



An Australian Government Initiative



Phase Farming with Trees

Field validation of the cropping phase

by R.A. Sudmeyer, L., Abbott and H. Jones

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Foreword

Environmental degradation resulting from agriculture poses a problem across southern Australia. In 1999, 36 % of farmers reported some form of significant land degradation; this occurred over an estimated 410 Mha of broadacre farmland. Phase farming with trees (PFT) is a prospective method for ameliorating degraded soils, particularly those at risk from salinisation through rising ground water. PFT involves establishing and growing short rotation woody crops (SRWC) on agricultural land for a period of 3-5 years during which time they utilise soil water stored below the rooting depth of conventional crops and pastures. When soil water is depleted the SRWC is harvested for fibre, timber or fuel and conventional agricultural production is resumed. The soil water deficit established by the SRWC subsequently allows at least a decade of agricultural production without groundwater recharge. When the soil again reaches field capacity the tree phase is repeated. In addition to the hydrological benefits, the hypothesis is that PFT may also benefit agriculture by improving soil physical, chemical and biological characters and by reducing the costs of weed and disease control. If shown to be feasible, phase farming with trees would offer land managers new income streams and a flexible method of mitigating some of the land degradation currently occurring on farmland.

This work details changes in soil water storage, crop and pasture growth and soil physical, chemical and biological characteristics in the first four years after harvesting SRWCs at two sites in Western Australia. The trial found that SRWCs can develop soil water deficits large enough to subsequently allow 8-17 years of conventional agriculture before the soil profile is fully recharged. The tree phase also reduced weed burdens in subsequent crops, but it was not possible to demonstrate clear improvements in soil biological activity, structure or fertility, nor a decrease in soil-borne disease or herbicide resistance in weeds. Crop and pasture growth was limited for 1-3 years by reduced soil fertility at the high rainfall site, and for 2-3 years by reduced plant available water at the low rainfall site. The reduction in returns from agriculture for up to three years after the tree phase means that the SRWC must return sufficient profit to the landholder to compensate for these losses. This could either be direct returns derived from SRWC biomass or by valuing the environmental services provided by the tree phase.

This study provides a detailed understanding of the hydrological and agronomic benefits of PFT for two different climatic and edaphic scenarios. These data and insights can be used when deciding the likely benefits of PFT in other situations, and in developing new industries based on PFT.

This project was funded by the Joint Venture Agroforestry Program (JVAP), which is supported by three R&D Corporations - Rural Industries Research and Development Corporation (RIRDC), Land & Water Australia (L&WA), and Forest and Wood Products Research and Development Corporation (FWPRDC). The Murray-Darling Basin Commission (MDBC) also contributed to the program during this project. The R&D Corporations are funded principally by the Australian Government. State and Australian Governments contribute funds to the MDBC.

This report is an addition to RIRDC's diverse range of over 1800 research publications. It forms part of our Agroforestry and Farm Forestry R&D program, which aims to integrate sustainable and productive agroforestry within Australian farming systems. The JVAP, under this program, is managed by RIRDC.

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Peter O'Brien

Managing Director

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Abbreviations

*AC	Treatment: cropping on continuous agricultural land
AM	arbuscular mycorrhizal fungi
*AP	Treatment: pasture on continuous agricultural land
B	boron
BA	basal area
BD	soil bulk density
Ca	calcium
CO ₂	carbon dioxide
Cu	copper
DAFWA	Department of Agriculture and Food Western Australia
DB	dry biomass
DBH	stem diameter over bark at 1.3 m
DOC	dissolved organic carbon
DSE	dry sheep equivalents
DW	dry weight of roots
FC	field capacity
Fe	iron
FW	fresh weight of roots
K	potassium
K _{sat}	saturated hydraulic conductivity
LSD	least significant difference ($P < 0.05$)
Mg	magnesium
Mn	manganese
N	nitrogen
P	phosphorous
PAWC	plant available water content
PFT	phase farming with trees
S	sulfur
SD	stem diameter at 0.1 m
SOC	soil organic carbon
SV	stem volume
SRWC	short rotation woody crop
*TC	Treatment: crop after tree phase
*TP	Treatment: pasture after tree phase
*T	Treatment: trees retained
Zn	zinc

* Abbreviations for treatments in this experiment

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Executive Summary

What the report is about

This report details the findings of a five year research project examining the effects of Phase-Farming with Trees on adjacent agriculture. Phase-Farming with Trees (PFT) has been identified as a new agroforestry system with potential salinity reduction and income diversification benefits. A key aim of PFT is to use trees to minimise groundwater recharge and subsequent salinisation and thus improve the situation for (subsequent) agriculture. PFT is similar to phase cropping with perennial pasture species; a woody biomass crop is grown until stored soil water is exhausted in three to five years. The woody crop is then harvested and conventional annual crops or pasture grown until soil water content is sufficient to repeat the rotation. This project aimed to resolve some of the uncertainties related to PFT effects on soil, agricultural yield and costs.

Who is the report targeted at?

This report is intended for researchers, policy makers, land managers and those interested in facilitating the development of new agroforestry systems which improve farm profitability and environmental sustainability, particularly for the medium and low rainfall agricultural areas of southern Australia.

Background

Conventional agricultural systems in southern Australia have left a legacy of environmental degradation that presents a growing problem for land managers. In 1999, 36 % of farmers reported some form of significant land degradation over an area of 410 Mha of broadacre farmland. Currently sodicity and acidity are the most extensive forms of degradation in Australia, and secondary salinity is significant and expected to increase. In south-western Australia, soil acidification, sodicity waterlogging, soil structure decline and subsoil compaction affect 3.0 Mha, 6.7 Mha, 1.8 Mha, 1.75 Mha and 8.5 Mha respectively. Salinisation is a greater problem in Western Australia than elsewhere in Australia, with 1.0 Mha currently at risk, and 5.4 Mha (29%) potentially at risk by 2075. The estimated cost to agriculture, rural towns, transport infrastructure and vegetation on public lands associated with salinity was estimated to be \$664 M annually in Western Australia in 2000. That figure was predicted to increase by \$452 m annually by 2050.

Consequently, new farming practices and systems are being sought that are less harmful to the environment. The principal strategy for slowing current trends in secondary salinisation is a rapid expansion of the area of agricultural land planted with perennial vegetation. For example, the Western Australian Salinity Actions plan identified the need to establish 3M ha of deep rooted, woody perennials to help manage the States' salinity problem. The scale of revegetation required means that options have to be economically comparable with current farming systems to have wide acceptance and adoption. This presents problems, particularly in the medium and lower rainfall areas where there are relatively few economically attractive options. Even where options do exist, farmer adoption has generally not been large enough to influence hydrological processes.

PFT as been suggested as an innovative farming system with the potential to counter many forms of land degradation particularly salinisation, while producing commercial wood fibre and biomass. A scoping study suggested that PFT may also benefit agriculture by reducing waterlogging, providing a weed and disease break and increasing soil fertility i.e. enhanced soil biological activity, improved soil porosity, increased soil organic carbon content and reduced soil erosion. If shown to be feasible, phase farming with trees would offer land managers new income streams and a flexible method of mitigating some of the land degradation occurring on farmland. PFT has a number of attributes that make it attractive to the farming community. As the rotation length is only three to five years, conventional crops remain part of the rotation and trees and crops are separated temporally. PFT also allows tree products to be produced in areas where longer rotation tree crops will suffer from moisture stress. It has been estimated that there are 5 million ha of land suitable for PFT. For the farm forestry

industry, planting 10% of this area would generate 4 million m³ of wood fibre, with a potential value of \$120 million annually. This revegetation would also help mitigate secondary salinity.

However some major uncertainties are whether SRWCs can actually de-water soil profiles in three to five years; the time before soils are again fully recharged; the likely costs and returns from SRWC; the most suitable tree species; how soil physical, chemical and biological characteristics change during the PFT rotation; and the productivity of crops and pastures in the following agricultural phase. This project builds on the R&D investment already made by JVAP through projects CAL-3A and CAL-6A, in addressing some of the perceived barriers to the integration of woody perennials in farming systems.

Aims/Objectives

The project tested the hypotheses that groundwater recharge is halted for a significant number of years, and crop and pasture growth are improved following a SRWC at two sites in Western Australia. This report provides an evaluation of the economic and agronomic feasibility of pasture and crop production after the tree phase of Phase Farming with Trees (PFT), and the potential of PFT to ameliorate declining soil structure, fertility and biological activity and to decrease excess recharge to groundwater.

Methods used

Two experimental sites were established in the southwest of Western Australia in November 2002, with monitoring continuing until March 2007. The Tincurrin site with 356 mm annual rainfall, lies within the low rainfall zone. The Howick site with 525 mm rainfall, lies within the high rainfall zone. The climate at both sites is Mediterranean, with warm, dry summers and cool, wet winters. Related soil types occupy approximately 175 000 ha and 968 000 ha respectively of agricultural land in southwestern Australia. Both sites had areas of planted trees and adjacent areas of agricultural land. At Tincurrin the trees were *Eucalyptus polybractea* (blue mallee) and at Howick they were *Eucalyptus globulus* (Tasmanian blue gum).

Beginning in November 2002, five treatments were established at each of the sites using a single large plot per treatment:

- cropping on agricultural land that had never been replanted to trees,
- pasture on agricultural land that had never been replanted to trees,
- trees removed and cropping established,
- trees removed and pasture established,
- trees retained.

Between 2003 and 2007, changes in weed biomass, weed herbicide resistance and soil-borne disease were monitored for the five treatments. Soil water content was monitored to determine recharge rates, and differences in soil fertility, soil structure and soil biological activity determined for the five treatments. Crop and pasture growth and grain yield were monitored as well as grain and pasture quality; input costs were recorded and these data were used to determine the economic returns from the four agricultural treatments from 2003 to 2005.

Results/Key findings

- Short rotation woody crops can develop soil water deficits sufficient to allow 1-2 decades of conventional agriculture before groundwater recharge is fully resumed.
- The physical characteristics of clay subsoils influence tree rooting depth, this has profound implications for the depth and magnitude of soil water depletion by trees, tree growth rates and soil-water recharge rates following the SRWC.

- While weed biomass was reduced for at least four years after the tree phase, the cost of herbicide application was largely similar in the continuous agriculture and post-tree phase crops (due to the use of preventative weed control in low weed situations). The results did not demonstrate either reduced herbicide resistance or soil borne disease four years after the tree phase.
- There was no clear evidence of improved soil physical properties in terms of increased plant root depth, decreased soil bulk density or increased hydraulic conductivity. Where removal of mounds and tree roots was undertaken it entailed considerable soil disturbance which reduced soil organic carbon concentrations and resulted in an increase in the bulk density of the topsoil.
- There was some evidence of trees accessing nutrients from subsoil clays unavailable to agricultural crops and pasture. However nutrient concentration in the soil and soil pH generally decreased during the tree phase in the absence of regular fertiliser applications.
- There was no clear increase in soil biological activity after the SRWC compared to continuous agriculture. After a SRWC, mycorrhizal colonisation was greater in pasture compared to crop.
- There were no consistent trends in nutrient concentration of crops grown continuously compared with those grown after a tree phase.
- Crop and pasture productivity were reduced for two to three years after the tree phase due to reduced soil fertility and plant available water content. At both sites, agricultural net returns were equivalent to continuous agriculture in the 3rd or 4th year after the tree phase.
- Even with greater input costs, net returns from cropping exceed those from grazing sheep following a tree phase.
- Where trees grown as a short rotation crop have access to stored soil water they can produce more above ground biomass than annual crops and pasture reliant solely on rainfall.

Implications for relevant stakeholders

The key implication of this research is that while phase farming with trees can have clear hydrological benefits, these benefits may not be returned to farmers in terms of increased agricultural production immediately (at least 3 years) after the SRWC is harvested. For phase farming with trees to be acceptable to land managers the SRWC must return sufficient income to compensate for the opportunity cost of shifting out of agricultural production during the tree phase and the possibility of decreased returns from agriculture immediately following the tree phase. This compensation can either be in the form of direct payment for SRWC biomass or payment for the environmental services provided by the SRWC. Any ecosystem service scheme should consider the long term recharge reduction benefits, and offset the loss to agricultural income during the tree phase and in the first 1-3 years of agriculture after PFT.

Recommendations

These recommendations are targeted at researchers and policy makers:

- The successful commercialisation of PFT will require the development of SRWCs that are profitable enough to pay for:
 - The opportunity cost of taking land out of agricultural production.
 - The application of sufficient fertiliser and lime to maintain soil fertility.
 - Reduced agricultural yields in the years immediately following harvest of the SRWC.

This may mean developing means of valuing environmental services and providing monetary returns to farmers.

- Commercialisation of PFT will require the development of appropriate fertiliser and lime application regimes to maintain soil fertility for the subsequent agricultural phase. This development should include investigation of:
 - The use of nitrogen fixing SRWCs as they may provide savings in fertiliser input costs.
 - The feasibility and economics of returning the nutrient rich leaf and twig fraction of the tree phase to the soil.
- Commercialisation of PFT will require careful site investigation prior to tree planting and a good understanding of how subsoil characteristics influence both tree growth and subsequent recharge. This may require further research and development.
- Harvest systems for SRWCs should be designed to minimise soil disturbance, in order to maintain soil organic carbon and soil structure.
- Biophysically based models should be used to extrapolate soil-water and groundwater recharge and agricultural production beyond the four and a half years spanned by this trial.

Introduction

Environmental degradation resulting from agriculture is posing a growing problem across southern Australia. In 1999, 36 % of farmers reported some form of significant land degradation on their farms; this amounted to an estimated area of 410 Mha on broadacre farmland (NLW Audit 2007). Currently sodicity and acidity are the most extensive forms of degradation affecting 23% and 4.5% of Australian agricultural land respectively (NLW Audit 2007). Secondary salinity currently affects 0.7% of agricultural land in Australia with the area at risk expected to grow to 1.4% by 2020. In south-western Australia, soil acidification, sodicity waterlogging, soil structure decline and subsoil compaction affect 3.0 Mha, 6.7 Mha, 1.8 Mha, 1.75 Mha and 8.5 Mha respectively (Nulsen 1993; Anon. 1997; Moore 1998; NLWR Audit, 2007). In south-western Australia, salinisation is a greater problem with 1.0 Mha currently at risk, and 5.4 Mha (29%) potentially at risk by 2075 (George *et al.*, 2005). Salinisation doesn't just affect farmland but has significant off-site impacts on public and private lands. Rising groundwaters, and resultant salinity, threaten agricultural land, rural and urban infrastructure, conservation reserves and water resources. Short and McConnel (2000) estimated the cost of high water tables and associated salinity to agriculture, rural towns, transport infrastructure and vegetation on public lands was \$664 M annually in Western Australia. By 2050 that figure was estimated to increase by a further \$452 m and possibly as much as \$783 M annually (Short and McConnel, 2000).

Consequently, a great deal of effort is being devoted to developing new farming practices and systems that are less harmful to the environment. The search for solutions to soil degradation has largely concentrated on improving agronomic practices. But a rapid expansion of the area of agricultural land planted with perennial vegetation is the principal strategy for slowing current trends in secondary salinisation (Anon., 2000). The scale of change required means that revegetation options have to be economically comparable with current farming systems to have wide acceptance and adoption. This presents problems, particularly in the medium and lower rainfall areas where there are relatively few economically attractive options (Zorzetto and Chudleigh, 1999). Even where options do exist, farmer adoption has generally not been great enough to influence hydrological processes (Pannell, 2001).

Phase farming with trees (PFT) is an innovative farming system than has potential to counter many forms of land degradation particularly salinisation (Harper *et al.*, 2000, Rockwood *et al.*, 2004). For dryland salinity, PFT intentionally depletes soil water as a buffer to agriculture in areas prone to rising saline groundwater. Under PFT a short rotation woody crop (SRWC) is grown in rotation with conventional agricultural crops and pastures. The SRWC grows for a period of 3-5 years during which time it utilises soil water stored below the rooting depth of conventional crops and pastures. When soil water is depleted and the growth rate of the SRWC begins to decline, the SRWC is harvested for fibre, timber, fuel, or some combination of these, and conventional agricultural production is resumed. The soil water deficit established by the SRWC subsequently allows conventional agricultural production without groundwater recharge. When the soil again reaches field capacity, which could be within two or three years on deep sandy soils, ten years for duplex soils with a deep watertable or decades on clayey soils, the tree phase is repeated (Harper *et al.*, 2000). It has been suggested that in addition to the hydrological and income diversification benefits of PFT, it may benefit agriculture by reducing waterlogging, providing a weed and disease break and increasing soil fertility i.e. enhanced soil biological activity, improved soil porosity, increased soil organic carbon content and reduced soil erosion (Harper *et al.*, 2000; Yunusa and Newton, 2003).

If shown to be feasible, phase farming with trees would offer land managers new income streams and a flexible method of mitigating some of the land degradation that is currently occurring on farmland. As it stands, PFT has a number of attributes that make it attractive to the farming community. PFT allows tree products to be produced in areas where longer rotation tree crops will suffer from moisture stress. Economically, there is the opportunity to diversify farm income. The rotation length is only three to five years; conventional crops remain part of the rotation and trees and crops are separated temporally. Some major uncertainties related to PFT remain. These are whether SRWC can actually

de-water soil profiles in three to five years, the time before soils are again fully recharged, the likely costs and returns from SRWC; the most suitable tree species; how soil physical, chemical and biological characteristics change during the PFT rotation; and the productivity of crops and pastures in the following agricultural phase.

This work aims to test the hypotheses that groundwater recharge is halted for a significant number of years and crop and pasture growth is improved following a SRWC at two sites in Western Australia. A complementary project has investigated the tree phase of PFT at one site (Corrigin) in Western Australia to evaluate soil water depletion and tree biomass with different species, planting densities and fertility regimes (Harper et al. 2008).

Methods

Sites

Two experimental sites were established in the southwest of Western Australia in November 2002, with monitoring continuing until March 2007. Limited measurements were made at a third site in 2002 only. The climate at all sites is Mediterranean, with warm, dry summers and cool, wet winters with approximately 75% of rain falling during the growing season (May-November).

The Tincurrin site is located 500 m southwest of the Tincurrin townsite (32° 58' 43'', 117° 46' 11''). Long-term (1914-2003) mean annual rainfall at Dudinin 17 km to the northeast was 402 mm. However, there has been a trend towards reduced rainfall in the last 30 years and the 1973-2003 average was 354 mm. The two soils identified at the site have 0.1 m of sandy loam over clay, with pallid zone clays from 1.5 m to bedrock (>25 m). P. Galloway (pers. comm., 2004) classified the soils as Melanic Mottled-Mesonatric Brown Sodosol and Ferric Mottled-Subnatric Yellow Sodosol (Isbell, 1996). Related soil types occupy approximately 175 000 ha of agricultural land in southwestern Australia. A groundwater observation well installed to 25 m remained dry for the duration of the trial.

The Howick site is located approximately 100 km east of the town of Esperance (33° 44' 15'', 122° 40' 50''). Mean annual rainfall (1962-2002) 7 km to the east of the Howick site was 525 mm. The soil consists of 0.5-0.7 m of fine sand with 60-70% of the sand volume occupied by pisolithic gravels with an abrupt boundary to clays derived from Tertiary marine sediments. B. Nicholas (pers. comm., 2003) classified the soil as Ferric Mesonatric Yellow Sodosol (Isbell, 1996). Related soil types occupy approximately 968 000 ha of agricultural land in southwestern Australia. A piezometer was installed at the site in 1993 (Figure 1), since then groundwater depth has fluctuated between 12 and 11.5 m. This water is saline, with an electrical conductivity of 3200 mS/m.

The native vegetation was cleared for agriculture in the 1920s at Tincurrin and in the early 1960s at Howick. The entire area of each site was then subject to the same agricultural regime until blocks of trees were established on part of each trial site. At Tincurrin, *Eucalyptus polybractea* (blue mallee) was planted in a block with seven two-row belts in 1996 (2 m by 2 m tree spacing with 8 m between belts). In 2002, they had a mean height of 6.0 m and 100% survival. At Howick, *E. globulus* (Tasmanian blue gum) was planted on mounds in a 12-row wide belt in 1992 (4 m by 2 m spacing). By 2002 they had a mean height of 8.8 m and 88% survival. Tree-lines were deep-ripped prior to planting at both sites. The regime on the remaining agricultural land at Tincurrin was wheat (*Triticum aestivum*), canola (*Brassica napus*), wheat, barley (*Hordeum vulgare*), pasture, pasture and wheat from 1996 to 2002 respectively. At Howick, the agricultural regime was pasture (1992-99), canola, wheat then pasture in 2002. Pasture at both sites was based on subterranean clover (*Trifolium subterraneum*) and annual ryegrass (*Lolium multiflorum*).

The East Wickepin site is located approximately 14 km north of the Tincurrin site and 13 km west of Dudinin (33° 44' 39'', 117° 51' 52''). The soil was coarse white sand overlying clay at 1 m. The trees at the site were a variety of *Acacia saligna* that suckered from the roots. The exact age of the trees at the time of sampling is not known, but the landowner suggested they were "12 to 15 years old". The adjacent area of agricultural land was under pasture when sampled.

Treatments

Beginning in November 2002, five treatments were established at each of the Tincurrin and Howick sites: cropping on agricultural land that had never been replanted to trees (AC), pasture on agricultural land that had never been replanted to trees (AP), trees removed and cropping established (TC), trees removed and pasture established (TP) and trees retained (T).

Treatment plots were 30 m wide by 55 m long, and were not replicated (Figure 1). Each site was selected for uniformity of soil, topography and agricultural history so that plots pre-treatment were similar. Trees were removed from treatments TC and TP in November 2002. At Tincurrin, the trees were cut at ground level using an articulated slasher, and the above-ground biomass then removed from the trial site. Soil disturbance was minimal during this operation. At Howick, where the trees had been planted on mounds, the trees, root boles and mounds were removed using a bulldozer fitted with a scrub rake, this entailed considerable soil disturbance.

Treatments AC and TC were sown with barley, canola, wheat and oats (*Avena sativa*) at Howick, and barley, field peas (*Pisum sativum*), wheat and field peas at Tincurrin in 2003, 2004, 2005 and 2006 respectively (Table 1). Crops and pastures were sown with a disked seeding implement that was able to sow over stumps and roots.

Treatment TP, at Howick, was sown with a subterranean clover and serradella (*Ornithopus sativus*) mix in 2003 and resown with clover in 2004 due to poor initial establishment. The existing pasture was left unchanged in treatment AP at Howick. At Tincurrin, treatments AP and TP were sown with clover in 2003.

The rates of fertiliser applied (Table 1) were based on nutrient concentrations in the top 0.1 m of the soil profile, determined in the summer prior to the growing season each year. Because of low pH at the Howick site, 1.1 t/ha of lime was applied to treatments AP, AC, TP and TC at the start of the 2004 growing season.

Measurements

All samples were random within each block, each time they were sampled.

Crops

Growth

Each year crop establishment density was determined in 10 (7 in 2003) 1 m² quadrats for each crop treatment at each site; tiller number was also recorded at Howick in 2003. Crop biomass was determined when crops were around mid tillering or start of stem elongation, just prior to anthesis and at physiological maturity. Biomass samples were collected from 9 (7 for first two measurements at Howick in 2003) 1 m² quadrates in each treatment in 2003 and 2004, and ten quadrates in 2005 and 2006. Samples were dried at 70 °C and dry biomass determined. A mechanical harvester was used to determine grain yield from ten 41.5 m² plots each year at Howick and in 2003 at Tincurrin, plot size was 34 m² at Tincurrin from 2004 to 2006.

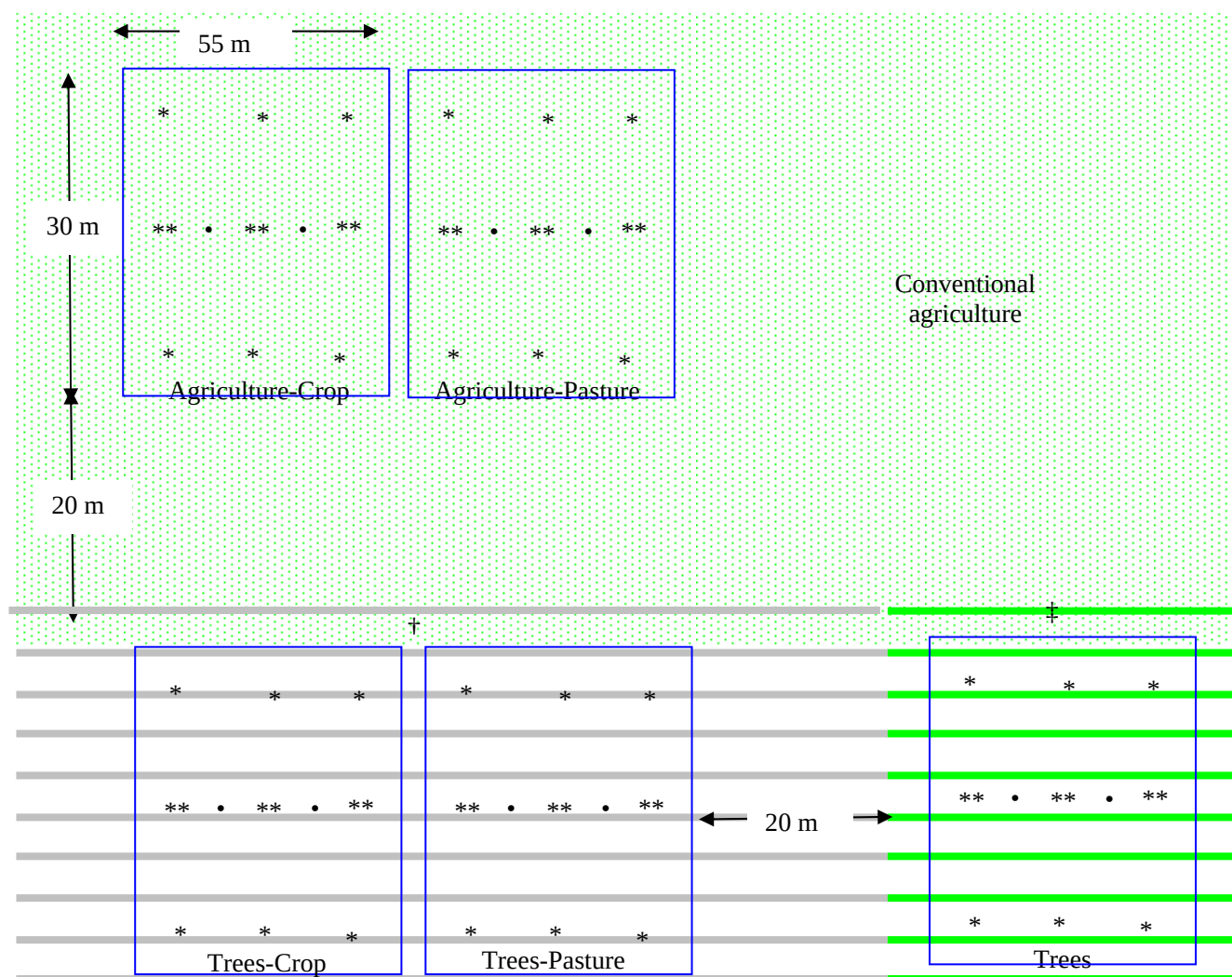
Grain samples were submitted to the grain handling company Cooperative Bulk Handling and assessed using their standard quality analysis. The barley from Tincurrin in 2003 was not assessed.

Nutrient content

Sub-samples from the first crop biomass sampling date (second in 2005) were analysed for nutrient content at the Western Australian State Chemistry Laboratories. Five samples were analysed from each treatment in 2003, nine in 2004 and ten in 2005 and 2006. Nitrogen (N) was determined colorimetrically using indophenol blue after digestion with sulphuric acid and hydrogen peroxide (Yuen and Pollard, 1954). Phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulphur (S), boron (B), copper (Cu), iron (Fe), manganese (Mn) and zinc (Zn) were determined by inductively coupled plasma atomic emission spectroscopy (ICP-AES) after digestion with a mixture of nitric and perchloric acids (McQuaker et al., 1979).

Herbicide resistance

The tolerance of annual ryegrass to commonly used herbicides Logran, Verdict and Roundup was determined in 2006. Ryegrass seeds were collected in November 2006 from treatments AC and TC at the Tincurrin and Howick sites and sent to Plant Science Consulting, who offer a commercial service to land managers. The seeds were germinated and exposed to recommended application rates of the herbicides. Three weeks after exposure the percentage of plants surviving was recorded and compared with untreated control plants. To cross-reference the sample, a known sensitive biotype and resistant biotype were included in the test.



KEY

- ** 9 m deep NMM access tube
- * 6 m deep NMM access tube
- perched water observation bore
- † tipping bucket rain gauge
- ‡ groundwater observation bore
- treeline removed
- treeline retained

Figure 1. Layout of treatments plots and instrumentation at the Howick site. Plot size and instrumentation is similar at the Tincurrin site, though plot layout is different.

Table 1. Crops sown and nutrients applied to treatments agriculture–pasture (AP), trees–pasture (TP), agriculture–crop (AC) and trees–crop (TC) at the Tincurrin site from 2003 to 2006.

Site	Year	Treatment	Crop/ pasture sown	Variety	Rate sown kg/ha	Nutrients applied in fertiliser kg/ha								
						N	P	K	S	Ca	Cu	Zn	Mo	Mn
Tincurrin	2003	TP	Clover	Dalkeith	15	-	12.7	-	15.4	28.0	-	-	-	-
		AP	Clover	Dalkeith	15	-	12.7	-	15.4	28.0	-	-	-	-
		TC	Barley	Hamelin	65	11.4	13.0	-	0.8	-	-	-	0.001	0.01
		AC	Barley	Hamelin	65	11.4	13.0	-	0.8	-	-	-	0.001	0.01
	2004	TP	-	-	-	-	-	-	-	-	-	-	-	-
		AP	-	-	-	-	-	-	-	-	-	-	-	-
		TC	Field peas	Kaspar	130	13.4	13.3	-	8.9	-	-	0.04	0.001	-
		AP	Field peas	Kaspar	130	13.4	13.3	-	8.9	-	-	0.04	0.001	-
	2005	TP	-	-	-	12.1	21.2	-	18.9	20.0	0.09	0.18	-	-
		AP	-	-	-	12.1	12.1	-	7.9		0.09	0.18	-	-
		TC	Wheat	Wyalcatchem	70	35.1	24.1	-	22.4	26.4	0.09	0.18	-	-
		AC	Wheat	Wyalcatchem	70	35.1	12.1	-	7.9		0.09	0.18	-	-
	2006	TP	-	-	-	-	13.8	-	6.8	14.0	-	-	-	5.2
		AP	-	-	-	-	13.8	-	6.8	14.0	-	-	-	5.2
		TC	Field Peas	Kaspar	130	-	16.6	-	8.2	16.8	-	-	-	6.3
		AP	Field peas	Kaspar	130	-	16.6	-	8.2	16.8	-	-	-	6.3
	Total	TP				12.1	47.7	0	41.1	62	0.09	0.18	0	5.2
		AP				12.1	38.6	0	30.1	42	0.09	0.18	0	5.2
		TC				59.9	67.0	0	40.3	43.2	0.09	0.22	0.002	6.3
		AC				59.9	55.0	0	25.8	16.8	0.09	0.22	0.002	6.3

Table 1 cont. Crops sown and nutrients applied to treatments agriculture–pasture (AP), trees–pasture (TP), agriculture–crop (AC) and trees–crop (TC) at the Howick site from 2003 to 2006.

Site	Year	Treatment	Crop/ pasture sown	Variety	Rate sown kg/ha	Nutrients applied in fertiliser kg/ha								
						N	P	K	S	Ca	Cu	Zn	Mo	Mn
Howick	2003	TP	Clover	Dalkeith	10	-	11.0	-	6.0	8.4	-	-	-	-
			Serradella	Cadiz	5	-	11.0	-	6.0	8.4	-	-	-	-
		AP	-			-	18.3	-	10.0	14	-	-	-	-
		TC	Barley	Baudin	70	42.7	16.5	-	17.6	-	0.10	-	-	-
		AC	Barley	Baudin	70	37.7	10.9	-	11.8	-	0.10	-	-	-
	2004	TP	Clover	Dalkeith	10	-	12.9	22	9.1	11.8	-	-	-	-
		AP	-	-	-	-	27.5	31	16.8	23.0	-	-	-	-
		TC	Canola	Hyder	5	104.9	14.9	50	16.8	-	0.11	0.21	-	-
		AC	Canola	Hyder	5	81.8	12.8	22	14.1	-	0.09	0.18	-	-
	2005	TP	-	-	-	-	14.0	-	7.7	10.8	-	-	-	-
		AP	-	-	-	-	14.0	-	7.7	10.8	-	-	-	-
		TC	Wheat	Eagle rock	70	54.5	20.0	-	20.3	-	0.14	0.30	0.001	0.03
		AC	Wheat	Eagle rock	70	41.1	15.2	-	15.5	-	0.10	0.21	0.001	0.02
	2006	TP	-	-	-	-	12.2	-	6.5	9.1	-	-	-	-
		AP	-	-	-	-	12.2	-	6.5	9.1	-	-	-	-
		TC	Oats	Kojonup	100	50.6	15.5	-	15.8	-	0.11	0.21	0.001	0.02
		AP	Oats	Kojonup	100	50.6	15.5	-	15.8	-	0.11	0.21	0.001	0.02
	Total	TP				0	50.1	22	29.3	40.1	0	0	0	0
		AP				0	72	31	41.0	56.9	0	0	0	0
		TC				252.7	66.9	50	70.5	0	0.46	0.72	0.002	0.05
		AC				211.2	54.4	22	57.2	0	0.40	0.60	0.002	0.04

Weed growth

The above-ground weed biomass was collected from the same quadrates used to assess crop biomass. Samples were dried at 70 °C and dry biomass determined. No samples were collected from Tincurrin when crops were near anthesis in 2003 and 2004.

Pasture

Growth

Treatments AP and TP were mown 20-30 mm above ground-level at monthly intervals during the growing season to simulate livestock grazing. Pasture growth was determined by mowing five 17.6 m² plots each month. The mown pasture was collected and sub-sampled, the sub-sample was then dried at 70 °C and the dry weight of the entire sample estimated.

Feed quality

Sub-samples from one of the early spring measurements were retained each year and five replicates from each treatment were analysed to determine feed quality at the Department of Agriculture and Food Western Australia (DAFWA).

Trees

Growth

Trees were measured in treatments TC, TP, and T in November 2002 and annually thereafter in treatment T at the Tincurrin and Howick sites. Measurement plots were 32 m by 10 m at Howick and 25 m by 10 m at Tincurrin. Three measurement plots were established in each treatment (two in treatments TC and TP at Howick). Tree height and stem diameter over bark (SD) at 1.3 m at Howick and at 0.1 m at Tincurrin, were measured. Stem volume (SV) was estimated assuming the stem was conical i.e. $\frac{1}{3} \text{tree height} (\pi (\text{SD}/2)^2)$.

In 2002 and again in 2006, ten trees were cut at ground level and the above ground biomass was sub-sampled at each site. At Tincurrin biomass from each tree was separated into dead material, leaf/branches <8 mm diameter and stems/branches >8 mm diameter. At Howick the biomass from each tree was separated into leaf/branches <8 mm diameter, stems/branches <100 mm diameter and stems >100 mm diameter. The wet weight of each fraction was determined, a sub-sample was then taken and dried at 70°C and the dry weight of each fraction estimated. In 2002, the relationship between the root boles that had been removed by the bulldozer and SD was determined at Howick.

The height and SD at 0.1 m of trees at the East Wickpin site was measured in three, 10 m by 10 m plots in 2002. The dry weight of the tree biomass was determined using a similar method to that used at Tincurrin and Howick, with the addition that the leaf litter was also sampled and weighed.

Nutrient content

Sub-samples of the various fractions of the ten trees measured in 2002 at the Tincurrin, Howick and East Wickpin sites were analysed for nutrient content using the same analysis as for crop tissue.

Soil

Soil bulk density and particle size

The bulk density (BD) of the soil in treatments AC and AP at Tincurrin and Howick was determined to a depth of 2 m when the neutron moisture meter was calibrated. A Campbell Pacific Nuclear™ gamma probe was used to estimate bulk density below 2 m where the soil was dry. This enabled estimation of bulk density to 9 m at Tincurrin and to 3 m at Howick. Undisturbed soil cores taken at a site with similar subsoil clays were used to give an indication of bulk density below 3 m at Howick.

The particle size distribution of the soil was determined in 0.1 m increments down to 1 m at the Howick and Tincurrin sites. A sub-sample from one of the samples collected from agricultural land at each site in 2002 was submitted to the Western Australian Chemistry Centre for this analysis (see below).

Soil chemistry

The nutrient content of the soil was determined in 0.1 m increments down to 1 m in November 2002 and January–March of 2005 and 2007. The 2002 measurement was made prior to the cropping or pasture treatments being installed with soil samples collected from the tree blocks and agricultural area. In 2005 and 2007 samples were collected from each of the five treatments. In 2002, samples were collected at 0.1 m intervals down the profile to 1 m using a 50 mm diameter auger. Samples were obtained from three auger holes and combined to give a single bulked sample for each depth interval. Three replicates for each depth interval were obtained in this way from the agricultural land at each site. Three replicates were collected from within and three between the tree belts at Tincurrin. Three replicates were collected from the top of the mounds, three from the base of the mounds and three between the tree rows at Howick. Each bulked sample was dried at 70 °C for 48 hours. The soil fraction with a diameter greater than 2 mm was removed and the remainder submitted for analysis. In 2005 and 2007, samples were collected from three backhoe pits in each treatment with a single replicate collected from each pit.

In November 2002, the East Wickepin site was sampled to a depth of one metre in 0.1 m increments. Three replicate samples at each depth were collected from an area planted to *A. saligna* and one replicate sample from an adjacent area of pasture. Samples were collected using an auger method similar to that described above.

Total N was measured as ammonium-N by automated colorimetry (nitroprusside-dichloro-S-triazine modification (Blakemore *et al.* 1987) of the Berthelot indophenol reaction), after Kjeldahl digestion of soil using copper-sulphate-potassium-sulphate catalyst (Rayment and Higginson, 1992). Total P was measured by colorimetry on the Kjeldahl digest for total N, using a modification of the Murphy and Riley (1962) molybdenum blue procedure. Exchangeable cations were measured using inductively coupled plasma atomic emission spectroscopy. A 1M NH₄Cl solution at pH 7.0 was used for neutral soils (6.5 < pH (H₂O) < 8) and a 1 M BaCl₂ solution was used for acidic soils (pH < 6.5) (Rayment and Higginson, 1992).

In January 2004, 2005, and 2006, topsoil samples were collected from each treatment at each site using a core sampler with a diameter of 15 mm pushed 0.1 m into the soil. Approximately 20 cores were collected to make up one sample. The number of sample replicates collected from each treatment and site are shown in Table 2. These samples were submitted to CSBP for analysis.

Table 2. The number of topsoil sample replicates collected from agriculture–pasture (AP), trees–pasture (TP), agriculture–crop (AC), trees–crop (TC) and tree (T) treatments at the Tincurrin and Howick sites from 2004 to 2006.

Treatment	Tincurrin			Howick		
	2004	2005	2006	2004	2005	2006
T	4	2	2	4	2	2
TC	4	3	3	3	2	3
TP	3	2	2	4	3	3
AC	4	3	3	3	2	3
AP	3	2	2	4	3	3

At Tincurrin and Howick, the amount of nutrients added with fertilisers and removed with agricultural product or leached below the root zone of crop and pasture from the year trees were planted until 2002 was estimated based on land manager records and data given in Glendinning (1999) for N and Fisher *et al.* (1998) for P, K, S, CA and Mg.

Soil permeability

Saturated and unsaturated hydraulic conductivity was measured using Commonwealth Scientific and Industrial Research Organisation (CSIRO) type disc permeameters, as described by McKenzie *et al.* (2002), with a 100 mm diameter infiltrometer supply base. The water reservoirs had been fitted with Dataflow capacitance probes and data loggers to record the rate of water level drop in the reservoir. The methodology for measuring non-saturated flow was similar to that described by McKenzie *et al.* (2002). Hydraulic conductivity at various suctions was calculated using a sequence of steady-state flows measured at successive potentials as per the procedure of Reynolds and Elrick (1991). Saturated hydraulic flow was measured using the same equipment, but with a 100 mm diameter ring to pond water with a 10 mm head, using the method described by White *et al.* (1992).

Measurements were made at the soil surface and at the top of subsoil clay (0.15 m at Tincurrin and 0.7 m at Howick) during January/February 2003 and 2005. Because of non-wetting topsoil at Howick in 2003, the topsoil was soaked with water containing a wetting agent and allowed to drain immediately prior to measurement. In 2005, the soil was saturated (without wetting agent) and allowed to drain for 1 week prior to measurement while covered with plastic sheeting. No water was added to clay subsoil prior to measurement.

In 2003, measurements were made at the following potentials; -60 mm, -40 mm, -20 mm, -10 mm (topsoil only) and +10mm (saturated flow). There were 3 replicates at each potential (6 at +10 mm at Tincurrin). Each measurement was made on a new sand pad i.e. different soil position. Because of data variability, steady state flow values were averaged before calculating hydraulic conductivity.

In 2005, measurements were made at the following potentials; -80 mm, -50 mm, -30 mm, -10 mm (topsoil only) and +10 (saturated flow). With measurements at each potential replicated six times. Measurement at each potential in sequence were made on same sand pad except for +10 mm which was made in new location for each replicate.

The mean characteristic pore size at +10mm potential was calculated using the method of White *et al.* (1992). The number of straight cylindrical pores of radius r mm/m² was calculated using the method described by Coughlan *et al.* (1991), where $r = 1.5 \times 10^{-2} / \text{potential (mm)}$ (Marshall and Holmes, 1988)

Soil biology

At Tincurrin and Howick, soil samples were collected in September each year. In 2002, samples were collected from agricultural land and land under trees prior to the imposition of treatments. From 2003 to 2006, samples were collected from each treatment. For soil fauna, there were 15 cores (50mm deep) for each treatment in 2002, and ten cores for each treatment in 2003. In subsequent years, nine cores (50mm deep) were collected from each treatment for fauna analyses. For other analyses, a bulk sample of soil (0 to 10cm deep) was collected from nine points in each treatment. Soil samples from each treatment were bulked and prepared into three replicate pots for mycorrhizal assessments and into three replications for the other analyses.

Organic carbon

Dissolved organic carbon (DOC), microbial biomass carbon and microbial activity were assessed using the bulk soil samples

DOC was measured in 2002, soil samples were mixed with water in a ratio of 1:4, the sample was then filtered and the filtrate analysed in a TOC analyzer (Zsolnay and Grolitz, 1994). In 2002, microbial biomass carbon was measured using the chloroform-fumigation extraction method according to Vance *et al.* (1987). For samples collected from 2004 to 2006, microbial activity (respiration) of soil was determined after incubation in air-tight jars. CO₂ evolution was measured in a gas analyser and active microbial biomass carbon was calculated from this measurement.

Soil mesofauna counts

Soil mesofauna was assessed using the soil cores (Osler and Murphy, 2005). Cores were placed in Tullgren funnels and illuminated from above with 60W light bulbs, the light intensity being regulated by a rheostat. Soil fauna were allowed to move downwards through the core into the funnel for 24 hours, animals falling through the funnel were preserved in 70% alcohol. After extraction, the different groups of arthropods were sorted using a stereoscopic microscope.

Mycorrhizal bioassay

The infectivity of arbuscular mycorrhizal (AM) fungi present in field soil was assessed in mycorrhizal bioassays conducted using the bulk soil samples (Solaiman and Abbott 2003). Bulk soil for each treatment was transferred to three replicate 600 ml capacity plastic-lined pots. The pots were then stored in a cold room for about two weeks. Subterranean clover seeds were immersed in aerated water overnight then six seeds were planted in each pot. Pots were placed in a temperature controlled water tank at 20 °C in a glasshouse. After emergence, the number of plants was reduced to three in each pot. The plants were watered daily to maintain soil moisture at field capacity. For 2002 bioassays, plants were harvested after both three and six weeks. For later years, plants were harvested four weeks after sowing. Dry weight of shoots (DW), fresh weight of roots (FW), and root length colonised by AM fungi were recorded. The roots were cut into 1 cm lengths then about 0.5 g sub-samples were taken at random. Sub-samples of roots were cleared and stained with Trypan Blue (Abbott and Robson, 1981) before mycorrhizal root length was measured by a line intersect method (Newman, 1966).

Soil-borne disease

In July 2006, a single soil sample (bulk of several smaller samples taken from across treatment plot) was collected from the top 0.1 m of the soil profile in each treatment at Tincurrin and Howick. Samples were analysed for root disease levels and risk at the South Australian Agricultural Research Institute (SARDI).

Soil water content

Soil water content was determined using the neutron method (Greacen, 1981). Six PVC access tubes were installed to 6 m and three to 9 m (10 m at Tincurrin in treatments TC, TP, AC and AP) in each treatment at each site in January 2003 (Figure 1). Measurements were made on a monthly basis during the growing season and bimonthly outside the growing season using a Campbell Pacific Nuclear™ neutron moisture meter. Calibration equations for each soil horizon were determined in the field to a depth of 1.8 m using wet and dry soil profiles (Greacen, 1981). Count ratio explained 85% of the variability in volumetric soil water content at Tincurrin and 91% (top 0.1 m) and 69% (greater than 0.1 m depth) at Howick.

Measurements were made to the full depth of the access tubes from May 2003 to May 2004 and to 4 m, with measurements to the full depth of the access tube every third measurement date, after May 2004.

Field capacity (FC) was taken as the maximum recorded soil water content in the AC and AP treatments at Tincurrin, and after waterlogging ceased in late 2003 at Howick. These estimates agreed with the values obtained during calibration of the neutron moisture meter, when the soil was saturated and then allowed to drain. The soil water deficit was estimated as the difference from FC for each measurement date. It was assumed that the trees dried the top 1 m of the soil to wilting point in late summer 2003 at Tincurrin and November 2004 at Howick. Accordingly plant available water content (PAWC) was estimated as the difference between this lower limit and the measured soil water content on each measurement date.

The depth to which crops and pastures extracted soil water was estimated using neutron moisture meter values for maximum soil water content during the growing season and soil water content at the end of the growing season. Where there was a decline in soil water content >2 mm this was assumed to be due to water use. It should be noted that this analysis does not account for drainage below the root zone and so may over-estimate rooting depth.

Perched watertable

The depth of any perched watertable was measured using two Dataflow™ loggers and capacitance probes in each treatment (Figure 1). Probes were installed in observation wells drilled 0.1 m into the top of the clay subsoil at Howick and to 0.5 m at Tincurrin. Sensors were measured at five minute intervals and hourly averages logged.

Deep drainage

Drainage below the root zone of crops and pastures was estimated using AgET (Raper et al., 1999). Dudinin (1970-1993) and Esperance rainfall data (1954-94 adjusted to Howick mean annual value) were used for the Tincurrin and Howick sites respectively. Default values were used with the following exceptions: soil horizon depth, crop and pasture rooting depth, FC and wilting point (determined from soil water data for each site), and saturated conductivity (K_{sat}) for the A/B horizon. At Tincurrin K_{sat} was set at 10 mm/day to account for cracking at the A/B horizon interface.

Economic analysis

Comparisons were made of the gross margins for sheep production and cropping between the continuous agriculture and trees-agriculture treatments at each site. For each rotation, only the returns from agriculture were considered in the four years after the trees were removed. No account was taken of either the net returns from the tree phase or continuous agriculture during the period when the adjacent area was planted to trees. It should be noted that in order to make a complete analysis of the effect of tree plantings these entire scenarios would need to be covered (and potentially also the long term effects of salinity on agriculture).

Only the variable costs and potential cash revenues were evaluated. Stocking rates are estimates provided by Mr Matt Ryan (pers. comm. 2006) based on the pasture growth and quality at each site. Sheep income was based on stocking rate capacities and *pro rata* wool and livestock sales estimates from DAFWA's gross margin publications for 2003 and 2005. Prices for 2004 and 2006 were based on Australian Bureau of Agricultural and Resource Economics indices. Costs in addition to the pasture inputs recorded at each site were also based on DAFWA's gross margin publications.

For the cropping paddocks, the majority of costs were associated with seed, fertiliser, herbicides and pesticides. Additional inputs included harvesting and repairs for machinery and nominal application costs. Revenues were based on the yields and respective pool prices for the various crops after accounting for marketing costs.

Results

Annual rainfall at Tincurrin was 339, 359, 352 and 341 mm in 2002, 2003, 2004 and 2005 respectively. While these values are all close to the 1970-2002 average, there were differences in how rainfall was distributed over each growing season (Figure 2b). Growing season rainfall was greatest in 2005 and least in 2006.

Annual rainfall at Howick was greater and more variable than at Tincurrin with 652, 415, 465 and 391 mm falling in 2002, 2003, 2004 and 2005 respectively. The 2006 growing season was particularly dry as 76 mm of rain fell outside the growing season in January (Figure 2d).

Crops

Growth

Compared to treatment AC, crop emergence was greater in the TC treatment at Tincurrin in 2005 but similar in other years (Table 3). At Howick, emergence was greater on the AC treatment in 2004 and 2005 but similar in 2003 and 2006 (Table 4).

At Tincurrin in 2003, biomass growth and grain yield were less in treatment TC compared to AC (Table 3). In 2004, biomass growth was generally similar but the TC treatment again yielded less grain than the AC treatment. In 2005, there was consistently greater biomass growth and grain yield in the TC compared to AC treatment (Table 3). In 2006, biomass growth in the AC treatment was similar or greater than in the TC treatment but grain yield was not statistically different. The protein concentration in grain at Tincurrin was greater in treatment AC in 2004 and greater in treatment TC in 2005 and 2006 (Table 3). Grain size was greater in the TC treatment compared to AC in 2005 and similar in 2006.

At Howick, biomass growth in 2003 was generally less in the treatment TC compared to AC and grain yield was significantly less (Table 4). In 2004, 2005 and 2006, biomass growth was generally similar in treatments AC and TC, but grain yield was greater in treatment AC in 2005 and TC in 2006. The protein concentration in grain at Howick was greater in treatment AC in 2003, 2004 and 2005 and similar in 2006 (Table 4). There was no difference between treatments in the oil content of the canola grain in 2004. Cereal grain size was greater in the AC treatment in 2003 and similar in 2005 and 2006.

Nutrient Concentration

At Howick, the above-ground biomass of plants in treatment TC had significantly lower concentrations of macro-nutrients compared to plants in treatment AC in 2003 (Table 4). In subsequent years, there were no consistent trends in macro-nutrient concentration, though concentrations of Cu, Fe and Mn were generally greater in treatment TC compared to AC.

At Tincurrin in 2003, plants in treatments TC and AC had generally similar nutrient concentrations in their above-ground biomass (Table 3). In subsequent years there were no consistent trends in nutrient concentration.

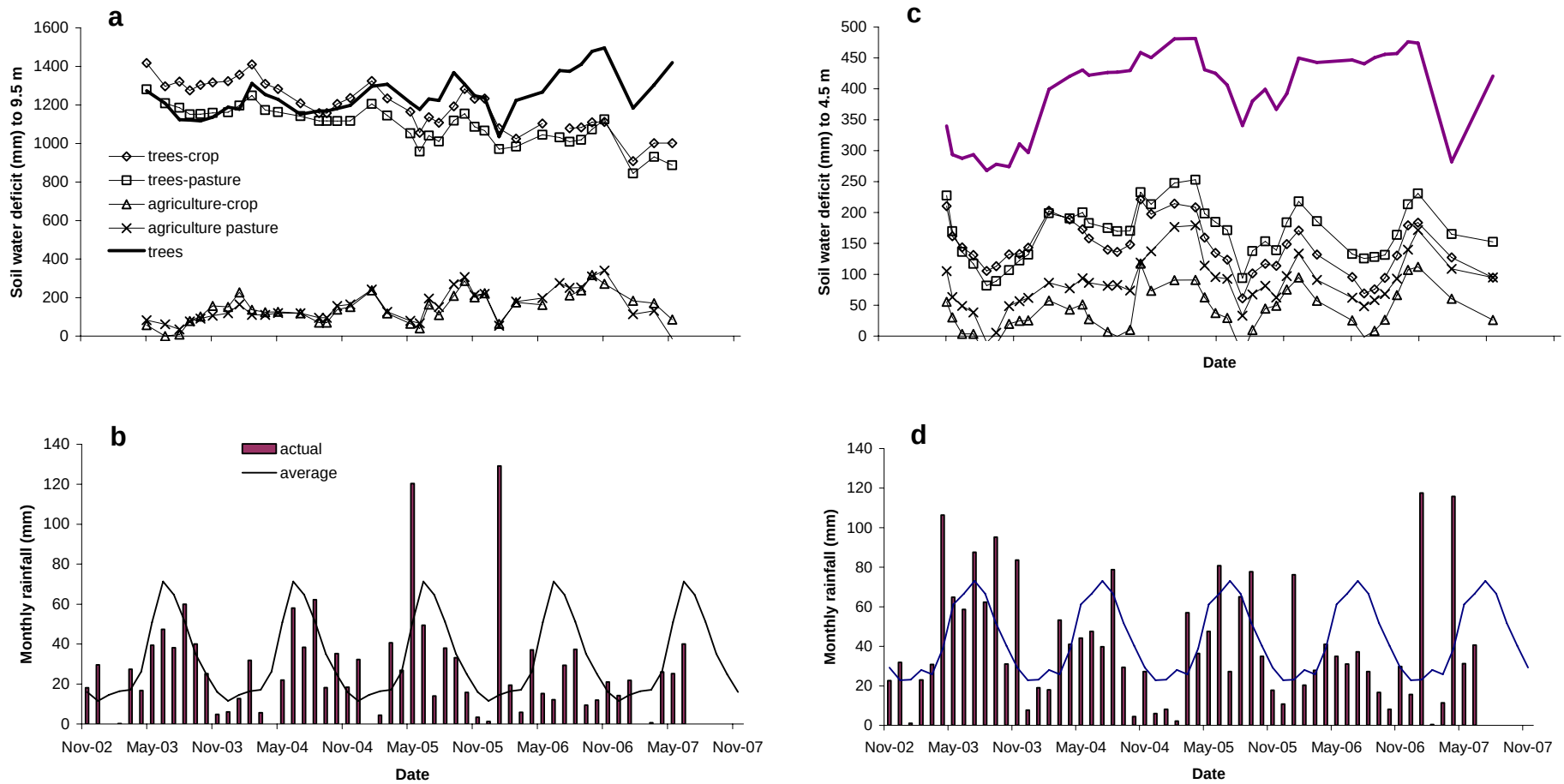


Figure 2. Soil water deficit at Tincurrin, to 9.5 m depth (a) and Howick, to 4.5 m depth (c) and monthly rainfall from November 2002 to May 2007 at Tincurrin (b) and Howick (d).

Table 3. Tincurrin crop and weed above-ground biomass when crop tillering or just starting stem elongation (wt1), just prior to anthesis (wt2) and when crop physiologically mature (wt3), crop grain quality parameters and nutrient concentrations in crop above-ground biomass at tillering/stem elongation (2003, 2004 and 2006) and anthesis in 2005 in agriculture-crop (AC) and tree-crop (TC) treatments. LSD = least significant difference at $P < 0.05$.

	2003				2004				2005				2006			
	Treatment		LSD	$P < 0.05$	Treatment		LSD	$P < 0.05$	Treatment		LSD	$P < 0.05$	Treatment		LSD	$P < 0.05$
	TC	AC			TC	AC			TC	AC			TC	AC		
Growth																
Plants/m ²	62	70	13	0.188	31	38	9	0.115	82	56	21	0.021	49	45	16	0.663
crop wt1 (g/m ²)	113	178	53	0.020	5	8	2	0.004	22	14	4	0.001	17	23	5	0.013
crop wt2 (g/m ²)	-	-	-	-	133	160	42	0.198	807	541	147	0.001	120	107	26	0.300
crop wt3 (g/m ²)	404	523	80	0.006	374	350	107	0.655	749	601	93	0.004	140	185	34	0.014
weed wt1 (g/m ²)	2.7	4.4	3.8	0.350	0.4	0.1	0.6	0.406	0.2	11.6	7.2	0.003	3.2	4.9	4.6	0.425
weed wt2 (g/m ²)	-	-	-	-	-	-	-	-	8.1	13.7	0.9	0.224	1.8	6.0	4.5	0.058
weed wt3 (g/m ²)	1.2	1.5	2.7	0.850	1.1	14.3	12.0	0.033	17.5	8.7	18.3	0.323	1.9	0.1	2.4	0.133
Grain yield (t/ha)	1.48a	2.10b	0.17	<0.001	1.37a	1.73b	0.17	<0.001	2.79b	2.34a	0.32	0.008	0.70	0.58	0.13	0.079
Grain quality																
100 seed wt (g)#	-	-	-	-	-	-	-	-	396	402	2	<0.001	187	188	5	0.749
Protein (%)	-	-	-	-	21.1	21.3	0.3	0.048	11.3	9.4	0.5	<0.001	22.2	21.6	0.3	<0.001
HI	0.44	0.45	0.02	0.221	0.38	0.38	0.03	0.861	0.29	0.35	0.10	0.210	0.39	0.59	0.18	0.032
Stained (%)	-	-	-	-	-	-	-	-	3.80	2.80	2.25	0.363	-	-	-	-
Tissue analysis																
N (%)	1.55	1.48	0.57	0.790	4.91	5.41	0.36	0.010	1.37	1.29	0.23	0.507	4.40	4.19	0.19	0.031
P (%)	0.16	0.17	0.03	0.520	0.55	0.49	0.05	0.391	0.17	0.15	0.03	0.159	0.43	0.39	0.03	0.005
K (%)	2.14	2.08	0.66	0.848	3.15	3.60	0.41	0.036	2.08	1.82	0.29	0.077	0.35	3.32	0.29	0.137
Na (%)	0.38	0.57	0.19	0.063	0.23	0.22	0.10	0.786	0.03	0.03	0.01	1.000	0.15	0.12	0.06	0.276
Ca (%)	0.21	0.21	0.07	0.849	0.54	0.75	0.07	<0.001	0.08	0.10	0.03	0.204	0.79	0.83	0.08	0.276
Mg (%)	0.22	0.21	0.02	0.276	0.48	0.47	0.04	0.393	0.14	0.14	0.03	0.683	0.55	0.46	0.03	<0.001
S (%)	0.18	0.18	0.01	0.727	0.37	0.37	0.03	0.933	0.1	0.1	0.0	0.361	0.30	0.30	0.02	0.564
B (mg/kg)	12.0	9.8	3.9	0.227	20.1	17.1	1.2	<0.001	7.8	8.7	1.6	0.259	24.6	21.0	2.1	0.002
Cu (mg/kg)	2.0	2.6	0.4	0.006	5.6	4.8	0.6	0.016	1.7	2.3	0.4	0.004	3.9	4.7	0.6	0.019
Fe (mg/kg)	128	92	35	0.049	229	266	42	0.081	73	85	14	0.094	292	384	131	0.156
Mn (mg/kg)	26	25	8	0.822	35	31	6	0.199	31	26	5	0.045	112	118	24	0.629
Zn (mg/kg)	11	15	2	0.001	38	38	4	0.851	10.23	9.16	1.836	0.237	32	36	4	0.017

hectolitre weight (g) in 2005. $n=9$

Table 4. Howick crop and weed aboveground biomass when crop tillering or just starting stem elongation (wt1), just prior to anthesis (wt2) and when crop physiologically mature (wt3), crop grain quality parameters and nutrient concentrations in crop at tillering/stem elongation (2003, 2004 and 2006) and anthesis in 2005 in agriculture-crop (AC) and tree-crop (TC) treatments at Howick. LSD = least significant difference at $P < 0.05$.

	2003				2004				2005				2006			
	Treatment		LSD	$P < 0.05$	Treatment		LSD	$P < 0.05$	Treatment		LSD	$P < 0.05$	Treatment		LSD	$P < 0.05$
	TC	AC			TC	AC			TC	AC			TC	AC		
Grow																
Plants/m ²	134	136	30	0.885	31	16	11	0.008	62	77	10	0.005	177	180	38	0.863
Tillers /m ²	691	635	108	0.285	-	-	-	-	-	-	--	-	-	-	-	-
crop wt1 (g/m ²)	54	75	16	0.013	77	57	8	<0.001	52	40	12	0.047	17	17	4	0.957
crop wt2 (g/m ²)	93	103	47	0.669	365	298	88	0.125	736	795	226	0.589	424	356	82	0.099
crop wt3 (g/m ²)	123	164	47	0.080	500	510	119	0.866	904	988	179	0.338	542	502	64	0.207
weed wt1 (g/m ²)	2.4	6.7	3.2	0.011	0.0	1.1	1.3	0.078	0.0	1.9	2.1	0.084	0.8	3.8	1.9	0.004
weed wt2 (g/m ²)	19.0	68.0	63.8	0.118	13.2	7.8	27.2	0.679	3.6	42.2	19.6	<0.001	18.1	73.3	20.7	<0.001
weed wt3 (g/m ²)	132.0	255.0	60.5	<0.001	1.2	6.0	5.5	0.084	16.3	58.1	37.0	0.029	7.2	40.0	13.1	<0.001
Grain yield (t/ha)	0.34a	0.81b	0.14	<0.001	1.33	1.31	0.11	0.726	3.33a	4.02b	0.19	<0.001	2.56b	2.46a	0.09	0.038
Grain quality																
100 seed wt (g)#	3.47	3.78	0.2	0.012					378.6	376.9	5.5	0.534	252.8	253.5	4.1	0.765
Protein (%)	11.3	11.9	0.4	0.013	22.0	22.6	0.5	0.013	10.76	11.33	0.22	<0.001	10.5	10.0	0.7	0.146
Oil (%)	-	-	-	-	41.9	41.6	0.5	0.340	-	-	-	-	-	-	-	-
Stained (%)	26.5	39.2	4.9	<0.001					33.90	30.30	10.28	0.471	-	-	-	-
Tissue analysis																
N (%)	1.67	1.89	0.16	0.016	5.84	5.44	0.89	0.362	1.425	1.649	0.191	0.024	4.80	4.89	0.46	0.666
P (%)	0.22	0.32	0.01	<0.001	0.55	0.59	0.04	0.061	0.196	0.222	0.025	0.043	1.00	1.04	0.10	0.425
K (%)	1.28	2.55	0.15	<0.001	5.66	5.44	0.44	0.308	2.466	2.190	0.243	0.028	4.34	2.93	0.37	0.031
Na (%)	0.24	0.16	0.02	<0.001	0.61	0.24	0.10	<0.001	0.095	0.090	0.014	0.468	0.35	0.62	0.18	0.005
Ca (%)	0.20	0.28	0.02	<0.001	1.02	1.42	0.11	<0.001	0.159	0.232	0.044	0.003	0.40	0.43	0.03	0.031
Mg (%)	0.13	0.14	0.01	0.036	0.37	0.34	0.03	0.057	0.122	0.132	0.011	0.077	0.23	0.24	0.03	0.816
S (%)	0.14	0.18	0.01	<0.001	0.49	0.31	0.05	<0.001	0.147	0.150	0.012	0.595	0.35	0.34	0.03	0.638
B (mg/kg)	6	5	0.2	0.001	33.3	34.7	2.0	0.179	5.1	4.3	0.5	0.005	4.8	4.8	0.6	1.000
Cu (mg/kg)	2	1	0.1	<0.001	6.7	5.6	0.4	<0.001	2.7	2.2	0.3	0.023	6.4	6.2	0.9	0.662
Fe (mg/kg)	140	79	26	<0.001	133	112	73.8	0.547	68	69	31	0.917	161	140	19	0.029
Mn (mg/kg)	33	22	5	0.001	62	37	7.4	<0.001	114	31	20	<0.001	83	57	8	<0.001
Zn (mg/kg)	8	13	3	0.001	56	56	7.4	0.975	17	16	2	0.567	36	41	5	0.033

hectolitre weight (g) in 2005. $n=9$

Weed growth

Waterlogging in 2003 severely affected crop growth at Howick and made weed control difficult. There was less weed biomass throughout each growing season in the TC treatment compared to the AC treatment at Howick, with the single exception of the anthesis measurement in 2004 (Table 4). These differences were significant at the end of the 2003, 2005 and 2006 growing seasons. Reduced weed biomass resulted in less herbicide being applied to treatment TC at Howick in 2003.

At Tincurrin trends in weed growth were more variable between treatments, but on the two occasions that differences were significant there was less weed biomass in the TC treatment compared to the AC treatment (Table 3).

Herbicide resistance

Annual ryegrass was strongly resistant to herbicides in the B-SU and A-Fop groups at Tincurrin and resistant or strongly resistant to a herbicide in the B-SU group at Howick (Table 5). There was no evidence of reduced herbicide resistance of annual ryegrass in the TC treatments four years after the tree phase.

Table 5. Herbicide resistance of annual ryegrass as determined weeks after herbicide treatments were applied. Values are % survival as compared to unsprayed control plants (100% refers to all plants surviving and 0% refers to death). Values are the mean of two replicates (pots) per herbicide rate. To cross-reference the sample, a known sensitive biotype 'S' and resistant biotype 'R' was included in the test.

the test.								
Herbicide	Rate (g or ml/ha)	Herbicide Group	Tree-Crop		Agriculture-Crop		S	R
			Survival (%)	Rating	Survival (%)	Rating	Survival (%)	Survival (%)
Howick								
Verdict + 1% Hasten	85	A-FOP	0	S	0	S	0	100
Logran + 0.2% BS1000	40	B-SU	100	RRR	65	RR	0	100
Roundup PowerMax + 0.2% BS1000	1000	M	0	S	0	S	0	85
Tincurrin								
Verdict + 1% Hasten	85	A-FOP	95	RRR	90	RRR	0	100
Logran + 0.2% BS1000	40	B-SU	95	RRR	95	RRR	0	100
Roundup PowerMax + 0.2% BS1000	1000	M	0	S	0	S	0	85

RRR - indicates plants tested have strong herbicide resistance

RR- indicates medium-level herbicide resistance

R- indicates low-level but detectable herbicide resistance

S- indicates no detection of herbicide resistance.

Pasture

Growth

At Tincurrin, pasture growth in treatment TP was less compared to AP for the first three years after removal of the trees, and similar in the fourth year (Figure 3, Table 6). Dry conditions at Tincurrin in 2003 and 2006 resulted in poor pasture growth. At Howick, pasture production was significantly less in treatment TP in 2003 and similar or greater compared to AP in subsequent years (Table 6). Waterlogging at Howick in 2003 resulted in poor clover establishment and growth in treatment TP.

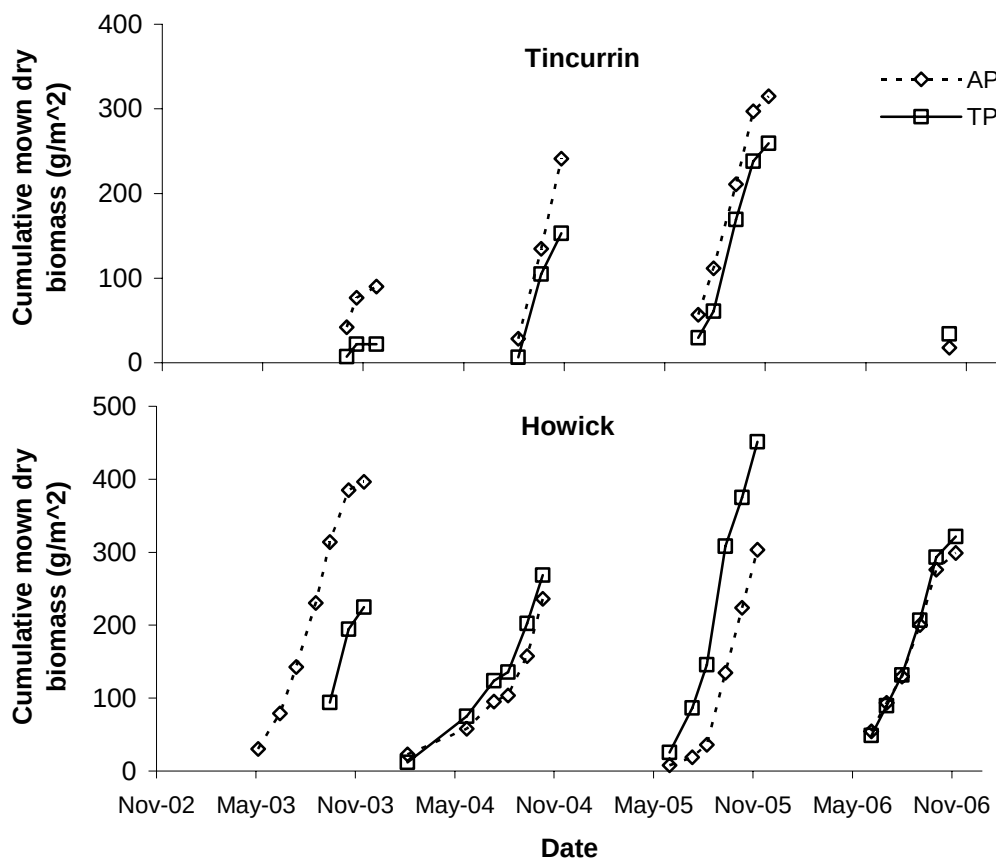


Figure 3. Cumulative pasture growth in the agriculture-pasture (AP) and tree-pasture (TP) treatments at Tincurrin and Howick between 2002 and 2006. These values do not account for the pasture left uncut by the mower.

In May 2003 the amount of pasture left uncut by the mower was assessed for treatment AP at Howick and estimated to be about 1.6 t/ha.

Quality

The feed quality of the pasture was generally similar for the two pasture treatments when compared within individual years or for the mean values for all years at Tincurrin (Table 6). At Howick there were differences between treatments, but they were not consistent across years. Differences between years at both sites may reflect differing sample dates and seasonal conditions.

Table 6. Pasture quality of the agriculture-pasture (AP) and tree-pasture (TP) treatments at Tincurrin and Howick respectively. For each site and parameter, values followed by a different letter are significantly different at $P < 0.05$.

	Crude protein %		Dry matter digestibility %		Metabolisable energy (mj/kgDM)		Biomass production (t/ha)*	
	AP	TP	AP	TP	AP	TP	AP	TP
Tincurrin								
2003	11.0	13.8	64.4	69.0	9.0	9.7	0.90b	0.22a
2004	21.7	15.5	56.8	55.6	7.7	7.4	2.41d	1.53c
2005 winter	18.9	20.1	57.9	56.6	7.8	7.6	3.15e	2.59d
2005 spring	26.1	26.2	72.8	73.9	10.4	10.6		
2006	13.6	11.7	59.6	59.1	8.1	8.1	0.18a	0.34a
LSD	5.0		3.9		0.7		0.273	
all years	18.3	17.4	62.3	8.6	8.7	62.8	1.66b	1.17a
LSD	2.3		1.8		0.3		0.14	
Howick								
2003	15.4b	11.8a	66.6b	69.0cd	9.3b	9.8bc	3.97d	2.25a
2004	16.1bc	18.3cd	75.1e	63.2a	10.8d	8.7a	2.75b	3.10c
2005 winter	19.0de	18.3cd	63.0a	67.0c	8.7a	9.4b	3.03c	4.10d
2005 spring	18.7cd	18.8cd	62.7a	67.5c	8.7a	9.5b		
2006	21.8e	22.3e	74.0de	71.2d	10.6cd	10.1d	2.99bc	3.21c
LSD	2.4		2.9		0.5		0.32	
all years	18.2	17.9	68.3	9.6	9.5	67.6	3.19	3.17
LSD	1.1		1.3		0.2		0.23	

*Does not include biomass left uncut by mower

Trees

Growth

Basal area explained 97.3% of the variability in above-ground dry biomass at Howick and 95.5% at Tincurrin (Table 7). Stem diameter at 1.3 m (DBH) explained 68% of the variability in root bole biomass at Howick. There was no difference in the relationships for data collected in 2002 and 2005 so data from both years was combined. These relationships were used to calculate the tree biomass and nutrients removed from treatments TP and TC in 2002 and annual biomass growth in treatment T.

The above-ground dry biomass of the trees in November 2002 was 37.6 t/ha at Tincurrin and 42.4 t/ha at Howick. Including the root boles, a total of 52.0 t/ha of tree biomass was removed at Howick. Mean annual above-ground tree growth for the first six years after planting was 6.3 t/ha at Tincurrin and 4.2 t/ha for the first ten years at Howick. Ten year old trees at Tincurrin had similar standing biomass (54.7 t/ha) to ten year old trees at Howick (Figure 4). Subsequent annual biomass growth of the remaining trees was 4.9, 3.2, 4.5 and 2.9 t/ha in 2003, 2004, 2005 and 2006 respectively at Tincurrin and 5.6, 1.9, 3.1 and 3.2 t/ha respectively at Howick. Growth was largely independent of rainfall at Tincurrin, but correlated with rainfall at Howick (Figure 5).

Table 7. Relationship between basal area at 0.1 m height (BA) and dry biomass (DB) of leaves and branches < 8 mm diameter, stems and branches > 8 mm diameter and total aboveground biomass (kg/tree) at Tincurrin. Relationship between Diameter at Breast Height (DBH) and dry biomass of leaves and branches < 8 mm diameter, stems and branches > 8 mm diameter, stems > 8 mm diameter and total aboveground biomass (kg/tree) at Howick. Also shown is the relationship between DBH and dry biomass for the root bole at Howick. Values in brackets are regression coefficients.

Tree fraction	Dry biomass (kg/tree)	
	Tincurrin	Howick
Leaf/branches<8 mm	DB = 946 BA ($r^2 = 0.72$)	DB = 1070.7 BA - 1.5665 ($r^2 = 0.93$)
Stems/branches<100 mm	DB = 2279 BA ($r^2 = 0.96$)	DB = 798.49 BA + 1.6095 ($r^2 = 0.86$)
Stems/branches>100 mm	-	DB = 3490.3 BA - 6.9385 ($r^2 = 0.955$)
Total aboveground	DB = 3302 BA ($r^2 = 0.96$)	DB = 5359.5 BA - 6.8955 ($r^2 = 0.97$)
Root bole	-	DB = 1,2161 DBH - 4.1786 ($r^2 = 0.68$)

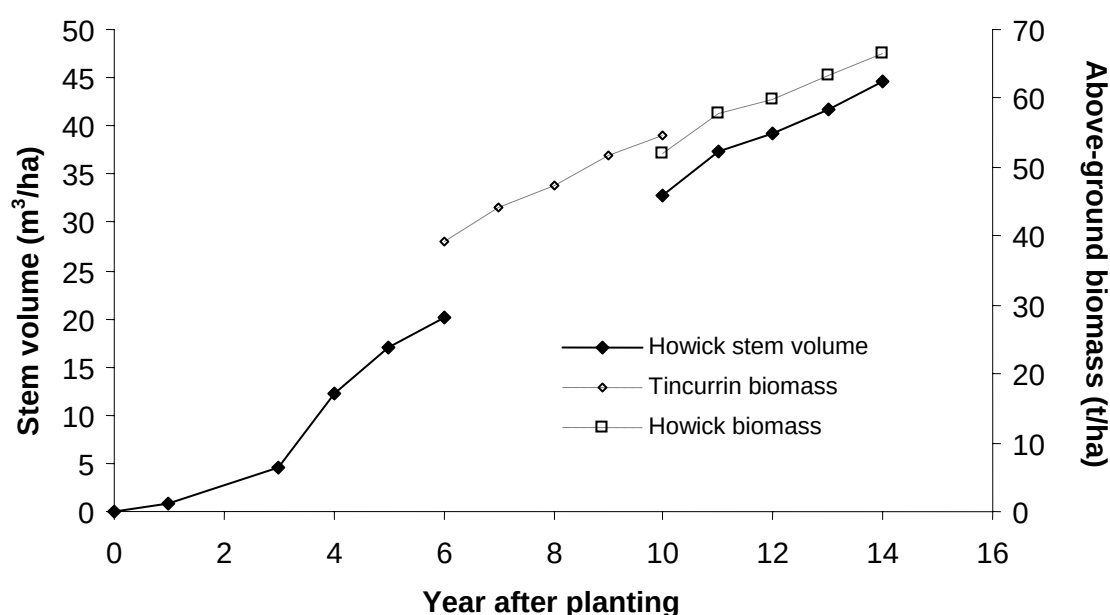


Figure 4. Tree stem volume and above-ground biomass at Howick and above-ground biomass at Tincurrin. Data for the first 6 years at the Howick site are courtesy of the Forest Products Commission.

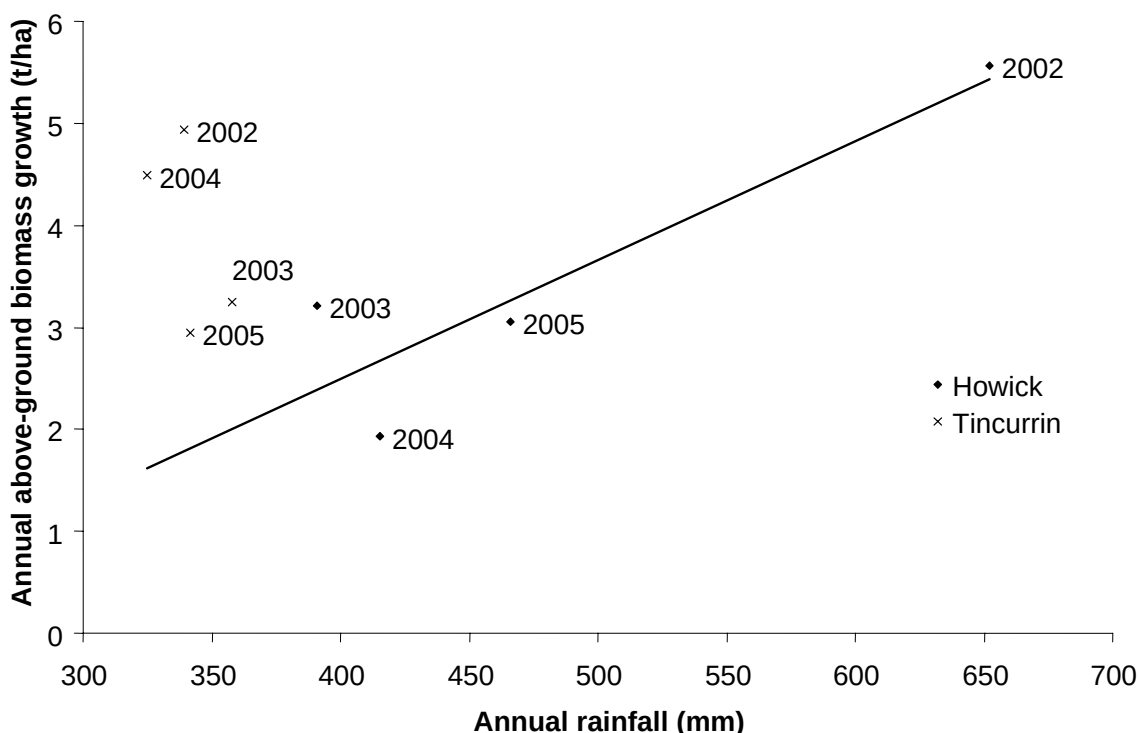


Figure 5. Tree annual biomass growth as a function of annual rainfall at Tincurrin and Howick. The year measurements were taken is shown next to each datum. The correlation coefficient for the line of best fit for the Howick data was 0.82.

Nutrient content

Nutrient concentrations in the tree biomass were generally greatest at Tincurrin and least at East Wickepin (data not presented). A notable exception was the much greater concentration of N in the Acacia biomass at East Wickepin. As a consequence, the amount of nutrients in the above ground tree biomass in 2002 (also the root boles at Howick) was similar at Tincurrin and Howick despite the tree biomass being greater at Howick (Table 8).

Soil

Soil bulk density and particle size

At Howick, the BD of the sand matrix between the gravels in the A horizons varied between 1.53 and 1.60 g/cm³, while BD in the clay subsoil ranged from 1.77 g/cm³ at 0.9 m to 1.95 g/cm³ at 1.8 m (Figure 6). Gamma probe measurements at Howick and soil cores from a site at Neridup with similar subsoil suggest that bulk density between 2 and 9 m depth was generally greater than 1.8 g/cm³. At Tincurrin, the BD was 1.74 g/cm³ in the top 0.1 m of the soil profile, increased to 1.87 g/cm³ at 0.5 m then decreased to 1.63 g/cm³ at 2 m. Gamma probe measurements indicated that bulk density between 2 and 9 m remained less than 1.6 g/cm³.

The bulk density of the top 0.1 m of the topsoil was greater in the TP treatment compared to treatments T or AP at Howick in 2003 and 2005, differences in the top 0.1 m of the clay subsoil were not significant (Table 9). At Tincurrin, the bulk density of both the top 0.1 m of the topsoil and clay subsoil were similar in the AC and TC treatments in 2003, and greater in treatment AC compared to TC in 2005 (Table 10).

Table 8. Dry weight and nutrient content of various factions of tree biomass at the Tincurrin (*E. polybractea*), Howick (*E. globulus*) and East Wickepin (*A. saligna*) sites in November 2002.

Site	Biomass faction	dry biomass kg/ha	N kg/ha	P kg/ha	K kg/ha	Na kg/ha	Ca kg/ha	Mg kg/ha	S kg/ha	B kg/ha	Cu kg/ha	Fe kg/ha	Mn kg/ha	Zn kg/ha
Howick	leaf and twig <8 mm	7941	55	5	34	15	96	17	6	0.84	0.84	0.03	0.37	1.32
	stem and branch <100 mm	8988	16	4	15	5	54	12	2	0.10	0.10	0.02	0.16	1.29
	tree stem >100 mm	23837	38	17	35	14	162	44	5	0.28	0.28	0.02	0.48	1.25
	root bole	9223	15	6	14	6	63	17	2	0.11	0.11	0.01	0.18	0.48
	Total	49990	124	32	98	40	375	90	15	1.33	1.33	0.09	1.20	4.34
Tincurrin	leaf and twig <8 mm	11025	113	4	95	5	126	23	12	1.11	1.11	0.01	1.08	0.58
	stem and branch > 8mm	26564	84	3	66	4	182	29	12	0.39	0.39	0.03	6.02	1.04
	Total	37589	197	7	161	8	308	52	23	1.50	1.50	0.04	7.10	1.62
East Wickepin	leaf and twig <8 mm	7560	116	6	36	5	36	17	7	0	0	2	0	0
	stem and branch > 8mm	28326	201	8	74	3	57	11	8	0	0	1	0	0
	Total	35886	318	15	109	7	93	28	15	0	0	2	0	0
	leaf litter	13509	258	7	16	3	120	38	18	0	0	5	1	0

Table 9. Bulk density, hydraulic conductivity (K) and number of pores with a mean diameter of 0.61 and 1.31 mm at the soil surface and top of the clay subsoil for agriculture-pasture and agriculture-crop (A) and trees-pasture and trees-crop (TA) treatments at the Howick and Tincurrin sites respectively in January 2003. The “TA crack” measurement was taken in the trees agriculture treatment where the permeameter was positioned over a crack in the soil . LSD = least significant difference at $P < 0.05$.

Soil Horizon	Treat.	Howick							Tincurrin						
		bulk density	Suction (mm)					mean pore diameter (mm)	bulk density	Suction (mm)				mean pore diameter (mm)	
			10	-10	-15	-30	-50			0.80	1.50	10	-10		-30
A (topsoil)	K (mm/h)	A	1.42a	214	96	70	67	51a		1.42	115	37	7	5	12.5
		TA	1.63b	237	118	90	237	55a		1.66	172	33	5	6	6.2
		TA crack									96				
		T	1.37a	341	155	119	85	106b							
		<i>LSD</i>	0.14	142	67	86	228	31		0.47	213	23	3	5	
	pores (no./m^2)	A							38.7	2.3					
		TA							7.8	10.8					
		T							-	6.2					
B (clay)	K (mm/h)	A	1.71	23	127	-	9	3		1.81	48a	16	5	24	
		TA	1.59	16	8	-	6	5		1.88	76a	22	15	3	
		TA crack									770b				
		<i>LSD</i>	0.31	34	137	-	8	5		0.36	78	14	17	77	
	pores (no./m^2)	A							4.1						8.2
		TA							4.4						39.4

* $P < 0.06$

Table 10. Bulk density, hydraulic conductivity and number of pores with a mean diameter of 0.61 and 1.31 mm at soil surface and at top of clay subsoil for agriculture-pasture and agriculture-crop (AC) and trees-pasture and trees-crop (TA) treatments at Howick and Tincurrin sites respectively in March 2005. LSD = least significant difference at $P < 0.05$.

Soil Horizon	Treat.	Howick						Tincurrin								
		bulk density	Suction (mm)				mean pore diameter (mm)		bulk density	Suction (mm)				mean pore diameter (mm)		
			10	-20	-40	-65	0.61	1.31		10	-20	-40	-65	0.61	1.31	
A (topsoil)	K (mm/h)	AC	1.33 a	151	97.8 a	62.8 a	35.0 a		1.62 a	167	7.9	2.8	0.43			
		TA	1.64 b	160	59.3 b	40.5 b	21.5 b		1.46 b	151	19.3*	2	0.65			
		LSD	0.18	90	15.5	11.1	8.4		0.14	143	11.5	1.6	0.59			
	pores (no./m^2)	AC						232	25 a					17		
		TA						159*	13 b					14	12	
		LSD						74	9					14		
	B (clay)	K (mm/h)	AC	1.62	14.5		4.4	2.5		1.93 a	52		2.2	0.97		
			TA	1.56	14.2		5.9	1.9		1.78 b	58		1.5	0.99		
			LSD	0.07	7.9		2.6	1.2		0.06	81		1.6	1.02		
pores (no./m^2)		AC						16						10		
		TA						33						7		
		LSD						19						10		

*significantly different at $P < 0.06$

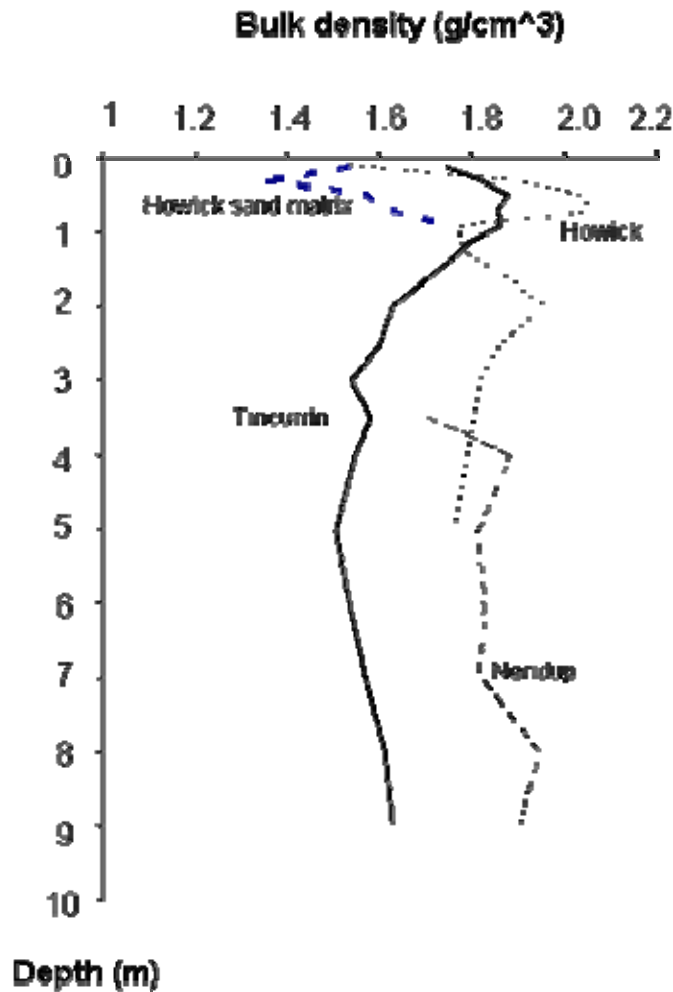


Figure 6. Soil bulk density at the Howick and Tincurrin sites. The thin dotted line shows values for the bulk soil at Howick, the thick dotted line is values for the sand matrix between the gravel in the topsoil at Howick, the thin dashed line shows values at Neridup for similar sub-soil to that found at Howick. The solid line shows soil bulk density at Tincurrin.

Topsoil at the Howick site is dominated by sands and ironstone gravels (> 2 mm fraction) with very little clay until an abrupt change to the subsoil clay at about 0.7 m (Figure 7). At Tincurrin there was little ironstone gravel, though coarse sand was evident throughout the top 1 m of the soil profile. There was more clay throughout the soil profile at Tincurrin compared to Howick and the topsoil was only 0.15 – 0.25 m deep.

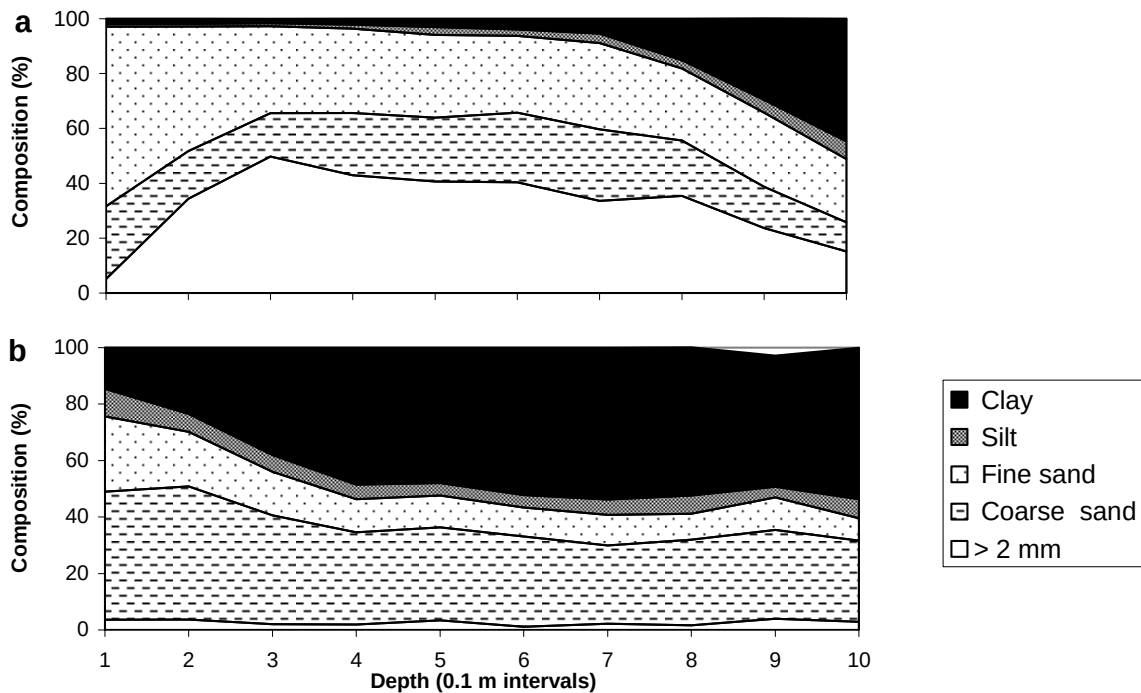


Figure 7. Particle size analysis for top 1 m of soil profile at Tincurrin (a) and Howick (b).

Soil Chemistry

The soil at Tincurrin generally had the greatest nutrient concentrations while east Wickepin had the least regardless of treatment (Tables 11, 12 and 13). There were also differences in how nutrients were distributed down the soil profile. N was concentrated in the topsoil while K and Mg were concentrated in the subsoil at Howick while N, P and K were concentrated in the topsoil with relatively uniform concentrations at depth at Tincurrin (Figure 8).

At Tincurrin in 2003, differences in the concentration of soil organic carbon (SOC) and most cations in the top metre of the soil profile of agricultural land or tree blocks were generally not significant (Table 11). The exceptions were less K, Co and Cu in the soil under the trees. In 2005, K remained less in treatments T, TP and TC, P was less in T and Ca was least in T and greatest in AC. There were also differences in Fe and Zn concentrations among treatments. In the top 0.1 m of the soil profile at Tincurrin, N and K concentrations were generally least in treatment T, and greatest in treatment AP (Table 12). Reactive iron and P concentrations were generally least in treatments TP and TC. Other analytes did not show consistent trends between treatments between 2004 and 2006.

At Howick in 2003, differences between SOC and cation concentrations in the top metre of the soil profile of agricultural land and tree blocks were generally not significant (Table 11). In 2005, P and K concentrations were greatest in treatments AC and TC and Fe and Mg concentrations were greatest in treatments TP and TC. There were also significant differences in Na, and Zn concentrations among treatments. In the top 0.1 m of the soil profile, most analytes were least in treatment T between 2004 and 2006. SOC was consistently greater in treatments AC and AP compared to other treatments.

Measurements of soil fertility in the top 0.1 m of the profile indicated that additional fertiliser needed to be applied to treatments TP and TC compared to AP and AC at both sites (see Table 1 for details).

Table 11. Nutrient content of top 1 m of soil profile expressed as kg/ha at Tincurrin, Howick and East Wickepin.

Site / Year	Treatment	Org C	N	P	K	B	Ca	Co	Cu	Fe	Mg	Mn	Na	Ni	S	Zn
Tincurrin																
2003	A	82149	5143	2227	3162	136	13920	6.25	10.33	914	14187	116	7515	8.20	369	2.56
	T	82381	5177	1891	1343	111	10749	3.76	8.15	978	11439	72	6389	12.90	402	2.20
	LSD	14724	1545	538	767	26	13150	1.93	2.13	186	3408	52	3380	6.65	114	1.28
	P	0.967	0.954	0.157	0.003	0.052	0.540	0.023	0.047	0.394	0.089	0.079	0.407	0.117	0.475	0.484
2005	AC		5376	2289bc	2657bc	151.8	27190bc	4.55	7.07	1095a	15782	150	10515	4.3	586	9.56ab
	AP		4523	2015b	3285c	167.7	13745ab	4.62	8.44	1372b	14203	128	14450	4.6	545	8.09a
	T		4688	1559a	1748a	116.8	8928a	5.73	8.33	2084c	11247	89	9797	4.1	302	13.66ab
	TC		4711	2353c	1774a	132.2	20660b	4.92	7.44	1090a	14387	143	5544	0.0	381	14.25b
	TP		5571	2007b	2090ab	175.7	18049ab	4.55	7.26	1226ab	15313	182	8521	5.0	556	7.51a
	LSD		927	317	978	52	11390	3.5	2.4	247	3682	69	5633.3	1.2	273	5.085
	P		0.107	0.002	0.025	0.135	0.044	0.930	0.602	<0.001	0.132	0.118	0.058	<0.001	0.157	0.039
Howick																
2003	A	48875	3816	529	1861	11	2713	0.75	2.36	844	2806	3	1170	14.70	294	3.61
	T	55554	4030	582	1829	13	3273	0.75	3.46	920	3135	15	1268	5.60	271	2.15
	LSD	11557	778	91	318	6	846	0.23	1.42	260	481	3	369	8.24	45	1.42
	P	0.184	0.488	0.180	0.798	0.427	0.140	0.951	0.099	0.467	0.131	<0.001	0.504	0.037	0.232	0.046
2005	AC		5994	770b	2904b		5289	1.525	3.29	2334c	4973ab		2515b	2.40	314	24.8b
	AP		4981	667ab	2336a		4182	1.297	2.48	1369a	4058ab		1615a	2.01	302	14.9a
	T		5083	549a	2353a		5022	0.934	2.59	1581ab	3866a		1506a	2.49	209	17.0ab
	TC		6021	781b	3129b		4692	1.639	2.73	2232c	5471b		2548b	2.68	292	19.7b
	TP		5446	670ab	2620ab		5685	1.42	3.01	1997bc	5078b		2081ab	2.41	268	11.3a
	LSD		1540	143	563		1356	0.488	0.95	551	1138		659	0.581	77	6.8
	P		0.449	0.028	0.040		0.210	0.069	0.382	0.012	0.043		0.014	0.215	0.079	0.013
East Wickepin																
2003	A	14065	662	333	107	15	539	0	4	320	84	4	4	3	29	1
	T	32406	1687	269	215	15	633	0	3	235	233	6	57	4	28	2

Table 12. Chemical analysis of top 0.1 m of topsoil in tree (T), tree-crop (TC), tree-pasture (TP), agriculture-crop (AC) and agriculture-pasture (AP) at Tincurrin.

Analyte	Year	Treatment					P
		AP	AC	T	TC	TP	
EC d/S/m	2004	0.187b	0.175b	0.136a	0.136a	0.131a	0.012
	2005	0.146	0.113	0.142	0.150	0.129	0.15
	2006	0.090a	0.174c	0.082a	0.137b	0.171bc	0.002
pH (CaCl ₂)	2004	5.13bc	5.00a	6.33c	5.70b	5.10a	<0.001
	2005	5.13bc	5.10b	4.95a	5.30d	5.25cd	0.002
	2006	4.93	4.87	4.77	5.07	4.87	0.135
Org C (%)	2004	2.2	2.1	2.3	2.1	2.0	0.694
	2005	2.3a	2.4	2.5	2.6	2.1	0.004
	2006	1.7a	1.9ab	2.2b	2.2b	1.8a	0.008
N ammonium (mg/kg)	2004	4a	6ab	3a	9b	7b	0.018
	2005	4b	9d	2a	6c	5c	<0.001
	2006	1a	7b	1a	2a	5b	<0.001
N nitrate (mg/kg)	2004	36c	37c	7a	15ab	16b	<0.001
	2005	30c	16ab	8a	28c	22bc	0.009
	2006	20b	27c	2a	21b	16b	<0.001
P (mg/kg)	2004	50bc	54c	57c	35a	44b	<0.001
	2005	46d	39bc	44cd	35b	28a	<0.001
	2006	49b	35a	48b	33a	34a	<0.001
K (mg/kg)	2004	276c	224b	81a	226b	188b	<0.001
	2005	256c	177b	62a	244c	184b	<0.001
	2006	227c	142ab	63a	219b	107a	0.011
Reactive iron (mg/kg)	2004	709	582	616	514	485	0.059
	2005	759b	732b	733b	622a	610a	0.015
	2006	825d	716c	738c	586b	536a	<0.001
S (mg/kg)	2004	19	21.6	17.2	16.8	19.8	0.639
	2005	16.2	14.6	21.7	20.8	14.1	0.245
	2006	13.3a	17.0a	12.3a	19.3a	31.9b	0.018
Total N (mg/kg)	2004	40c	43c	10a	24b	23b	<0.001

Table 13. Chemical analysis of top 0.1 m of topsoil in tree (T), tree-crop (TC), tree-pasture (TP), agriculture-crop (AC) and agriculture-pasture (AP) at Howick.

Analyte	Year	Treatment					P
		AP	AC	T	TC	TP	
EC m/S/m	2004	0.064b	0.075b	0.026a	0.070b	0.066b	< 0.001
	2005	0.119	0.395	0.050	0.099	0.097	0.481
	2006	0.076b	0.074b	0.050a	0.081b	0.080b	0.007
pH (CaCl ₂)	2004	4.37b	4.55c	4.18a	4.37b	4.43bc	< 0.001
	2005	4.65bc	5.73cd	4.20a	4.55b	4.80d	< 0.001
	2006	4.57bc	4.50b	4.20a	4.80c	4.57bc	0.006
Org C (%)	2004	1.6	1.5	1.5	1.1	1.0	0.082
	2005	2.0b	2.0b	1.4a	1.3a	1.2a	0.005
	2006	1.9b	1.7b	1.4a	1.2a	1.3a	0.002
N ammonium (mg/kg)	2004	1a	3b	1a	3b	5c	< 0.001
	2005	4b	3a	3a	5c	5c	< 0.001
	2006	1	2	3	1	3	0.108
N nitrate (mg/kg)	2004	11c	18d	2a	2a	6b	< 0.001
	2005	18e	4b	1a	11d	7c	< 0.001
	2006	18b	19b	1a	18b	19b	< 0.001
P (mg/kg)	2004	24b	17b	10a	24b	18b	< 0.001
	2005	21c	15b	9a	18bc	22c	< 0.001
	2006	23c	15b	9a	18b	17b	< 0.001
K (mg/kg)	2004	66b	75b	43a	41a	47a	0.001
	2005	85b	124c	54a	111c	101bc	0.003
	2006	54a	78a	54a	58a	108b	0.005
Reactive iron (mg/kg)	2004	344d	191a	240b	349d	289c	< 0.001
	2005	340c	186a	193a	330c	271b	< 0.001
	2006	247b	156a	193a	306c	195b	0.002
S (mg/kg)	2004	3.0ab	4.1b	2.4a	4.2b	4.0b	0.05
	2005	9.1c	4.5a	4.3a	10.1d	7.7b	< 0.001
	2006	4.5b	2.8a	4.3b	5.7c	4.1b	0.006
Total N (mg/kg)	2004	12b	20.5c	2.75a	4.67a	10.25b	< 0.001

As measurements were not replicated in the agriculture treatment at East Wickepin it is not possible to compare treatments statistically, however SOC, N, P and Ca were greater in the tree treatment compared to agriculture while K was less.

Results from the 2007 soil sampling were not available at the time this report was compiled.

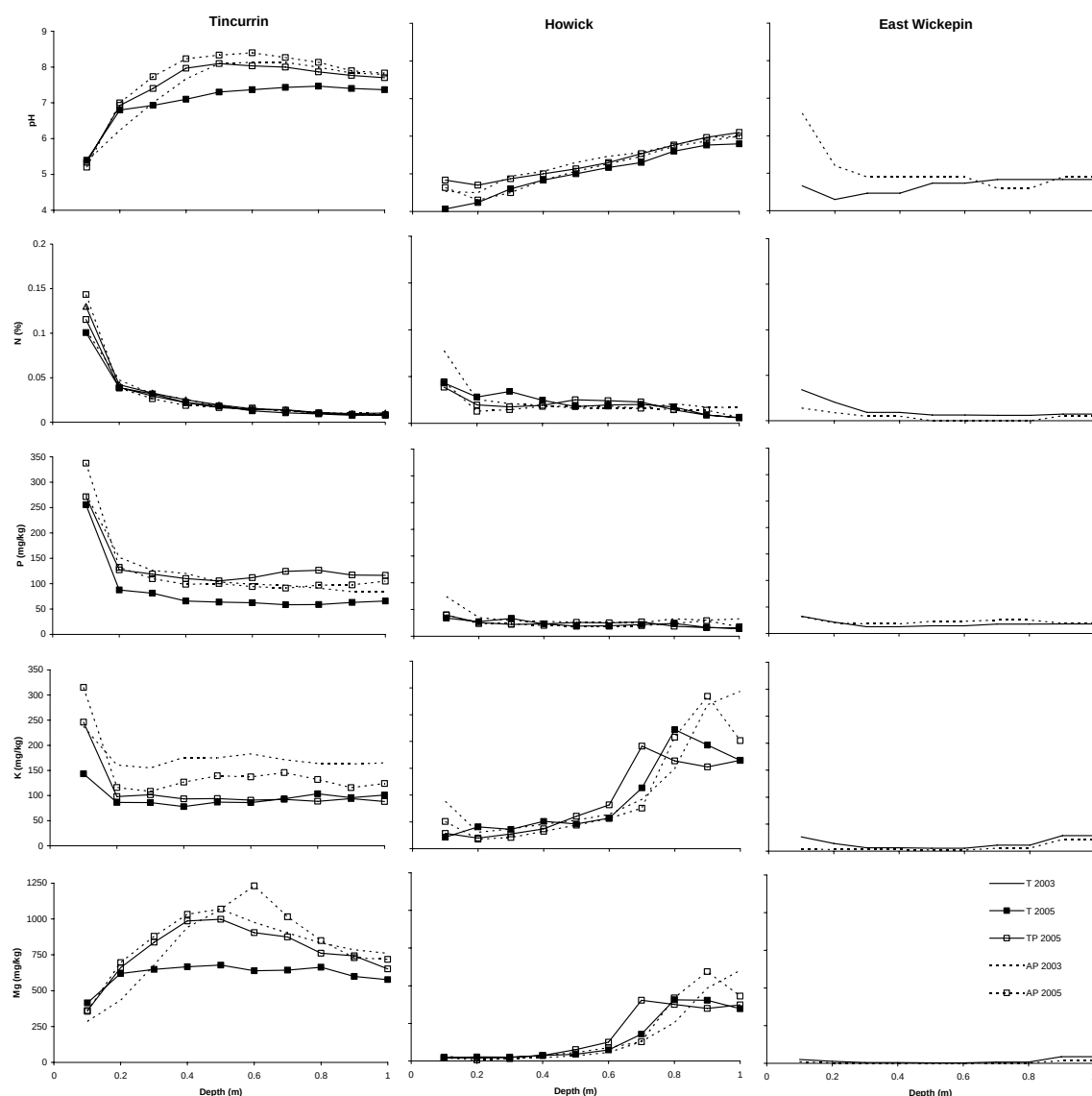


Figure 8. pH (CaCl_2) and concentration of total N, P, K and Mg down the soil profile for tree (T), continuous agriculture (A) and tree-agriculture (TA) treatments at Tincurrin and Howick in 2003, 2005 and 2007 and at East Wickepin in 2003.

At Tincurrin, the amount of N, S and Mg removed in agricultural product and leaching was similar to what was removed in the tree biomass (Table 14). More K and Ca were removed in tree biomass compared to agricultural product. The amount of K removed in tree biomass was not great enough to account for the difference in K in the soil between the tree and agriculture treatment even if the K added as fertiliser to the agriculture treatment is considered.

At Howick, more N, P, K, S and Mg were removed in agricultural product and leaching than tree biomass, while more Ca was removed in tree biomass (Table 14). In the case of N, P, S and Ca the addition of fertiliser replaced the nutrients that were removed from the agricultural treatment. The net removal of Mg from the soil in the agriculture treatment appeared to reduce the amount of Mg in the soil relative to the tree treatment. Although more Ca was removed in the tree biomass and was not replaced with fertiliser in the tree treatment, the Ca content of the top metre of the soil profile was greater under the trees compared to the agriculture treatment.

It should be noted that N added to the soil by leguminous pastures or crops was not accounted for in this analysis.

Table 14. Nutrient content of top 1 m of soil profile for agriculture and tree treatments at the Tincurrin and Howick sites in 2003. The amount of nutrients applied as fertilisers from the time trees planted (1996 at Tincurrin and 1992 at Howick) to the end of 2002. The amount of nutrients removed in above-ground biomass of trees or crop over the same period at Tincurrin and Howick (including root bole biomass).

			Nutrients in soil, applied as fertiliser or removed by leaching and with tree, crop or pasture biomass (kg/ha)					
			N	P	K	S	Ca	Mg
			Tincurrin					
Soil	Agriculture		5143	2227	3162	369	13920	14187
	Trees		5177	1891	1343	402	10749	11439
Nutrients applied in fertiliser	Agriculture		479	82	60	101	19	0
	Trees		0	0	0	0	0	0
Nutrients removed	Agriculture	Leached		0	7	14	14	28
		Product	211	31	50	24	14	17
	Trees	Biomass	197	7	161	23	308	52
			Howick					
Soil	Agriculture		3816	529	1861	294	2713	2806
	Trees		4030	582	1829	271	3273	3135
Nutrients applied in fertiliser	Agriculture		126	114	0	125	171	0
	Trees		40	41	0	24	0	0
Nutrients removed	Agriculture	Leached		55	55	110	110	220
		Product	272	66	155	50	77	42
	Trees	Biomass	124	32	98	15	375	90

Permeability

At Tincurrin, differences in hydraulic conductivity at a particular suction were not significantly different in the TC and AC treatments for the topsoil and bulk clay subsoil (Tables 9 and 10). The exception was where the drier subsoil of the TA treatment had cracked and consequently had greater saturated hydraulic conductivity compared to the wetter AC subsoil. These cracks were observed to extend about a meter into the clay.

Except for greater conductivity at -50 mm suction in the topsoil under the trees in 2003, the hydraulic conductivity of the topsoil and clay subsoil was largely similar between treatments at Howick in 2003 (Table 9). In 2005, the hydraulic conductivity of the topsoil was greater in the AP treatment compared to the TP treatment (Table 10).

Soil biology

In 2002, prior to the imposition of treatments, dissolved organic carbon (DOC) was similar for continuous agriculture and the tree treatment at Howick whereas it was higher in the continuous agriculture treatment at Tincurrin (Table 15). Total microbial biomass carbon (MBC) and respiration (microbial activity) were higher in the continuous agriculture compared to the tree-retained treatment at Howick. They were similar at the Tincurrin site at this sampling time for both treatments (Table 15). There were fewer mites under continuous agriculture compared to the tree-retained treatment at the Howick site but the reverse was observed at Tincurrin. There were also fewer collembola under continuous agriculture at the Howick, but no difference at Tincurrin (Table 15). For the mycorrhizal bioassay in 2002, shoot and root DW of subterranean clover did not differ between treatments even though mycorrhizal colonisation was higher in continuous agriculture after three weeks of the bioassay for Howick (Table 16). At six weeks in the bioassay, mycorrhizal colonisation was higher in the continuous agriculture treatment at both sites.

Table 15. Effect of phase farming with trees on dissolved organic carbon (DOC), microbial biomass and activity (at 0-50 and 50-100 mm) and fauna counts (at 0-50 mm) during spring 2002.

Site and treatment	DOC ($\mu\text{g C/g soil}$)	Respiration ($\mu\text{g CO}_2\text{-C/g soil/h}$)	Total microbial biomass ($\mu\text{g C/g soil}$)	Mesofauna counts (No./soil core)			
				Mites (M)	Collembola (C)	Total M + C	C:M ratio
Howick							
Agriculture	84.7 a	0.44 a	231.0 a	3 b	28 b	31 b	9.3 a
Trees	80.7 a	0.29 b	156.5 b	14 a	202 a	216 a	14.4 a
Tincurrin							
Agriculture	112.8 a	0.23 a	175.4 a	22 a	169 a	191 a	7.7 b
Trees	96.2 b	0.22 ab	174.9 a	6 b	127 a	133 a	21.2 a

Within columns, means followed by the same letter(s) are not significantly different ($P < 0.05$) by Tukey's multiple comparison test.

Table 16. Effect of phase farming with trees on arbuscular mycorrhizal potential as shown by root colonisation of subterranean clover in bioassay (soil collected at 0-50 mm) during spring 2002.

Site and treatment	3 weeks after planting			6 weeks after planting		
	Shoot DW (g/plant)	Root FW (g/plant)	AM colonisation (%)	Shoot DW (g/plant)	Root FW (g/plant)	AM colonisation (%)
Howick						
Agriculture	1.7 a	1.7 b	37 a	6.4 a	5.6 a	84 a
Trees	1.4 a	2.8 b	15 b	5.0 a	6.7 a	51 b
Tincurrin						
Agriculture	1.5 a	2.1 a	37 a	7.3 a	8.2 a	63 a
Trees	1.2 a	1.8 a	29 a	5.4 b	5.5 b	53 b

Within columns, means followed by the same letter(s) are not significantly different ($P < 0.05$) by Tukey's multiple comparison test. Mycorrhizal colonisation was assessed using a glasshouse bioassay sampled 3 and 6 weeks after sowing subterranean clover into the field-collected soil.

In 2003, the total microbial biomass carbon was higher in the AC treatment at Howick while at Tincurrin it was higher for the AC, AP and T treatments compared to the TC and TP treatments (Table 17). Microbial activity (respiration) was not greatly influenced by tree history at either site (Table 17). It was slightly higher for AC at Howick and AP at Tincurrin. At Howick, mites were generally present in higher numbers where trees were retained or removed compared to continuous agriculture whereas collembolan numbers were higher in the continuous agriculture treatments (Table 17). In contrast, collembolan numbers were generally higher with continuous crop or pasture at Howick, but they were lower where trees were retained or removed (Table 17). There were no marked effects of treatments on either mite or collembolan numbers at Tincurrin. Mycorrhizal colonisation was higher in the T treatment and least in the AC and TC treatments at Howick whereas at Tincurrin it was higher in the AC treatment (Table 17). Mycorrhizal colonisation was greater in treatment TP compared to TC at both sites.

Table 17. Effect of phase farming with trees on soil biological properties (at 0-5 cm) during spring 2003.

Site and treatment	Respiration (µg CO ₂ - C/g soil/h)	Total microbial biomass C(µg C/g soil)	Mesofauna counts (No./soil core)				Mycorrhizal colonisation (%) 3 weeks
			Mites	Collembola	Total	C : M ratio	
Howick							
AC	0.49 a	259.9 a	37 ab	225 a	262 a	8.4 b	12 c
AP	0.28 b	169.2 b	12 b	257 a	268 a	22.6 a	19 b
T	0.20 b	161.5 b	79 a	57 b	135 b	0.9 c	28 a
TC	0.30 b	116.5 b	73 a	55 b	128 b	1.8 c	12 c
TP	0.27 b	119.0 b	30 ab	26 b	56 b	1.5 c	18 b
Tincurrin							
AC	0.34 b	181.9 a	28 a	38 b	65 b	1.6 a	21 a
AP	0.55 a	180.3 a	73 a	124 a	197 a	2.1 a	14 b
T	0.33 b	175.7 a	88 a	6 b	94 b	0.1 a	9 c
TC	0.26 b	136.5 b	54 a	55 b	110 ab	2.0 a	9 c
TP	0.27 b	135.5 b	56 a	34 b	90 b	1.5 a	18 ab

Within columns, means followed by the same letter(s) are not significantly different ($P<0.05$) by Tukey's multiple comparison test

In 2004 at Howick, microbial respiration was least in the TP treatment, and there was no difference between the other treatments. Active microbial biomass carbon was not influenced by treatment history at either site (Table 18). At Howick, mites were present in higher numbers in treatment T compared to continuous agriculture but collembola were more abundant for continuous agricultural treatments compared with treatments where trees were retained or removed. At Tincurrin, there were no marked effects of treatment on mite abundance but collembola were less abundant in treatment T (Table 18). Mycorrhizal colonisation of bioassay plants was greatest in the treatment T at Howick, whereas at Tincurrin, it was least where trees were retained or replaced by crops (Table 18).

Table 18. Effect of phase farming with trees on soil biological properties (at 0-50 mm) during spring 2004.

2004.

Site and treatment	Respiration ($\mu\text{g CO}_2\text{-C/g soil/h}$)	Active microbial biomass C ($\mu\text{g CO}_2\text{-C/g soil}$)	Mesofauna counts (No./soil core)				Mycorrhizal colonisation
			Mites	Collembola	Total	C : M ratio	
Howick							
AC	1.16 a	37.8 a	33 b	339 a	372 ab	10.3 b	10 b
AP	0.54 b	24.7 a	11 b	596 a	606 a	54.2 a	10 b
T	0.70 ab	27.2 a	160 a	65 b	225 b	0.4 b	35 a
TC	0.60 ab	31.9 a	89 ab	76 b	165 b	0.9 b	7 b
TP	0.80 ab	36.4 a	28 b	22 b	51 b	0.8 b	23 ab
Tincurrin							
AC	0.35 a	16.2 a	23 b	33 bc	56 b	1.4 a	26 a
AP	0.41 a	19.1 a	69 ab	104 a	173 a	1.5 a	10 ab
T	0.35 a	16.2 a	86 a	5 c	91 b	0.1 a	3 b
TC	0.42 a	19.6 a	49 ab	51 b	100 a	1.0 a	3 b
TP	0.34 a	16.0 a	65 ab	37 bc	102 a	0.6 a	21 ab

Within columns, means followed by the same letter(s) are not significantly different ($P<0.05$) by Tukey's multiple comparison test. Mycorrhizal colonisation was assessed in a 3 week bioassay.

In 2005, both microbial respiration and active microbial biomass was greatest treatments TP and TC at Howick but at Tincurrin, there was little difference between treatments (Table 19). Mites were present in greater numbers in pasture after tree removal at Howick but at Tincurrin they were present in the greatest number in treatment AP. Collembola were most abundant in treatments AC at Howick and AP at Tincurrin and least in treatment T at both sites (Table 19).

Table 19. Effect of phase farming with tree on soil biological properties (at 0-50 mm) during 2005

Site and treatment	Respiration ($\mu\text{g CO}_2\text{-C/g soil/h}$)	Active microbial biomass C ($\mu\text{g CO}_2\text{-C/g soil}$)	Mesofauna counts (No./soil core)				Mycorrhizal colonisation (%) 3 weeks
			Mites	Collembola	Total	C : M ratio	
Howick							
AC	0.20 c	9.2 c	19 b	571 a	590 a	33.5 a	ND
AP	0.08 c	3.7 c	4 b	116 b	120 bc	46.5 a	ND
T	0.14 c	6.1 c	7 b	40 b	47 c	7.7 b	ND
TC	0.43 b	19.6 b	41 b	56 b	97 c	2.6 b	ND
TP	0.81 a	36.8 a	108 a	207 b	314 b	3.4 b	ND
Tincurrin							
AC	0.08 b	3.7 b	22 b	34 ab	56 b	1.9 ab	ND
AP	0.12 ab	5.7 ab	134 a	58 a	191 a	0.5 b	ND
T	0.05 b	2.4 b	55 b	6 b	54 b	0.2 b	ND
TC	0.22 a	10.0 a	23 b	33 ab	56 b	3.5 a	ND
TP	0.03 b	1.4 b	54 b	36 ab	90 b	0.6 b	ND

ND=not determined. Within columns, means followed by the same letter(s) are not significantly different ($P<0.05$) by Tukey's multiple comparison test.

In 2006, both microbial respiration and active microbial biomass were greatest in treatment TP at Howick but at Tincurrin they were both greater in treatment AP (Table 20). Mite numbers were greater in treatments TC and TP at Howick but collembolan numbers were greatest in treatment AC (Table 20). Mites and collembola were most abundant in treatment AP at Tincurrin. Mycorrhizal colonisation was greatest in treatments T and TP at Howick (Table 20). At Tincurrin, mycorrhizal colonisation was least in treatment TC, this was also observed at Howick.

Table 20. Effect of phase farming with tree on soil biological properties (at 0-5 cm) during spring 2006.

Site and treatment	Respiration ($\mu\text{g CO}_2\text{-C/g soil/h}$)	Active microbial biomass C ($\mu\text{g CO}_2\text{-C/g soil}$)	Mesofauna counts (No./soil core)				Mycorrhizal colonisation (%) 3 weeks
			Mites	Collembola	Total	C : M ratio	
Howick							
AC	0.29 b	13.0 b	26 bc	490 a	516 a	19.0 a	29 c
AP	0.22 b	10.2 b	9 c	115 b	125 bc	17.5 a	21 d
T	0.17 b	7.8 b	10 c	44 b	54 c	4.6 b	45 a
TC	0.45 ab	20.4 ab	52 ab	43 b	94 bc	1.1 b	11 e
TP	0.71 a	32.6 a	57 a	198 b	254 b	4.5 b	36 b
Tincurrin							
AC	0.12 b	5.4 b	25 b	30 b	55 b	1.6 a	24 ab
AP	0.27 a	12.6 a	135 a	65 a	197	0.6 ab	19 bc
T	0.11 b	5.3 b	41 b	9 b	49 b	0.2 b	14 cd
TC	0.18 ab	8.2 ab	29 b	26 b	55 b	1.4 ab	9 d
TP	0.07 b	3.5 b	59 b	36 ab	96	0.8 ab	25 a

ND=not determined. Within columns, means followed by the same letter(s) are not significantly different ($P<0.05$) by Tukey's multiple comparison test.

Soil-borne disease

Soil-borne disease risk was generally low at both sites (Table 21). Nematodes (*Pratylenchus neglectus*) were present at greater densities in treatments AC and AP at Tincurrin compared to treatments TP and TC, though even where present the risk was rated as "low". Crown rot (*Fusarium culmorum*) DNA was present at greater concentrations in the tree-agriculture treatments compared to the continuous agriculture treatments at Howick. The risk was described as "medium" for one sample and "low for the remaining samples. Blackspot risk ranged from "medium" to "high" in the crop treatments at Tincurrin, but there was no difference between treatments AP and AC and TP and TC.

Soil water content

The soil at Tincurrin had a greater water holding capacity than at Howick. In the top 1 m of the soil in treatment AC, soil water content ranged between 341-233 mm at Tincurrin and 130 and 243 mm at Howick. To a depth of 9.5 m, values ranged from 3290-3608 mm and 2818-2998 mm at Tincurrin and Howick respectively. Trees appeared to reduce the soil water content to a depth of at least 10 m at Tincurrin and to 4 m at Howick.

Table 21. Soil borne disease at the Howick and Tincurrin sites, soil samples collected in January 2006 from agriculture–crop (AC), agriculture–pasture (AP), tree–crop (TC), tree–pasture (TP) and tree (T) treatments. BDL = Below Detectable Limits, lsd = least significant difference at $P < 0.05$.

Site	Treatment	Cereal Cyst Nematode eggs / g soil	Take-all (standardised risk rating)	Take-all oat race (+/-)	Rhizoctonia (standardised risk rating)	<i>Pratylenchus</i> <i>neglectus</i> / g soil	<i>Pratylenchus</i> <i>thornei</i> / g soil	Stem Nematode / 100 g soil	Total <i>Fusarium.</i> <i>pseudogrami</i> <i>nearum</i> pg DNA/ g soil	Crown Rot <i>Fusarium</i> <i>culmorum</i> pg DNA / g soil	Common root rot (<i>Bipolaris</i>) pg DNA / g soil	Blackspot complex (standardised risk rating)
Tincurrin	TC	BDL	BDL	BDL	BDL	<1	BDL	BDL	3.25	BDL	BDL	2.2
	TP	BDL	BDL	BDL	BDL	<1	BDL	BDL	BDL	BDL	6.5	63.8
	AC	BDL	BDL	BDL	BDL	1	BDL	BDL	0.50	BDL	4.0	2.2
	AP	BDL	BDL	BDL	BDL	2	BDL	BDL	BDL	BDL	BDL	74.0
	T	BDL	BDL	BDL	BDL	<1	BDL	BDL	BDL	BDL	BDL	4.0
	TC	BDL	BDL	BDL	BDL	<1	BDL	BDL	BDL	103	2.8	BDL
	TP	BDL	BDL	BDL	BDL	<1	BDL	BDL	BDL	2	BDL	4.0
	AC	BDL	BDL	BDL	BDL	<1	BDL	BDL	BDL	14	1.3	1.5
	AP	BDL	BDL	BDL	BDL	<1	BDL	BDL	BDL	1	BDL	6.2
	T	BDL	BDL	BDL	BDL	<1	BDL	BDL	BDL	BDL	BDL	BDL
<i>P</i> (<0.05)						<0.001			0.531	0.04	0.706	<0.001
lsd						0.5121			3.094	48.78	7.783	27.26

When soil water monitoring began in May 2003 at Tincurrin, treatments TP, TC and T had similar volumetric water contents in the top metre of the soil profile, suggesting there had been little recharge from the 97 mm of rain which fell after the trees were removed in November 2002 (Figure 2). At Howick, 209 mm of rain fell between November 2002 and May 2003, with 106 mm falling in February 2003. Unlike Tincurrin, this rainfall increased the soil water content to a depth of 2.5 m (Figure 9) and decreased the soil water deficit in treatments TC and TP by 130 and 113 mm respectively compared to treatment T (Figure 2).

At Tincurrin in May 2003, the soil water deficit (down to 9.5 m) was 53 and 69 mm in treatments AC and AP respectively, compared with 1329-1473 mm in treatments T, TP and TC. The deficit down to 10.5 m was 1563 and 1406 mm in treatments TC and TP respectively. Over the next four years to May 2007, soil water deficit (down to 9.5 m) decreased by 416 and 394 mm in treatments TC and TP respectively (Figure 2a) as water moved down the soil profile to a depth of 5 m (Figures 9b and 9e). In the 4.5 years after clearing the trees, soil water recharge averaged approximately 90 mm/yr in treatments TP and TC, though annual recharge ranged from a minimum of 7 mm in treatment TP in the 12 months between May 2005 and 2006 to a maximum of 158 mm between May 2006 and 2007. Between May 2004 and May 2007, soil water deficit decreased by 96 mm in treatment AP and increased by 149, and 29 mm in treatments T and AC respectively.

Plant available water content (PAWC) at Tincurrin in 2003 was consistently less in treatments TP, TC and T compared to treatments AP and AC (Figure 11). During the 2004 growing season, PAWC was less in treatment TC compared to AC until August, after which it was similar. PAWC remained less in treatment TP compared to AP until the 2005 growing season. During the 2005 and 2006 growing seasons PAWC in treatments AC, AP, TC and TP was similar. The soil water content below 1 m remained near FC in the AP and AC treatments throughout 2003-07, but was consistently less in the TP, TC and T treatments (Figure 9e).

At Howick, installation of the NMM access tubes revealed the presence of an intermittent layer of sandy clay. This was evident as a layer with lower soil water content between 5 and 6 m deep in treatments AP and AC (Figures 10a and 10d). This layer was not recorded when drilling in treatment T, and is not evident in Figure 10c. In treatments TC and TP, the sandy clay layer was recorded when drilling but the upper boundary is not clearly defined by a change in soil water content (Figures 10b and 10e). The depth of soil water extraction appeared to be 4 m in treatment T (Figure 10c), but cannot be determined in treatments TP and TC because of the sandy clay layer. Consequently, soil water deficits at Howick were calculated to a depth of 4.5 m on the assumption that tree rooting depth was 4 m as observed in treatment T.

As at Tincurrin, soil water content at Howick in May 2003 was near FC deeper than 1 m in treatments AP and AC, and less than FC at 2-4 m deep in treatments T, TC and TP. At this time, the soil water deficit under treatments AC and AP was 56 and 105 mm respectively compared with 340, 227 and 210 mm under T, TP and TC respectively. By May 2007, soil water deficits had decreased by 75 and 116 mm in treatments TP and TC respectively (Figure 2c) as water moved further down the soil profile to a depth of 4 m (Figures 10b and 10e). In the 4.5 years after clearing the trees, soil water recharge averaged 55 and 42 mm/yr on treatments TC and TP respectively. The greatest recharge occurred in the 6 months immediately after the trees were cleared (130 and 113 mm in treatments TC and TP respectively). After that, recharge ranged from a minimum of 1 mm in treatment TC in the 12 months between May 2006 and 2007 and a maximum of 52 mm between May 2005 and 2006. Between May 2004 and May 2007, soil water deficit decreased by 10 and 30 mm in treatments AP and AC respectively and increased by 119 mm in treatment T.

PAWC at Howick was similar in treatments AP, AC, TP and TC in 2003. From 2004 to 2007, PAWC was greater in treatments TC and AC compared to treatments TP and AP. PAWC was consistently least in treatment T (Figure 11b).

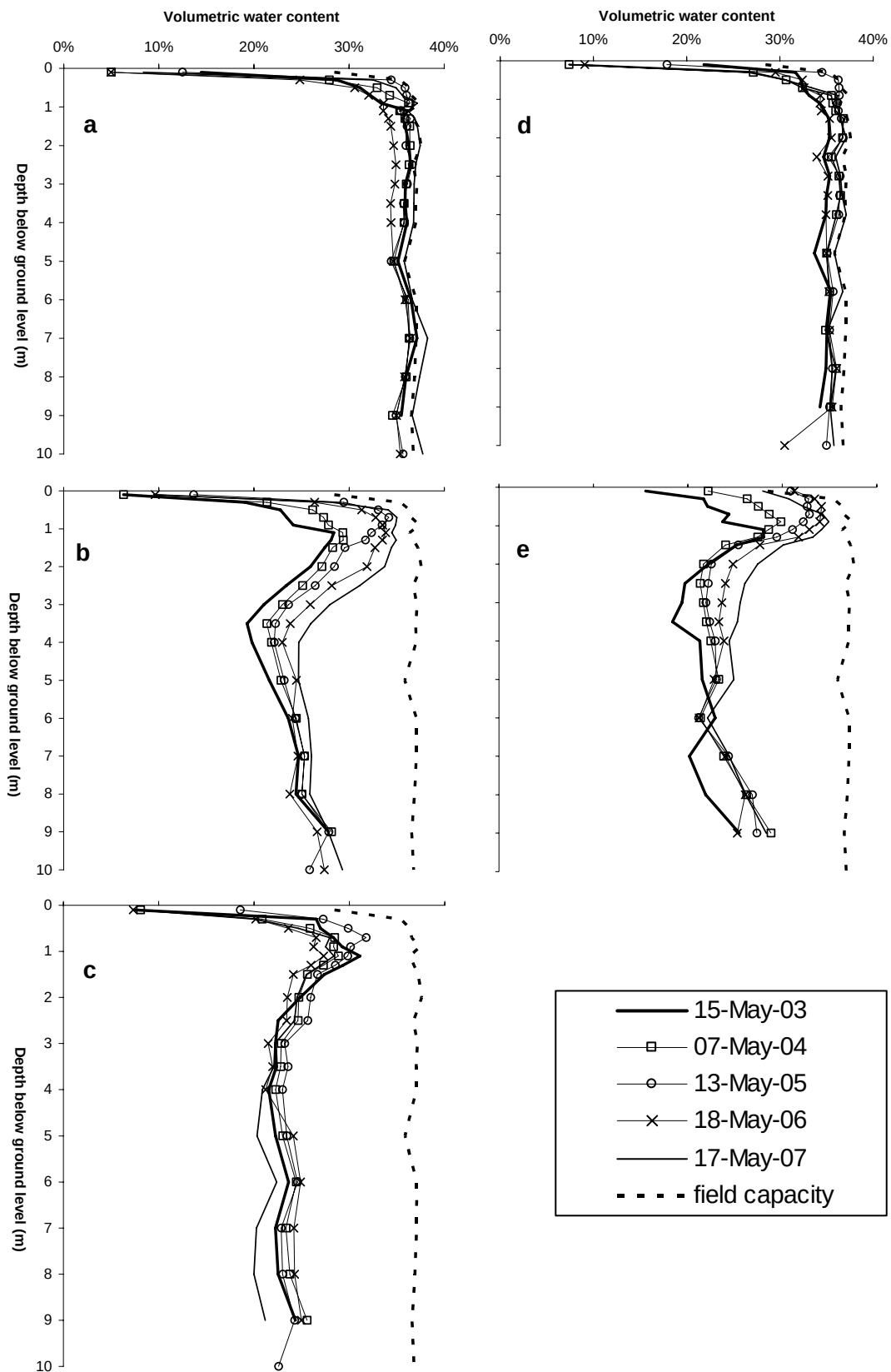


Figure 9. Volumetric water content and estimated field capacity down the soil profile at Tincurrin for agriculture–pasture (a), trees–pasture (b), trees (c), agriculture–crop (d) and trees–crop (e).

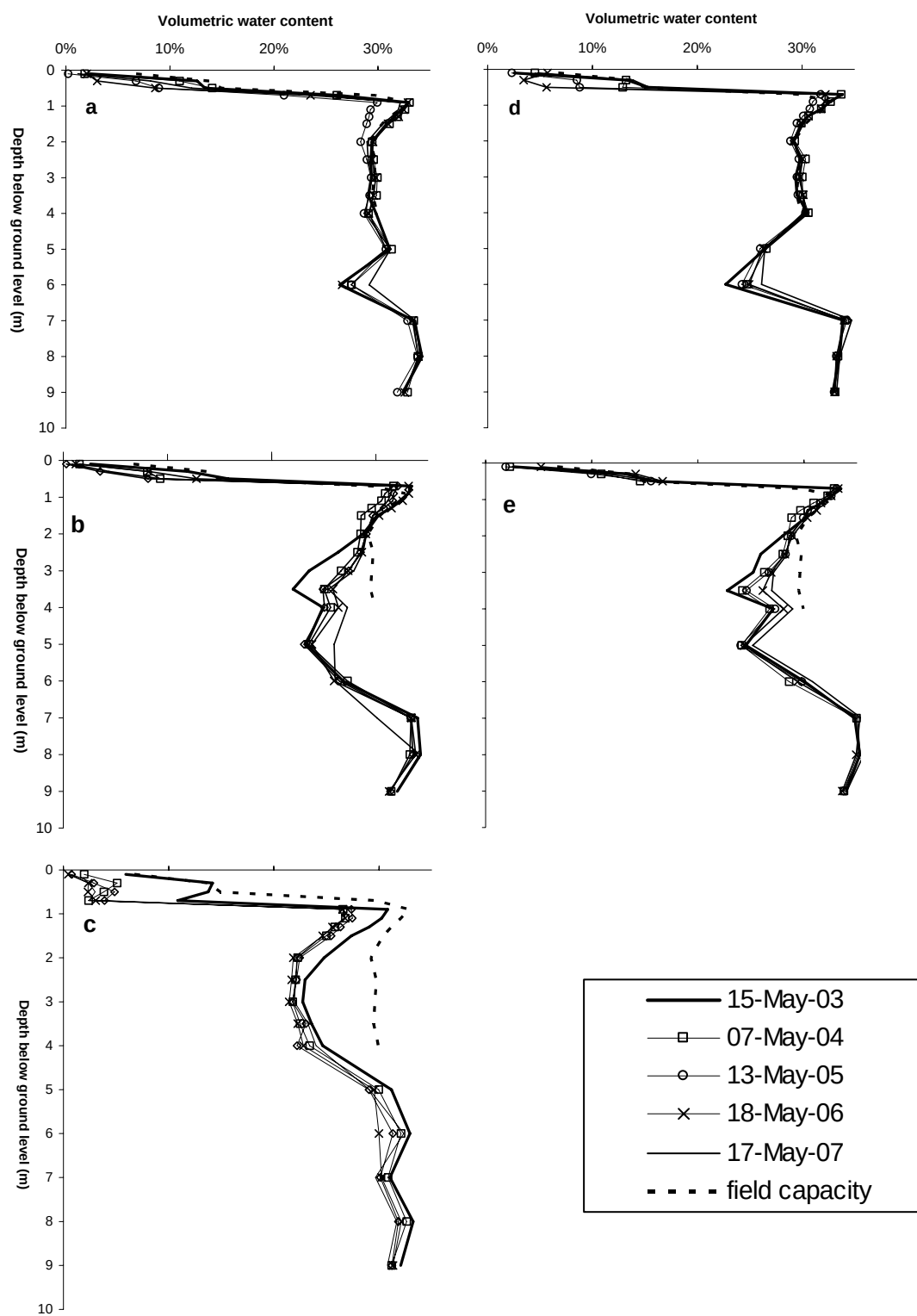


Figure 10. Volumetric water content and estimated field capacity down the soil profile at Howick for agriculture–pasture (a), trees–pasture (b), trees (c), agriculture–crop (d) and trees–crop (e).

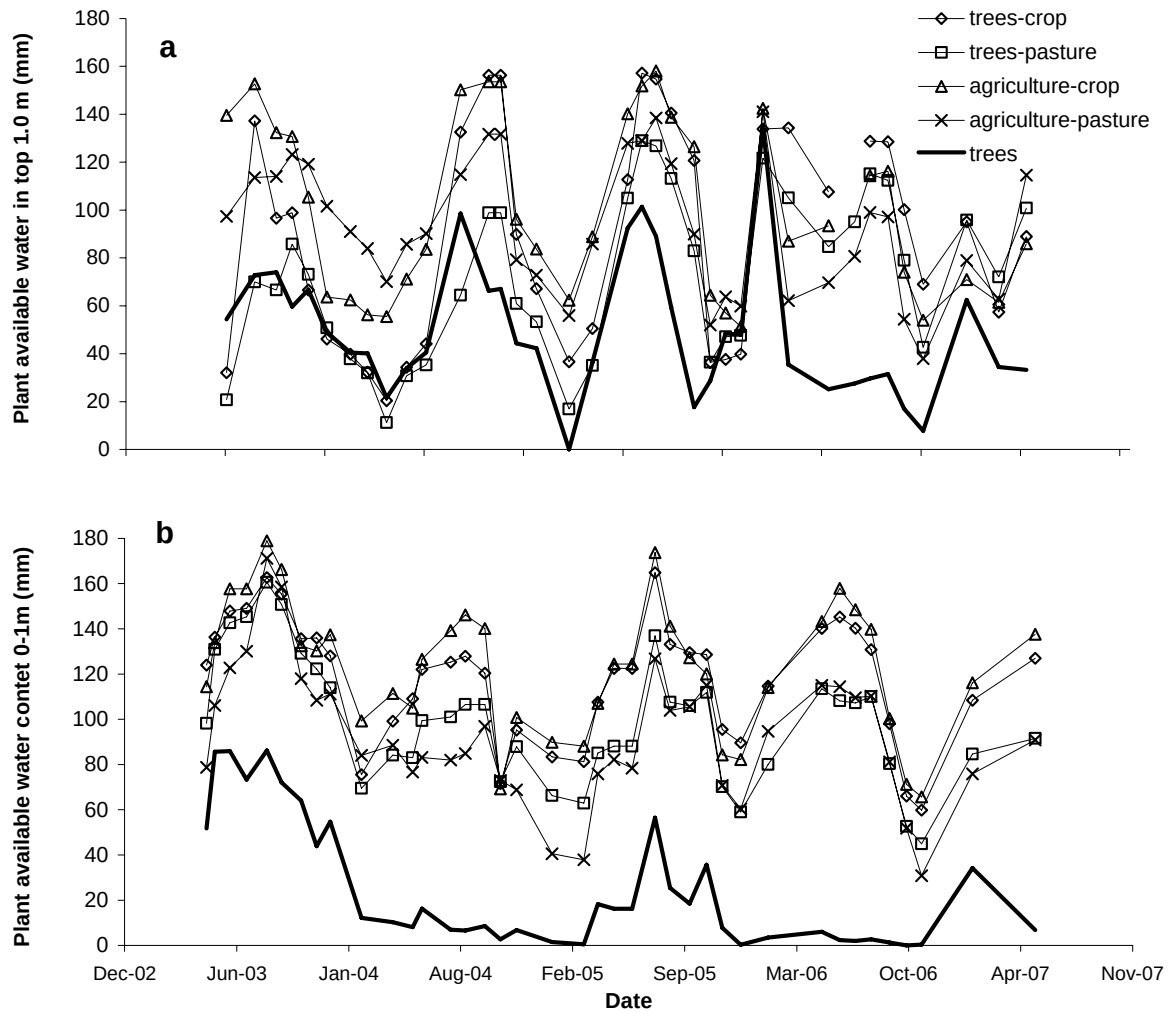


Figure 11. Plant-available water in the top 1 m of the soil profile for various treatments between May 2003 and May 2007 at Tincurrin (a) and Howick (b).

While surface runoff was not measured at either site, runoff was observed from treatment TP at Tincurrin but not from the other treatments. At Howick the site was relatively flat and no surface flow was observed, a 1 m drain 25 m to the north of the treatments TC and AC may have removed some perched water during waterlogging events, but while water was observed in the drain it was never seen to flow.

Given the limitation of the method used to estimate the depth of soil water extraction there were no clear differences between the continuous agriculture and tree agriculture treatments at either site (Table 22). Extraction was to a depth of 0.7 – 0.9 m at Tincurrin and 0.5-0.6 m at Howick suggesting there was no extraction from the subsoil clay at Howick.

Perched Water

Heavy rainfall at Howick in 2003 and 2005 caused waterlogging in treatments TP, TC, AP and AC, though not in treatment T (Figure 12). In the affected treatments, the soil immediately above the clay subsoil was saturated from early June to early October. The depth of the saturated layer varied spatially and temporally across the site. For some weeks in 2003 the entire A horizon was saturated to the point where there was water ponded on the soil surface. There was no waterlogging at Howick in

2004. There was transitory waterlogging in the summer of 2006 (instruments were not installed at this time) but none during the growing season.

Table 22. Estimated depth of soil water extraction by crop or pastures at Tincurrin and Howick in treatments agriculture–crop (AC), agriculture–pasture (AP), tree–crop (TC), tree–pasture (TP).

Site	Year	Treatment			
		TC	TP	AC	AP
Tincurrin	2003	0.7	0.7	0.7	0.5
	2004	0.9	0.7	0.7	0.7
	2005	0.9	0.9	0.9	0.9
	2006	0.7	0.9	0.7	0.7
Howick	2003	0.5	0.5	0.5	0.5
	2004	0.5	0.5	0.6	0.5
	2005	0.5	0.6	0.5	0.5
	2006	0.5	0.6	0.5	0.6

There was no evidence of reduced waterlogging in treatments TP and TC compared to AP or AC. The greater depth of water over the clay B horizon in treatments AC and AP compared to TC and TP reflects greater topsoil depth in treatments AC and AP and all plots had water ponded on the soil surface at times during the growing season. There was little difference in the time that continuous agriculture treatments were waterlogged compared to agriculture after trees. There appears to be a consistent trend in both years for pasture plots to become water logged slightly later in the season compared to crop plots and for the pasture plots to stay waterlogged for slightly longer at the end of the growing season.

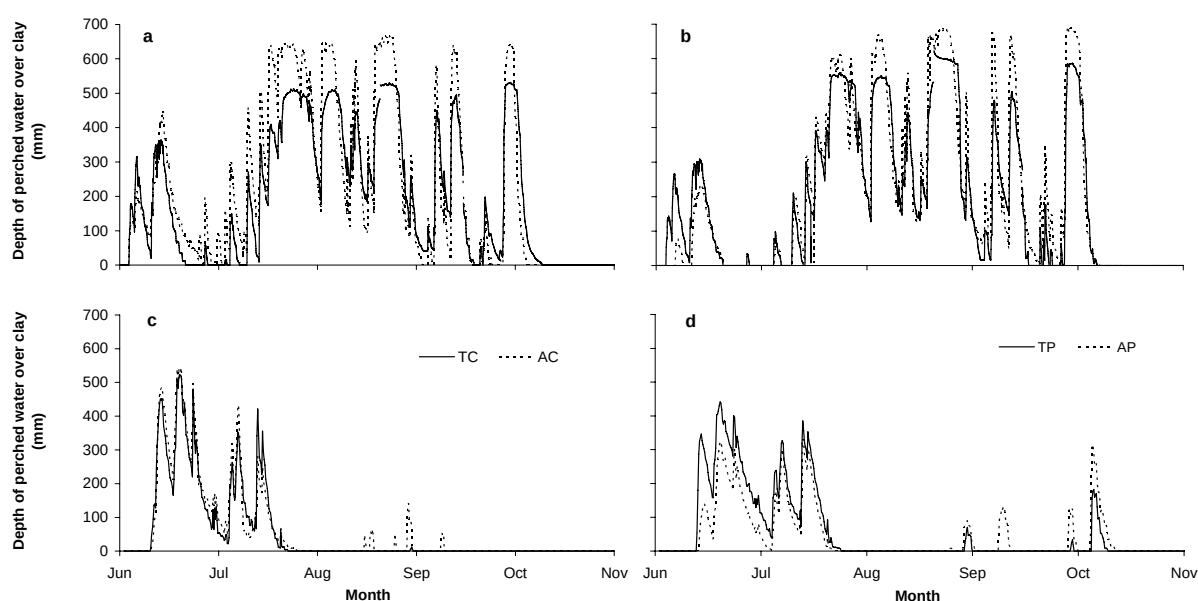


Figure 12. Depth of perched water below ground level in treatments TC and AC (a) and TP and AP (b) in 2005 and TC and AC (c) and TP and AP (d) in 2005 at Howick.

At Tincurrin, waterlogging only occurred in 2005. As the topsoil at Tincurrin is only 0.1-0.2 m deep the observation wells were installed into the clay subsoil. Consequently as waterlogging events occurred the observation wells filled with water and the gradual decline in apparent waterlogging is a function of water in the wells draining through the clay rather than actual perched water on the A/B horizon interface (Figure 13). The rapid increases in apparent water depth indicated in Figure 14 show events when there was free water perched on the clay subsoil but not the duration of perching. From these data it would appear that there was greater depth of perching in treatments AC and TC compared to TC and AP respectively.

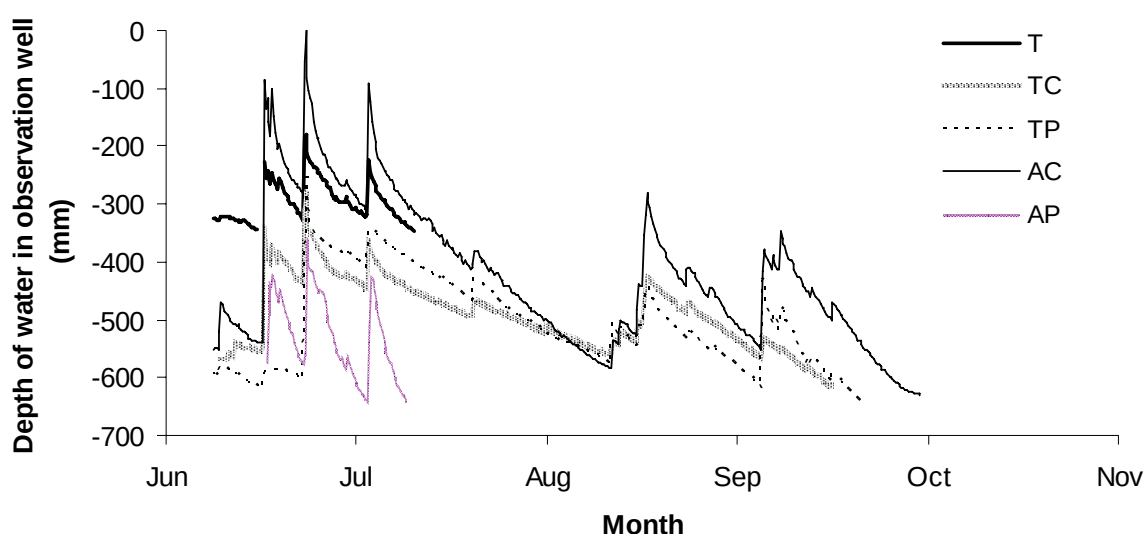


Figure 13. Depth of perched water in observation wells at Tincurrin in 2006.

Deep drainage

Estimates of soil water recharge made using AgET were greater than measured values at Howick and slightly less than measured values at Tincurrin.

At Tincurrin, estimated mean annual drainage below the root zone and change in soil water storage was 78 and 52 mm for continuous pasture and continuous crop rotations respectively. This compares to measured values of recharge of 88 and 92 mm/yr for treatments TP and TC respectively. Again it should be noted that AgET estimated similar runoff (about 20 mm) from each treatment, and while runoff was observed on treatment TP none was observed from TC.

At Howick, the estimated mean annual drainage below the root zone and change in soil water storage was 73 and 69 mm for treatments AP and AC respectively. This compares with mean measured soil water recharge of 42 and 55 mm/yr in treatments TP and TC respectively. The low measured K_{sat} value for the A/B interface that was used in the model resulted high values of estimated runoff (123 mm and 69 mm for treatments TP and TC respectively). However, it should be noted that no runoff was observed from either treatment.

Measurements of groundwater depth at Howick showed groundwater to be rising at a relatively constant 52 mm/yr between 1993 and 2006 (Figure 14).

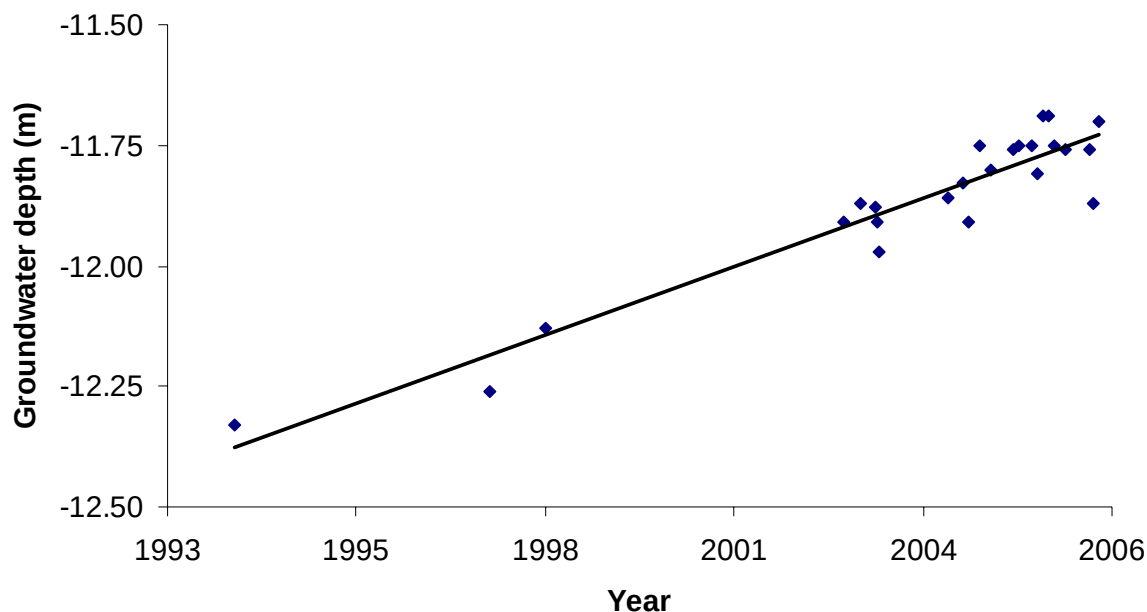


Figure 14. Groundwater depth at Howick between 1993 and 2006.

Economics

It should be noted that this analysis is for the four years of agricultural production after tree removal and doesn't include any of the costs and returns associated with the tree crop. At both the Howick and Tincurrin sites the gross margins for continuous sheep grazing (estimated) and cropping were higher than the margins where trees were removed. The difference was greater for the higher rainfall district of Howick than for Tincurrin. The gross margin for cropping was greater than for sheep grazing at both sites with or without a tree phase.

At Tincurrin, the cumulative net returns after four years was \$45/ha greater for treatment AP compared to TP (Table 23). Treatment AC had \$90/ha advantage in returns over the previous four years compared to treatment TC. This reflects lower returns from agricultural products after the tree phase for three years in the case of sheep production and two years in the case of cropping. Input costs were less for one to two years after the tree phase due to lower herbicide and insecticide application costs and lower sheep maintenance costs due to lower stocking rates. Annual net returns after the tree phase were equal or greater compared to continuous agriculture three years after the tree phase for cropping and four years for sheep grazing.

At Howick, the cumulative net returns after four years was \$188/ha greater for treatment AP compared to TP (Table 23). Treatment AC had a \$220/ha advantage in returns over the previous four years compared to treatment TC. Input costs were less for cropping in the first year after the tree phase compared to continuous agriculture due to reduced herbicide costs. Subsequent costs for cropping and pasture after a tree phase were greater compared to continuous agriculture, principally due to greater fertiliser costs for the first three years after tree removal. However, by year four the annual costs were similar. Annual net returns after the tree phase were equal or greater compared to continuous agriculture four years after the tree phase for cropping and three years for sheep grazing.

Table 23. Costs and returns from cropping or sheep production on the tree-crop (TC), agriculture-crop (AC) or tree-pasture (TP), agriculture-pasture (AP) treatments in the four years after tree removal at Howick and Tincurrin (2004 – 2006).

Site	Treatment		2003	2004	2005	2006	Total period
Howick	AP	Stocking rate, DSEs/ha	4.1	2.2	3.3	3.2	
		Costs, \$/ha	91	141	128	111	471
		Returns, \$/ha	164	82	109	112	467
		Net returns	73	-59	-19	-1	-3
	TP	Stocking rate, DSEs/ha	2.5	2.5	4.6	3.4	
		Costs, \$/ha	240	153	149	114	655
		Returns, \$/ha	100	93	152	119	464
		Net returns	-140	-60	3	5	-191
	AC	Crop	Barley	Canola	Wheat	Oats	
		Yield, t/ha	0.81	1.31	4.02	2.46	
		Costs, \$/ha	258	306	203	197	964
		Returns, \$/ha	162	419	563	541	1685
		Net returns	-96	113	360	344	721
	TC	Crop					
		Yield, t/ha	0.34	1.33	3.33	2.56	
		Costs, \$/ha	243	352	229	196	1022
		Returns, \$/ha	68	426	466	563	1523
Tincurrin	AP	Net returns	-176	73	237	366	501
		Stocking rate, DSEs/ha	1.3	2.7	3.4	0.6	
		Costs, \$/ha	143	47	123	65	377
		Returns, \$/ha	45	87	239	44	415
	TP	Net returns	-98	40	117	-20	38
		Stocking rate, DSEs/ha	0.7	1.9	2.9	0.8	
		Costs, \$/ha	112	37	140	67	356
		Returns, \$/ha	24	61	204	59	348
		Net returns	-88	25	64	-8	-7
	AC	Crop	Barley	Peas	Wheat	Peas	
		Yield, t/ha	2.1	1.73	2.34	0.58	
		Costs, \$/ha	218	214	245	211	888
		Returns, \$/ha	420	387	328	128	1263
		Net returns	202	174	83	-85	374
	TC	Crop					
		Yield, t/ha	1.48	1.37	2.79	0.7	
		Costs, \$/ha	163	214	275	212	863
		Returns, \$/ha	296	307	391	154	1148
		Net returns	134	93	116	-58	284

DSE = dry sheep equivalents

Discussion

Phase Farming with Trees (PFT) has been proposed as a new farming system which has potential to ameliorate salinity by reducing soil water storage and groundwater recharge. In addition to salinity amelioration, claimed benefits include enhanced soil biological processes, improved soil physical characteristics, utilisation of nutrients unavailable to conventional crops and pastures, reduced weed burdens and herbicide resistance and a disease break for conventional crops and pasture. If these benefits can be achieved it may be possible to introduce trees as a new cash crop into farming rotations, improve overall productivity and reduce the deleterious environmental impact of conventional crops and pasture.

This trial has examined many of the claimed benefits of PFT in the first four years after the tree phase at two sites in Western Australia with differing climatic and edaphic conditions. The Howick site is in a medium/high rainfall zone and has deep (0.7 m) topsoils which are inherently infertile and have low water holding capacity. The sub-soil clays are of sedimentary origin and are dense and hostile to root growth. The Tincurrin site is in a medium/low rainfall area and has loamy clay soils that are comparatively fertile and have high water holding capacity. The subsoil clays are comparatively amenable to tree root growth. Results indicated that, on suitable soils, the tree phase of PFT can indeed create substantial soil water deficits and so prevent groundwater recharge during an extended agricultural phase. However, the evidence for some of the other claimed benefits was less clear.

As the experiment was only done at two sites the question must be asked; how robust are the findings and how much will they vary geographically? Clearly edaphic and climatic conditions and agronomic practices will influence the productivity of agriculture after a tree phase. However, there are some key findings that we suggest can be extrapolated beyond these sites:

- Soil water deficits are great enough after the tree phase to allow at least a decade of agriculture with minimal recharge on duplex soils with deep water tables.
- The hydraulic conductivity of sub-soil clays is at least as important as the amount of rainfall in terms of determining the rate of recharge.
- Weed biomass is reduced for at least four years after the tree phase.
- Adequate fertiliser needs to be applied during the tree phase.
- Any improvements in soil physical and biological characteristics after a tree phase will not improve agricultural yields if yield is constrained by the availability of water or nutrients.
- The magnitude of the effects of agronomic practices and a tree phase are similar in terms of soil biology.

The results and implications of each component of the trial are discussed in turn, beginning with the effect of PFT on soil-water recharge.

Soil water recharge

In terms of reducing groundwater recharge, the results at Tincurrin showed most promise, with *E. polybractea* reducing the amount of water stored in the top 10 m of the soil profile by up to 1560 mm within six years of being planted. It should be noted that this may be less than the actual soil water deficit as measurements were not made below 10 m. Results at Howick were less promising; the *E. globulus* only dried the soil to 4 m and created a maximum soil water deficit of 447 mm after 12 years. It should be noted that this deficit may have been achieved prior to 2002. Indeed, Dr. Richard Harper (pers. com. 2004) reported trees planted in SRWC configurations depleted stored soil water to a depth of 6.5 m in 36 months in south-western Australia (see also Harper et al. 2008).

Following harvesting of the trees, it is estimated that annual crops and pasture could be grown for approximately seventeen years before the soil again reached field capacity at Tincurrin, and eight to

eleven years at Howick (assuming groundwater recharge continues at same rates as recorded between 2003 and 2007). The modelling conducted for the feasibility study of PFT (Harper *et al.* 2000) suggested that agricultural phases of around 10 or more years would be sufficient for PFT to be feasible; this condition appears to have been met at both sites.

The large soil water deficit at Tincurrin is particularly interesting in light of a recent study which suggests that for several valleys in south-western Australia, salinisation of the valley floors is due to *in situ* recharge rather than recharge further upslope (George *et al.*, 2004). Consequently, those authors suggest that recharge management in the valley floors is more effective than whole of catchment approaches. However, to achieve significant reductions in salinisation, recharge would have to be reduced by at least 50%, a target the authors describe as “problematic” given current management systems, while reducing recharge by 50-75% is described as “not possible at any meaningful scale”. If the technical and economic uncertainties related to the tree phase of PFT can be removed, PFT may be attractive to farmers interested in actively managing recharge and reaping the benefits on their own properties. Currently, growing lucerne (*Medicago sativa*) in phase rotations with annual crops is the only system that is being widely promoted and adopted for both economic and recharge control benefits (Poole *et al.*, 2002; Bailey and Dawson, 2004). While deep drainage is less under lucerne than under annual crops and pasture, some deep drainage still occurs (Ward *et al.* 2002). It should be noted that the soil water deficits developed under the trees at both sites were greater than under lucerne pastures in Western Australia (Latta *et al.*, 2001; Latta *et al.*, 2002; Ward *et al.*, 2002; Ward *et al.*, 2004). Indeed, Newton and Yunusa (2002) suggested that while the economics of PFT remain unclear, PFT may provide more environmental benefits than lucerne phase farming.

On those areas where groundwater is still deeper than 10 m, the question remains: can trees develop significant soil water deficits in the sedimentary soils of the valley floors? While tree rooting depths of up to 10 m have been observed at many sites in south-western Australia (Robinson *et al.*, 2002; Harper *et al.*, 2004), *Eucalyptus globulus* was only able to extract water down to 4 m in the marine sediments of the southern sandplain. It is not clear if this is simply a reflection of differences between the tree species in maximum rooting depth and ability to use soil water (Robinson *et al.*, 2002; White *et al.*, 2002), or a result of the dense subsoils at Howick providing a greater barrier to root growth than the *in situ* weathered subsoils at Tincurrin. While the dense subsoil at Howick limited the development of a large soil water deficit, it appeared to provide some benefit in that the hydraulic conductivity was less at Howick compared to at Tincurrin. Consequently, the rate of soil-water recharge was less at Howick despite Howick receiving significantly more rainfall than Tincurrin. The successful use of PFT would require careful site investigation prior to tree planting and a good understanding of how subsoil characteristics will influence both tree growth and subsequent recharge.

As soil water was only measured for 4.5 years after trees were removed there remain some uncertainties about recharge rates in the longer term. This is particularly so at the Howick site where soil water contents had begun to increase at 4 m depth (the limit of tree rooting depth at the site) by year four of the agricultural phase. Some of this uncertainty could be addressed by using process based models to estimate recharge beyond year five. It should be noted that further monitoring at these sites is no longer possible as trees were replanted on the sites in 2007 as requested by the landholders at the outset of the trial. While AgET was used to estimate soil water recharge, the designers of this model are explicit in stating that it is not intended to provide absolute estimates of deep drainage. Rather, it provides comparative estimates for various land use scenarios.

When AgET is used in this way it does raise some questions about the measured recharge at each site. Firstly it suggests that recharge should have been greater under pasture compared to crop, however this was not the case at Howick or the TP treatment at Tincurrin. At Howick, the explanation lies in pasture water-use. The relatively long growing season at Howick allowed pasture species to germinate and establish earlier in the growing season compared to crops, while at the end of the growing season the pasture became dominated by deep rooted biennial species such as flat weed (*Hypochoeris spp.*) which continued to transpire after crops had been harvested. This allowed the development and maintenance of drier soil over summer and early in the growing season and delayed the development

of perched water on the clay subsoil in 2003 and 2005. At Tincurrin, the explanation lies in the fact that runoff was observed from the TP treatment but not from the treatments AP, AC or TC. Pasture establishment in treatment TP was comparatively slow and areas of soil remained bare throughout the trial and became smooth inhibiting pasture establishment and allowing water to run off. In contrast, cultivation in the cropping plot maintained a rough soil surface which limited runoff.

The other issue the AgEt output highlights is the discrepancy between measured and estimated recharge at Howick. Measured recharge was less than estimated by AgEt, this discrepancy is increased if the surface runoff estimated by AgEt (but not observed in the field) is also considered. While there is no reason to reject the measured data, and indeed the measured values of recharge fall inside the range of estimated and measured drainage reported in the literature (Harper *et al.* 2000; Tennant and Hall, 2001; Ward *et al.*, 2006), the AgEt estimates do sound a warning note. Given the sedimentary nature of the soils at Howick, and particularly the presence of layers of sandier soils, there is the possibility that preferential recharge paths allowed percolating water to bypass the bulk soil matrix. Indeed, the fact that measured soil water recharge was 55 to 42 mm/yr while groundwater rise was just 55 mm/yr indicates that there must be lateral movement of groundwater at least.

Increasing the default value for hydraulic conductivity of the clay subsoil in the model to account for the cracking of the clay observed in the field achieved reasonable agreement between the AgEt estimate and measured recharge at Tincurrin. However the 90 mm of annual recharge is considerably greater than estimated values for similar soils and rainfall (Ward *et al.* 2006). Clearly cracking of the dense upper 1 m of the clay subsoil allowed increased water infiltration into the less dense underlying pallid zone clays and had a significant impact on recharge at Tincurrin. It is not clear for how long the cracks will influence drainage rates after removal of the trees, and it is possible that recharges rates will decline over time.

While waterlogging was eliminated during the tree phase at Howick and greatly reduced at Tincurrin, there was no evidence of reduced duration of waterlogging after the tree phase at either site. Rapid recharge of the A horizon at Howick, and the lack of measurable changes in hydraulic conductivity at the top of the B horizon after the tree phase may account for this.

Weed and disease control

Harper *et al.* (2000) suggested that one of the benefits SRWCs would provide to subsequent agricultural phases would be a reduction in both the number and herbicide resistance of crop weeds and a disease break for crops and pasture. This trial has been able to clearly demonstrate a reduction in weed biomass for at least four years after the tree phase. This reduced the number of herbicide applications in the first year after the tree phase compared to continuous agriculture. In subsequent years, agronomic advice was that herbicide use should be similar on both treatments despite reduced weed burdens after the tree phase. The principle reason for this was that if the comparatively low weed numbers after the tree phase were not controlled, the weeds would rapidly multiply and compromise the trial.

In economic terms, although greater weed densities were present in the continuous agriculture treatment, by year two the cost of herbicide application was similar in the continuous agriculture and post tree phase crops.

Despite reduced weed burdens after the tree phase it was not possible to demonstrate a reduction in herbicide resistance or soil borne disease four years after the tree phase at either site. This suggests that caution should be exercised in making claims about the disease and herbicide resistance benefits of PFT. However, it should be noted that the area occupied by trees was relatively small and surrounded by conventional agriculture which may have facilitated the movement of seed and disease from the agricultural area into the area occupied by the trees. In addition sheep may have been vectors for seed and disease dispersal at Tincurrin as they had free access to the tree area prior to the trial and grazed stubbles after tree removal. Cattle and sheep were largely excluded from the trees at Howick and were totally excluded during the trial area between 2002 and 2006.

Soil structure and fertility

Australian studies have shown improvements in soil structure and crop rooting depths following SRWCs (Yunusa et al., 2001; Yunusa et al., 2002; Devine et al., 2002), however this trial found no clear evidence of increased crop or pasture rooting depth at either site, and while sub-soil bulk density was less in the TC compared to the AC treatment at Tincurrin in 2005 it was similar in 2003. While saturated hydraulic conductivity of clay subsoil was increased at Tincurrin where cracks in the dry subsoil had developed, there was no decrease in unsaturated conductivity at either site. It is not clear whether crops and pastures will benefit from the development and closing of sub-soil cracks over time. Yunusa et al. suggested that it may take three or more years for larger tree roots to decay to leave macropores and so increase soil porosity.

Changes in soil nutrient content under tree phases have been shown to vary considerably from site to site (Grove et al., 2001; Mele et al., 2003; Sudmeyer et al., 2004). These differences can often be explained by inherent differences in soil properties, tree species or agricultural practices, particularly crop and pasture rotations and fertiliser applications. At Tincurrin, where the soil was relatively fertile, particularly in the top 0.2 m of the profile, the concentration of both macro and micro nutrients generally declined during the tree phase with no evidence of the trees utilising nutrients unavailable to annual crop and pasture roots. However, the soil at Howick was characterised by relatively infertile, highly leached A horizons with the concentration of many cations greatest in the clay subsoil. The decline in soil fertility was less evident under the trees at Howick, possibly because trees were accessing nutrients from the more fertile subsoil e.g. K and Mg (Figure 8). A similar trend was evident at the east Wickiepin site which also had very infertile coarse sandy topsoil overlying clay subsoil at 1 m. Notably at east Wickiepin, the nitrogen concentration under the trees was greater than under the continuous agricultural land highlighting the potential value of using a leguminous species during the tree phase.

The pH of the soil declined under the tree phase at all three sites indicating that PFT would not be an appropriate method for addressing soil acidification. Soil organic carbon levels were largely unchanged at Tincurrin, but decreased in the top 0.1 m of the soil profile when trees were removed at Howick, presumably due to the high level of soil disturbance entailed in removal of the stumps and mounds. This disturbance is also evidenced in the increase in bulk density of the top 0.1 m of the soil due to disturbance bringing gravels to the soil surface. Again this sounds a warning note against harvest methods which entail excessive soil disturbance for example if tree stumps were to be harvested along with above-ground biomass. Across the south coast, many *E. globulus* plantations have been established with mounding, and it could be expected that where this land is returned to agriculture and it is necessary to remove stumps or mounds, there will be a decline in soil organic carbon in the topsoil.

It should be noted that although changes in nutrient concentrations during the tree phase were less at Howick compared to Tincurrin, these changes had a more negative impact on crop growth at Howick because soil nutrients were more limiting to crop growth at Howick (see below). The general decline in nutrient concentrations under the tree phase meant that additional fertilisers had to be applied to crops and pastures. This is not surprising given fertiliser was only applied twice during the tree phase at Howick and not at all at Tincurrin. Appropriate fertiliser applications during the tree phase would maximise tree growth and eliminate the need for additional fertiliser applications going into the crop phase.

Soil biology

Inconsistent changes in active microbial biomass and respiration were observed across treatments and time. They may be associated with differences in soil conditions within sites, including moisture and easily degradable organic matter present at each phase of the rotation. There was no consistent pattern in dynamics or amount of microbial biomass and respiration in the agricultural sites with or without a recent tree history. However, the time of sampling the soil could influence the amount of microbial

biomass measured (Wick *et al.* 2002). Differences in rotational history for the two scenarios (with or without a tree phase) could lead to differences in both microbial biomass and activity. Changes in these measurements were not correlated with changes in infectivity of mycorrhizal fungi (using a soil bioassay) or mite and collembolan abundance.

Although some patterns in relative abundance of mites and collembola were observed (e.g. at Howick in 2004), they were not consistent for the two sites. Other factors, including the dynamics of organic matter associated with the different rotational histories, may be important in determining mite and collembolan numbers at any point in time (Osler and Murphy, 2005). Observed differences in soil fauna between the two sites are likely to reflect site differences in soil physical and chemical properties as well as climatic and edaphic factors.

At the start of the experiment, mycorrhizal colonisation was higher under continuous agriculture compared to under trees. After a rotational sequence of barley, canola, wheat and oats (at Howick) and barley, field peas, wheat and field peas (at Tincurrin), there were less distinct differences between treatments. Differences in root length, differences in the ability of the different plants to form mycorrhizas, and fertiliser history (according to the plant grown in the rotation) could all influence the infectivity of mycorrhizal fungi (Abbott and Robson, 1991). Overall, there was a decline in the infectivity of mycorrhizal fungi present in the soil in association with cropping following tree removal, but this did not occur when pasture was grown. Generally, the differences in level of mycorrhizal colonisation were not very great, except that they were consistently low at both sites when cropping after tree removal. Pastures following tree removal were more effective in maintaining communities of mycorrhizal fungi at higher levels than were crops following tree removal. This distinction between crop and pasture was not consistently evident in the continuous agriculture treatments. The data demonstrate variation in levels of infectivity of mycorrhizal fungi with rotation. The changes could have long-term effects associated with degree of mycorrhizal dependency of crops and level of fertiliser used. Changes in the relative abundance of mycorrhizal fungi across the rotational stages could have an influence on soil aggregation associated with hyphae formed in soil. Greater soil aggregation, even aggregation with low levels of stability, could provide benefits for soil fertility through protection of organic matter. Thus, the contributions of mycorrhizal fungi may be through aspects of physical soil fertility as well as phosphorus use efficiency.

Agricultural and tree production and economics

Agricultural production provides a measure of the net effect of changes in soil fertility, soil water content and reduced weed burden that have been discussed above.

At Howick, crop production following the tree phase was lower compared with continuous agriculture in years one and three after the tree phase and similar in years two and four. There was very rapid recharge of the top 2 m of the soil profile in 2003 following the tree phase, and by the start of the growing season in 2003, plant available water in the top 1 m of the profile was similar for the PFT and continuous agriculture systems. Later in the 2003 growing season, waterlogging affected both systems similarly. Access to nutrients appeared to be the principal factor limiting crop growth after the tree phase in 2003, and 2005. In 2003, the concentration of most nutrients in the aboveground biomass of barley after the tree phase was lower compared with barley from continuous agriculture. In 2005, the concentration of N and P was lower in the stem and leaf tissues, and protein content was lower in the grain of the crop following a tree phase. In 2004 and 2006, when crop yields were similar in the PFT system compared to the continuous agriculture system, nutrient concentrations in crop stem and leaf tissue were generally similar or greater in the crop following the tree phase compared to crop in a continuous agriculture system.

While nutrition appears to have been critical in determining crop growth at Howick, nutrient concentrations in the top 1 m of the soil were generally statistically similar for the tree and agriculture phases in 2002 and treatments AC and TC subsequently. However, analysis of the top 0.1 m did show some critical differences; notably reduced soil organic carbon (and hence presumably soil nitrogen), K and pH. Topsoil pH < 4.5 for the first two years following the tree phase may have been critical in

limiting nutrient uptake by crops. The need to apply additional nutrients to crops and pasture after a SRWC has been reported by Devine *et al.* (2002).

In an effort to improve crop yields an additional 41.5, 22.5, 28.0 and 13.3 kg/ha of N, P, K and S respectively were applied to crops in the first three years following the tree phase. The application of additional K in year two appeared to be particularly beneficial in increasing K concentrations in crop tissue in 2004 and subsequent years. The application of lime to all of the pasture and crop treatments in 2004 went some way to increasing soil pH, and plant ability to access nutrients. While fertiliser is a significant cost in a cropping program it would appear that for a site with low fertility such as Howick, and where a SRWC has further reduced soil fertility, the responsiveness of crops to the application of additional nutrients justifies the additional expense.

Pasture growth two years after the tree phase exceeded growth in the continuous agriculture system at Howick, and remained greater until the end of the trial. The leguminous pasture appeared better able to cope with reduced soil fertility than crops. This may reflect the ability of subclover and medics to fix atmospheric nitrogen and also greater mycorrhizal colonisation in pasture compared to crops after the tree phase. Although biomass growth was greater and pasture quality was largely unchanged after the tree phase, the economic returns from pasture after the tree phase were the least of all four agricultural treatments, reflecting additional seeding and fertiliser costs and the relatively low returns from sheep enterprises compared to cropping.

After the tree phase at Tincurrin, plant available soil water was reduced throughout the first growing season and for much of the second growing season compared to continuous agriculture. This reduction in plant available soil water appeared to be critical in limiting crop and pasture growth in the first two years following the tree phase. In the third and fourth year after the tree phase, soil water content was similar in the continuous agriculture and tree phase systems. Tissue analysis at Tincurrin showed similar nutrient concentrations in the tissues of crops grown after the SRWC or in the continuous agriculture system from years 1-4 after the tree phase. Additional nutrients were only applied to the crop three years after the tree phase, and this was the only year in which crop yield after the tree phase was statistically greater than from continuous agriculture, suggesting there may have been some benefit to applying additional fertiliser to both treatments. Reduced crop growth due to less plant available water for the first two years after a SRWC has been reported by Mele and Yunusa (2001) and Devine *et al.* (2002).

Pasture growth was reduced for three years after the tree phase at Tincurrin compared to just one year at Howick. Again, this was probably due to reduced plant available water after the tree phase at Tincurrin. It may have been possible to improve pasture growth at Tincurrin by sowing more clover seed into the establishing pasture in year two as was done at Howick. This would have roughened the soil surface and may have provided a more rapid pasture cover so reducing run-off and evaporation losses. However given the Howick data, the extra cost entailed in this may not have been justified in terms of increased net financial returns.

Some idea of the longer term changes in crops and pasture productivity after the SRWC may be elucidated by the use of process-based modelling. Data from the two sites in the first four years after a tree phase suggests that economic returns would be greater from cropping than sheep grazing, and that the SRWC would have to be sufficiently profitable to allow for the application of nutrients during the tree phase and to offset the cost of reduced production following the return to agriculture. In practice, the feasibility and optimal management of PFT systems will depend on the relative returns from the various phases and the rate of soil water replenishment (Mueller *et al.*, 1999).

Despite the differences in tree species and edaphic and climatic conditions between Tincurrin and Howick, tree biomass growth was similar. When trees were 10 years old, which was in 2002 at Howick and 2006 at Tincurrin, above ground standing biomass was 54.7 and 52.0 t/ha respectively. Interestingly, tree water use over that period appears to have been remarkably similar at the two sites. Rainfall and soil water depletion during the first ten years of tree growth was 3795 and 1636 mm

respectively (totalling 5431 mm) at Tincurrin and 5910 and 235 mm (totalling 6245 mm) at Howick. If the trees at Tincurrin had extracted water from below the 10 m measurement depth then the apparent difference in tree water use between the sites would be less. The fact that tree growth was correlated with rainfall at Howick but not at Tincurrin suggests the trees at Tincurrin were continuing to access stored soil water below 10 m. The greater growth rate at Tincurrin in years 1-6 compared to years 6-10 suggests this was happening to a greater extent in the first six years after planting. Clearly the ability of trees to access stored soil water is critical to early tree growth at low rainfall sites and has a major impact on the environmental outcomes from PFT. There needs to be a better understanding of tree rooting depth, and soil water extraction patterns, for a range of Australian soil types and tree species if PFT is to be effectively commercialised.

Over the four years 2003-2006, biological productivity in terms of above ground biomass growth was generally greater for the cropping system than the trees. Total tree growth at Tincurrin and Howick was 15.5 and 13.8 t/ha respectively while total crop and weed growth was 16.6 and 25.3 t/ha at Tincurrin and Howick respectively. At Howick, pasture growth in the continuous agriculture treatment would have been about 19 t/ha over the same period (if the 1.6 t/ha left uncut by the mower is included each year). While tree growth over the four years was generally less than crop growth, it was more consistent and did not show the large fluctuations exhibited by crop growth such as when conditions were very wet at Howick in 2003 or dry at Tincurrin in 2006.

It should be noted that the above ground biomass growth of trees in the first six years after planting at Tincurrin was 37.6 t/ha, which is greater than could be expected from crops over the same period. Presumably this reflects the greater soil water available to the trees over that period. This has implications if the aim is to produce a biomass crop; it would appear that if trees in low rainfall areas have access to stored soil water then biomass growth will be greater from the trees than from annual crops and pastures. Other benefits of the trees would include only one planting and harvest operation compared to multiple operations for annual crops, more continuous soil cover and the removal of less nutrients in the tree biomass (the exceptions to this are K and Ca). Possible disadvantages of the tree biomass system compared to annual production systems would include greater establishment and harvesting costs, and issues of increased risk and cash flow associated with longer rotation times.

The issue of appropriate nutrient management during the tree phase is critical to the economics of the following agricultural phase. Further work is required to determine appropriate fertiliser and lime application rates and timing during tree phases to ensure that soil pH and fertility are maintained for subsequent crops and pasture. There is also scope for using alternate tree species, or returning some of the tree biomass to the site to maintain soil fertility. Nitrogen-fixing SRWCs such as the *A. saligna* at the east Wickpin site could be used to maintain or even improve soil nitrogen status. For the tree species in this study, leaf and twigs <8 mm in diameter made up less than 30% of biomass but contributed over 50% of the nutrients removed when trees were harvested. There would be merit in examining the practicalities and economics of retaining the nutrient rich fraction of the tree biomass after harvest. A similar recommendation was made by Grove et al. (2007) for repeated coppice harvesting systems using mallee. This would necessitate an understanding of how these nutrients would become available as the biomass decays in subsequent years.

The economic analysis in this study was limited to the four years after removal of the tree crop and did not consider the tree component. Some indication of the economics of the tree phase can be gained from a recent economic study funded by JVAP (Abadi *et al.*, 2006). This study found that the AEV from a PFT system where the trees yielded 67 t/ha of biomass after four years was \$140 /ha compared to \$176 /ha from a wheat pasture rotation. This assumes the tree phase had no effect on subsequent agricultural yields. If agricultural yields were reduced by 30% in the first year after tree harvest, 10% in the second then reverted to normal in the third year the AEV from PFT fell to \$129 /ha. If tree biomass yield declined by 25%, AEV for PFT was \$122 /ha. Given that tree yields were 37.6 t/ha after six years at Tincurrin and 42.4 t/ha after ten years at Howick and agricultural yields were reduced for 1-3 years, it could be expected that the AEV for the PFT systems at these sites would be less than

those calculated by Abadi *et al.* (2006). Clearly the yield and or price of the tree biomass would need to increase substantially for PFT to break even with conventional agriculture.

The cost of not addressing salinity or other forms of land degradation has not been factored into either of these analyses but should be kept in mind. The difficulty is in correctly attributing the cost of doing nothing. Water tables were deep at the Tincurrin and Howick sites and given their position in the landscape it is possible that neither site would suffer from salinity. In other sites this may be more of an issue. How then does one return the true cost of doing nothing to address salinity to an individual farmer and likewise the benefits of more sustainable (though less profitable in terms of product) farming systems?

Key findings and recommendations

1. Future use of process-based models. Short rotation woody crops can develop soil water deficits sufficient to allow 1-2 decades of conventional agriculture before groundwater recharge is fully resumed. However, as soil water was only measured for 4.5 years after the tree phase there remain some uncertainties about recharge rates in the longer term. Process based models should be used to extrapolate soil-water and groundwater recharge beyond 4 years after the tree phase.

2. Careful site investigation including subsoil characteristics prior to planting. The physical characteristics of clay subsoils influence tree rooting depth, this has profound implications for the depth and magnitude of soil water depletion by trees; consequent tree growth rates and soil-water recharge rates following the SRWC. The successful use of PFT will require careful site investigation prior to tree planting and a good understanding of how subsoil characteristics influence both tree growth and subsequent recharge.

3. Larger treatment plots to examine weed biomass, herbicide resistance and soil borne disease. There were statistically significant reductions in weed biomass for at least four years after the tree phase. However, the cost of herbicide application was largely similar in the continuous agriculture and post tree phase crops (due to the use of herbicides as a preventative measure even with reduced weed levels). There was no reduction in herbicide resistance or soil borne disease four years after the tree phase compared to continuous agriculture. However, it may be that larger treatment plots are needed to fully test this aspect of PFT.

4. Minimise soil disturbance during SRWC harvest. There was no clear evidence of improved soil physical properties in terms of increased plant root depth, decreased soil bulk density or increased hydraulic conductivity. Where removal of mounds and tree roots was undertaken it entailed considerable soil disturbance which reduced soil organic carbon concentrations and resulted in an increase in the bulk density of the topsoil. Harvest systems for SRWCs should be designed to minimise soil disturbance.

5. Appropriate fertiliser and lime application. There was some evidence of tree accessing nutrients from subsoil clays that were unavailable to agricultural crops and pasture. However nutrient concentration in the soil and soil pH generally decreased during the tree phase in the absence of regular fertiliser applications. Successful use of PFT will require the development of appropriate fertiliser and lime application regimes to maintain soil fertility for the subsequent agricultural phase.

6. Investigate nitrogen-fixing tree species. The use of nitrogen fixing SRWCs should be further investigated as they may provide savings in fertiliser input costs.

7. Returning biomass nutrient to the site. The feasibility and economics of returning the nutrient rich leaf and twig fraction of the tree phase to the soil should be further investigated.

8. Estimate longer term trends in agricultural production following the tree phase using appropriate models. Longer term trials, ideally including a control site with continuous agriculture no trees should be conducted. This will clarify whether the results observed within this study apply over a longer term. In this study, there was no clear increase in soil biological activity after the SRWC compared to continuous agriculture. After a SRWC, mycorrhizal colonisation was greater in pasture compared to crop. Crop and pasture productivity were reduced for two to three years after the tree phase due to reduced soil fertility and plant available soil water. Even with greater input costs, net returns from cropping exceeded those from grazing sheep following a tree phase.

9. Commercialisation will require development of new markets for biomass energy crops and/or ecosystem services payments. Based on other economic analysis, the returns from tree biomass would not have been great enough at either site for PFT to break even with conventional agriculture.

The successful commercialisation of PFT will require the development of SRWCs that are profitable enough to maintain soil fertility through the application of fertiliser and lime, and to compensate for possibly reduced agricultural productivity in the years immediately following the tree phase. This may mean developing means of valuing environmental services and providing monetary returns to farmers. Any ecosystem service scheme should both consider the recharge reduction benefits (e.g. compare with the long term economic and environmental effects of no action about salinity, and consider the locations at which PFT would have the most significant benefits in terms of soil type and salinity risk) and offset the loss to agricultural income during the tree phase and in the first 1-3 years of agriculture after PFT.

10. Consider site choice for PFT (including for ecosystem service markets or payments). Where trees grown as a short rotation crop have access to stored soil water they can produce more above-ground biomass than annual crops and pasture reliant solely on rainfall.

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