soils (25% of farm area) are the least fertile, whereas the sandy gravels (LMU4) are the most fertile (50% of farm area). Rotational options for the LMU are presented in table 2. LMU1 and 2 are generally not suitable for cropping and, although there are allowances in GSM, cropping on these soils is only rarely selected in the optimal solution (yields are dependent on soil type). Canola production is only suitable on the heavier soils LMU4 and 5 (70% of farm area). To increase the model's accuracy as a representation of reality, a number of interdependencies between enterprises are represented in GSM. The three main interdependencies are the rotational benefits between phases in a rotation, the grazing of stubble by sheep and the subsequent grazing of remnant grain in the paddock after harvest.

Table 3 Global-warming potential of greenhouse gases relative to carbon dioxide

	Greenhouse gas				
	CO_2	CH_4	N_2O	CO	NMVOC
Global-warming potential relative to CO_2	1	21	310	1	1

NMVOC, non-methane volatile organic compounds.

2.1.2 Greenhouse gas emissions

Greenhouse gases are assumed to have four main sources: sheep in the form of methane (CH_4), nitrogenous fertiliser application in the form of nitrous oxide (N_2O), fuel use in the form of carbon dioxide (CO_2) and stubble burning (which creates a range of greenhouse compounds). All these emissions are modelled according to the National Greenhouse Gas Inventory (NGGI) published by the Australian Greenhouse Office (National Greenhouse Gas Inventory 1998a, 1998b, 1998c, 1998d). Emissions are converted to carbon dioxide equivalents (CO_2-e) through multiplication by their average global warming potentials. These relative potentials are presented in table 3. For a detailed exposition on the modelling of greenhouse gas emissions in the GSM, the reader is referred to Petersen *et al.* (2003).

2.2 Modelling of the commercial tree crop

Two species of commercial trees are considered to be suitable for the Great Southern region of Western Australia. Oil mallees are a group of *Eucalyptus* species with high oil content in their leaves that grow in the mallee form (many trunks forming a spreading habit). Most oil mallee production in Australia is from improved natural stands of *Eucalyptus polybractea* (Boland 1991). Oil mallees are native to Australia. They have potential as a short rotation tree crop producing eucalyptus oil for the pharmaceutical industry as inhalants, soaps, gargles, lozenges, perfumery and disinfectants; and for industrial applications as solvents and hand cleaners (Boland 1991; Barton and Knight 1997). The aboveground biomass also has potential as a fuel for electricity production and for the manufacture of charcoal and activated carbon (Shea *et al.* 1998; Rural Industries Research and Development Corporation 1999). The mallees are harvested by cutting them off a few centimetres above the ground (Abbott 1989). The trees resprout from underground lignotubers using energy stored in these tubers (Canadell and Lopez-Soria 1998).

The second species of tree crop suitable for the Great Southern region is *Pinus pinaster* or maritime pine. Unlike oil mallees, maritime pines are not native to Australia (they are native to Portugal), but have been grown in Australia for more than 80 years. They require sandy, free-draining soils (Shea *et al*. 1998). Hence, their use is limited to LMU3 (deep sands), which constitutes just 5% of GSM. Because of their negative profitability under most realistic scenarios, maritime pines are not included in the present analysis.

Commercial plantings of oil mallee started in 1994 and approximately 20 million trees on nearly 8000 hectares had been planted on south-western Australian farming systems by the end of 2001 (Bartle and Shea 2002). As yet, the oil mallee industry is in its infancy with a 20 000 tonne demonstration-scale plant (that processes the trees to simultaneously produce eucalyptus oil, electricity and activated carbon), currently under construction in Narrogin, expected to consume most of the established mallees within 50 km of the plant over the next few years. Upon successful completion of this demonstration, the plant is expected to expand to 100 000 tonne capacity in the subsequent 5 years and up to nine full-scale plants (100 000 tonne capacity) are likely to be built in the low-to-medium rainfall agricultural region of south-western Australia (Chegwidden *et al*. 2000). The oil mallee industry is aiming for 500 million plantings by 2025 (Bartle and Shea 2002), which Holt (2001) calculates could supply enough activated carbon to fulfil present market requirements for activated carbon, less than 5% of the world's solvent market and approximately 11% of Western Power's forecast increase in electricity demand to 10 years.

Oil mallees were included in GSM for this analysis as a source of income from their timber and eucalyptus oil products and as a sink for greenhouse gases and groundwater recharge. They perform poorly on saline or waterlogged soils; hence, they were modelled only on LMU3, 4 and 5 in GSM. The productivity of the mallees is assumed to be equivalent on each LMU with the assumption that different species will be grown on each soil type for maximum productivity. This assumption is realistic given that oil mallees are native and, hence, well adapted to the soils and climate of the Great Southern region (Cooper 1999). Furthermore, Wildy (2000) found that soil nutrient level had no effect on oil mallee growth rates in the Western Australian wheat belt, giving weight to this argument.

2.2.1 Economics and carbon sequestration rates

Establishment costs of oil mallees are listed in table 4. It is assumed that the farmer uses available farm labour to establish the trees; hence, no contracting labour requirement is included.[1] The benefits and costs of a 30-year

[1] It is assumed that the opportunity cost (and marginal cost) of labour for tree establishment is zero because the farmer does the planting when no other work is required on the farm.

Table 4 Establishment costs of oil mallees

	Cost ($/ha)
Site preparation	30
Delivery of plants	35
Ripping, mounding and scalping	150
Pest management	5
Weed control	70
Seedlings	720*
Planting	0
Total	1010

*Assuming 2667 seedlings/ha at 27 cents/seedling.

Table 5 Maintenance costs of oil mallees (in real terms)

Year of cost	Cost description	Maintenance cost ($/ha)
1	Cost of replanting if failure*	51
1	Weed control	35
Harvest years	Pest control	10
Harvest years	Weed control	35
Each year	Maintenance of firebreaks	5
Each year	Insurance	5
Total		791

*Five per cent of establishment cost.

rotation are estimated, although, in reality, oil mallees can keep producing timber and oil indefinitely. However, for modelling purposes, the time-frame needs to be specified. When modelling an enterprise where most benefits and costs are accrued in the future in a single-period model, such as MIDAS, certain assumptions need to be applied. First, it is assumed that the annuity is received at the end of the year, so that no interest on these benefits is received throughout the year. Second, future benefits (in real terms) need to be discounted by the real interest rate a farmer would face. The maintenance costs of the oil mallees presented in table 5 are in real terms.

In recognition of the argument that carbon sequestered in trees is temporary, in the present analysis only carbon sequestered by the trees in the long term is considered. It is assumed that each time carbon is removed from the farm through tree harvests, the on-farm pool of carbon is reduced by the same amount. Hence, it is assumed that all sequestered carbon is released again through time in the various uses of the biomass. In the case of mallees that can be thought of as a perennial crop harvested initially after 6 years and then every 3 years, this means that only the carbon sequestered by the trees during the 6 years before the first harvest (because subsequent harvests will be offset by the growth of trees prior to the next harvest), and the carbon accumulated in the rootstock, is used to offset other emissions on the farm. It is also assumed that the planting of trees is permanent, although benefits and costs are only calculated for a 30 year time period. In time, if the trees are destumped, the only abatement benefits from tree planting are from buying of time for the development of less-polluting technologies (e.g. solar and wind technologies). Although not part of the following calculations, and depending on price fluctuations, it may also be an advantage to sell carbon credits ahead of timber harvest, because this can provide income earlier in the production cycle.

The typical proposed rotation for the oil mallees is to harvest first in year 6 and then every 3 years subsequently. Hence, in the 30 year life of the plantation the crop will be harvested 9 times. The maximum aboveground biomass at harvest is 25 kg/tree (Herbert 2000). Each subsequent triennial coppice is the same as the first harvest. Assuming a seeding rate of 2667 trees/ha, 10% mortality of trees (so 2400 trees/ha survive), nine harvests in the 30 year rotation, total biomass harvested is 540 tonnes/ha (or 18 tonnes/ha per year on average). The gross price received for the oil mallees is $30 /tonne over the 30 years. However, transport, harvest and harvest coordination costs are approximately $15 /tonne, hence the net price received is $15 /tonne (Herbert 2000). This $15 /tonne is received for all aboveground biomass. This price assumes that the study farm is within 40 km of the processing plant.

Financial returns of the oil mallees are presented in table 6. The annuity is the net present value (using a 3% real discount rate) divided by the length of the rotation (30 years) and represents the average benefit received in each year. This is regarded as the annual gross margin of the tree enterprise. The gross margin of the sheep enterprise is typically between $70 /ha and $200 / ha depending on the class of sheep, wool and meat prices, grazing rotation and stocking rate. The main class of sheep is ewes sold at 5 years of age, which have a gross margin of approximately $110 /ha. Hence, the annuity

Table 6 Financial returns of oil mallees*

Discounted total costs ($/ha)	1533
Discounted total returns ($/ha)	4884
Net present value @ 3% ($/ha)	3351
Annuity ($/ha)	112

*The annuity can be equated with the gross margin of the enterprise. A 3% real discount rate is used.

of the oil mallees ($112 /ha) is slightly larger than the gross margin of the majority of the sheep enterprises, the main production activity of the GSM, and will be selected in preference to some sheep activities in the optimal (profit-maximising) solution.

Because research into carbon sequestration by plantations is still in its infancy, no data are available at present for oil mallees. Hence, sequestration rates were estimated through use of the following assumptions:

1. Aboveground biomass production is a sigmoid function resulting in 25 kg/tree at first (year 6) and subsequent harvests (every 3 years);
2. Aboveground biomass in the first year after coppice is 6 kg/tree, in the second year after coppice it is 15 kg/tree and in the third year after coppice it is 25 kg/tree prior to the next coppice (A. McCarthy, pers. comm.[2]);
3. Dry weight of the above-ground biomass is 50% of the wet weight (Shea 1999);
4. Carbon weight of the biomass is 50% of the dry weight (Hassall and Associates 1996); and
5. Below-ground biomass is 20% of aboveground biomass (Hassall and Associates 1996) until the first harvest, after which the roots grow at 2% each year.

Given these assumptions, and converting carbon weight to carbon dioxide weight (by multiplying by approximately 3.67),[3] the carbon dioxide sequestration rates for oil mallees (including aboveground biomass to the first harvest and all below-ground biomass) are 73 tonnes CO_2/ha over 30 years and 2.4 tonnes CO_2/ha annually. These rates are low compared with those quoted in the published literature.[4] However, it is considered safer to err on the side of caution given the uncertainty still surrounding the properties of tree crops as carbon sinks.

[2] Andrew McCarthy, Department of Conservation and Land Management (CALM), South Perth, WA, Australia.

[3] This is done by multiplying the carbon weight by the atomic weight of carbon dioxide (44) and dividing by the atomic weight of carbon (12).

[4] Shea *et al.* (1998) quote the average annual carbon sequestration rate of oil mallees (including above- and below-ground biomass) to be 114 tonnes/ha, but do not offer an explanation for how they obtained this number. This is approximately fivefold the calculation made in the present analysis (24 tonnes/ha) when above- and below-ground biomass is considered over the 30 year production period. Because we are only considering aboveground biomass to the first harvest (year 6), the figure used in the present analysis is 2.4 tonnes/ha. To the authors' knowledge, no other studies have presented sequestration rates for oil mallees. Further research in this area is necessary.

Table 7 Recharge levels for each rotation in the Great Southern MIDAS model (mm/year)*

	LMU1	LMU2	LMU3	LMU4	LMU5
PC	5	5	57	49	28
PPC	11	6	61	55	31
4PC	13	7	62	55	31
8PC	17	9	64	58	32
5PCC	12	8	57	56	28
5PLC	12	8	57	56	28
5PCCC	12	8	57	49	28
5PCLC	12	8	57	49	28
PPPP	17	15	65	60	33
5PS	14	8	62	57	32
5PNC				56	28
Oil mallees	0	0	0	0	0

*Note that the Great Southern aquifers have a storage coefficient of between 0.1 and 0.2, so that 10 mm of recharge equates to 50–100 mm groundwater rise.
P, pasture; C, cereal; L, lupin; S, fodder crop; N, canola; 4PC, 4 years pasture followed by 1 year cereal rotation; LMU, land management unit.

2.3 Recharge flows from the system

Recharge values for each rotation are presented in table 7. Values were obtained using the AgET Water Balance Calculator,[5] using rainfall data for Kojonup for the years 1954–1993. The first author, in consultation with Paul Raper,[6] specifically created data files that matched the biological and physical characteristics of the GSM LMU. The recharge values depend on the type, number and order of crop and pasture phases in each rotation. Recharge is assumed to be negligible under oil mallees given that studies have demonstrated that recharge under native vegetation is less than 1 mm/year (Allison *et al.* 1990; Kennett-Smith *et al.* 1992; Salama *et al.* 1993). Although tree plantations may not mimic native vegetation that includes a combination of pasture and trees, a large number of hydrologists and agronomists estimate that trees will lower water tables and, therefore, recover saline and water-logged land. Hence, the assumption of zero recharge under tree plantations is considered reasonable.

[5] AgET was developed by the Department of Agriculture – Western Australia and The University of Melbourne. It can be obtained from the Agriculture Western Australia website (http://www.agric.wa.gov.au/).

[6] Paul Raper, Research Hydrologist, Department of Agriculture-Western Australia, Bunbury, WA, Australia.

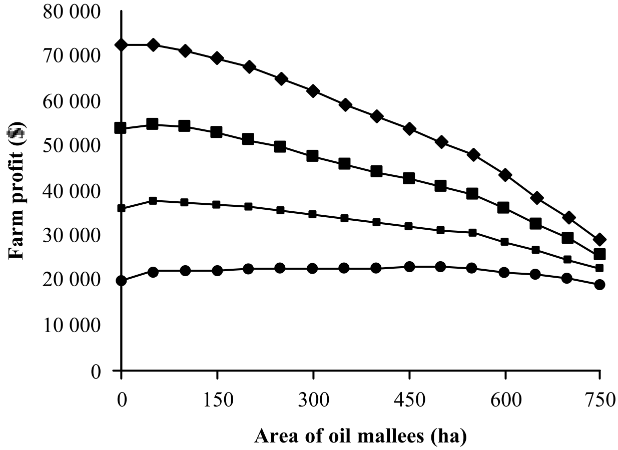

Figure 1 The impact of the introduction of oil mallees on farm profit for varying wool prices (wool price is given in cents (c)/kg greasy) in the absence of any greenhouse penalties. –◆–, 450 c/kg; –■–, 400 c/kg; –▪–, 350 c/kg; –●–, 300 c/kg.

3. Results and discussion

This section comprises three parts. First, the economic performance of oil mallees in the Great Southern region is presented. Second, the economics of oil mallees for greenhouse gas abatement is discussed. Third, the recharge abatement value of greenhouse gas abatement policies is demonstrated.

3.1 Economic performance of the tree crops in the Great Southern

Figure 1 presents farm profit for increasing areas of oil mallees under different wool prices. First, farm profit, especially in the absence of oil mallees, is highly dependent on wool price: it varies, in the benchmark system, from approximately $20 000 to $73 000 as wool prices increase from 300 to 450 cents/kg greasy. This is not surprising given the dependence of the system on sheep production (85% of the farm is typically allocated to sheep production). Second, the optimal area of land planted to oil mallees increases with decreasing wool price. This occurs as the farm substitutes oil mallees for sheep production as the profitability of the sheep enterprise decreases. Optimal mallee area for each wool price is 50 ha (450 cents/kg greasy), 50 ha (400 cents/kg greasy), 59 ha (350 cents/kg greasy) and 484 ha (300 cents/kg greasy). Note that the optimal area of oil mallees depends on the farmer's attitude towards risk. A formal risk analysis is not included in the present study, but it follows that a risk-averse farmer would consider the irreversibility of the planting decision when assessing his/her investment. This should also be equated with the riskiness of the tree crop enterprise,

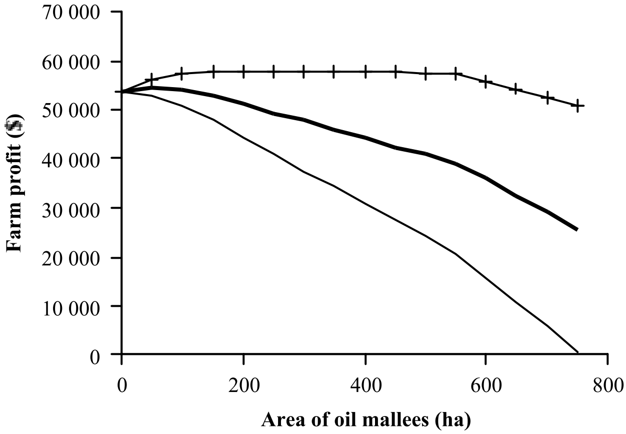

Figure 2 Sensitivity on oil mallee annuity. Note: sensitivity includes 70, 100 and 130% of the oil mallee annuity of $112 /ha.
—, 70 per cent; —, 100 per cent; -+-, 130 per cent.

including price, production, flood and fire risks, relative to risk associated with other enterprises (particularly the wool enterprise).

It is profitable to plant part of the farm to oil mallees even at a high wool price. At the two highest wool prices (450 and 400 cents/kg greasy), it is optimal to plant all LMU3 (deep sands) to the mallees. LMU3 is less suited to crop and pasture production than LMU4 and 5 (see table 1); hence, the opportunity cost of growing mallees on LMU3 is the smallest. With decreasing wool price, it is optimal to plant more mallees on LMU5 and then LMU4, because the opportunity cost of planting the mallees on LMU5 is less than that of LMU 4. Note, also, that for all soil types and wool prices, mallees generally replace both crop and pasture land simultaneously, although the rate of replacement is faster on cropped land than pasture because cropping is the less profitable of the two enterprises on such soil types. The medium term forecast of wool price is currently 400 cents/kg greasy.[7] All subsequent results will be presented assuming this forecast price. At this price, the optimal farm plan without trees yields approximately $54 000 profit.

3.1.1 Sensitivity analysis

Results presented so far have assumed the financial details presented in table 6. Figure 2 is a presentation of the impact of varying the annuity for oil mallees on farm profit for different oil mallee areas. Farm profitability is highly sensitive to this annuity, especially with relatively large areas of

[7] This was the forecast at the time the present paper was written.

land allocated to the mallees. It is important to note that while farm profit is increased substantially with increased mallee annuity, the mallee enterprise becomes unprofitable on all soil types if the annuity is decreased. It must be remembered for all subsequent results that mallee production is profitable under present or more optimistic financial assumptions, but is not profitable under less optimistic financial assumptions.

Results presented so far are dependent on the relative areas of each LMU. A sensitivity analysis on these relative proportions is not included in the present study; however, it is clear that a farm with greater proportions of the productive LMU (i.e. LMU4 and 5) would be more profitable than farms with greater proportions of the more marginal LMU (i.e. LMU1, 2 and 3). In addition, the commercial potential of oil mallees would be larger for a more marginal farm (at least one with a higher proportion of LMU3) due to the smaller opportunity cost of crop or livestock production associated with marginal land compared with productive land.

3.2 Greenhouse abatement options

Petersen *et al*. (2003) found that, in the absence of on-farm greenhouse gas sinks, any farm-level policy for greenhouse gas abatement in the Great Southern region would have dramatic negative consequences on the farm enterprise and, without technological change, would cause the current farming systems to fail and be replaced by alternative land uses. However, Petersen *et al*. (2003) compared an emissions restriction policy (where the farmer is legally required to restrict emissions but is not charged for the restricted emissions) with an emissions taxation policy (where the farmer is taxed for his/her net emissions) for the Great Southern region of Western Australia. The emissions restriction policy was found to be more effective and economically efficient (because the farmer is not charged for emissions) than the taxation policy.[8] With the emissions restriction policy, it was found that farmers were able to remain profitable while abating up to 48% (850 tonnes CO_2-e) of their emission levels. They did this by substituting out of pasture production into crop production on the most productive soil types (LMU3, 4 and 5), where sheep emit more greenhouse gas emissions than cropping activities. Note that the farmers are not financially compensated for meeting these restrictions. A policy of restricting greenhouse gas emissions is the tool considered in this section.

[8] This is because the cost of substituting into less-polluting enterprises (which are still profitable) is less than the cost of bearing the penalty of a tax on emissions. This was found to be true when comparing a wide range of tax levels (0 to approximately \$100 /tonnes CO_2-e) with regulations required to restrict emissions by equivalent amounts. However, other farms with different biophysical characteristics may find taxation to be less costly than regulation.

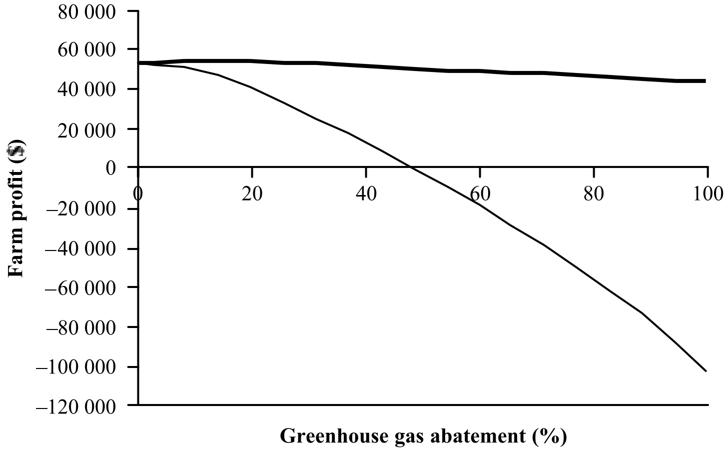

Figure 3 Impact of greenhouse gas abatement on farm profit.
—, without mallees; **—**, with mallees.

The impact of varying levels of emissions restrictions on profit with and without the inclusion of a tree crop is presented in figure 3. As was found by Petersen *et al.* (2003), in the absence of tree crops, the farm falls to zero profits at a level of 48% abatement. In the presence of oil mallees as a carbon sink, higher levels of abatement have a smaller effect on farm profit, although this is highly dependent on the assumptions behind the oil mallee annuity. Without emission restrictions, the profit-maximising area of mallees is 50 ha (5% of farm area), where profit increases by $1000 (or 2%) and where emissions are reduced by 12%. To be emissions neutral, the area of oil mallees needed is 421 ha, 42% of farm area (sequestering 1745 tonnes CO_2-e). The cost to the farmer of emissions neutrality would be $12 000 (or 22%) in the presence of tree crops (which is $11 000 or 20% less than the maximum farm profit in the absence of oil mallees).[9] A sensitivity analysis on sequestration efficiencies was conducted and although the results are not presented here, they showed that these findings are robust. Areas of oil mallees required for emission neutrality vary little with moderate changes in sequestration efficiencies.[10]

[9] Note that we are not indicating that emissions neutrality in south-western Australian farming systems is possible or desirable, we use it solely as a benchmark for illustrating the costs of carbon sequestration.

[10] Note that the assumed sequestration rates are low compared with those estimated in the published literature. Hence, areas of oil mallees needed for emission neutrality are over-estimated, if anything, because more areas of mallees are needed to achieve equivalent rates of sequestration. Analysis of maritime pines for carbon sequestration in the region was also analysed, although results are not presented here. It was found that maritime pines are not profitable under current financial assumptions, although their carbon sequestration efficiency is superior to that of oil mallees.

With the indicative profitability of oil mallees chosen here ($112 /ha), the marginal cost of abatement varies from –$1.5 /tonnes CO_2-e, where emissions are reduced by 10% (oil mallees are profitable enough to increase emissions by more than 10%, hence the negative marginal cost), to just under $8 /tonnes CO_2-e, where the farm is emissions neutral. Note that these marginal costs are very sensitive to the profitability of oil mallees. These figures are much smaller than in the absence of the tree crop, where the marginal cost of abatement ranges from $20 to $220 /tonnes CO_2-e, where emissions are reduced by 10 and 100%, respectively. While these latter figures are substantial when compared with predictions of carbon permit prices (which vary between $10 to $50 /tonnes CO_2-e depending on Kyoto Protocol scenarios and prediction technique; (Australian Greenhouse Office 1999), the former figures suggest that in the Great Southern region farmers who incorporate commercial tree crops into their system are likely to find carbon-trading schemes at posited prices quite attractive.

So far it has been assumed that farmers are not compensated for restricting emissions. Petersen *et al.* (2003) found that it would cost the regulator approximately $3.5 million a year in subsidies to achieve approximately 10% abatement in the Great Southern region alone (based on a marginal cost of abatement of $20 /tonnes CO_2-e mentioned above for 175 tonnes of CO_2-e for the 1000 farms in the region). If commercial plantations were credited as a source of sequestration, greater than a 10% reduction in net emissions would be achieved with current financial conditions without the need for regulation (the optimal area of mallees reduces net emissions by 12%). In addition, the value of the tree crops is increased in the presence of this policy and would be especially so if tradeable emission permits were introduced. Such a mechanism is likely to encourage faster growth of the tree crop industry in the Great Southern of Western Australia. Expansion in tree crop areas has external benefits other than greenhouse gas abatement, one of which is salinity abatement through reduced water recharge in the soil profile.

3.3 Abatement of water recharge for salinity control

Recharge abatement is of interest for two reasons. First, recharge abatement could have downstream benefits in saving public assets from salinity damage. So, governments may be interested in compensating or penalising farmers for the damages saved or caused downstream. Second, if sufficient abatement occurs, then some water-logged and saline land would be reclaimed as arable. Note that salinity abatement is likely to have dynamic elements that MIDAS, a static model, is not able to capture. For example, the abatement of recharge will reduce the areas of saline and water-logged

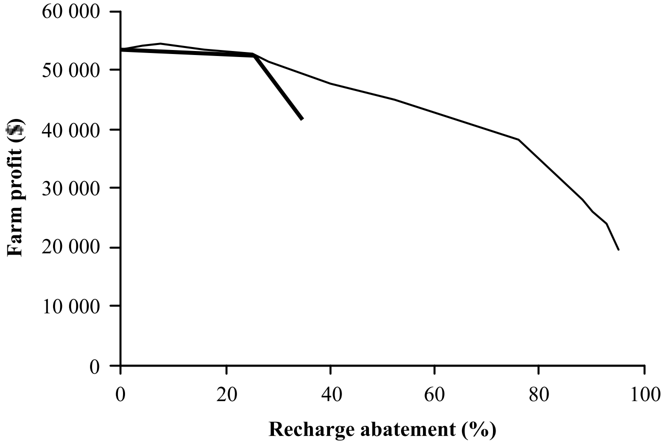

Figure 4 Effect of recharge abatement on farm profit.
—, without trees; —, with trees.

soils (LMU1 and 2), so, with time, provided the trees were to be very water efficient on site, saline and water-logged areas would no longer be constraints to oil mallee plantations. Hence, the optimal area of mallees and the opportunity cost of salinity abatement are likely to be underestimated.

First, consider the impact of recharge abatement on farm profit (figure 4). In the absence of tree crop production, farm profit is relatively insensitive to low levels of recharge abatement. At approximately 20% abatement, profit decreases relatively quickly as the system substitutes into more crop-intensive enterprises due to their relative recharge abatement efficiency (see table 7). It is only possible to abate 35% of recharge without trees because no enterprise uses all the rainfall. When mallee production is introduced, farm profit is maximised at a level of approximately 8% recharge abatement where 50 ha of oil mallees are planted. Greater levels of abatement come at a cost. Note that it is still not possible to abate 100% of recharge with oil mallees alone because only 75% of land is suitable for commercial oil mallee production (although other species could initially be used in water-logged and saline areas). A maximum of 95% of recharge can be achieved with a decrease in annual profit of approximately $35 000 (65% of maximum farm profit).

The relationship between greenhouse gas abatement and recharge abatement is presented in figure 5. The model was run to maximise farm profit with greenhouse gas emissions constrained and recharge unconstrained. The curve is non-linear to approximately 18% greenhouse gas abatement because this abatement is achieved through decreasing the feed intake of

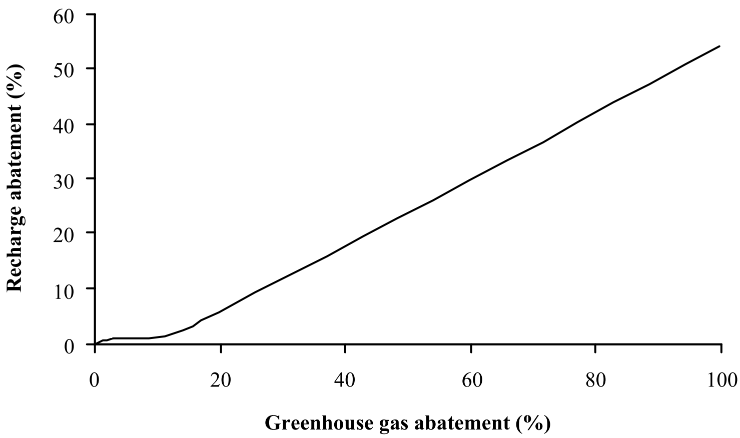

Figure 5 Effect of greenhouse gas abatement on recharge abatement.

sheep, thereby decreasing the quantity of greenhouse emissions from sheep. The curve is linear and positive at greater than 18% greenhouse gas abatement, reflecting increases in the area planted to oil mallees with increased greenhouse gas abatement.

4. Conclusions

The present study focuses on the introduction of a tree crop to the predominantly grazing systems of the Great Southern region of Western Australia. Oil mallees, a native to the region, were found to be a profitable enterprise. The lower the wool price, the larger the profit-maximizing area planted to oil mallees. This is understandable, given the reliance of the system on sheep production. Farm profit was found to be extremely sensitive to the oil mallee annuity. At standard and increased rates of annuity, farm profit increased as oil mallee production was introduced. However, decreases in the mallee annuity caused decreases in farm profit and a decrease in area of oil mallee selected in the optimal solution, highlighting the importance of the financial assumptions for all subsequent results. The profitability of mallees under standard assumptions gives some explanation for the growth of the mallee industry in Western Australia in recent years. At the end of 2001, there were 20 million oil mallees planted and the oil mallee industry is aiming for 500 million plantings by 2025 (Bartle and Shea 2002). Holt (2001) calculates that 500 million plantings could supply enough activated carbon to fulfil present market requirements for activated carbon, less than 5% of the world's solvent market and approximately 11% of Western Power's forecast increase in electricity demand to 2011.

With the inclusion of an emissions restriction policy, the system falls to zero profits at 48% greenhouse gas abatement in the absence of the tree crop. In the presence of the tree crop, the variance of farm profit with increasing levels of abatement is much smaller. The optimal area of oil mallees is 5% of the farm area, leading to a 12% reduction in net emissions, and farm profit increases by $1000 (2%) from a no-trees scenario. The area of oil mallees needed for the farm to be emissions neutral is 42% of farm area (causing farm profit to decrease by $12 000 or 20%). However, because the annuity of the mallee enterprise is extremely sensitive to the discount rate, price and yield assumptions, and the relative profitability of other farm enterprises, the focus of the results should not be on the numerical values, but on the general ability of mallees to achieve greenhouse and recharge abatement. Also note that the accreditation of tree crops as carbon sinks (especially in the presence of emissions trading) is likely to increase their profitability and, hence, lead to the expansion of area allocated to commercial plantations in Western Australia, in turn further increasing greenhouse gas sequestration.

The accreditation of tree crops as carbon sinks is a contentious issue. The results of the present analysis show that a long-term tree crop plantation is effective at reducing emissions from a predominantly grazing farming system. This environmental policy would have greater benefits if used in conjunction with the government's salinity abatement policy, where the positioning of the tree crops in the landscape will be a defining factor in the policy's success. Note that because of this positioning requirement, recharge abatement is often more difficult to achieve than greenhouse gas abatement. If the Australian government pursues policies for reducing greenhouse gas emissions, activities that sequester greenhouse gas emissions may be just as important to farmers as activities that produce emissions.

Petersen *et al.* (2003) and the present analysis have focused on greenhouse gas abatement in the predominantly grazing systems of south-western Australia. Further analysis should focus on similar studies of the predominantly cropping systems of the drier regions of south-western Australia. Predominantly cropping systems are not so dependent on ruminant livestock and may have other options for cost-effective greenhouse gas abatement, such as stubble retention, lowering or changing fertiliser inputs, lowering fuel use and minimum tillage. Howden *et al.* (1994) found these options to be cost-effective and efficient at reducing emissions for the Wimmera region of Victoria. Furthermore, commercial or non-commercial plantations are not so prevalent in the predominantly crop-based farming systems of Western Australia east of the Great Southern region studied here, due to rainfall constraints. Accreditation of trees as carbon sinks may add sufficient value to the trees to encourage expansion of tree plantings in these areas.

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