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Phase Farming With Trees:

Field validation of the tree phase

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Foreword

Salinity is a major issue for the sustainability of rural Australia. Any treatment will have to be applied across broad swathes of land. Although the reforestation of farmland can contribute to the reversal of salinity, this is not commercially feasible for much of Australia's low rainfall farmland due to the displacement of, or competition with crops, coupled with uncertain markets for forestry products. An alternative approach, phase farming with trees, is based on the premise that a short rotation (3-5 years) of trees will provide a substantial buffer of dry soil to mitigate leakage from subsequent agricultural pursuits and thus reduce recharge, the major factor contributing to the spread of secondary salinity.

This report describes a field study that tested the phase farming with trees concept in a dryland cropping environment in Western Australia. The results are promising and show that the basic premise of the system is correct, with significant soil water depletion beneath 3 year rotations of trees planted at high densities. There are however significant barriers to adoption, such as a lack of cheap establishment and harvesting techniques and a profitable market for the products. Two options for overcoming these barriers are raised. First, use of species that are amenable to lower cost direct seeding with existing farm equipment, are not harvested and provide environmental benefits including soil water depletion, grazing benefits and soil fertility improvement. Importantly, the challenge that confronts almost all dryland salinity treatments is that there is no direct reward to the landholder for reducing recharge and developing a sustainable farming system. The second option is that the tree phase is grown as potential feedstock for bioenergy production or manufactured wood products.

The phase farming system, when used with trees, can produce considerable amounts of biomass. Markets for biomass await the development of renewable energy targets and market scale and in the case of liquid biofuels, the development of enabling technologies that allow the industrial-scale conversion of woody biomass to liquids. The ultimate development of these renewable energy markets will thus provide a means of tackling increasing carbon emissions rates and the capital to deploy sustainable farming systems across southern Australia.

The results of this research provide technical demonstration that it is possible to rapidly control recharge across dryland agricultural regions. Adoption of the results is currently impeded by lack of markets, but they indicate the likely rates of biomass production that can be achieved in low rainfall environments, as a basis for future renewable energy policy and planning.

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This report is an addition to RIRDC's diverse range of over 1700 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

PFT	Phase farming with trees
NMM	Neutron moisture meter

Contents

Executive Summary

What the report is about
This report presents the results of a field trial using phase farming with trees, a system designed to grow tree crops in short rotations of 3-5 years to intentionally deplete soil water as a buffer for agriculture in areas prone to dryland salinity. The trial showed that on suitable soils, a short tree phase will deplete soil water sufficiently to allow a subsequent return to agriculture for a 11-20 year rotation. Biomass production from the tree phase was also measured, with a view to emerging biomass energy and biofuel production systems. Some of the technical and policy issues that need resolution before this farming system can be introduced in southern Australia are discussed.

Who is the report targeted at?
The report is targeted at industry, policy and researchers who are concerned with developing integrated systems to achieve sustainable farming, environmental services, and second generation feedstock supply for biomass energy or biofuel production, particularly in Western Australia.

Background
The salinisation of land and water resources is a major environmental problem in Australia, with up to 17 million hectares of farmland likely to be affected by 2050. Salinity threatens long term agricultural production and will also have profound effects on biodiversity conservation, water supplies, and rural infrastructure. This hydrologic imbalance has been caused by the replacement of deep-rooted natural vegetation with shallow-rooted agricultural plants, and reforestation is often advocated as a treatment. Current approaches with reforestation are limited in lower rainfall environments (e.g. <500 mm mean annual rainfall). Several studies suggest that it will be necessary to replant up to 80% of the landscape, the hydrologic impacts of trees in dryland-farming landscapes are often localized, and belts of trees can compete with crops for water and nutrients. Dispersal of trees across paddocks interferes with crop production.

Another approach is to insert short rotations (3-5 years) of trees into existing agricultural systems on a 20-25 year cycle. This is analogous to phase farming systems using perennial legumes such as lucerne (*Medicago sativa*), differing in terms of likely rates of soil water depletion. The premise of phase farming with trees is that the trees will rapidly de-water soil profiles to several metres depth and thus create a buffer of dry soil, with this being refilled during the subsequent agricultural phase. Moreover, it will be possible to distribute trees across the whole landscape, without displacing or competing with agricultural production.

This project field tests the recommendations of an earlier JVAP-funded scoping study. (RIRDC Publication 00/48)

Aims/Objectives
In this study we set out to determine
(a) Whether the fundamental premise of the system, that rapid de-watering of soil profiles to several metres depth, was valid.
(b) Whether the amount of soil water depletion, and thus the tree rotation length, could be manipulated by species selection or silvicultural management.
(c) The rates of biomass production from the system.

The field experimental site also formed the basis of an extension program and allowed practical difficulties such as stump removal to be resolved.

Methods used
The project tested phase farming with trees in a field experiment on land normally used for cereal production near Corrigin, WA (300 mm/year annual rainfall). Here we manipulated leaf area through variations in tree species (*Eucalyptus globulus, E. occidentalis, Acacia celastrifolia, Pinus radiata and Allocasuarina huegeliana*), planting density (500, 1000, 2000 and 4000 trees/ha) and fertility to

determine (a) if the premise of soil water depletion to depths of several metres in 3-4 years was justified, and (b) if it is feasible to accelerate the rate of water depletion by intensifying stocking rates and hence decrease the duration of the forestry phase. Tree survival, diameter and other growth attributes were measured to allometric relationships which indicate biomass and product options. Rates of biomass production from 3 year old trees were estimated. Destructive samples of above- and below-ground tree components were taken to determine harvest options. Soil water content was measured using neutron moisture meter tubes, and soil water deficits calculated.

Results/Key findings

The results from the phase farming with trees experiment are very promising with significant soil water depletion of 440 to 780 mm occurring beneath high density (4000 stems/ha) plantings of *E. occidentalis* occurring within 3 years of planting. Assuming a recharge rate of 40 mm/year under annual cropping, this could result in a rotation of 3 years trees, followed by 11 to 20 years of agriculture. Biomass production was dependent on high stocking densities and optimal slope position, with biomass yields of 15-22 t/ha/3 yr possible. When averaged across the landscape, yields were more modest and ranged from 12-14 t/ha/3 yr. Similarly, other species may have faster growth rates.

Implications for relevant stakeholders

The results are promising and show that the basic premise of the system is correct, with significant soil water depletion beneath 3 year rotations of trees planted at high densities. To maximize biomass production and water use, a balance is required between planting density and water availability and matching different species to different sites. Further improvements in water use and thus a decrease in the duration of the forestry component of the rotation are likely to be achieved by manipulating these elements. The report also highlights the importance of systematically measuring both moisture and biomass responses, when attempting to design new hydrologically balanced farming systems based on the introduction of new species.

The implementation of phase farming systems using trees relies on several unresolved issues such as cheap establishment and harvesting techniques, and a market for the products. With regard to cheap establishment, an alternative approach is to use species that are amenable to direct seeding, such as nitrogen-fixing *Acacia* species. This may have merit and offer a pathway to more rapid adoption. Unlike phase farming with trees this would involve using existing farm equipment, forgoing harvesting and providing value in terms of recharge control, grazing benefits and soil fertility improvement. *Acacia celastrifolia* produced a water deficit of 368 to 479 mm, with high density plantings, after 3 years, and could result in a rotation of 3 years *Acacia* and 9 to 12 years of agriculture. In common with all salinity treatments, there is currently a lack of a reward or environmental payment for restoring landscape hydrology.

The markets for biomass-based products, such as bioenergy, are currently speculative and require significant changes in renewable energy policy and investment. The biomass produced in this system could also provide a feedstock for liquid biofuel production. However, there are currently some technological barriers for industrial scale wood to liquid fuel conversion. Large future markets may develop when enabling technologies, such as the conversion of woody biomass to liquid fuels, are developed. When that occurs phase farming with trees offers considerable promise as a method of producing both food and fuel from the same land, while increasing agricultural sustainability.

Recommendations

- It is essential that the likely environmental benefits of phase farming with trees are valued in some form if the system is to be adopted as a routine component of sustainable farming systems.
- Further improvement is required to increase the reliability of direct seeding establishment methods before large scale application of the system.
- Further research would be appropriate to determine whether biomass yields can be increased using even higher planting densities of species such as *Eucalyptus occidentalis*.

Introduction

The replacement of native vegetation with agricultural systems has resulted in a hydrologic imbalance and expanding areas of dryland salinity across southern Australia. Current estimates predict over 17 million hectares will be affected by 2050 (National Land and Water Resources Audit 2001). In Western Australia alone the area of farmland currently affected by secondary salinity is estimated to be 1.8 million hectares, and it is predicted that a further 7 million hectares will become saline. Annual crops are shallow-rooted and only transpire water for part of the year. As a consequence, recharge under agricultural systems is one to two orders of magnitude greater than under native vegetation (Allison *et al.* 1990; Tennant and Hall 2001), resulting in rising watertables and the mobilisation of salt stored within the regolith (Peck and Hatton 2002).

Incorporation of deep-rooted perennial species into catchments dominated by annual crops and pastures forms part of the strategy for managing dryland salinity in southern Australia (Stirzaker *et al.* 2002) and such revegetation may also remediate other environmental problems such as erosion and loss of biodiversity through habitat removal. The proposition that reforestation can reverse the salinisation of agricultural catchments has been supported by studies of both large (Bari *et al.* 2004) and small (Clarke *et al.* 2002) catchments in Western Australia.

In low rainfall areas, however, permanently placed trees can often be uneconomic due to the displacement of existing, profitable cropping systems, reductions in crop yield due to competition for water and low value products or a lack of markets for the tree products. Additionally, some studies have suggested that trees only have a local effect on hydrology and therefore need to be planted over as much as 80% of the landscape to reduce salinity (George *et al.* 1999) thereby displacing the existing farming systems. Thus, the prospects for widespread reforestation across these regions appear poor.

A solution is needed that integrates the benefits of trees into dryland farming systems, whilst still allowing farming to occur over an area that is sufficiently large to be economic. Harper et al. (2000) proposed, in an earlier JVAP project, the insertion of short rotations (3-5 years) of high-water using tree species into dryland farming systems. This was termed phase farming with trees (PFT). Resultant benefits could include not only the cessation of recharge, by creation of dry soil buffer zones over the depth of the tree roots, but also improvements in soil structure, fertility and the control of herbicide resistant weeds in the subsequent cropping systems. The trees themselves would represent a feedstock of biomass for bioenergy production or extractives for other, undefined industries (Harper *et al.* 2000). The PFT system, based on short tree rotations followed by extended cropping periods, could thus eliminate the potential for crop yield reductions that occur in agroforestry systems with closely spaced permanent tree belts (Knight *et al.* 2002; Stirzaker *et al.* 2002).

Ultra-short rotation tree plantations have been used for biomass production in higher rainfall areas (Joslin and Schoenholtz 1997; Thornton *et al.* 1998), or the maintenance of soil fertility in developing countries (Sanchez 2002). In the latter case, the system termed ‘short term tree fallows’ uses nitrogen-fixing trees of the genera *Sesbania, Tephrosia, Crotalaria, Glyricidia,* and *Cajanus* intercropped with maize to produce a food output, fix nitrogen and produce firewood.

The use of fast-growing perennial tree species to deplete stored soil water in low rainfall areas is untested. PFT is broadly analogous to the inclusion of perennial pastures such as lucerne (*Medicago sativa*) in cropping rotations for increasing water-use and reducing recharge (Crawford and MacFarlane 1995; Ward *et al.* 2002). Although lucerne uses comparatively more water than annual crops and pastures as it is deeper rooting, and has an extended period of water uptake (Ward *et al.* 2001), it is intolerant of acidic, waterlogged or saline soils as well as intensive grazing (Humphries and Auricht 2001). These limitations restrict the use of lucerne to selected areas. Trees, and particularly native Australian species, are suited to a broader range of soil conditions and also have the potential to be deeper rooting than lucerne. For example, in Western Australia Dolling et al. (2005) report that lucerne was able to produce a drainage buffer to a depth of 1.5 m on a duplex soil over 3 years. The depth of extraction was deeper on sandy soils but these are not the target of the PFT system. Robinson et al. (2006) found evidence of water depletion to depths of up to 10 m beneath 7 year old mallee eucalypts on similar duplex soils.

In the earlier JVAP project (Harper *et al.* 2000) the PFT system was simulated using the WAVES model (Zhang and Dawes 1998) for a number of sites in both Western Australia (Merredin, mean rainfall 320 mm, potential evaporation 1800 mm) and the Murray Darling Basin (Walpeup, Victoria-340 mm, 1750 mm and Hillston, NSW-581 mm, 1750 mm). This modelling was based on the assumption that the rooting depth of *Eucalyptus globulus* was at least 10 m within three to fives years of establishment. Several scenarios were examined, and these suggested broad differences in the likely response to the PFT system:

1) 20 m deep sandy soils. Here PFT depleted soil water storage and stopped the recharge under agriculture (100 mm yr^{-1}) within 2-3 years of planting. The high recharge rates resumed 3 years into the next agricultural phase. PFT was deemed unsuitable for such soils with the best strategy being permanent blocks of trees.
2) Soils with 1 m of sand overlying 2 m of clay, with and without a fresh water table and with a saline water table. Here recharge rates returned to a maximum within 1-5 years of clearing the trees. It is likely that soil salinity will accumulate under the trees grown over a saline water-table, with this requiring leaching before another rotation is possible. Permanent plantations of salt tolerant perennials are recommended in these situations.
3) Soils with a clayey surface horizon. Here the rates of recharge were very low (1 mm yr^{-1}) under agriculture and trees may only be required at very long rotation intervals (~decades) or the sites may not require treatment at all
4) Soils with 1 m of sand overlying 9 m of clay. Here PFT depleted soil water storage and stopped recharge within two years of planting and leaf area index equilibrated with rainfall after five years. It was predicted that recharge would not commence under the subsequent agricultural systems for 15 years. These results suggest the possibility of a crop-tree rotation of five years of trees followed by 15-20 years of crops or pasture.

The sites where the technique appears to be most applicable therefore require soil profiles extending to several metres depth, without any root inhibiting layers such as hardpans or watertables. In Western Australia such profiles are likely to occur under the ubiquitous deeply weathered laterite soils (McArthur 1991). The extent of such profiles in eastern Australia is unclear. Much soil survey has proceeded on the basis of the examination of the surface horizons of soils and the nature of the deeper regolith is often undefined. There are some indications that layers of root impenetrable silcrete may occur in some of the deep weathered profiles in the north-eastern agricultural zone of Western Australia (Pracilio *et al.* 2006), however the regional extent of such materials is unclear.

Apart from the presence of deep soil profiles, another assumption of the PFT system is that tree roots can extend to several meters depth within three to five years. While there are many observations of tree roots at depth (Canadell *et al.* 1996; Stone and Kalisz 1991) these are invariably for older trees and the physical and chemical constraints to tree root growth and rate of soil exploration by roots are not well defined. As reported, Robinson et al. (2006) found evidence of root extension, as measured by soil water depletion, to depths of at least 10 m at several sites. Some of the clayey subsoils in that study had bulk densities of up to 2.0 g cm^{-3}.

In this study we set out to determine (a) whether the fundamental premise of the system is valid, i.e. rapid de-watering of soil profiles to several metres depth (b) whether the amount of soil water depletion and thus the tree rotation length, could be manipulated by species selection or silvicultural management and (c) the rates of biomass production from the system such that the profitability of potential products could be assessed. The field experimental site also formed the basis of an extension program, with visits by conference tours and small groups, and allowed practical difficulties such as stump removal to be resolved. The results were also presented at several national and international conferences, during the course of the study.

As the aim of the PFT system is to remove water as quickly as possible from the greatest possible soil volume, a number of techniques that would sensibly be avoided in normal low rainfall forestry were explored. These include high planting densities, the use of fertilisers to promote growth and the use of faster growing species from higher rainfall areas.

Five species were selected for the experiment on the basis of existing markets for products, potential markets (bioenergy, grazing value), rapid growth and future establishment techniques (e.g. direct seeding potential for some species). The species were:

1. *Eucalyptus globulus*: Existing markets for products, suitable as a bioenergy feedstock, fast growing, site requirements are for non-saline conditions.

2. *Eucalyptus occidentalis*: Fast growing, suitable as a bioenergy feedstock, natural habitat is adjacent to saline playas and it thus may have capacity to interact with saline groundwaters.

3. *Pinus radiata*: Extension of existing markets for products (e.g. MDF), suitable as a bioenergy feedstock, site requirements are for non-saline conditions.

4. *Allocasuarina huegeliana*: Fast growing, suitable as bioenergy feedstock, nitrogen fixation, direct seeding potential.

5. *Acacia celastrifolia*: Reputed as fast growing, possible grazing values, nitrogen fixation, direct seeding potential.

The temporal integration of trees into agriculture also raises a series of issues, and in particular the nature and size of potential markets for biomass and valuing the benefits of reducing recharge and producing a sustainable farming system. There are also a range of technical issues including the practicality of removing the tree stumps at the end of the tree rotation, most efficient harvesting systems and determining the optimum silvicultural regimes for different sites. These issues were not canvassed in this study.

Materials and Methods

Site details

Location

The study site, was located on Valema Farms near Corrigin, Western Australia, approximately 240 km east of Perth (Figure 1, 117°41’47.13”E; 32°23’24.67”S). This site was selected as having soils and landforms representative of the general region (McArthur 1991), which has a semi-arid Mediterranean climate, with a seasonal drought from November to April

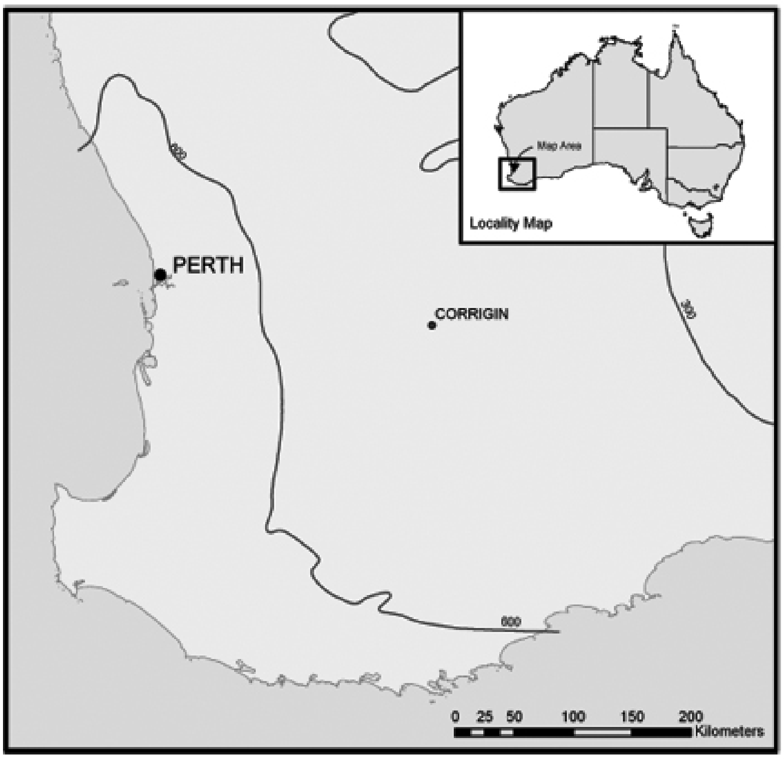


Figure 1 Location of the Corrigin experimental site, Western Australia, with the 300 mm and 600 mm rainfall isohyets.

Climate

The site has a mean annual rainfall (1889-2006) of 367 mm/yr and mean annual evaporation of 1803 mm/yr. The climatic conditions during the year prior to planting, and the subsequent six years of the experiment are given in
Table **1.** Climatic data were obtained from SILO (Jeffrey *et al.* 2001).

Table 1 Summary of the climate of the experimental site, Valema Farms, Corrigin, WA.

Year	Temperature		Rainfall	Pan Evaporation
	Max. (ºC)	Min. (ºC)	(mm)	(mm)
2000	23.6	9.8	404	1734
2001(planted)	23.4	9.3	403	1729
2002	24.2	9.8	288	1671
2003	23.8	10.3	222	1826
2004	23.9	10.0	366	1826
2005	23.4	9.6	303	1836
2006	24.0	9.7	373	1755

Farming systems

Conventional farming involves annual rotations of cereal (*Triticum aestivum, Hordeum vulgare*) or legume (*Lupinus angustifolius*) crops with improved annual legume (*Trifolium subterraneum*) and grass (*Lolium rigidum*) pastures, grown during the winter rainfall season. It is thus similar to the farming systems of broad areas of southern Australia (Squires and Tow 1991).

Experimental details

Trial design

An experiment was established in August 2001 (i.e. winter) to determine the potential of short rotation tree crops to remove excess soil water to depth and create a buffer of dry soil to capture the leakage that occurs below the shallow root zone of subsequent annual crops. The experiment was designed to determine whether water use and biomass production could be manipulated by species selection, planting density or fertilizer application.

The experiment comprised a randomized complete block design consisting of three replicate blocks, each with 25 treatments. The treatments comprised five species (*Eucalyptus globulus*, *Eucalyptus occidentalis*, *Pinus radiata*, *Allocasuarina huegeliana* and *Acacia celastrifolia*) planted at four densities (500, 1000, 2000 and 4000 stems/ha), as well as 500 stems/ha plus nitrogen fertilizer applied at 100 kg N /ha. There was no response to the fertilizer treatment, thus these plots are not considered further here.

The three blocks were situated in the same paddock, but arrayed in different landscape positions. Block 2 (upper-slope) was on a gravelly ridge, Block 1 (mid-slope) in a concavity with a sandy duplex profile and Block 3 (lower-slope) with a sandy duplex profile with a moderately saline water table at 2-3 m (Figure 2). Test drilling was undertaken at each of the sites prior to trial establishment, with each having deeply weathered profiles, typical of the region, to at least 10 m depth.

Tree establishment

Trees were planted by hand in early August 2001 in 50 x 50 m treatment plots. This followed ripping to a depth of 50 cm and treatment of the site with standard cropping herbicides. The site was not mounded.

Biomass

Biomass estimation

Measurement of stand biomass

Measurements were made of all treatments, on an annual basis, to obtain estimates of biomass. Predictor variables likely to be used in the allometric relationships were measured on all trees within 20 by 20 m permanent measurement plots. Plots of this size were considered unlikely to be affected by edge effects between contrasting treatments. Attributes measured included diameter at 10 cm, diameter at 130 cm and height. Survival was estimated as a proportion of the plants alive at the time of measurement compared to the number planted.

Allometric relationships were developed (below) and applied to the plot data to develop estimates of the biomass of different tree components and total biomass. Yield data were analysed by analysis of variance using XLSTAT software.

No estimates were made of the energy content of the materials produced in this study.

Figure 2 The Corrigin experimental site, looking south, photographed in May 2004, when the trees were 33 months old. The site has subdued relief with Block 2 in an upper slope position, Block 1 midslope and Block 3, lower slope.

Development of allometric relationships

Allometric equations relate the growth of one part of an organism to another part or the whole organism, and in the case of tree biomass are typically related to easily measured predictor variables, for example diameter, height or crown volume (Keith *et al.* 1999). Tree size, age or form will affect what parameters are measured as predictor variables. For example, although crown volume has been used in other studies, it could not be used to develop allometric equations here due to crown closure at 4000 stems/ha. The development of allometric relationships for 3 year old trees in this experiment is described in more detail in Sochacki *et al.* (2007).

Allometric relationships were developed at 3 years of age in August 2004 for the species suitable for biomass production, with the sample including a range of tree sizes and form representative of the stand. Ten trees were selected per treatment (500, 1000, 2000 and 4000 stems/ha) at each of the 3 landscape positions, with 110 in total from *E. globulus* and *E. occidentalis* and 120 from *P. radiata*. Further trees were sampled at 57 months of age in May 2006 to extend the allometric relationships to larger trees.

Predictor variables measured were tree height, crown volume and diameter over bark (DOB) at 10, 50 and 130 cm above ground level. *E. occidentalis* often had more than one stem at 130 cm and a diameter equivalent was calculated when more than one stem was measured (Avery and Burkhart 1983).

Destructive sampling

Above-ground biomass

Estimates of the yields of different tree components were made, to allow the assessment of different harvesting strategies. For example, biomass harvesting could include whole tops only, could comprise defoliated stems or comprise whole plants (tops and roots).

The procedures of Snowdon et al. (2002) were used for biomass sampling. Following the measurement of predictor variables, trees were felled and total fresh weight was measured using a system of bi-pod frame, pulleys and scales. Measurements were made to an accuracy of 0.1 kg. Four above-ground tree component categories were measured: (1) leaf and twig (<15 mm diameter); (2) stems and branches (>15 mm diameter); (3) dead branches and (4) ground litter. A nominal branch diameter of 15 mm was used to differentiate components (1) and (2) and attain more homogenous material and therefore more consistent moisture values.

To determine the dry biomass without having to dry and weigh the whole tree, sub-samples were taken to derive moisture ratios. Component sub-samples of 300-1000 g were collected and weighed at the time of sampling and placed in calico bags for oven drying at 70ºC to constant weight. Dry weights of sub-samples were used to calculate moisture ratios which were then applied to the tree component fresh weights.

Following drying, sub-samples were selected to determine leaf:twig ratios and bark:stem ratios. These were then applied to the total weights for each treatment and site. Ground litter (leaf litter) was collected from a circle with a diameter of 1 m from around the base of trees with the use of a lawn rake. Quantities of litter collected were small and were dried as a whole sample.

Below-ground biomass

Tree proximal roots were excavated with an excavator and collected by hand to a nominal root diameter limit of 5 mm, which corresponded to a maximum soil depth of approximately 0.35 m. Specht and West (2003) also excavated roots by hand to a minimum of 5 mm diameter with the aid of water. Excavation took place within two weeks of the above-ground sampling under dry soil conditions, which enabled any adhering soil to be removed by agitating the root system with the excavator bucket. Other detailed techniques such as bulk sieving and coring that are typically used to sample distal roots were not employed, due to budget constraints. Most of the root systems excavated were dried and weighed whole, using the procedure described above, with only very large roots weighed fresh and sub-sampled.

The methods used for above-ground biomass sampling were typical of procedures used in biomass measurement by other recent studies (Ritson and Sochacki 2003). However, sampling of below-ground biomass focused on the major root system and did not involve sampling the distal and fine root systems. The aim was to collect root material in a manner similar to harvesting methods that may be employed if short rotation tree crops were integrated into dryland farming systems for commercial biomass production. It is envisaged that the whole tree would be harvested for biomass fuel and the tree roots would be removed to allow for resumption of cropping (Harper *et al.* 2000). The procedure used here thus provides an estimate of the tree root biomass that would be recovered in an operational system.

Water

Soil water measurements

Neutron moisture meter

A neutron moisture meter was used to estimate changes in soil moisture content. Neutron moisture meter tubes were installed in selected treatment plots in January 2002 in all three landscape positions. This encompassed all planting densities of *E. globulus* and the 1000 and 4000 stem/ha treatments for the other species. The slurry method as described by Greacen (1981) was applied, using a bentonite-soil slurry. This method is advantageous for stony soils or where deep access tubes are to be installed.

Holes were drilled to 9 m and 50 mm polyvinyl chloride (PVC) tubes were capped and inserted into the slurry. PVC was chosen over other tube materials due to concerns of corrosion as a result of the saline soil profiles. The installation of a 50 mm PVC tube resulted in a clearance of less than 4 mm inside the access tube and thus reducing error due to eccentric positioning of the probe.

The first measurements using a neutron moisture meter were made in March 2002, with measurements subsequently made at bi-monthly intervals. Soil water contents to 8 m were also measured in a blank plot (i.e. with volunteer pasture) in each replicate and a tube in the adjacent paddock that is still being cropped.

Estimation of soil water content

The neutron moisture meter presented results in terms of counts/second. These were converted to gravimetric soil moisture values (g/g) using a calibration equation provided by Dr Phil Ward (CSIRO Plant Industry). These were converted to volumetric values (mm^3/mm^3) using an assumed bulk density of 1.7 g/cm^3, a value obtained from the regional study of Robinson et al. (2006).

Soil water deficits were calculated from these data by assuming the measurements in June 2002 (i.e. at 1 year after establishment) represented a baseline, and subtracting the volumetric soil moisture contents for each subsequent measurement. Values were summed over the first 8 m of the neutron moisture tube.

Results

Soil Water

Variation in soil moisture deficit with landscape position, species, planting density and age

The most important component of the phase farming with trees is the amount of water depletion, as measured by the soil water deficit at the end of each summer (March/April) prior to the winter rains Changes in soil water deficit (mm) from 1 to 5 years are plotted in Figure 3 for each slope position, species and planting density, with each of these factors contributing to differences in response.

Over all plots and years, the best soil water depletion was achieved by the 4000 stems/ha treatment of *E. occidentalis* in an upper slope position at 3 years, with this reaching -777 mm. Across all plots there was clearly a smaller amount of water depletion with 1000 stems/ha compared to 4000 stems/ha, with these having mean respective values across all treatments of -248 vs -351 mm. Thus, in this section overall soil water depletion is described for each species and slope position (Table 2), for each year, for the 4000 stems/ha treatment only. The 4000 stems/ha *A. huegeliana* mid-slope plot was not planted, in error, and thus no data are available.

Table 2 The progressive change in early autumn soil water deficits (mm) for the 4000 stem/ha treatments for each species and slope position. The moisture deficit is summed to 8 m deep.

Species	Age	Soil water deficit (mm)			
		Slope position			
		Lower	Mid	Upper	Mean
A. celastrifolia	2	-199	-299	-228	-242
	3	-401	-412	-474	-429
	4	-368	-440	-479	-429
	5	-410	-452	-500	-454
A. huegeliana	2	-142	N/A	-166	-154
	3	-261	N/A	-329	-295
	4	-251	N/A	-407	-329
	5	-298	N/A	-293	-296
E. globulus	2	-199	-190	-269	-220
	3	-257	-346	-495	-366
	4	-256	-449	-577	-427
	5	-226	Plot death	Plot death	-226
E. occidentalis	2	-360	-371	-487	-406
	3	-443	-485	-777	-568
	4	-506	Plot death	Plot death	-506
	5	-483			-483
P. radiata	2	-149	-137	-205	-164
	3	-203	-301	-440	-315
	4	-259	-293	-464	-338
	5	-244	Plot death	-530	-387
Mean		-296	-348	-419	-354

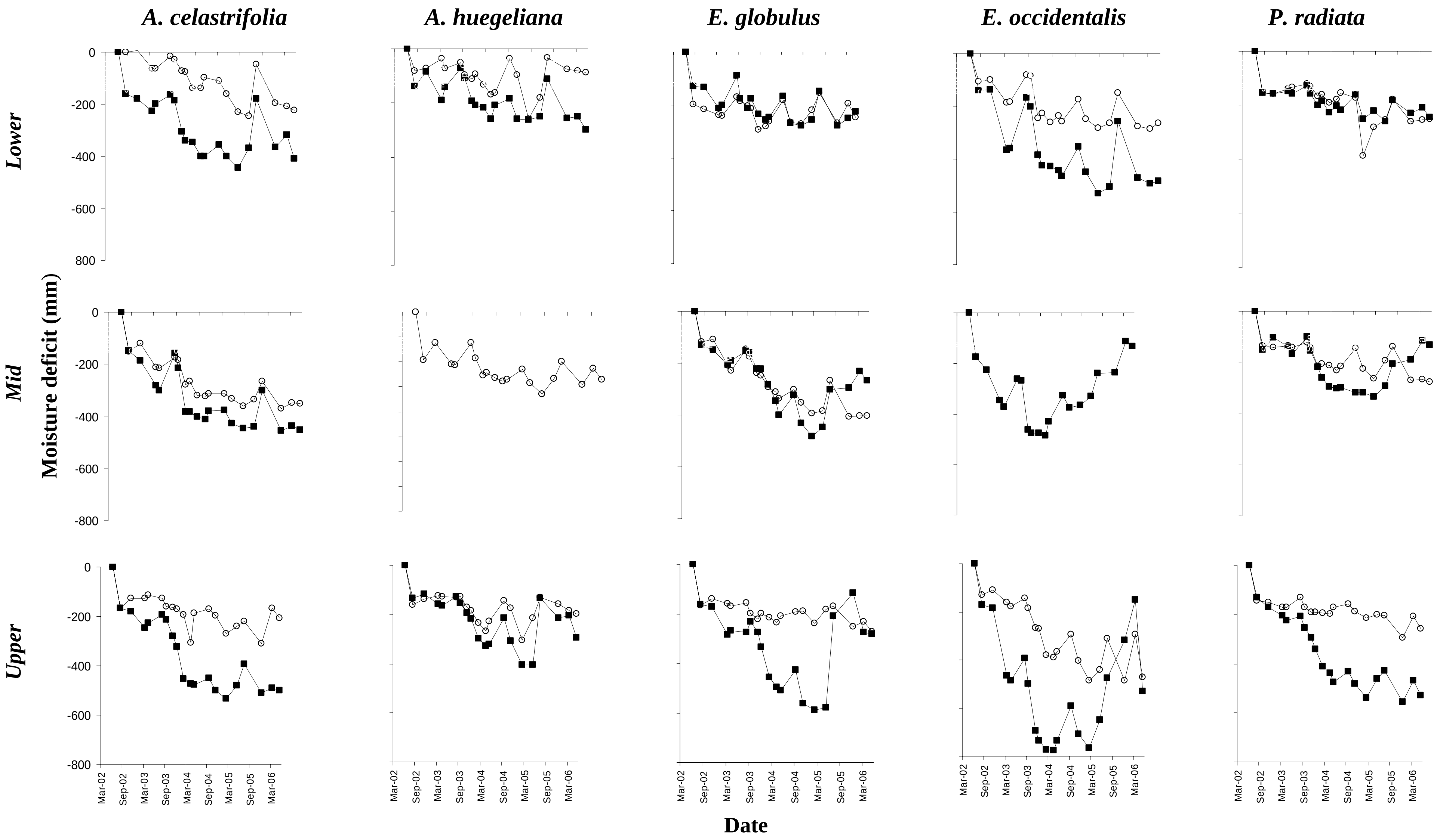


Figure 3 Change in total soil water deficit (mm) over time for each slope position, species and planting density. Open circles 1000 stems/ha, closed squares 4000 stems/ha. The moisture deficit is summed to 8 m deep.

Mean soil water deficit, across all the 4000 stems/ha plots were -237, -394, -406 and -369 mm respectively, at 2, 3, 4 and 5 years (Table 3). The reduction in year 5 partly reflects the complete death of trees in some of the more successful *E. occidentalis* and *E. globulus* plots, this occurring from age 3 onwards.

At age 3, when the water depletion was most pronounced, there were clear differences in soil water depletion with slope position (Table 3), with this being greatest in the upper slope positions, with respective values of -503, -386 and -313 mm, for the upper, mid and lower slope positions respectively, when averaged across all species. This is despite the opposite trend in growth with slope position – as will be seen later; the trees in the lower slope positions had total yields of up to twice those in upper slope positions.

Table 3 The progressive change in soil water deficits (mm) for the 4000 stem/ha treatments for each slope position, averaged across all species.

Age	Soil water deficit (mm)			
	Slope position			
	Lower	Mid	Upper	Mean
2	-210	-249	-271	-237
3	-313	-386	-503	-394
4	-328	-394	-481	-406
5	-332	-452	-441	-369

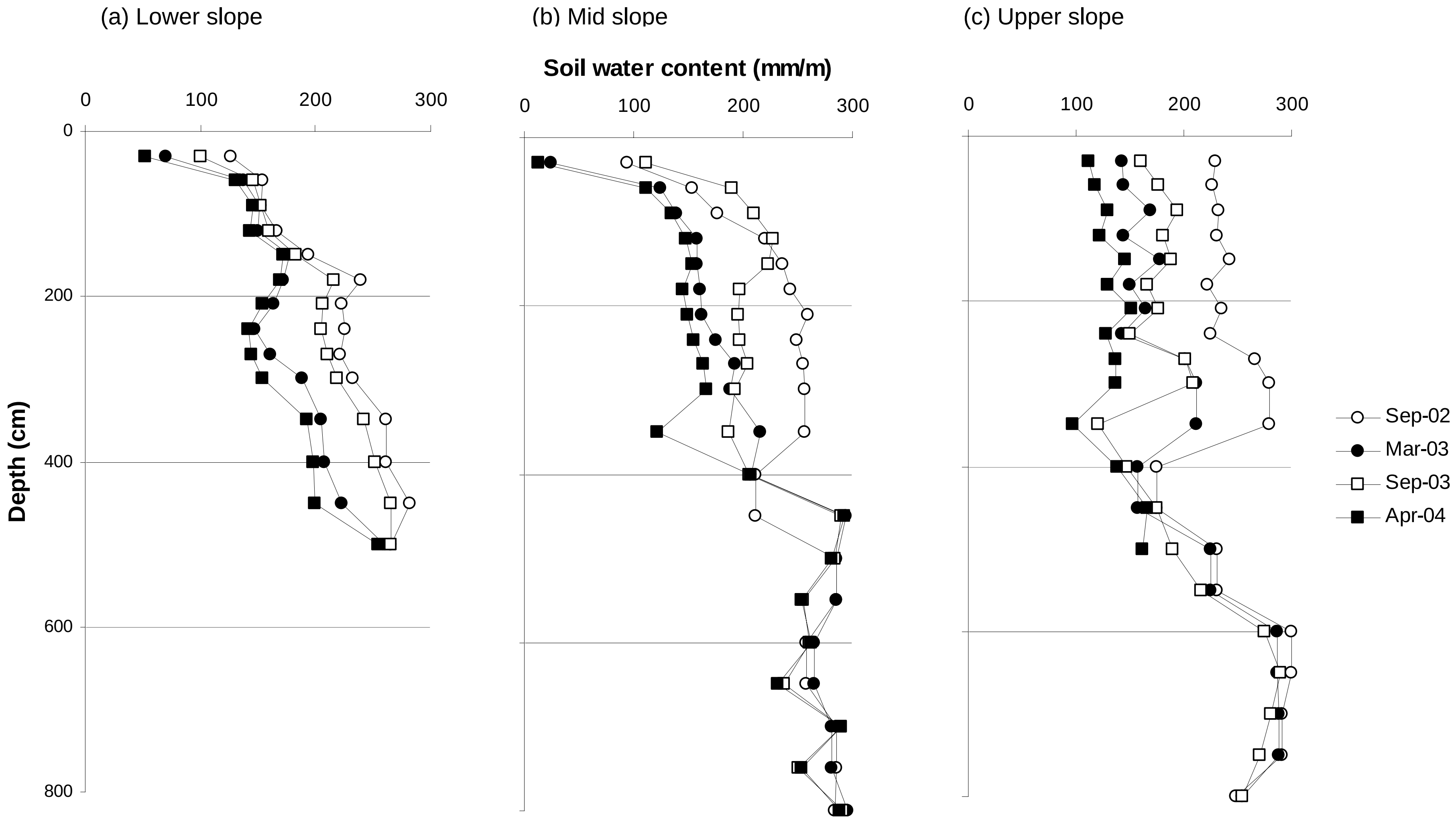
Two major features are apparent in the induction of the soil water deficit by different species (Table 2). Firstly, on average *E. occidentalis* consistently outperformed the other species in each year with mean values of -406, -568, -506 and -483 mm in each of years 2 to 5. There was some apparent refilling of the soil profile, following the death of the trees at age 3. This was followed by *E. globulus* and *A. celastrifolia* (-366 and -429 mm at 3 years) and then *A. huegeliana* and *P. radiata* (-295 and -315 mm at 3 years). The second feature was the improvement in water depletion by both *A. celastrifolia* and *P. radiata* over time, with water depletion at 5 years increasing to -454 mm and -387 mm, respectively.

Variation in soil moisture with depth

In the previous section, the soil moisture deficit provides an indication of the overall effect of the trees. This section discusses patterns of water depletion with depth and season, which provide an insight into the components of the change. For example, changes in water content between early spring (September) and late autumn (March-April) provide an indication of the depth of rooting, as generally summer rainfall does not occur in this region.

As the highest rates of water depletion occurred under the 4000 stems/ha treatment of *E. occidentalis* this species was examined in more detail (Figure 4). Within 2 years of planting, there had been a reduction in soil water content at depths of up to 4.0– 5.5 m in the different landscape positions (Figure 4). Whereas this change persisted in the upper slope position (Figure 4c), it did not (Figure 4a) in lower landscape positions, indicating rapid refilling of the soil profile.

A similar pattern in water depletion with landscape position also occurred with the 4000 stems/ha treatment of *A. celastrifolia* (Figure 5), with refilling in the lower landscape position each winter. For this species, the depth of rooting was around 4 m, however in contrast to *E. occidentalis* this took three years to achieve, this being consistent with the slower rate of overall water depletion for this species.



(a) Lower slope

(b) Mid slope

(c) Upper slope

Figure 4 **Change in soil moisture content (mm/m) with depth for *E. occidentalis* planted at 4000 stems/ha for different slope positions.**

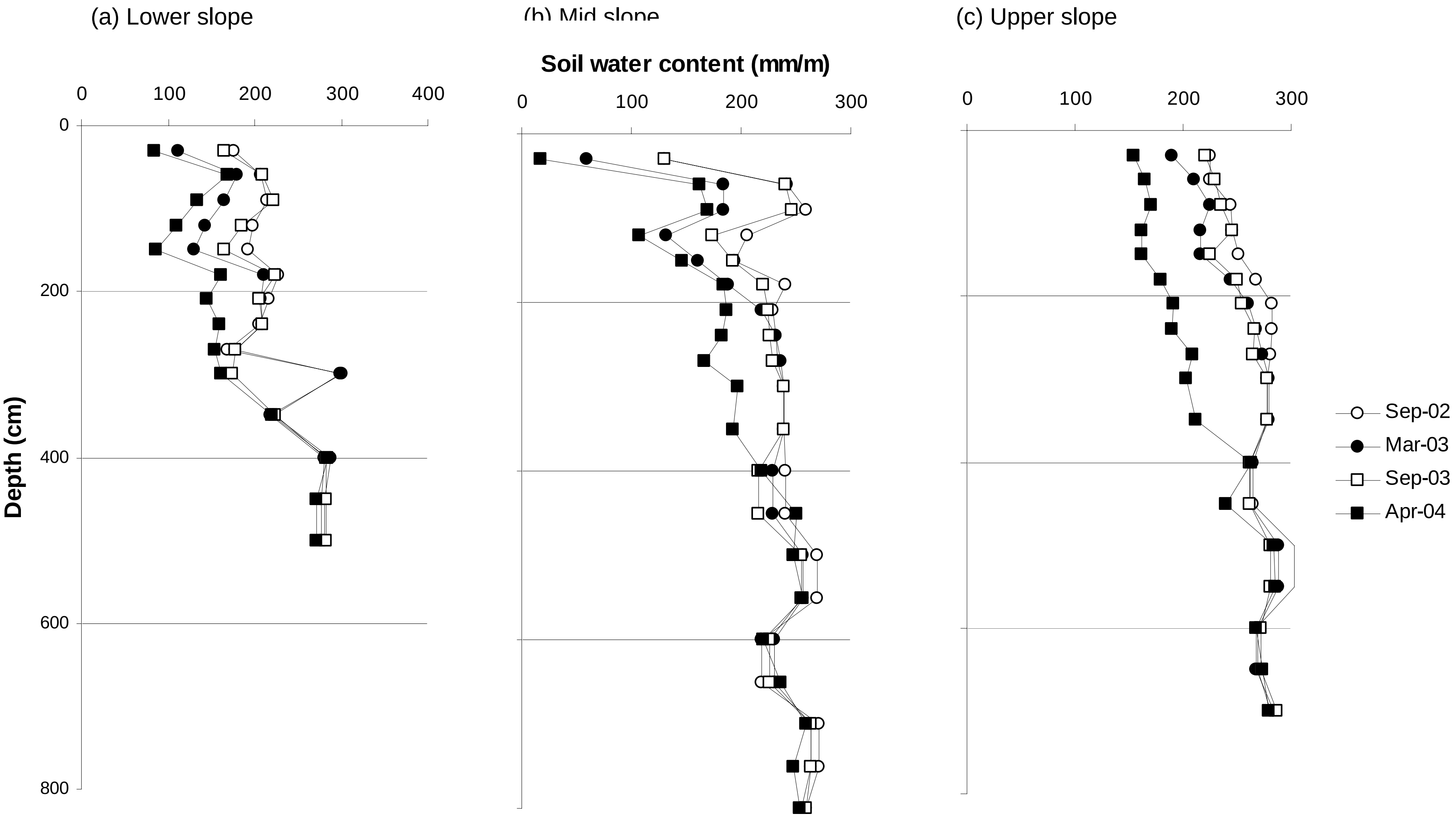


Figure 5 **Change in soil moisture content (mm/m) with depth for *A. celastrifolia* planted at 4000 stems/ha for different slope positions.**

Recharge after death of trees

There was complete death of trees on several plots by age 3 (Table 5), due to depletion of all available soil moisture. The change of water content over the subsequent two years indicates the rate of profile refilling (Figure 3). For several plots, such as the high density *E. occidentalis* (mid and upper slope positions), the soil water deficit rapidly diminishes and approaches that of the pre-treatment. This change exceeds annual rainfall, and suggests that (a) additional water is entering the soil profile, either via preferred pathways and overland flow from upslope or seepage from local groundwater systems, or (b) that the neutron access tubes in these plots are faulty. These neutron tubes are currently being assessed for reliability and gravimetric soil moisture samples are being taken to ascertain if there has been localised leakage around the access tubes.

Biomass

Tree growth

Because the trees had the greatest leaf area, and hence transpiration at age 3, estimates of tree growth were made for that age (Table 5). The largest trees occurred in the 500 stem/ha treatments with ranges in tree mass for the three species of 0.2 to 32.1 kg/tree for *E. globulus*, 0.3 to 31.1 kg/tree for *E. occidentalis* and 0.8 to 10.7 kg/tree for *P. radiata* (Table 4). The growth of the lower and upper slope 4000 stems/ha *E. occidentalis* plots at 34 months of age is shown in Figure 6.

Figure 6 High density (4000 stems/ha) *E. occidentalis* plots, at 34 months of age in June 2004 in lower (left) and upper (right) landscape positions. Respective biomass yields (tops and shoots) are 22 and 9 t/ha. All trees had died in the upper landscape position.

Table 4 Ranges in tree height, stem diameter at breast height (1.3 m) and total above and below ground tree biomass for the 3 year old trees used to develop the allometric equations at Corrigin.

Species	n	Tree height (m)	Stem diameter at 1.3m (cm)	Total tree biomass (kg)
E. globulus	110	0.9 - 5.8	0.9 - 9.7	0.2 – 32.1
E. occidentalis	110	1.2 - 4.9	0.8 - 9.3	0.3 – 31.1
P. radiata	120	1.2 - 3.7	1.0 - 7.4	0.82 – 10.7

n =number of sample trees

Tree survival

The surviving tree densities at the end of 1 and 3 years, as a proportion of the nominal planting density, are presented in Table 5. Although the experiment was planted at a series of set planting densities (500 to 4000 stems/ha), weed competition and insect attack, dry conditions when planting seedlings resulted in variable survival. For all treatments, apart from the 2000 and 4000 stems/ha *E. occidentalis* treatment and the 4000 stems/ha *E. globulus* treatment, all trees that had survived to 1 year were also alive at 3 years.

Variation in biomass yield, with tree species, slope position and density at age 3

Estimates of biomass yield were calculated for each treatment by applying the allometric relationships to individual tree data from within the permanent sampling plots. This procedure took into account the variable final stocking in the plots. Mean total biomass yields ranged from 0.5 to 16.6 t/ha/3 yr for *E. globulus*, 4.0 to 22.2 t/ha/3 yr for *E. occidentalis* and 1.6 to 15.4 t/ha/3 yr for *P. radiata*.

For each species there was a general increase in yield with planting density, and slope position with these increases being highly significant (*P*<0.001). The highest biomass yields for *E. globulus* and *E. occidentalis* were from 4000 stems/ha treatments located on the lower-slope site (Table 6). For a density of around 2000 stems/ha at age one, *E. globulus* yields were 8.5, 10.6 and 11.0 t/ha/3 yr for upper, mid and lower slope sites, respectively (Table 6). For *P. radiata*, the highest yields were observed at 4000 stems/ha in the upper-slope site. Mean yields of the three species, in the high planting density plots, were not significantly different and ranged from 12-14 t/ha/3 yr.

Table 5 Survival of trees between 1 and 5 years (%) as a proportion of the initial planting density for each species, treatment and site. Data for plots where there were significant drought deaths are presented in bold.

Species	Slope position	Tree survival (%)							
		1000 stems/ha				4000 stems/ha			
		1 yr	3 yr	4 yr	5 yr	1 yr	3 yr	4 yr	5 yr
A. celastrifolia	upper-slope	70	65			62	62		
	mid-slope	98	98			89	81		
	lower-slope	50	50			85	85		
A. huegeliana	upper-slope	60	60			53	53		
	mid-slope	100	100			100	100		
	lower-slope	95	95			68	68		
E. globulus	upper-slope	50	**25**	**23**	**23**	44	35	**19**	**19**
	mid-slope	88	88	88	88	89	62	**1**	**1**
	lower-slope	98	93	38	38	100	82	74	74
E. occidentalis	upper-slope	85	85	85	85	79	**5**	**5**	**5**
	mid-slope					99	**2**	**2**	**2**
	lower-slope	93	93	93	93	99	97	97	97
P. radiata	upper-slope	53	53	53	53	98	97	90	90
	mid-slope	100	100	100	100	96	96	**29**	**28**
	lower-slope	83	83	83	83	85	85	85	85

Variation in partitioning between tree components for different species, planting densities and slope position

The proportion of stem-wood varied from 17% for *E. occidentalis* to 21 and 23% for *E. globulus* and *P. radiata* respectively. The proportion of leaves varied from around 23% for the two eucalypt species to 30% for *P. radiata*. The proportion of roots was similar for both *E. globulus* and *P. radiata*, with mean values of 23 and 24% respectively, whereas the values for *E. occidentalis* were much higher at 33%. Expressed as root:shoot (R:S) ratios, these represent values of 0.31 and 0.51.

Table 6 Estimates of total biomass produced (t/ha/3 yr) at 3 years, with actual stocking (stems/ha) at 1 year in brackets, for each species, treatment and site.

Species	Slope position	Total biomass (t/ha/3 yr)							
		500 stems/ha		1000 stems/ha		2000 stems/ha		4000 stems/ha	
E. globulus	upper-slope	0.5	(150)	1.7	(500)	4.0	(1020)	8.1	(1840)
	mid-slope	5.8	(475)	11.3	(880)	10.0	(2000)	8.4	(3560)
	lower-slope	8.3	(475)	9.1	(980)	10.4	(1920)	15.8	(4000)
E. occidentalis	upper-slope	3.9	(400)	5.5	(850)	5.5	(1460)	8.6	(3160)
	mid-slope	5.5	(475)			8.1	(1960)	9.0	(3960)
	lower-slope	10.5	(500)	13.5	(930)	11.7	(1920)	21.5	(3960)
P. radiata	upper-slope	1.5	(500)	1.6	(530)	5.4	(1960)	15.1	(3920)
	mid-slope	2.1	(500)	3.0	(1000)	12.8	(1980)	14.6	(3840)
	lower-slope	2.4	(425)	11.1	(830)	14.7	(1880)	5.0	(3400)

Discussion

Managing soil water in dryland farming systems with tree phases

The results from this study support the basic premise of the phase farming with trees system. That is, short rotations of trees can rapidly deplete soil water over the depth of rooting that can be used as a buffer against leakage from subsequent agricultural crops. Moreover, this deficit can be substantial, with *E. occidentalis* planted at 4000 stems/ha, having a soil water deficit ranging between 443 to 777 mm at 3 years of age.

The marked variation in soil water depletion between different species and with planting density suggests that the amount of soil water depletion could be further increased by manipulating these factors. Thus, it may be possible to further increase the soil water deficit with higher planting densities or by selection of other species. With the wide genetic diversity within the *Eucalyptus* genera alone, there is obviously potential for exploration of the water depletion potential of different species in different environments. Although rotations longer than 3 years resulted in more water depletion for species such as *P. radiata* and *A. huegeliana*, the water deficit for these species still did not approach that of *E. occidentalis* at 3 years

There were also differences in tree response to landscape position across the site, both in terms of biomass production and soil water depletion. Soil water was depleted more effectively in the upper landscape positions, despite only half the biomass production of sites in lower landscape positions. This is most likely due to the redistribution of water across the landscape, particularly following peak rainfall events. The trees in the lower landscape positions thus produce a smaller soil water deficit due to a greater supply of water. The extra accession of water into these lower landscape positions suggests that trees or other woody perennials should be maintained in some of these areas on a permanent basis.

These results highlight the importance of systematically measuring both moisture and biomass responses, when attempting to design new hydrologically balanced farming systems based on the introduction of new species.

The water deficit produced by *A. celastrifolia* was 368 to 479 mm after 3 years (Table 2), with this clearly less than that achieved by *E. occidentalis*. *A. celastrifolia* should not however be discounted as an option for inclusion in phase farming systems, as adoption will depend on a number of factors including the cost of establishment, the costs of harvest and the market for products. An *Acacia* species was included in the experiment as it was a species that was amenable to direct seeding using existing farm equipment.

The results suggest that the phase farming concept can proceed in two possible directions, either:

a) based on trees, such as *E. occidentalis*, with the rapid development of a substantial soil water deficit and the production of biomass as a feedstock for bioenergy, or

b) based on a grazing system using an *Acacia* spp or other perennial leguminous plants (Harper et al. 2000, p. 12) in a manner analogous to the short term tree fallows advocated in Africa (Sanchez 2002) and in Western Australia (Bartle *et al.* 2002).

The key elements of these two systems are summarized in Table 7. These are considered in more detail below.

Establishment

Although the high density *E. occidentalis* treatment is the most favourable in terms of soil water depletion, using seedlings would cost approximately $1000/ha for the seedlings alone. The costs of planting and site preparation also need to be factored in. This is clearly untenable, on land valued at $400-500/ha, because a cheaper option for those concerned about losing land to salinity would be to purchase more land.

The cost of establishment could be dramatically reduced by direct seeding using existing farm equipment such as air-seeders; this would obviously require large supplies of seed. Although direct seeding has often been used for revegetation, survival rates are often relatively low with reported ranges for *Acacias* and *Eucalypts* of 10-40% and 2-20%, respectively. Further improvement is required to increase the reliability of this establishment method before large scale application.

Table 7 Comparison of the major attributes of phase farming systems based on *Acacia* and *Eucalyptus* spp.

Activity	*Acacia*	*Eucalyptus*
Silviculture		
Establishment	Direct seeding using existing farm equipment	Hand or machine planting of nursery raised seedlings. Development of new planting systems required.
Harvesting	None. Plantings heavily grazed or otherwise defoliated.	Harvest systems still to be developed for small piece size material.
Removal of roots	Disc ploughing at the end of the rotation.	Harvest systems still to be developed
Benefits/markets		
Water depletion	400-470 mm	440-780 mm
(rotation length)*	3 + (10-12)	3 + (11-20)
Grazing value	Possible with some species however reduced foliage will reduce transpiration	Marginal
Soil fertility	Addition of N to soil from leguminous plants Cycling of nutrients from subsoil	Cycling of nutrients from subsoil
Bioenergy	Not harvested	12 to 22 t/ha/3 yr of biomass dependent on site. No market or infrastructure in place
Extractives/industrial feedstock	Not harvested	No current market or infrastructure

*assuming recharge under agricultural systems of 40 mm/year

Harvesting and root removal

At the end of the tree rotation large areas of high density tree plantation will need to be converted back to a state suitable for annual cropping, and low cost methods of removing or working around stumps left after harvest need to be developed. The tree harvesting options will depend on the product. Biomass harvesters that reduce either the whole plant or stems into chips on-site may be cheaper than standard tree harvesting techniques. Machinery currently under development for harvesting of oil mallee eucalypts would be suitable; however for biomass production it may also be possible to harvest the upper portions of the stumps.

Problems such as harvesting and stump removal could be overcome by adapting methods used in other agroforestry systems. Nonetheless, they require serious consideration if the system is to become a normal part of farm practice across large areas of land. This will not be insurmountable, with Figure 6 illustrating the amounts of biomass involved. Methods to harvest trees together with their root systems have not yet been developed but alternative methods involving blade ploughs and reel rakes were routinely used for clearing of mallee woodlands in the past. The harvesting methods employed may be affected by tree size and their respective root systems, with the piece size smaller for trees grown at higher densities.

The other option is to leave the stumps and crop around them. Four and five-year-old sycamore (*Plantus occidentalis*) biomass crops have been successfully harvested and converted to a no-till corn system in Tennessee (Devine *et al.* 2002). After harvest stumps were treated with glyphosate to prevent sprouting. No mechanical problems were encountered when planting no-till corn over stumps in the first season following the woody biomass crop, and there was substantial decay of stumps in the second season and third season. For the first two years following conversion from sycamore there was an increased nitrogen fertiliser requirement for optimal corn yields. A similar option for PFT may be to follow the tree crop rotation with one or two years of pasture, which would allow some rotting of the stump and other debris.

Root:shoot (R:S) ratios did not vary significantly between planting density and slope position but were significantly different between species, *E. occidentalis* had a higher proportion of root biomass (0.51) than *E. globulus* (0.31) or *P. radiata* (0.33). This has implications for harvesting systems, both in terms of recovery of material, and for the removal of stumps in preparation for a return to cropping. It is envisaged that the whole tree would be harvested for biomass fuel and the tree roots would be removed in a manner to allow for resumption of cropping (Harper *et al.* 2000).

The suitability of root material as a biomass fuel is uncertain, due to soil contamination as this reduces heat exchange efficiency and results in down-time for maintenance and cleaning of furnaces. If the tree roots are not utilized for biomass fuel then they will need to be removed prior to the resumption of cereal cropping. In this case species with high R:S ratios, such as *E. occidentalis*, may not be desirable as relative recoveries will be lower. Selection of other species may however result in less effective removal of water and thus longer rotation lengths.

An alternative *Acacia* based system, would be to forgo any harvest and biomass production and either graze or chemically defoliate the plants at the end of the tree rotation. Any residues could be incorporated into the soil using large disc ploughs. As the rate of water use is related to the leaf area, it may in fact be beneficial to use plants that are not palatable to grazing animals. In this situation the annual volunteer pastures would produce some fodder for livestock, while the main role of the perennial component of the pasture would be to transpire water and fix nitrogen.

Bioenergy and other products

Both planting density and the position of trees in the landscape had a strong influence on biomass yield. There was a consistent increase in biomass yield with increasing planting density, indicating the benefits of high stocking to rapidly occupy the sites. If it is assumed that the three landscape positions occur in similar proportions across the landscape, mean total biomass yields at the highest planting density were 11.8, 13.5 and 11.9 t/ha/3 yr, for *E. globulus*, *E. occidentalis* and *P. radiata*, respectively.

Trees planted in lower landscape positions had greater yields and this is likely to be the result of greater water availability, either through the accumulation of run-off from up-slope areas or access to groundwater. For the highest (4000 stems/ha) planting density *E. globulus* achieved a yield of 16.6 t/ha/3 yr in this setting and *E. occidentalis* 22.2 t/ha/3 yr. As in this environment groundwater is semi-saline, the accessibility of this water for tree growth will vary between species. *Eucalyptus globulus* is a species from high rainfall regions and did not perform well on the upper-slope site where soil water was less available, however the lower yield on these sites was partially due to poor post planting survival (Table 5). *E. occidentalis* is a species with some salt tolerance as it naturally grows adjacent to saline playas. In contrast, the largest yield of *P radiata* (15.4 t/ha/3 yr) was achieved in the upper landscape site from a planting density of 4000 stems/ha with yields at this density in the lower landscape being relatively small. An obvious question relates to whether yields can be further promoted using even higher planting densities.

Potential products for existing markets include short rotation pulp and wood fibre for reconstituted wood products such as paper and fibre board. Low productivity together with the large distances to product markets currently makes most potential products uneconomic. The most likely markets for the PFT material are (a) biomass for power generation, (b) biomass for liquid transport fuel production and (c) restoring catchment water balances and reducing the risk of salinity.

There has been increasing interest in development of sustainable and renewable energy sources (Schuck 2006), with a pilot biomass energy plant built at Narrogin. The future size of this market will depend on renewable energy policy and targets.

There is also a large, concerted international research and development program on deriving liquid biofuels from woody materials (US Department of Energy 2006). This is based on the recognition that the development of these second-generation technologies will allow biofuels to have a bigger role in the world energy economy than technologies based on fuels from grains. In contrast to grains where ethanol is readily produced by conventional fermentation from sugars and starches, ethanol and other biofuels can also be derived from other much cheaper cellulosic or woody materials. Feedstocks can include trees, woody crops and agricultural wastes such as bagasse and straw. There are two main approaches to producing biofuels from woody materials – either fermentation or gasification. These technologies await full development and commercialization.

Developments in liquid biofuel technologies will open major opportunities for biofuel production from woody crops in WA and provide new opportunities for regional communities. Liquid fuel production from woody systems will be complementary to existing food production, by making farming systems more sustainable, rather than by displacing food production. Furthermore, woody crops require much less energy input in production giving them a fourfold advantage over grain crops when expressed as a ratio of energy contained in the product to the energy consumed in production. (Wu H *et al.* 2005)

Although there has been much discussion about valuing environmental services and the introduction of salinity credits, these markets are yet to be developed. Nonetheless, it is essential that the likely environmental benefits of PFT are valued in some form if the system is to be adopted as a routine component of sustainable farming systems.

Conclusions

The results from the phase farming with trees experiment are promising with significant soil water depletion beneath high density plantings of *E. occidentalis* occurring within 3 years of planting. Assuming a recharge rate of 40 mm/year this could result in a cropping rotation of 3 years trees then 11-20 years of agriculture.

However, implementation of phase farming systems using trees will rely on several unresolved issues such as cheap establishment techniques, harvesting techniques and a market for the products. The markets for biomass-based products, such as bioenergy, are currently speculative and require significant changes in renewable energy policy and investment. The biomass produced in this system could also provide a feedstock for liquid biofuel production. However, there are currently some technological barriers for industrial scale wood to liquid fuel conversion. Large future markets may develop when enabling technologies, such as the conversion of woody biomass to liquid fuels, are developed. When that occurs phase farming with trees offers considerable promise as a method of producing both food and fuel from the same land, while increasing agricultural sustainability.

The lack of a market payment for salinity benefits is common to all salinity treatments; the markets for biomass-based products, such as bioenergy, are currently speculative. Both require significant changes in policy and investment. The alternative approach of using species that are amenable to direct seeding with existing farm equipment, are not harvested and provide value in terms of grazing benefits and soil fertility improvement may have merit.

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Appendix 1 – Extension

This concepts and results of this project have been extended, on an ongoing basis, through a variety of means.

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2. Harper, R.J., Robinson, N., Smettem, K.R.J., Sochacki, S. (2005). Phase farming with trees: the acceleration of farm forestry to combat dryland salinity (Abstract). *International Forestry Review*, **7** (3), 276-7.
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10. Harper, R.J., Robinson, N. and Smettem, K.R.J. (2004). Phase farming with trees for bioenergy production and salinity control. Bioenergy Australia Conference, 29 November – 1 December, Adelaide, South Australia.
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12. Harper, R.J., Robinson, N., Smettem, K.R.J., Sochacki, S. (2005). Phase farming with trees: the acceleration of farm forestry to combat dryland salinity. XXII International Union of Forest Research Organizations World Congress, "Forests in the Balance: Linking Tradition and Technology", Brisbane, Australia, August 8-13, 2005.

13. Harper, R.J., Smettem, K.R.J., McGrath, J.F and Bartle, J.R. Broad-scale restoration of landscape function with timber, carbon and bioenergy investment. pp. 132-135, In Stanturf, J. (Ed) Proceedings of the IUFRO Conference on Forest Landscape Restoration, Seoul, South Korea, 14-19 May 2007. Korea Forest Research Institute, Seoul.
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21. “Putting Trees in Their Place”, Presentation to Australian Institute of Agricultural Science and Technology Workshop “The Farming Landscape – what is important?”, Narrogin, Western Australia, August 8, 2001.
22. Phase farming with trees. Lecture to Natural Resource Management 400, The University of Western Australia, 27 August, 2001.
23. Phase farming with trees. Lecture to Natural Resource Management 400, The University of Western Australia, 25 March, 2002.
24. Australia’s salinity catastrophe: implications for greenhouse science. CRC for Greenhouse Accounting Annual Science Meeting, Tanunda, SA, 9 April, 2002.
25. Environmental responses of plantations in a water limited environment: implications for greenhouse sequestration. Presentation to Asia Pacific Network (APN) for Global Change Research “2nd Workshop on Vegetation Recovery in Degraded Land Areas,” Kobe Japan. November 27, 2002. Revegetation for Salinity Control. Field excursion, Australian Forestry Council, Research Working Group 3 (Land and Water), Wickepin-Narrogin. June 12, 2003.
27. Hydrological challenges in inserting trees into the medium rainfall (500-700 mm/yr) farming landscapes of southern Australia. Cooperative Research Centre for Sustainable Forest Landscapes, Hobart, Tasmania. 27 July, 2005.
28. (a) Site evaluation and land selection, (b) New technologies for plantation establishment, (c) Plantation design for production and salinity control. Lectures to Forest Products Commission Training Course on Soils and Hydrology. Collie, Western Australia, 23-25 August, 2005.
29. Extreme silviculture: the acceleration of farm forestry to combat salinity. Presentation to Primary Industries Ministerial Council, Forestry and Forest Products Committee, Research Working Group 5 (Silviculture),’ Busselton, Western Australia, 15 November, 2005.

30. Trees, carbon and salinity. Workshop, Cooperative Research Centre for Plant Based Management of Dryland Salinity. The University of Western Australia, 21 February, 2006.

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31. CRC for Plant Based Management of Dryland Salinity, African Research delegation. Australian Agency for International Development. October 29, 2003. www.uwa.edu.au/media/statements/2003/october/african_visitors_to_learn_from_australian_agriculture (30 attendees).
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