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Integrate, Segregate or Rotate Trees with Crops?

Measuring the trade-off between yield
and recharge control



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A report for the RIRDC/Land & Water
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Joint Venture Agroforestry Program



Australian Government
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Development Corporation

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Foreword

Trees are incorporated into farming systems to provide shelter and additional income, and to improve the management of natural resources, such as soil and water. In the dryland cropping areas of southern Australia at risk of dryland salinity, trees can improve water management by accessing water unused by crops, but often with the trade-off of reduced crop yield through competition. This makes the design of agroforestry systems for water management important, especially where there are few direct markets for tree products.

The development of guidelines for the design of farm forestry is a focus of the Joint Venture Agroforestry Program (JVAP). Four guidelines have been published so far:

- *Design Principles for Farm Forestry*;
- *Trees, Water and Salt: an Australian guide to using trees for healthy catchments and productive farms*;
- *Trees for Shelter: a guide to using windbreaks on Australian farms*; and
- *Trees and Biodiversity: a guide for Australian farm forestry*.

This project contributes to our understanding of the environmental factors that influence the trade-off between yield loss and water management. It builds on two of the guidelines: ‘*Trees, Water and Salt*’ and ‘*Trees for Shelter*’, and especially informs the design of medium to low rainfall agroforestry.

The choices faced by landholders when incorporating trees into cropping systems are to integrate them (such as in alley farming), segregate them (in plantations or block plantings), or rotate them. This research examined 21 sites in the Western Australian wheatbelt and the Murray-Darling Basin to help inform this choice.

This project was a collaboration between the Joint Venture Agroforestry Program (JVAP) and the Grains Research and Development Corporation (GRDC), with support from the Natural Heritage Trust and the National Dryland Salinity Program. JVAP is funded by three R&D Corporations - Rural Industries Research and Development Corporation (RIRDC), Land & Water Australia, and Forest and Wood Products Research and Development Corporation (FWPRDC), together with the Murray-Darling Basin Commission (MDBC) - and managed by RIRDC.

This report, an addition to RIRDC’s diverse range of over 1,200 research publications, forms part of our Agroforestry and Farm Forestry R&D program, which aims to integrate sustainable and productive agroforestry within Australian farming systems.

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Peter O’Brien

Managing Director

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Abbreviations

APSIM	Agricultural Production Simulation Model
CI	Complementarity Index (ratio of the No-Recharge-Zone and No-Yield-Zone, see below)
EM38	Instrument designed to measure near-surface variation in the Earth's electromagnetic field as a surrogate measure of soil salinity
H	Distance from the edge of a tree belt in units of tree heights (m/tree height (m))
LAI	Leaf Area Index
NYZ	No-Yield-Zone (lateral distance from the trees over which yield is effectively reduced to zero by competition)
NRZ	No-Recharge-Zone (lateral distance from the trees over which recharge below the crop is effectively reduced to zero)
TDR	Time domain reflectometry, a technique for measuring real-time variation in soil moisture content

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Executive Summary

A challenge for Australian cropping systems is to minimize the trade-off between production and water conservation through designs that take advantage of site and system characteristics to minimise competition and maximise the trees' hydrologic footprint.

Early interest in agroforestry in Australia was influenced by research in the Northern Hemisphere demonstrating that windbreaks could improve crop yield, profitability and environmental protection. Some Australian research in the 1980s also indicated improvements in animal productivity through the use of shelter belts. More recent detailed research into the below- and above-ground interactions between trees and crops in water limited environments in Africa showed unacceptably high levels of competition for water, which frequently outweighed benefits to crops through microclimate, soil conservation and soil fertility. The conditions of this research were more similar to those experienced in Australia's cropping zone than the original windbreak research in the Northern Hemisphere. A review of the literature on agroforestry in semi-arid environments generally indicates that trees improve yield in a minority of cases only, and that the norm is a trade-off between productivity and conservation. Recent Australian experience from the National Windbreak Program (1993-1998) indicated some increase in crop yield through altered microclimate and soil fertility, but the benefits were small due to high climatic variability.

Informed by this earlier research, this project aimed to apply a simple index to quantitatively express the trade-off between loss of crop yield and gains in water management resulting from the addition of trees to cropping systems. It further aimed to identify ways in which agroforestry designs could be manipulated to optimise benefits to the environment at lowest cost.

Over a two-year period, 32 tree-crop interfaces were examined in the cropping zones of Western Australia and New South Wales. Crop gross margin were increased and recharge reduced through the presence of trees at 4 of the 32 sites. At a further 9 sites, a better than 30% reduction in recharge was achieved with a gross margin loss of under \$120/ha. At the majority of sites (19), there was a less than 30% reduction in recharge at the cost of a gross margin loss of over \$100/ha.

It was found that seasonal conditions had a strong influence on the trade-off between water management and yield at any one site, with some sites being positive one year and negative the next. Beyond the influence of season, this research demonstrated that the following combination of factors (in order of significance) is most likely to minimise competition with crops and maximise recharge management:

- water gaining sites (where trees have access to perched water tables or run-on water);
- a Westerly through to South Easterly aspect (crops protected from winds from 145 through to 270 degrees of a compass);
- tree age (> 10 years); and
- lower rainfall (<400 mm).

In this study, tree height proved to be a poor predictor of crop yield, and tree basal area was a poor predictor of leaf area across a wide range of species. Further development of integrals that are simple to measure, and adequately characterise the tree crop system over space and time, are needed to refine guidelines for agroforestry design. As agroforestry systems are long-lived, and therefore relatively inflexible to changes in management, further modelling work is required to adequately measure the trade-off between profit and water management over a long run of seasons.

1. Introduction

1.1 Introduction to research on tree-crop interactions

Australian studies conducted in the 1980s and 1990s suggested there could be beneficial interactions between trees, crops and pasture, with the measured improvements in yield and quality being attributed to reduced wind damage and modified microclimate (Lynch and Donnelly 1980, Bicknell 1991, Burke 1991, Sun and Dickinson 1994). In Esperance, Western Australia, Bicknell (1991) measured a paddock-scale yield increase of 30% in lupins and 10% in oats in the lee of wide spaced *Pinus pinaster* shelterbelts. Burke (1991) found a 25% increase in wheat yield in the 1.5 to 9 tree-height zone at Rutherglen in Victoria, but no increase in overall paddock yield.

International research has also indicated that windbreaks as an agroforestry practice can improve profitability, crop diversification and environmental protection (Garrett and Buck 1997). In a major review of research in the northern hemisphere, tree belts were shown to benefit crops with average yield increases of between 5 to 25% depending on crop type and environmental conditions (Kort 1988, Brandle *et al.* 1992). The sites which most benefited from windbreak trees were the cold climate areas of North America and continental Europe which often experience snow. For the mid-latitude marine regions with warm summers and mild winters such as Poland, The Netherlands, Germany and Denmark, yield increases ranged from 9 to 11%, 7 to 19%, 15 to 22% and 11 to 24%, respectively (Wilusz 1958, van Rhee 1959, van Eimern *et al.* 1964, Steubing 1952, Soegaard 1954, Anderson 1943, summarised by Kort 1988). For the tropical and subtropical regions of Pakistan and Mediterranean Italy, yield increases were 25 and 18%, respectively (Kort 1988).

Australian experience from the National Windbreak Program (1993-1998) indicated some increase in crop yield through altered microclimate and soil fertility, but overall the benefits were small due to high variability in wind climate which meant that the crops were found to be sheltered for a small proportion of the growing season (Cleugh *et al.* 2002). In terms of water management, it was also suggested that wide spaced windbreak systems would have little influence on recharge given the small proportion of the arable area influenced by the trees (Hall *et al.* 2002).

Alley cropping is a close-spaced agroforestry system originally developed for soil fertility management in the tropics. It has much higher proportion of trees than most windbreak systems making it a more realistic template for farming systems designed to manage recharge. While early African experience with alley cropping in wet areas showed positive results (Kang *et al.* 1992), more detailed examination of alley cropping research in drier areas showed unacceptably high levels of competition (Ong and Leakey 1999). Ong and Leakey (1999) suggested that the yield trade-off experienced in closely integrated systems such as alley cropping in semi-arid environments is commonly due to below-ground competition for water, which frequently outweighs the benefits conferred on yield through microclimate, soil conservation and improvements in soil fertility through the mulching effect of tree litter. This raised the prospect that alley systems, with a sufficiently high tree density to influence sub-soil water management, would be less productive than sole cropping, and that adding trees for natural resource management in water limiting environments was likely to result in a trade-off with productivity.

A trade-off in farm production through the incorporation of trees is likely to occur in two ways, through competition and through displacing land from crop production. This trade-off could potentially be reduced where trees provide recharge control over a greater area than they reduce crop production. In such circumstances, less area would be required under trees to meet a recharge target. The crop response to competition with trees could potentially range from yield enhancement (due to microclimate and seasonal influences) to yield loss. Australian and international research therefore suggests the need to understand how we might manipulate the design of agroforestry systems to achieve natural resource management outcomes at minimal cost to short term productivity. This in turn

requires an understanding of the relative importance of environmental and genotype influences on crop production in agroforestry systems.

1.2 Competition and complementarity between trees and crops

Australian and international tree-crop experiments have characterised the effect of shelter in the form of a windbreak signature (Figure 1) consisting of three distinct zones: a zone of competition commonly extending from 0 to 3 tree heights (H), a sheltered zone with increased or unchanged yield which extends from around 3 to 15 H, and an open paddock or open field zone extending from about 20 H over which yield returns to levels experienced in the unsheltered state (Marshall 1967, Bird 1998, Nuberg *et al.* 2002). A significant yield increase in the sheltered zone is required to offset the yield loss in the competition zone and the yield lost through displacement by the tree belt.

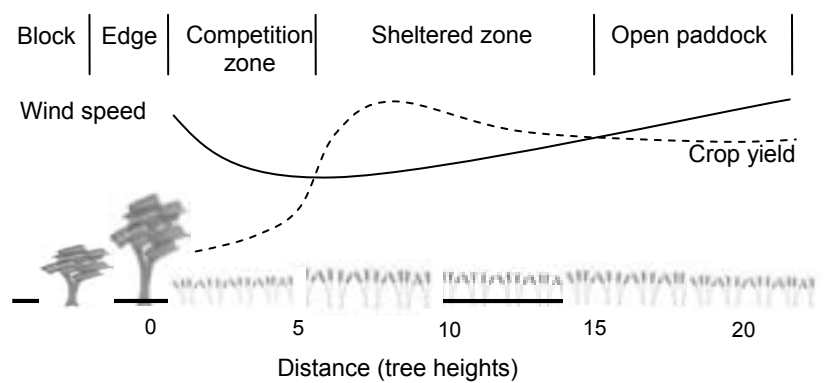


Figure 1. The typical windbreak signature, adapted from Huth *et al.* (2002).

The greatest opportunity for agroforestry exists where the trees capture resources which are under-utilised by crops without compromising crop yield (Sanchez 1995, Cannell *et al.* 1996, Ong and Leakey 1999). Whether trees interact with crops in an adverse, neutral or complementary way will depend on the age, size and density of the dominant species as well as the supply and accessibility of the limiting growth resource (Ong and Leakey 1999). If this concept of complementarity can be reliably demonstrated under Australian conditions then it has two potential benefits for the sustainability of our farming systems, 1) improved or more stable crop yield through a more favourable microclimate, and reduced wind damage to crops, and 2) more complete water use resulting in better management of erosion and dryland salinity.

For a tree-crop mixture to perform better than a single species, the complementarity between the species must outweigh the competition between them. Complementarity can be based on spatial differences between species (shallow *vs* deep root systems), temporal differences (annual *vs* perennial or summer active *vs* winter active) or functional differences (legume *vs* non-legume). Such complementarity can result in greater resource capture or more efficient resource capture. An Australian example of greater resource capture comes from the work of Connor *et al.* (1987) who showed that in a mixture of a deep-rooted perennial (pine) and shallow-rooted winter annuals (clover and ryegrass), pasture production was not affected by tree densities up to 277 stems/ha. An example of more efficient resource capture is the greater water use efficiency in the sheltered zone in the lee of the windbreak (Frota *et al.* 1987) and the greater water use efficiency of certain C₃ plants growing in light shade.

Detailed studies of the interactions between trees and crops in the semi-arid tropics presented a more complex picture than early agroforestry research in the humid tropics. In the semi-arid tropics, Ong

and Leakey (1999) found tree-crop interactions in agroforestry to be vastly different from tree-grass interactions in tropical savannahs. In natural savannah, the productivity of vegetation under trees increases as rainfall decreases, while in agroforestry the opposite occurs (Ong and Leakey 1999). The microclimatic benefits of lower temperature and lower evaporation losses appear to be greater with mature savannah trees given their higher ratio of branches and stems to foliage than the young, fast growing trees favoured in agroforestry systems. In contrast, any improvements in microclimate in alley cropping tended to be negated by increased tree transpiration and evaporation from the canopy.

The microclimate effect of reduced evaporative demand was also found to be the most important factor influencing crop yield in windbreaks in Esperance (Sudmeyer *et al.* 2002b). Reduced wind speed and potential evaporation early in the growing season often resulted in early vigour and earlier canopy development which has been linked to increased root depth and increased grain yield (Turner 1997 in Sudmeyer *et al.* 2002b). Lupins (*Lupinus angustifolius*) were shown to be generally more responsive to shelter than cereals (Bicknell 1991, Sudmeyer and Scott 2002b). However, crop yield response to shelter including lupins was seasonally variable even in similar rainfall years (Sudmeyer *et al.* 2002b). In drier years, the changes in microclimate appeared to be beneficial to the crops with a significant yield increase between 3 and 6 H compared to the open paddock yield (Sudmeyer and Scott 2002b, Nuberg *et al.* 2002). In wet years, Nuberg *et al.* (2002) found only faba beans (*Vicia faba*) had increased yield. Under very dry conditions, crop yield was reduced in the lee of shelterbelts due to reduced plant available water (Hall *et al.* 2002, Sudmeyer *et al.* 2002a).

The National Windbreak Program found that the paddock yield gains due to the effect of shelter on microclimate were smaller than expected based on international research, especially for cereals (Cleugh *et al.* 2002). Yield simulations conducted using the APSIM model and 20 years of historical climate data confirmed this result for longer periods and for other crop growing regions in Australia (Carberry *et al.* 2002). The modelling combined with economic analysis suggested an 8.6% yield advantage at 5 H for all tree species and crop types at the 17 sites. This did not compensate for competition, resulting in an average gross margin of -\$0.60/ha (Huth *et al.* 2002, Carberry *et al.* 2002a). Larger yield gains were simulated at locations where the latter part of the growing season was characterised by high atmospheric demand and a depleted soil water store. Part of the reason for the relatively small changes in yield measured at the field sites was the variable wind climate which meant that the crop was only sheltered for a small proportion of the growing season (Cleugh *et al.* 2002).

The assumption that spatial complementarity would be the norm in agroforestry systems, with trees using sub-soil water while crops relied on water from the topsoil, was soon questioned when substantial reductions in crop yield near trees was measured in semi-arid environments (Ong and Leakey 1999). Competition at the tree-crop interface in temperate alley cropping systems is primarily for soil water (Ong *et al.* 1991) with minor shading and nutrients effects (Miller and Pallardy 2001, Jose *et al.* 2000, Sudmeyer and Scott 2002b). As soil water becomes depleted, as in drought years, the competition between the trees and the crops for water causes a yield decline which may not be apparent in wet years (Ssekabembe *et al.* 1994, Jose *et al.* 2000).

The hydrological impact of the trees was significant at the Esperance site in the National Windbreak program with the trees reducing the soil water profile during the cropping season in the competition zone (0 to 2 H) and the sheltered zone (3 to 10 H) and fully depleting stored soil water in the competition zone over summer (Hall *et al.* 2002). The soil water storage was significantly lower between 3 and 10 H compared to the open paddock zone (>20 H), with the influence of the trees extending to 30 m, but only totally depleting the soil profile to 15 m (Hall *et al.* 2002).

The study of roots in agroforestry systems has shown considerable overlap between tree and crop roots, especially in the top 0.5 m of soil (Hauser 1993, Rao *et al.* 1993). Other studies of tree root architecture in maize agroforestry systems have indicated that their root distribution has been similar to that of maize (Jonsson *et al.* 1988, Gregory 1996). Where the tree roots are able to access groundwater, the effect of competition on the crop is reduced and spatial complementarity can be more evident (Ong and Leakey 1999). By accessing 80% of their water from below the crops, young *Grevillea robusta* trees in East Africa displayed strong spatial complementarity (Howard *et al.* 1995 in Ong *et al.* 1996).

Root pruning has been used to restrict tree roots from accessing near-surface soil water stores and enforce spatial complementarity. Ong *et al.* (2002), Miller and Pallardy (2001) and Singh *et al.* (1989) all measured higher soil water content in crops protected by root barriers compared to unprotected controls, indicating competition for surface soil water by trees. Root barriers also increased the yield of maize in alley cropping but not to the levels recorded in the centre of the alley (Ong *et al.* 2002).

The complex interactions between environmental conditions makes it difficult to predict their effect on the integrated yield (Sudmeyer *et al.* 2002b). In the low to medium rainfall areas of Australia the availability of water is likely to exert greater influence on crop productivity than variations in light or temperature due to the presence of the trees (Nuberg 1998, Bird 1998, Cleugh 1998, Cleugh *et al.* 1998) while variation in crop yield due to other sources such as soil depth and soil type can swamp the subtle effects of tree belts on yield (Nuberg and Mylius 2002). Ong and Leakey (1999) suggested that the trade-off experienced in closely integrated systems such as alley cropping in semi-arid environments is commonly due to below-ground competition for water which frequently outweighs the benefits of soil conservation and microclimate.

In water-limiting environments the successful design for alley cropping depends on managing the interface between the trees and crops to optimise the value of the trees and minimise competition (Lefroy and Stirzaker 1999). To do this requires an understanding of above- and below-ground impacts of adding trees to a cropping system in order to arrive at optimal designs. For instance, where trees and crops are known to have similar root distribution in the soil profile, and no temporal or functional complementarity exists, trees are best segregated from crops to reduce competition for water (Singh *et al.* 1989). Where no such information exists, the options are to match the trees with appropriate niches within the farm or landscape where competition will be minimal, such as on water-gaining sites (van Noordwijk and Ong 1996), or manage below-ground competition with root pruning (Ong *et al.* 2002). However these low risk strategies will not help us identify whether genuine complementarity exists within some tree-crop combinations or landscape positions. To find these requires simultaneous assessment of crop yield trade-off with the potential recharge benefit. A method to do this is described in the next section.

1.3 Conceptual framework for determining trade-offs

While traditional agroforestry research has focused on the complementarity of resource capture to the benefit of tree and crop, the emphasis has shifted to the interactions between crop yield and the broader environmental functions of farming systems (Ong *et al.* 2002). Using agroforestry as a method of managing dryland salinity in Australia will require an understanding of the interactions between the determinants of crop yield and the hydrological impacts of trees to provide economically and environmentally sustainable options (Lefroy and Stirzaker 1999, Lefroy *et al.* 2001, Stirzaker *et al.* 2002). However, from the literature review above, we can see that the interaction between trees and crops is a highly complex story, and it has taken researchers many years to gain an understanding of the impacts of windbreaks, and decades in the case of alley cropping. Hence the search for a simple framework described here.

The potential economic gains and losses associated with alley farming are shown in equation (1) and schematically in Figure 2 (Lefroy and Scott 1994). In the event that landholders are ever rewarded for managing recharge, the value of tree products would be expanded to include payment for the ecosystem service of water management.

$$Net\ Benefit = T + (Y_2 - 2Y_1) - D \quad (1)$$

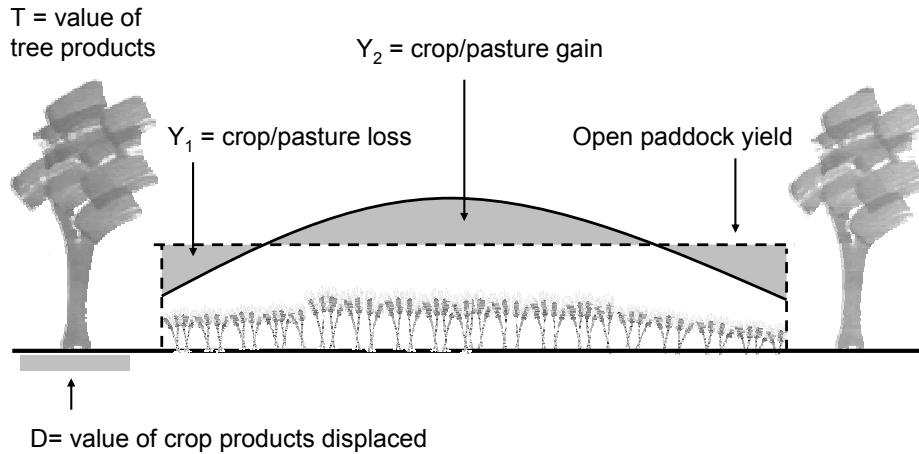


Figure 2. The potential gains and losses in alley farming including the value of the tree product value (T), the yield loss due to competition (Y₁) and yield gain due to shelter (Y₂) in relation to the open paddock yield and the value of the crop displaced by the trees (D). Redrawn from Lefroy and Scott (1994).

The theoretical conditions under which trees would be best integrated, segregated or rotated with crops was originally proposed by Stirzaker *et al.* (1999). Ideally trees in spaced belts would reduce recharge and salinity while allowing crops to be grown profitably in between. The complementarity that exists in a tree-crop system designed for water management has been quantified as the ratio of the No-Recharge-Zone (NRZ) and the No-Yield-Zone (NYZ) (Stirzaker *et al.* 2002, see Equation 2 and Figure 3). The ratio reflects the balance between the area of land protected by the trees against drainage (Ellis *et al.* 1999) and the area of land over which trees influence crop yield (Lefroy and Scott 1994). Where this ratio (referred to by Stirzaker *et al.* (2002) as the Complementarity Index) is greater than 1, there are more likely to be advantages in mixing trees and crops; where it is less than 1 the dual objectives of drainage control and productivity are more likely to be achieved through separate monocultures of trees and crops (Figure 3).

$$Complementarity\ Index = \frac{No-Recharge-Zone}{No-Yield-Zone} \quad (2)$$

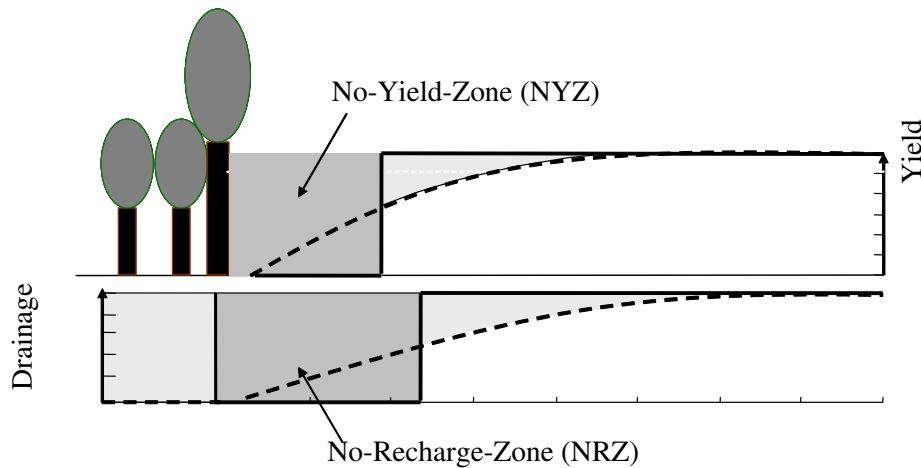


Figure 3. Yield and recharge are both zero at the base of the tree and increase with distance from the belt to levels characteristic of a sole crop. This is reduced to a step function to facilitate easy comparison of the magnitude of above- and below-ground effects. The NYZ is the lateral distance from the trees over which they effectively reduce yield to zero, while the NRZ is the distance from the trees over which they effectively reduce recharge to zero. Adapted from Stirzaker *et al.* (2002).

- The positive trade-off situation occurs where the impact of the trees on crop yield is less significant than the benefit from drainage reduction. Under this scenario alleys are the preferred option.
- The negative trade-off situation occurs when the yield loss is greater than any recharge reduction. Under this scenario, block plantations are the preferred option.
- The no trade-off situation occurs if a certain tree-crop combination produces a yield enhancement but may not always guarantee recharge control.

Empirical measurement of recharge in agroforestry systems has been attempted by Lefroy *et al.* (2001) and others (Hall *et al.* 2002 and White *et al.* 2002). These studies required a large amount of costly and time consuming data from neutron moisture meters, TDR, sapflow and isotope ratios to partition water use between trees and crops. Even with all these measurement, it is only possible to achieve an estimate of recharge. As such work cannot be repeated over a wide range of tree, crop, soil and climate combinations, a simplified approach is required. An integral which uses simple measurements to provide general approximations of recharge is a prerequisite of such an integral.

Ellis *et al.* (1999, 2001) proposed a method using leaf area as a surrogate measure of water use and hence drainage management by tree belts. It is based on the assumption that large edge trees must be accessing more water than the smaller inner trees in a belt, and this extra water must be coming from under the crops immediately adjacent to the tree belt. The equivalent NRZ is the lateral distance out from the belt over which the edge tree is accessing water and is calculated from the ratio of the leaf area index of the outer trees (LAI_{outer}) to the leaf area index of the inner trees (LAI_{inner}) multiplied by row width (Ellis *et al.* 1999, 2001). If there is no edge effect (as in a small alley) then the ratio of the leaf area index of the outer tree (LAI_{outer}) to the leaf area index of a native stand (LAI_{native}) is used. For Eucalypts, the native LAI can be estimated from rainfall and pan evaporation (Ellis *et al.* 1999).

The NRZ calculated from LAI in this way was shown to closely match No-Recharge-Zones measured in the medium rainfall zone of Australia (Ellis *et al.* 1999, 2001; Robinson *et al.* 2002). At six sites in the 300 to 700 mm rainfall zone, Ellis *et al.* (1999, 2001) found good agreement between the calculated NRZ compared to estimates based on measurement of soil water content. Robinson *et al.* (2002) also found good agreement between NRZ measured from soil water content of intact cores

drilled to a depth of 10 m and the NRZ calculated from the LAI of the tree belt and the LAI_{native} . In that study, the NRZ was calculated for five sites in Western Australia with 5-15 year old Mallee Eucalypts on soils ranging from deep sand to deep clay loam.

The NRZ appears to work best when applied to Eucalypts over six years old in equilibrium with rainfall. When the Ellis approach was applied to younger trees, the NRZ predicted from LAI_{native} was greater than that based on measurement of soil water content (Knight *et al.* 2002). This is most likely due to the fact that young trees accessing stored water in the profile have fast initial growth and high leaf area, which then reduces as the trees adapt to surviving on rainfall alone and venture out into the adjacent cropped zone in search of water.

While integrals are simpler to measure and combine individual processes occurring over time, care is required in their interpretation as the components of the integral measured may represent activity occurring over very different time periods. For example, the measurement of crop yield integrates the effect of tree water use from the competition zone over a season and includes the effects of variation in wind and rainfall over that season. By contrast, recharge predicted from soil water content (measured using neutron probe) is integrated over a few rainfall events; LAI integrates water use of the trees over one or two seasons; stem biomass is integrated over a number of years; EM38 measurement of electrical conductivity is over a longer period; and chloride profiles approximate drainage over decades.

The one thing the integrals have in common is they are easier to measure than drainage itself. There are so many complex interactions and variability in seasonal and edaphic conditions that normal measurement approaches will fail. This project therefore set out to use simple integrals of crop yield trade-off and recharge benefit to shed light on the nature of tree-crop interactions and identify ways in which agroforestry designs could be manipulated to optimise benefits to the environment at lowest cost.

2. Objectives

The aim of this study was to produce guidelines for agroforestry as a water management tool in dryland cropping areas based on measurement of the relative impacts of trees on yield and recharge for a range of tree-crop combinations across southern Australia.

While numerous studies in Australia and overseas have measured the impacts of trees on crop yield and a few studies have measured the impact of trees on recharge below adjacent crops, only a very few have measured both at the same site. The difficulty in assessing the hydrological impact of trees is the cost and time consuming nature of below-ground measurements. The work of Ellis *et al.* (1999, 2001) suggested a means of rapidly assessing the belowground influence of trees and it was this approach combined with crop yield measurements that formed the basis of this project.

The **objective** of this study was:

To measure the trade-off between recharge control and agricultural productivity for agroforestry species in the medium to low rainfall zone of Western Australia as a guide to the optimal design of agroforestry systems for water management.

The scope and objectives of the proposal were modified in June 2001 when the agencies jointly funding this project (RIRDC and LWA through JVAP, plus GRDC) requested that research into tree-crop interactions be extended to include cropping systems in the Murray-Darling Basin. Consequently the original objectives of measuring the trade-off between recharge control and agricultural productivity for five commercial or prospective agroforestry species in Western Australia was extended to involve twenty one sites (16 in WA and 5 in NSW) involving 10 tree species and five grain crops. The method was subsequently modified from the original proposed detailed assessment of the impact of tree-crop interactions on deep drainage at five sites in WA to a more rapid appraisal of fewer parameters to characterise the trade-off between water management and crop yield for different tree-crop combinations over a larger geographical area. The objective and outcomes however remained the same.

The primary **outcome** of this study was:

To calculate the recharge:yield ratio (or complementarity index) for agroforestry systems in the medium/low rainfall areas. This ratio can be used to indicate whether trees are best segregated (permanent plantations), rotated (short rotation forestry) or established in permanent spaced plantings (eg. alley cropping or parkland systems) in relation to crops to optimise water management and productivity.

The recharge:yield ratio, subsequently called the ratio of the No-Recharge-Zone and No-Yield-Zone (NRZ:NYZ) or the Complementarity Index (Stirzaker *et al.* 2002) is the ratio of the area over which trees reduce recharge to zero to the area over which they reduce yield to zero in a mixed agroforestry system. Where this ratio is >1 , trees influence drainage to a greater extent than they influence yield, and spaced or integrated systems are more advantageous than segregated or rotated systems; where it is <1 , the reverse is the case. The use of this ratio will reduce the amount of crop land inappropriately occupied by trees, increase tree productivity and lower the risk of inappropriate designs jeopardising the future adoption of agroforestry.

A secondary **outcome** was:

To identify the relative importance of system characteristics (tree species, tree age, crop type and management) and environmental factors (aspect, soil type, landscape position and hydrology) in determining the recharge:yield ratio and therefore the optimal agroforestry design.

3. Methodology

3.1 Site description

Twenty one sites in the 300 to 600 mm rainfall zone in the agricultural regions of Western Australia and New South Wales were selected to include different aspects, positions in landscape, soils, crop and tree species (Tables 1, 2 and 3). In 2001 the crop biomass, crop yield and tree belt characteristics were monitored at 16 sites in WA and five sites in NSW. Due to crop rotations and drought in 2002, only nine sites in WA and two sites in NSW were in crop and monitored (Figure 4).

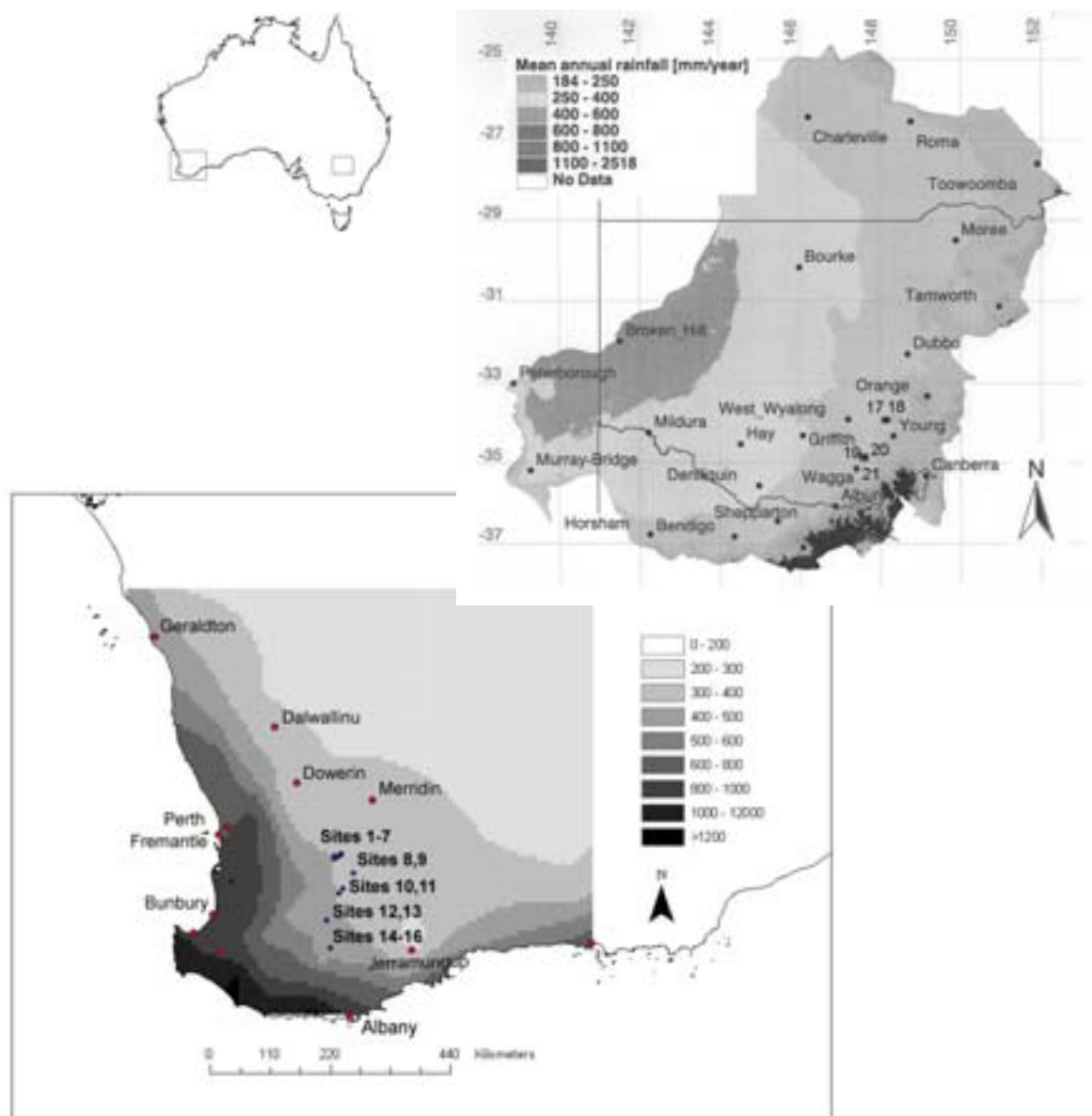


Figure 4. Site location and annual average rainfall for sites 1 to 16 in south western WA and sites 17 to 21 in the Murray-Darling Basin.

Crop yield was examined for the influence of environmental and genotypic factors by comparing yields with

- a) region (WA vs NSW)
- b) tree species (Eucalypt vs non-Eucalypt)
- c) crop type (cereal vs non-cereal)
- d) aspect (east to north west vs west to south east)
- e) soil type (sand and sandy clay vs duplex soils and heavy clays)
- f) landscape position (low and valley floor vs mid-slope to high)
- g) water gaining vs non-water gaining sites
- h) tree height (<8 m vs >8 m)
- i) tree age (>10 years vs <10 years)
- j) rainfall (>400 mm vs <400 mm)

The sites covered a range of landscape positions from valley floor, low-slope mid-slope and high positions in the landscape. The aspect (the direction from which the crop is protected by the trees) ranged across all points of the compass providing protection from a range of wind directions and different shading potential (Table 1). The aspect was grouped as a) east to north west (E, NE, N, NW) and b) west to south east (W, SW, S, SE)) as the direction of the wind in June to August was mainly from the west and south west at south western WA and eastern NSW (from the 3 pm wind speed roses, Bureau of Meteorology).

The soils ranged from sandy soils such as deep sand (Site 5) and sand with increasing to sandy loam (Sites 6 and 7), light duplex soil such as sand over a sandy clay loam (Sites 8, 9, 14, 15 and 16), medium duplex such as a sand over clay (Sites 1, 12, 13) and loamy sand over silty loam (Sites 2, 3) and heavy duplex such as a sandy loam over clay (Sites 10, 11, 4) (Table 2).

Five crop types were represented (wheat, lupin, barley, canola and peas) (Table 4) with the first row of crop ranging between 2 and 10 m from the trees due to the presence of fences and firebreaks (see photos in Appendix B). The trees included eight Eucalyptus species, one pine species (*Pinus radiata*) and tagasaste (*Chamaecytisus proliferus*). The Eucalyptus species were *E. sideroxylon*, *E. populnea*, *E. leucoxylon*, *E. polybractea*, *E. wandoo*, *E. camaldulensis*, *E. microcarpa* and one unidentified Eucalyptus spp. The trees ranged in age from 7 to 14 years and had an outer tree height of between 3 and 15 m. At all sites the trees belts were fenced and had little or no understorey growth.

The climate in the WA region is Mediterranean with cool, wet winters and hot, dry summers. The annual average rainfall at the WA sites ranged from 375 to 461 mm. All the sites in 2001 had a very dry start to the year with below average rainfall in February and April. Corrigin and Kulin (Figure 5) were very dry in 2002 with lower than average rainfall in all months except November and December.

The annual average rainfall at the NSW sites ranged from 528 to 649 mm. The NSW sites have an evenly distributed long term average monthly rainfall (Figure 6) and lack the pronounced seasonality of the WA sites. The monthly rainfall was lower than average in 2001 and 2002 except for a few storm events in February 2002 at all sites and June 2001 at Grenfell.

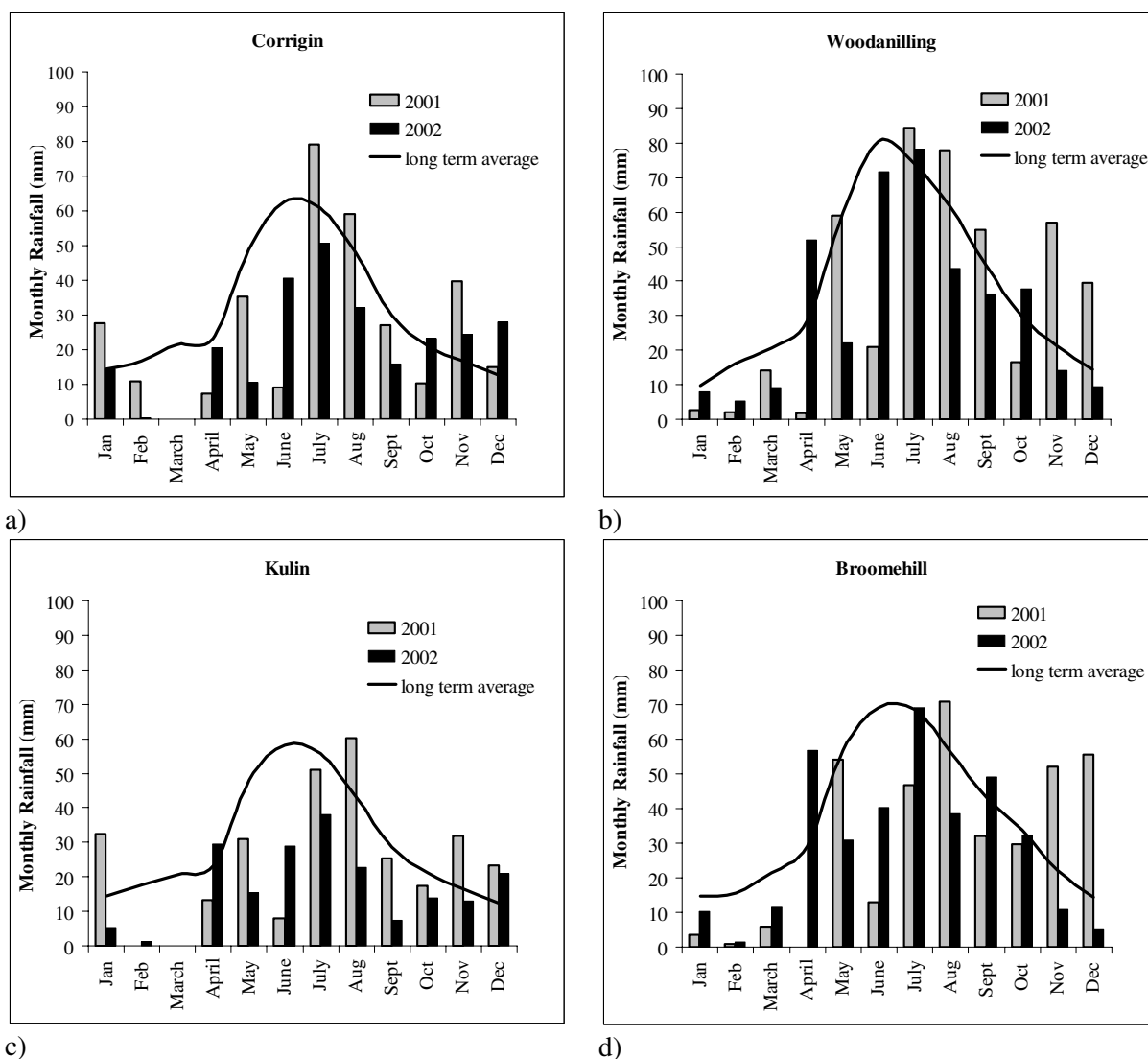


Figure 5. Monthly rainfall for 2001 and 2002 and long term monthly average rainfall from WA towns closest to sites: a) Corrigin, b) Woodanilling, c) Kulin and d) Broomehill.

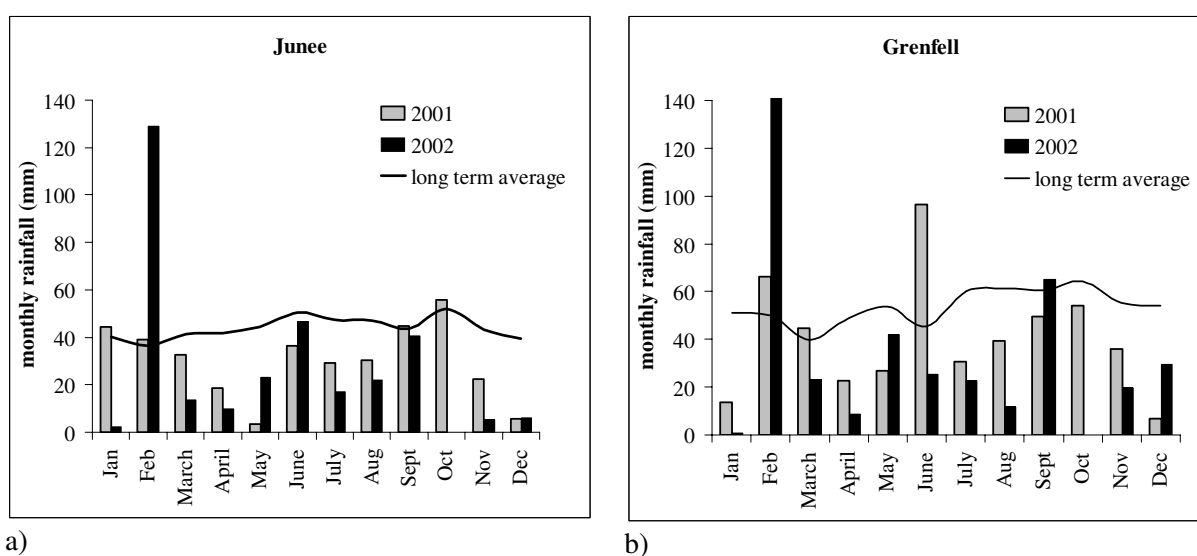
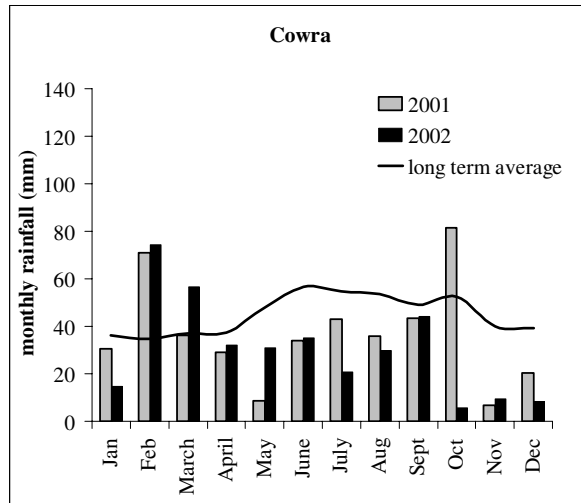


Figure 6ab. Monthly rainfall for 2001 and 2002 and long term monthly average rainfall from NSW towns closest to sites: a) Junee and b) Grenfell.



c)

Figure 6c. Monthly rainfall for 2001 and 2002 and long term monthly average rainfall from NSW towns closest to sites: c) Cowra.

Table 1. Site location and environment.

Site	Code	Location	Latitude (S)	Longitude (E)	Average annual rainfall	Aspect ¹	Position
<u>SE Western Australia</u>							
1 Pitman 1	P1	Corrigin	32° 22' 21.6"	117° 45' 1.0"	375	NE	valley
2 Pitman 2	P2	Corrigin	32° 22' 20.5"	117° 45' 0.3"	375	NE	valley
3 Pitman 3	P3	Corrigin	32° 22' 21.6"	117° 45' 0.0"	375	SW	valley
4 Pitman 4	P4	Corrigin	32° 22' 21.3"	117° 44' 59.3"	375	SW	valley
5 Ling 1	L1	Corrigin	32° 24' 35.2"	117° 42' 19.1"	375	W	mid-slope
6 Guinness 1	G1	Corrigin	32° 24' 4.8"	117° 39' 45.2"	375	SE	valley
7 Guinness 3	G3	Corrigin	32° 26' 34.4"	117° 39' 37.6"	375	E	mid-slope
8 Clayton 1	C1	Kulin	32° 41' 15.7"	117° 58' 23.5"	359	NE	mid-slope
9 Clayton 2	C2	Kulin	32° 41' 15.7"	117° 58' 23.5"	359	SW	mid-slope
10 McDougall 1	Mc1	Harrismith	32° 55' 35.5"	117° 47' 20.3"	390	N	low slope
11 McDougall 2	Mc2	Harrismith	33° 01' 5.6"	117° 43' 44.3"	401	W	low slope
12 Bessell-Browne 1	BB1	Woodanilling	33° 27' 9.0"	117° 31' 36.0"	461	W	mid-slope
13 Bessell-Browne 2	BB2	Woodanilling	33° 26' 59.6"	117° 31' 26.3"	461	S	mid-slope
14 Parnell 1	Pa1	Broomehill	33° 55' 3.0"	117° 35' 42.8"	444	N	mid-slope
15 Parnell 2	Pa2	Broomehill	33° 55' 4.7"	117° 35' 50.6"	444	N	mid-slope
16 Parnell 3	Pa3	Broomehill	33° 55' 12.4"	117° 35' 53.5"	444	SE	low slope
<u>NSW</u>							
17 Parker	Pk1	Cowra	33° 46' 43.5"	148° 47' 38.5"	540	NE	valley
18 Matchett 1	M1	Grenfell	33° 42' 34.2"	148° 5' 59.8"	649	E	valley
19 Hart 1	H1	Junee	34° 43' 44.5"	147° 32' 47.8"	528	E	valley
20 Hart 2	H2	Junee	34° 43' 44.7"	147° 32' 49.1"	528	E	low slope
21 Hart 3	H3	Junee	34° 43' 34.5"	147° 32' 45.9"	528	E	low slope

¹Aspect is the direction from which the crop is sheltered by trees.

3.2 Soil measurements

Soil descriptions were carried out for the Western Australian sites using hand augured samples taken at 0-10 cm, 10-20 cm, 50-60 cm and 100-110 cm in replicate holes 12 m from the tree belts. The soil samples were dried at 40°C and passed through a 2 mm sieve. The soil texture was calculated from the texture triangle after measurement of % sand, silt and clay by the pipette method (Gee 1979) (Table 2). The water content at 1500 kPa (crop lower limit) and 300 kPa and 100 kPa (drained upper limit or field capacity) was measured using cores repacked to field bulk density on pressure plates.

The pH was measured in a 1:5 soil to 0.01M CaCl₂ solution soil which was shaken for 1 hour and centrifuged for 10 minutes before analysis. The soils were grouped into acidic surface increasing in pH to slightly acidic with depth (Figure 7a), acidic surface increasing to neutral/slightly alkaline with depth (Figure 7b), acidic surface increasing to neutral/slightly alkaline with depth with the highest pH at 60 cm (Figure 7c) and one site which had neutral surface becoming acidic with depth (Figure 7d).

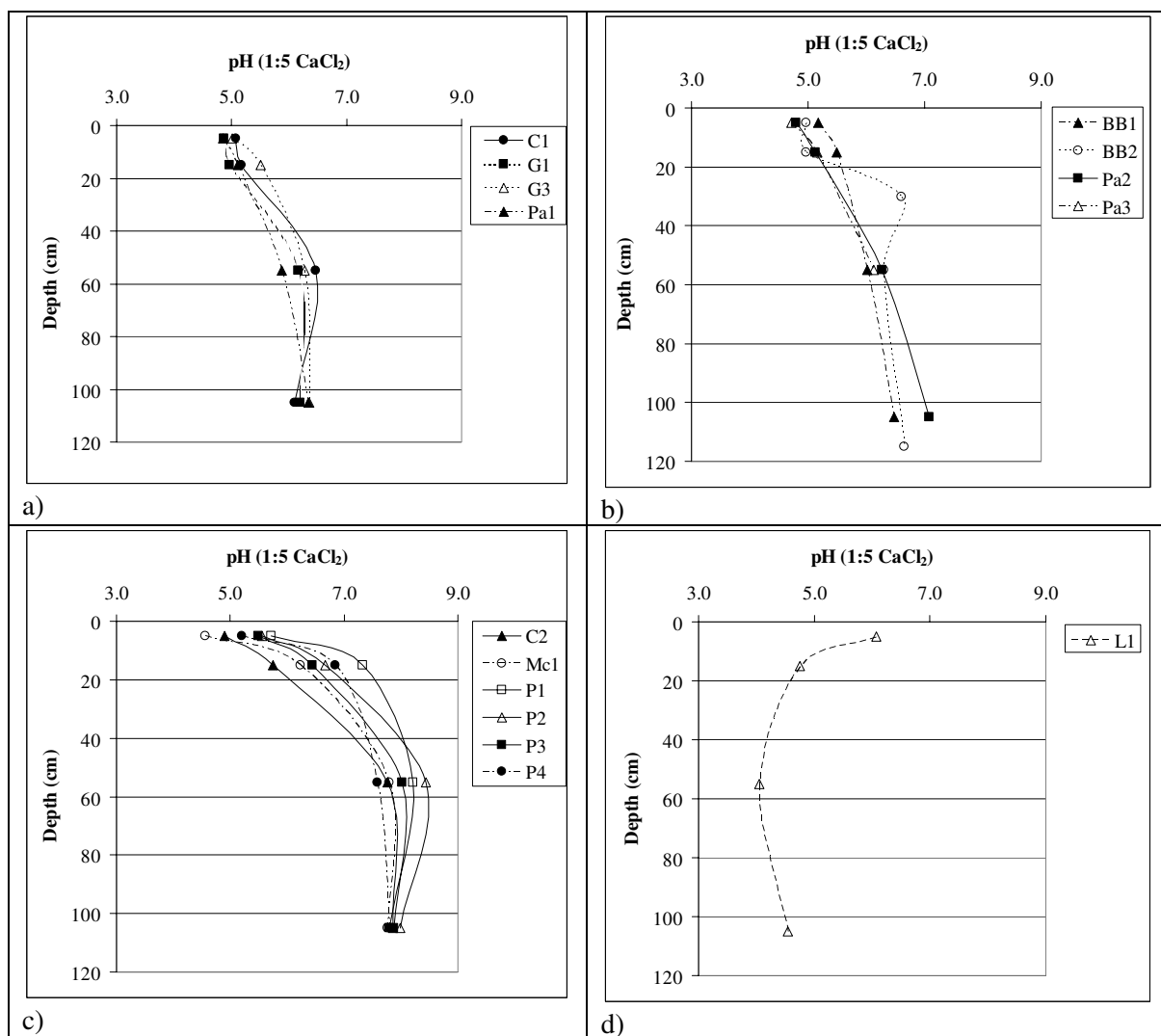


Figure 7. The soil pH (0.01M CaCl₂) of the WA sites grouped as (a) acidic surface increasing to slightly acidic with depth, (b) acidic surface increasing to neutral/slightly alkaline with depth, (c) acidic surface increasing to neutral/slightly alkaline with depth and (d) neutral surface becoming acidic with depth (for key to sites see Table 1).

The EC was measured in a 1:5 soil:deionised water solution which was shaken for 1 hour and centrifuged for 10 minutes before analysis. The soils were grouped into non-saline soils (<20 mS/m) (Figure 8a), non-saline increasing to slightly saline (20-40 mS/m) with depth (Figure 8b), slightly saline increasing to moderately saline (40-80 mS/m) with depth (Figure 8c) and non-saline to very saline (80-160 mS/m) with depth (Figure 8d).

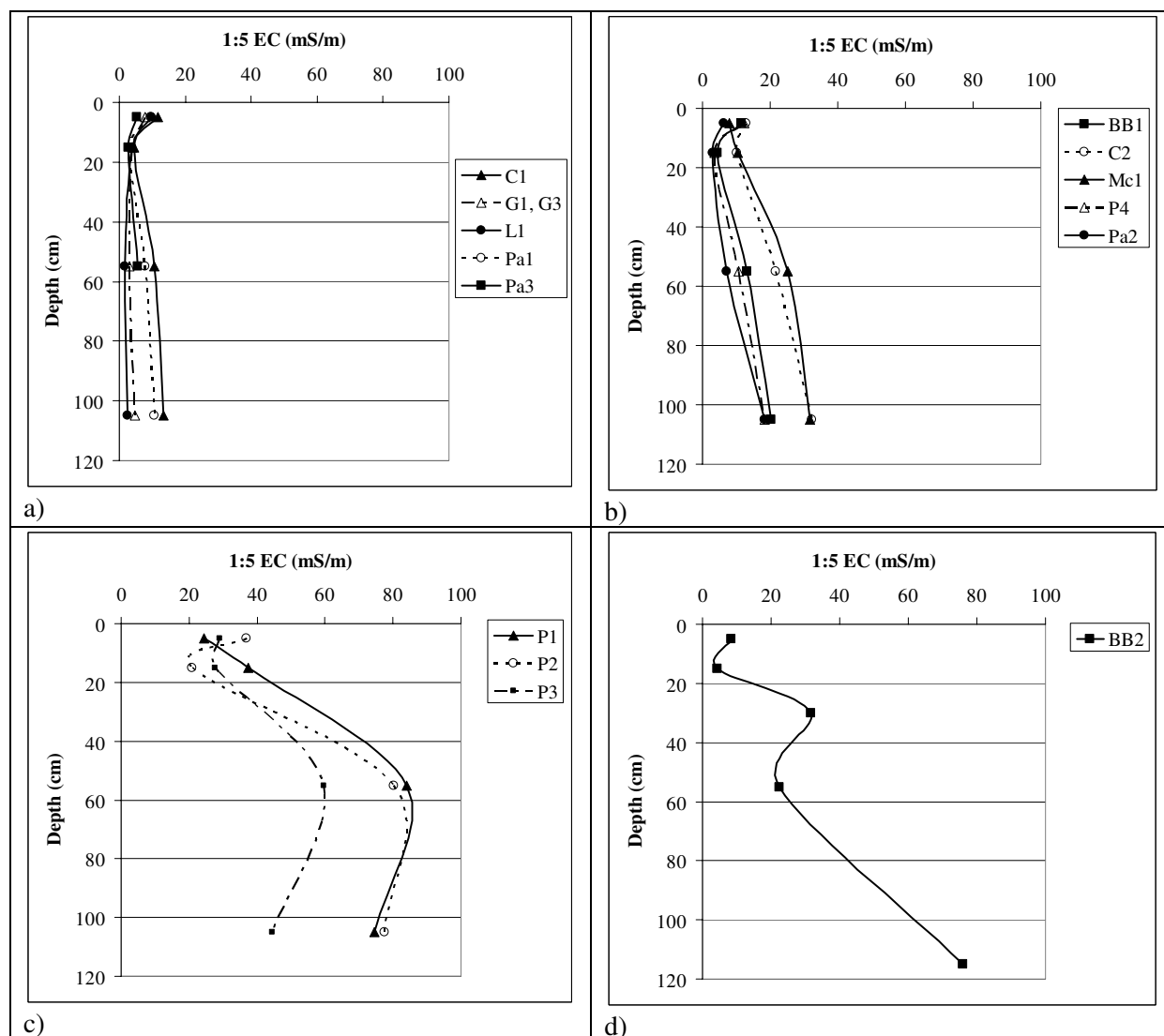


Figure 8. The soil EC (1:5 deionised water) of the Western Australian sites grouped as (a) non-saline soils (<20 mS/m), (b) non-saline increasing to slightly saline (20-40 mS/m) with depth, (c) slightly saline increasing to moderately saline (40-80 mS/m) with depth and (d) and non-saline to very saline (80-160 mS/m) with depth (for key to sites see Table 1).

Transects of EM38 readings were taken at the WA sites in April 2003 after approximately 20 mm rainfall in the previous month. The EM38 signal may be influenced by the salinity, water content and soil type in the top 10 cm for the horizontal mode and 20-30 cm for the vertical mode. Both modes are influenced by the salinity in the soil up to 150 cm. The EM38 reading can be interpreted as salinity classes ranging from non-saline (<50 mS/m), slightly saline (50-100 mS/m), moderately saline (100-150 mS/m), very saline (150-200 mS/m) to extremely saline (>200 mS/m). The EM38 reading may also be attributed to water content such that a higher EM38 reading relates to higher water content. This assumes the salinity level was similar and the increase in water in the soil increased the amount of salts solubilised.

Table 2. Soil descriptions for the WA and NSW sites.

No	Code	Soil Colour and Class	Depth to B ₁ , B ₂ (cm)	pH	EC (mS/m)
1	P1	Greyish brown loamy sand over grey clay loam the white silty clay loam	20, 100	Acidic topsoil alkaline subsoil	Slightly saline to moderately saline with depth
2	P2	Greyish brown sand over white clay	50	Acidic topsoil alkaline subsoil	Slightly saline to moderately saline with depth
3	P3	Greyish brown loamy sand over light yellowish brown sandy clay loam and brown clay loam	10, 50	Acidic topsoil alkaline subsoil	Slightly saline to moderately saline with depth
4	P4	Greyish brown sand over light yellowish brown clay	100	Acidic topsoil alkaline subsoil	Non-saline increasing to slightly saline with depth
5	L1	Light brown grey to yellow deep sand		Slightly acid topsoil acidic subsoil	Non-saline
6	G1	Light brownish grey sand over yellow sandy loam	50	Acidic topsoils slightly acidic subsoil	Non-saline
7	G3	Grey brown sand over brown gravely sandy loam	100	Acidic topsoils slightly acidic subsoil	Non-saline
8	C1	Brown sand over gravely light brown sandy clay	50	Acidic topsoils slightly acidic subsoil	Non-saline
9	C2	Brown sand over yellowish brown sandy clay	80	Acidic topsoils neutral subsoil	Non-saline increasing to slightly saline with depth
10	Mc1	Greyish brown sandy clay over pale yellow clay	100	Acidic topsoils neutral subsoil	Non-saline increasing to slightly saline with depth
11	Mc2	Greyish brown sandy clay over pale yellow sandy clay	100	Acidic topsoils neutral subsoil	Non-saline increasing to slightly saline with depth
12	BB1	Brown loamy sand over pink clay	50	Acidic topsoils slightly acidic subsoil	Non-saline increasing to slightly saline with depth
13	BB2	Brown loamy sand over light yellow clay to white clay	50, 100	Acidic topsoils slightly acidic subsoil	Non-saline to moderately saline with depth
14	Pa1	Brown sand over brown/brownish yellow clay	50	Acidic topsoils slightly acidic subsoil	Non-saline
15	Pa2	Dark grey brown loamy sand over yellowish brown clay	50,100	Acidic topsoils slightly acidic subsoil	Non-saline increasing to slightly saline with depth
16	Pa3	Brown sand over yellowish brown sandy clay loam	50	Acidic topsoils slightly acidic subsoil	Non-saline
17	Pk1	Sandy clay loam over clay	40	Neutral to slightly alkaline subsoil	
18	M1	Fine sandy clay over a clay	50	Neutral	
19	H1	Loam over a medium clay	20	Neutral	
20	H2	Loam over a medium clay	20	Neutral	
21	H3	Loam over a medium clay	20	Neutral	

¹1:5 EC class: non-saline = 0-20 mS/m, slightly saline = 20-40 mS/m, moderately saline = 40-80 mS/m, very saline = 80-160 mS/m. Note: NSW soil description was taken from locations near sites which have been described in detail in SALIS (NSW Department of Land and Water Conservation).

3.3 Crop biomass and yield

The biomass and yield were determined from triplicate quadrats (0.5 m × 0.5 m) cut at 2, 4, 8, 16, 32, 64 and 128 m from the tree base perpendicular to the tree belt. Yield data was collected for 21 sites in 2001 and 11 sites in 2002 due to drought and variations in crop rotation.

The yield at each distance was converted to relative yield by dividing by the open paddock yield (the yield at 128 m or 64 m depending on the maximum sampling distance) (Appendix A). Relative yields can be used to remove the variation in crop yields due to the crop species, rainfall zone, soil and agronomic practices enabling the different regions, tree species, aspect and other factors to be compared. The distance was also converted to tree heights for each site by dividing the distance from the tree belt by the outer tree height (Appendix A).

The net yield change (%) was calculated from the difference in the measured paddock yield (including yield loss and yield enhancement) and the open paddock yield (Figure 9 and Equation 4). The yield change was adjusted after assigning an equal yield value to points at greater than five tree heights which were not statistically significantly different. This percentage yield change was split into yield decline (Equation 2) and yield enhancement (Equation 3).

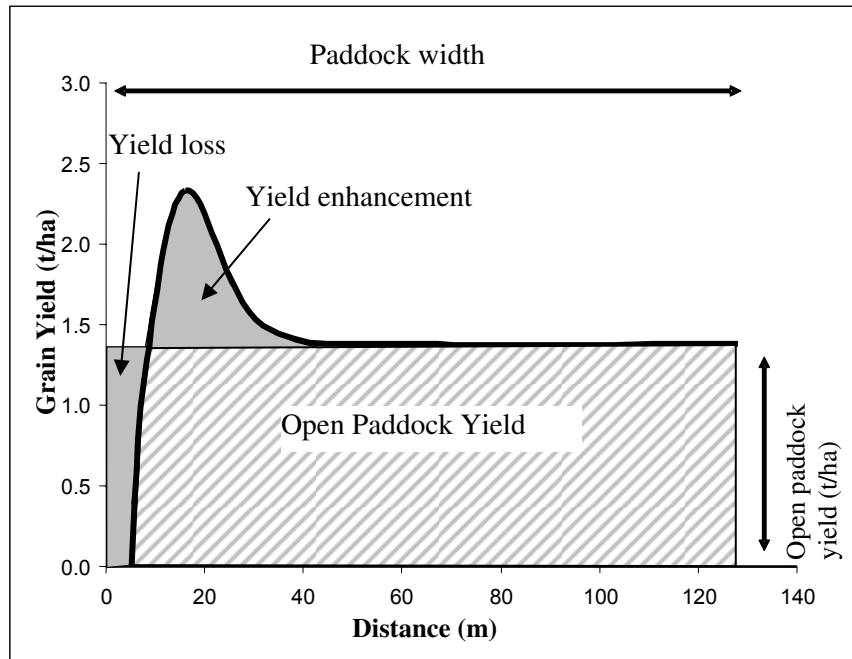


Figure 9. Grain yield at distances from the trees indicating yield loss, yield enhancement and open paddock yield. The open paddock yield area is calculated from the yield at the maximum sampling distance times the paddock width.

$$\% \text{ Yield loss} = 100 \times \frac{\text{Yield loss}}{\text{paddock width} \times \text{open paddock yield}} \quad (3)$$

$$\% \text{ Yield enhancement} = 100 \times \frac{\text{Yield enhancement}}{\text{paddock width} \times \text{open paddock yield}} \quad (4)$$

$$\% \text{ Net Yield change} = \% \text{ Yield loss} + \% \text{ Yield enhancement} \quad (5)$$

The No-Yield-Zone (m) is the distance away from the trees over which the yield is effectively reduced to zero and is calculated as the percentage yield change over 128 m, which takes into account both the yield enhancement and yield decline areas (Equation 6).

$$NYZ = \% \text{ net yield change} \times \text{paddock width (m)} \quad (6)$$

The width of the competition zone is calculated using only the percentage yield loss (Equation 2).

$$\text{Width of competition zone (m)} = \% \text{ yield loss} \times \text{paddock width (m)} \quad (7)$$

Carberry *et al.* (2002b) used a similar concept, also referred to as the No-Yield-Zone, which they defined as the width of the visually-determined zone with zero yield.

The relative yield (in metres and tree heights) and the NYZ were averaged for a) all the sites, b) WA vs NSW sites, c) Eucalypt vs non-Eucalypt sites, d) cereal vs non-cereal crop, e) aspect (grouped as east to north west (E, NE, N, NW) and west to south east (W, SW, S, SE)), f) light soils (sand and sandy clay) vs heavy soils (duplex clays and heavy clays), g) landscape position (low and valley vs high and mid-slope), h) water gaining sites (determined from the LAI of the trees compared to the native vegetation - see section 4.2.1, i) short trees (<8 m) vs tall trees (>8 m), j) old trees (>10 years) vs young trees (<10 years) and k) rainfall (>400 mm vs <400 mm). ANOVA tables were used to test the statistical significance using Genstat 6.

3.4 Tree measurements and No-Recharge-Zone calculation

The tree belts were measured to record orientation, width of belt, length of belt, diameter at breast height, tree height, canopy width of trees, distance between trees, distance between rows and leaf area of inner and outer tree rows. The diameter at breast height for multi-stemmed trees was measured for all leaf bearing stems and summed to produce a tree diameter at breast height.

The leaf area index (LAI) was measured using the Adelaide (module) technique (Andrew *et al.* 1979). Three outer trees and three inner trees were chosen at each site to represent the alley system. For each tree, a representative module (branch or part of a branch) was sampled and the number of representative modules on each tree was determined as the average of two recorders' values. The leaf area of the representative module was then measured using an electronic planimeter and the leaf area of the tree determined from the module leaf area multiplied by the number of modules in the tree. The leaf area index was determined from the leaf area of three trees divided by the ground area occupied by those trees (determined from row spacing and tree spacing).

For the Ellis method, it is assumed that trees in belts can access water under the crops, and will therefore be larger than native vegetation. From empirical forest studies, the native LAI is predicted from Equation 8.

$$LAI_{\text{native}} = 2.9 \frac{\text{Annual rainfall}}{\text{Annual Evaporation}} \quad (8)$$

For sites with outer trees having larger LAI than inner trees, it is assumed that the extra growth of the outer tree can be attributed to the extra water 'mined' from beneath the crops. The NRZ, calculated from Equation 9, uses the area occupied by the outer tree as indicated by the row spacing for that belt. As the NRZ extends into the crop from one side of the trees, half the row spacing is subtracted.

$$NRZ_{outer/inner} = \left(\frac{LAI_{outer}}{LAI_{inner}} \times row\ spacing \right) - \frac{1}{2} row\ spacing \quad (9)$$

The Ellis method (Equation 10) compares the LAI of the outer tree with the LAI of nearby native vegetation. This can be used for sites with or without an edge-tree effect.

$$NRZ_{outer/native} = \left(\frac{LAI_{outer}}{LAI_{native}} \times row\ spacing \right) - \frac{1}{2} row\ spacing \quad (10)$$

Table 3. Tree belt composition, structure and dimensions.

No	Site	Tree species	Age	No. rows	Belt width (m)	Tree spacing (m)	Row spacing (m)	Tree height (m)
1	P1	<i>E. sideroxylon</i>	14	6	19.0	3.0	4.0	5.3
2	P2	<i>E. populnea</i>	14	6	19.8	3.0	4.0	5.9
3	P3	<i>E. sideroxylon</i>	14	6	19.0	3.0	4.0	7.0
4	P4	<i>E. populnea</i>	14	6	19.8	3.0	4.0	6.2
5	L1	<i>Chamaecytisus proliferus</i>	6	hedge	10.0	5.0	3.5	4.7
6	G1	<i>Pinus radiata</i>	8	8	36.6	5.0	4.5	8.2
7	G3	<i>Chamaecytisus proliferus</i>	6	5	23.1	5.0	3.5	3.7
8	C1	<i>E. leucoxylon</i>	15	10	44.3	4.5	4.5	6.7
9	C2	<i>E. leucoxylon</i>	15	13	68.1	5.2	4.5	6.5
10	Mc1	<i>E. polybractea</i>	7	24	300.0	1.7	2.0	5.5
11	Mc2	Eucalyptus spp.	7	2	10.0	4.1	4.3	6.8
12	BB1	<i>E. polybractea</i>	6	4	9.4	2.3	1.5	6.0
13	BB2	<i>E. polybractea</i>	6	4	8.2	2.6	1.5	6.4
14	Pa1	<i>E. wandoo</i>	16	5	20.0	3.8	3.5	7.3
15	Pa2	<i>E. camaldulensis</i>	16	4	18.0	4.0	3.5	6.3
16	Pa3	<i>E. camaldulensis</i>	16	4	25.0	8.0	6.6	7.6
17	Pk1	<i>E. microcarpa</i>		5	29.0	15.5	3.5	22.7
18	M1	Eucalyptus spp.	12	3	10.9	7.0	2.7	9.0
19	H1	<i>Pinus radiata</i>	13	3	9.7	6.0	2.4	10.7
20	H2	<i>Pinus radiata</i>	13	3	9.3	6.0	2.4	9.0
21	H3	<i>E. sideroxylon</i>	10	3	7.9	3.0	2.0	12.6

4. The Complementarity Index (CI)

The Complementarity Index (CI) is the ratio of the No-Recharge-Zone (NRZ) and No-Yield-Zones (NYZ). It was first proposed Stirzaker *et al.* (2002) as a method of quantifying the trade-off between yield loss and recharge benefit. The yield loss is quantified as the NYZ, the distance from the trees over which the crop yield is effectively reduced to zero. When the overall paddock yield with trees is greater than that without trees, the NYZ becomes negative, and under these circumstances its value indicates the equivalent amount of extra crop land effectively added through the adoption of agroforestry.

The recharge benefit is quantified as the NRZ, the distance over which the trees effectively reduce recharge to zero, or to levels similar to that occurring under native vegetation.

When the NRZ is greater than the NYZ, and the CI is greater than 1, it is more likely to be beneficial to integrate trees closely with crops as the trees reduce recharge over a greater area than they reduce yield. When the CI is less than 1, segregating trees from crops in block plantings is more likely to be best way of managing recharge and growing crops as the area over which trees compete with crops is greater than that over which they reduce recharge. For the landholder, this decision will ultimately come down to the relative value of recharge management and crop production which is discussed in section 6.5 below.

The following section describes the calculation of the NYZ, NRZ and CI for each of the 32 sites.

4.1 Calculation of the No-Yield-Zone (NYZ)

To examine the influence of the tree belts over crop yield, the relative yield was plotted against distance from the tree belts in metres and tree heights (H) for the 2001 and 2002 data (Figure 11ab). The relative yield is the yield at any point along the transect out from the trees divided by the yield at the end of the transect, which is taken to be the open paddock yield or yield outside the influence of the trees. The yield in 2002 was generally lower and patchier than 2001 reflecting generally lower and uneven distribution of rainfall in that year (Figures 5 and 6).

The typical windbreak signature was observed in the yield data, with an area of low yield in the competition zone within the first 3 H (0 to 16 m). Yield enhancement in the sheltered zone (3 to 5 H or 16 to 50 m) occurred at one third of the sites (9 out of 21 sites in 2001 and 3 out of 11 sites in 2002, Table 4). The remaining sites exhibited some yield loss in the sheltered zone. The scatter in the open paddock zone (greater than 12 H or 50 m) indicated a high degree of variability in the open paddock yield.

When the distance from the tree belts in metres was converted to tree heights, some of the variation in the windbreak signature between the sites was removed (Figure 10ab). The remaining scatter is most likely due to other site factors such as soil type, crop type, tree species, aspect, wind direction and rainfall.

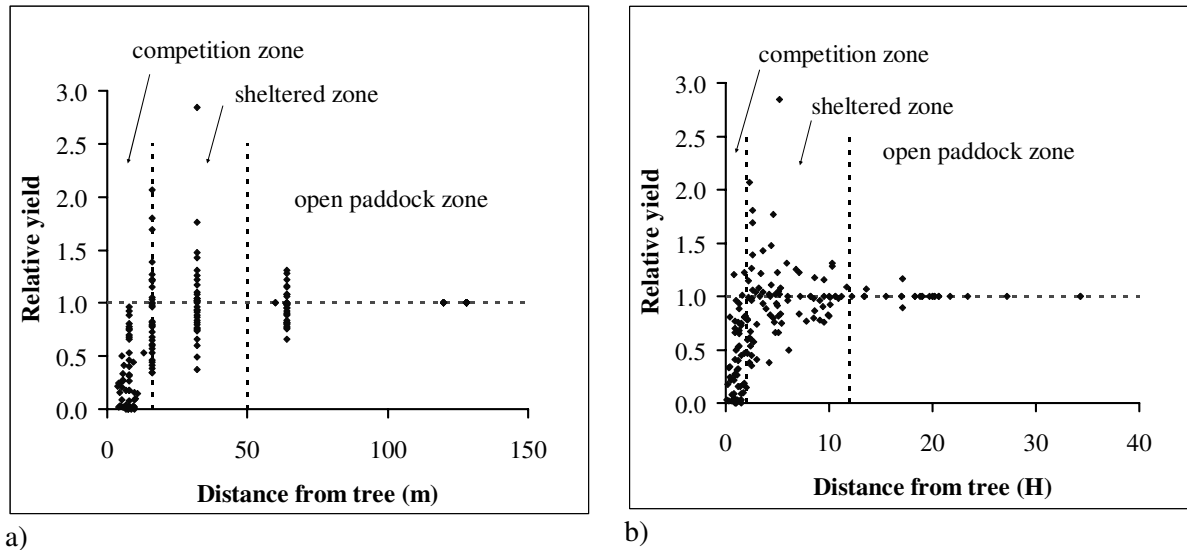


Figure 10. The relative yield (yield/yield at 128 m) at distance from the tree belts in (a) metres and (b) tree heights (metres/height of tree) (H).

The percentage yield change over the 128 m transect ranged from a 37% yield enhancement to a 38% yield loss with an average 8.6% yield loss (Table 4). This percentage yield change included both the yield loss and the yield enhancement (Figure 9).

Across all sites, the width of the competition zone ranged from 5 to 50 m (0.4 to 6.4 H) away from the trees (Table 4), with an average width of 16.5 m or 2.3 H (Table 4).

At eight of the 12 sites at which yield enhancement was measured, the percentage yield enhancement was greater than percentage yield loss (i.e. there was a net yield gain, and a negative NYZ). The negative value of the NYZ in these cases (ranging from -0.9 to -46.8 m or -0.2 to -7.5 H) indicates the equivalent extra crop land gained under this tree-crop combination in that season. At the other four sites, the percentage yield enhancement was less than the percentage yield loss. Therefore at these sites the NYZ was lower than the width of the competition (Table 4).

For all sites the average NYZ extended 11.0 m or 1.5 H into the paddock and ranged from a loss of 48.6 m into the crop to an effective gain of 46.8 m of extra land. The NYZ for each site is used to determine the Complementarity Index in section 4.3.

Table 4. Open paddock crop yield, percentage yield change as a loss (which corresponds to width of competition zone), enhancement and net yield change and No-Yield-Zone in metres (m) and tree heights (H). See Figure 8 for an explanation of percentage yield enhancement and percentage yield loss. Note: Negative NYZ = effective gain in cropped land.

Site	Crop Species	Open paddock yield t/ha	% Yield change over 128 m transect			Width of competition zone		NYZ	
			Loss	Enhancement	Net change	m	H	m	H
P1	wheat	3.47	-24.3	0.0	-24.3	31.1	5.9	31.1	5.9
P2	wheat	3.37	-18.0	0.0	-18.0	23.0	3.9	23.0	3.9
P3	lupins	1.50	-25.1	0.0	-25.1	32.1	4.6	32.1	4.6
P4	lupins	1.09	-7.5	16.5	9.0	9.5	1.5	-11.6	-1.9
L1	barley	0.86	-8.2	4.9	-3.3	10.5	2.2	4.2	0.9
G1	wheat	2.40	-3.5	0.0	-3.5	5.0	0.6	4.4	0.5
G3	wheat	1.94	-5.7	0.0	-5.7	7.3	2.0	7.3	2.0
C1	lupins	1.62	-12.3	0.0	-12.3	15.8	2.3	15.8	2.4
C2	barley	2.19	-5.6	0.0	-5.6	7.2	1.1	7.2	1.1
Mc1	wheat	1.85	-5.8	5.2	-0.5	7.4	1.4	0.7	0.1
Mc2	wheat	2.22	-17.4	0.0	-17.4	22.3	3.3	22.3	3.3
BB1	canola	1.38	-5.1	5.9	0.7	6.6	1.1	-0.9	-0.2
BB2	canola	1.45	-5.2	6.4	1.2	6.6	1.0	-1.5	-0.2
Pa1	wheat	2.67	-7.6	10.0	2.3	9.8	1.3	-3.0	-0.4
Pa2	wheat	3.78	-18.8	0.0	-18.8	24.0	3.8	24.0	3.8
Pa3	wheat	2.87	-10.3	0.0	-10.3	13.2	1.8	13.2	1.7
Pk1	canola	0.37	-5.6	0.7	-4.9	7.2	0.4	6.3	0.3
M1	wheat	1.48	-7.3	8.7	1.5	9.3	1.0	-1.9	-0.2
H1	peas	0.42	-11.0	0.0	-11.0	14.1	1.4	14.1	1.4
H2	wheat	0.57	-5.8	10.6	4.8	7.4	0.8	-6.2	-0.7
H3	canola	0.12	-32.6	0.0	-32.6	41.7	3.3	41.7	3.3
P3b	wheat	0.70	-7.9	21.2	13.2	10.1	1.4	-16.9	-2.4
P4b	wheat	0.77	-9.9	46.5	36.6	12.7	2.0	-46.8	-7.5
G3b	wheat	1.00	-8.5	0.0	-8.5	10.8	2.9	10.8	2.9
C1b	wheat	1.61	-27.8	0.0	-27.8	35.6	5.3	35.6	5.3
BB1b	wheat	2.87	-7.3	1.7	-5.7	9.4	1.6	7.3	1.2
BB2b	wheat	3.42	-16.0	0.0	-16.0	20.5	3.2	20.5	3.2
Pa1b	barley	1.90	-9.3	0.0	-9.3	11.9	1.6	11.9	1.6
Pa2b	barley	1.93	-14.7	0.0	-14.7	18.8	3.0	18.8	3.0
Pa3b	barley	2.85	-38.0	0.0	-38.0	48.6	6.4	48.6	6.4
M1b	wheat	1.14	-13.8	0.0	-13.8	17.6	2.0	17.6	2.0
H1b	canola	0.39	-16.4	0.0	-16.4	21.0	2.0	21.0	2.0

Note: Negative NYZ = effective gain in cropped land. 2002 sites labelled b.

4.2 Calculation of the No-Recharge-Zone (NRZ)

The No-Recharge-Zone (NRZ) is the distance from the tree belt over which recharge is effectively reduced to zero, or to the recharge rate occurring under native vegetation in the region. The prediction of the NRZ is based on the Ellis method (Ellis *et al.* 1999, 2001) which uses the width occupied by the outer tree in a belt (Table 3) and the ratio of the LAI of inner and outer trees, or LAI of the belt and LAI of native vegetation in the region (Table 5). The LAI of native vegetation was predicted from rainfall and evaporation (Equation 8). The tree belt properties at each site are shown in Table 5.

Table 5. Tree height, wood volume, diameter at breast height, leaf area index and predicted leaf area index (from equation 8) for the WA and NSW sites.

Site	Tree height (m)		Wood volume (m ³)		Diameter at breast height (m)		Average LAI (m ² /m ²)		Predicted LAI (m ² /m ²)
	Outer tree	Inner tree	Outer tree	Inner tree	Outer tree	Inner tree	Outer tree	Inner tree	Native
P1	5.3	5.8	0.7	0.2	0.44	0.25	2.8	0.6	0.60
P2	5.9	6.1	1.8	1.5	0.44	0.39	3.7	2.6	0.60
P3	7.0	6.7	1.1	0.3	0.54	0.41	2.6	0.6	0.60
P4	6.2	6.6	2.1	0.5	0.67	0.60	4.9	1.7	0.60
L1	4.7	^A	7.3	^A	0.64	0.46	2.7	^A	0.60
G1	8.2	8.3	0.8	0.6	0.56	0.44	3.8	2.5	0.60
G3	3.7	3.7	3.2	2.1	0.49	0.25	3.5	4.8	0.60
C1	6.7	5.1	4.2	1.5	0.58	0.28	1.3	0.5	0.55
C2	6.5	6.0	5.5	3.2	0.68	0.27	2.3	0.4	0.55
Mc1	5.5	4.4	0.7	0.3	0.71	0.32	4.2	1.8	0.70
Mc2	6.8	^A	11.3	^A	0.97	0.45	4.4	^A	0.70
BB1	6.0	5.5	0.4	0.5	1.24	0.54	2.8	1.6	0.90
BB2	6.4	5.8	0.9	0.6	1.54	0.47	4.0	1.7	0.90
Pa1	7.3	6.8	7.0	2.0	1.16	0.35	3.3	2.1	0.90
Pa2	6.3	6.4	2.3	1.1	0.78	0.29	4.7	1.9	0.90
Pa3	7.6	^B	18.9	0.8	0.39	0.34	3.8	^B	0.90
Pk1	22.7	22.8	53.9	20.7	0.65	0.45	1.4	0.2	1.00
M1	9.0	7.4	5.1	2.5	0.87	0.52	0.4	0.2	1.00
H1	10.7	10.5	3.7	2.4	1.02	0.85	6.1	6.2	1.10
H2	9.0	8.6	1.6	2.2	0.93	0.93	5.8	7.8	1.10
H3	12.6	12.1	36.0	5.3	0.94	0.63	0.4	0.5	1.10

^A the tree belt had only two rows (no inner row), ^B Inner trees were two years younger than outer trees.

The $NRZ_{outer/inner}$ (see equation 9, p.27) is based on the difference in LAI of outer and inner belt trees, and therefore is assumed to reflect the relative water use of outer and inner trees and the access they have to water in the adjacent cropped zone under the same site, nutrient and soil conditions. The $NRZ_{outer/inner}$ therefore compares local scale processes. The $NRZ_{outer/native}$ on the other hand represents the extra growth of the planted outer trees compared to native vegetation, which survive on rainfall alone, and includes differences due to access to water under crops, as well as access to groundwater and runoff.

The predicted $NRZ_{outer/inner}$ ranged from 0.6 to 25 m (0.1 to 3.8 H) while the $NRZ_{outer/native}$ ranged from 0.1 to 30.4 m (0.1 to 4.9 H) (Table 6). The $NRZ_{outer/inner}$ was generally lower than the $NRZ_{outer/native}$, reflecting the fact that the inner belt trees in this study had higher LAI than that expected for native trees with four exceptions where the trees appear to have been poorly adapted to those sites. A low

NRZ_{outer/native} indicates the trees do not provide much additional recharge control than the area the trees occupy as they are performing much like the native vegetation and are surviving on rainfall alone.

The NRZ_{outer/native} has been found to closely agree with NRZ determined from soil water content in a number of soils and sites across Australia by Ellis *et al.* (1999, 2001) and Robinson *et al.* (2002). For Eucalyptus species, Ellis *et al.* (1999, 2001) found the measured NRZ ranged from 25 to 60 m compared to a predicted NRZ of 10 to 60 m. Robinson *et al.* (2002) found the measured NRZ for five sites planted to Mallee Eucalypts ranged from 7 to 12 m (2.4 to 5 H) while the predicted NRZ ranged from 8 to 15 m (2 to 7 H). This provides some confidence in the predicted NRZ based on leaf area as used in this study.

Table 6. No-Recharge-Zone (NRZ) predicted from the edge-tree effect (difference between LAI of outer and inner belt trees) and the difference between outer belt trees and native vegetation.

Site	NRZ outer/inner (m)	NRZ outer/native (m)	NRZ outer/inner (H)	NRZ outer/native (H)
P1	17.3	16.6	3.3	3.2
P2	3.8	22.7	0.6	3.9
P3	14.2	15.5	2.0	2.2
P4	9.5	30.4	1.5	4.9
L1	^A	14.2		3.0
G1	4.8	26.5	0.6	3.2
G3	0.8	18.4	0.2	4.9
C1	9.3	8.5	1.4	1.3
C2	24.9	16.4	3.8	2.5
Mc1	3.7	11.0	0.7	2.0
Mc2	^A	24.7		3.6
BB1	1.8	3.9	0.3	0.6
BB2	2.7	6.0	0.4	0.9
Pa1	3.6	11.0	0.5	1.5
Pa2	7.1	16.7	1.1	2.6
Pa3	^B	24.3		3.2
Pk1	24.4	2.0	1.1	0.1
M1	5.3	^C	0.6	^C
H1	1.2	10.0	0.1	0.9
H2	0.6	9.4	0.1	1.0
H3	0.8	^C	0.1	^C

^A the tree belt had only two rows (no inner row), ^B Inner trees were two years younger than outer trees, ^C LAI_{outer} < LAI_{native}.

4.2.1 Where trees access water: the effect on the predicted NRZ

Comparing the LAI_{outer}, LAI_{inner} and LAI_{native} gives some insight into the water use by the trees, in particular whether they are accessing additional groundwater or runoff (Table 5).

The LAI_{outer} was higher than the LAI_{inner} at all but three sites indicating that, as expected, the outer trees were growing better than the inner trees, most likely due to better access to water and other resources. The exceptions (G3, H1 and H2) were all sites with non-Eucalypts (tagasaste and pines) which may reflect the fact that determination of leaf area is more problematic with these species (Table 5).

There were three distinct categories of sites based on the LAI of belt trees and the predicted LAI of native trees (Table 5). These categories can be used to describe three plausible scenarios for the impact of planted belts of trees on soil water management.

1. $LAI_{outer} > LAI_{inner} < LAI_{native}$. These are sites with poor tree growth but still featuring an edge effect. The outer trees obtain extra water from under crops and out-compete inner trees but the LAI of the inner trees suggest they are not reaching the environmental potential of the site. In this case, the NRZ calculated from the ratio of LAI_{outer} over LAI_{native} is likely to overestimate the impact of the trees on water management. Six sites in this study fell into this category: C1, C2, M1, Pk1, H3, and Pa3.
2. $LAI_{outer} > LAI_{inner} \approx LAI_{native}$. This is the classic case where the outer trees experience enhanced growth over inner trees due to better access to resources, and the growth of inner trees approximates that of native vegetation. The NRZ calculated from either the ratio of LAI_{outer} over LAI_{inner} or the ratio of LAI_{outer} over LAI_{native} should equally describe the influence of the trees on soil water under the crops. Two sites fell into this category: P1 and P3.
3. $LAI_{outer} > LAI_{inner} > LAI_{native}$. Enhanced tree growth, with edge effect. Both inner and outer trees access groundwater or seep water, with the outer trees also accessing water under the crops. The $NRZ_{outer/inner}$ may be high but does not include the groundwater removed. The $NRZ_{outer/native}$ includes both groundwater and the water under the crops. The inner trees may also have been shaded by the outer tree, which would cause the $NRZ_{outer/inner}$ to be high. Eleven sites fell into this category: P2, P4, G1, G3, Mc1, BB1, BB2, Pa1, Pa2, H1 and H2. A second possibility for this category is that both inner and outer trees are accessing stored soil water, a situation more likely at sites with trees younger than those in this study.

Sites in Category 3 are referred to from here on as water gaining sites, as the trees obtain more water than is available from rainfall (through access to groundwater, seeps or runoff), in addition to accessing water under adjacent crops.

4.3 Determining the Complementarity Index

The Complementarity Index is the ratio of the NRZ (the distance into the paddock over which the trees reduce recharge to zero) to the NYZ (the distance into the paddock over which the yield is reduced to zero). Figure 3 illustrates the NRZ and NYZ as relative distances away from the trees. The relationship between the influence of the trees over yield and recharge has been graphed using the NRZ calculated from the ratio of the LAI_{outer} and LAI_{inner} ($NRZ_{outer/inner}$ Figure 11a,) and the ratio of LAI_{outer} and LAI_{native} ($NRZ_{outer/native}$ Figure 11b). The difference between these two forms of expressing the yield-recharge trade-off is that the $NRZ_{outer/native}$ represents uptake of both soil water and groundwater, and is therefore likely to be a better indicator of the hydrologic influence of the trees.

For any site there are three potential outcomes in terms of the complementarity of trees and crops and the trade-off between yield and recharge.

1. Where there is a net yield increase in the presence of trees, a no trade-off scenario results. The Complementarity Index cannot be calculated for these sites (Table 7) as it is based on the assumption that competition always exists and is meaningless where the NYZ is negative. The trade-off between yield and recharge is better represented by the relationship between the size of the NRZ and the percentage change in yield compared to the open paddock or no-tree scenario (Figure 11). Alley farming is the most favourable strategy in a no trade-off situation in terms of crop production, while the impact on recharge management will vary depending on environmental and genotypic factors such as availability of groundwater, tree species and aspect.

2. If the Complementarity Index is greater than one, the trees are preventing recharge over a greater area of land than they are causing a yield penalty (Table 7) and a positive trade-off occurs. This is seen in Figure 11 as the area above the dotted line, on the left hand side of the graph. Alley farming is likely to be a more appropriate design strategy than block plantations in this case.
3. If the Complementarity Index is less than one, the trees are preventing recharge over a smaller area of land than they are causing a yield penalty (Table 7) and a negative trade-off occurs. This is seen in Figure 11 as those sites below the dotted line. In these cases, block plantations are more likely to be the optimal strategy for water management and crop production.

It is important to note that these scenarios provide a guide only, and that the decision as to which planting design to use will ultimately depend on the relative value of recharge management and crop production to the landholder. This question of value is dealt with in section 6.5 below.

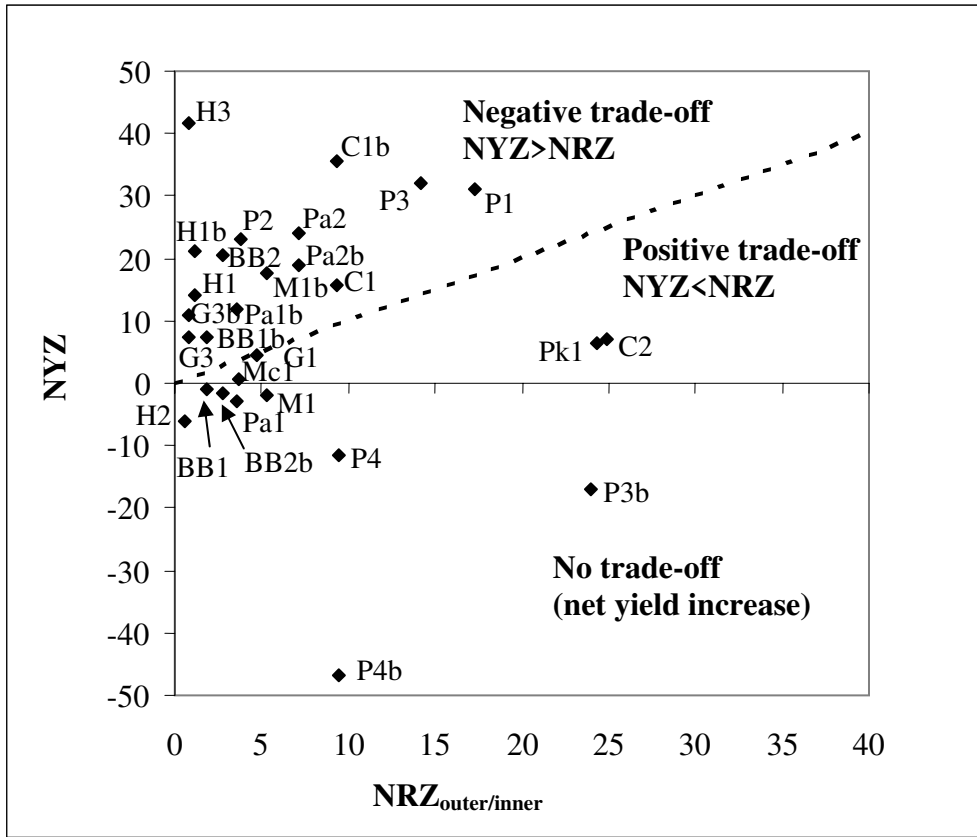
Positive trade-off occurred at four of the 28 sites based on the $NRZ_{outer/inner}$ (C2, Pk1, G1 and Mc1, Figure 11a). Using the larger $NRZ_{outer/native}$ based on the difference between the LAI of belt and native trees, nine of the 32 sites had a positive trade-off (C2, G1, Mc1, Pa3, P2, Mc2, L1, G3 in 2001 and G3b in 2002). P2 is the only site which moved from negative trade-off with the $NRZ_{outer/inner}$ to positive trade-off using the $NRZ_{outer/native}$. There were four sites with single rows of trees for which the $NRZ_{outer/inner}$ calculation was not possible (L1, G3, G3b and Mc1).

Negative trade-off occurred at 16 of the 28 sites when using the $NRZ_{outer/inner}$ and 15 of the 32 sites when using the $NRZ_{outer/native}$ (P1, P3, P1, P2, C1, BB2, H1, Mc2, G3, H3 in 2001 and BB1b, M1b, C1b, Pa2b, H1b and G3b in 2002).

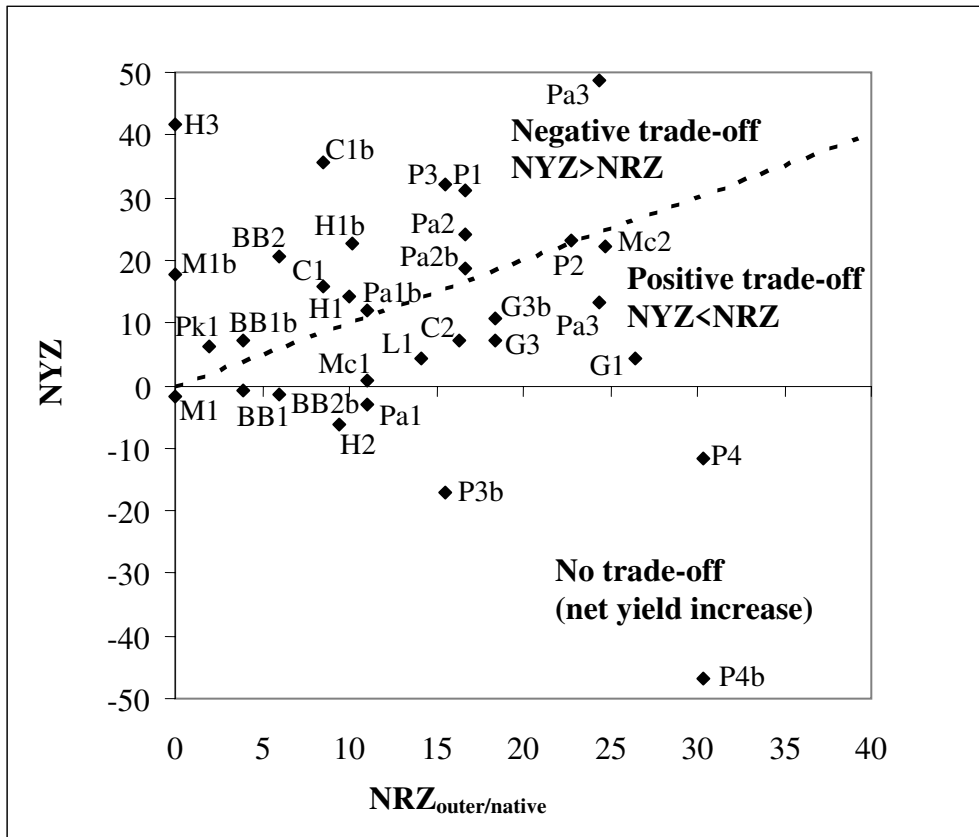
The no trade-off scenario occurred at eight sites, however at only three of these sites was there likely to be a significant impact on recharge, based on the difference in LAI between belt trees and native vegetation (P3 and P4 in 2001 and P3b in 2002). The majority of no trade-off situations occurred on water gaining sites. This relates to the reduced competition between the trees and the crops due to the greater availability of water, from seep, groundwater or runoff sources. However, this could not be predicted by landscape position as only five of the eight no-trade-off sites were low in the landscape. Another major impact was aspect, with more sites protected from the south, south-east, south west and west having a greater potential for yield enhancement creating a no trade-off situation. There was also a combined effect of water gaining sites and aspect. Positive trade-off also occurred on sites with non-Eucalypts (tagasaste and pine) predominantly on deep sand in WA.

Over all three scenarios, half of the sites have alley farming potential as they illustrated either a positive trade-off or a net yield increase. This amounted to 14 of the 21 sites in 2001 and three of the 11 sites in 2002. Lower rainfall reduced the chance of positive trade-offs in 2002, possibly due to a greater competition for water.

Drier seasonal conditions appeared more likely to produce a negative trade-off. Not all sites were measured in 2002 due to crop rotations and drought. For those that were measured in both years, only two had a positive trade-off in both years (P4 and G3). The majority of the positive trade-off sites in 2001 became negative trade-off in 2002 (BB1, BB2, Pa1, M1, Pa3) while sites which had negative trade-off in 2001 also had negative trade-off in 2002 (C1, H1, and Pa2) except one site (P3).



a)



b)

Figure 11. NYZ vs (a) NRZ from LAI_{outer}/LAI_{inner} and (b) NRZ from LAI_{outer}/LAI_{native} , the dotted line represents a Complementarity Index of 1 (for codes see Table 1).

Table 7. The Complementarity Indices showing genotypic (tree species and crop type) and environmental influences (soil type, landscape position, aspect and water gaining potential) for 2001 and 2002.

Genotype						Environment					
Site	Year	Tree species	Crop	State	Soil type	Position	Aspect	Aspect class	Water gaining	CI outer/native	CI outer/inner
No trade-off (yield benefit), large effect on recharge											
P3b	2002	<i>E. sideroxylon</i>	wheat	WA	Light duplex	valley	SW	W-SE	N	na	na
P4	2001	<i>E. populnea</i>	lupins	WA	Heavy duplex	valley	SW	W-SE	Y	na	na
P4b	2002	<i>E. populnea</i>	wheat	WA	Heavy duplex	valley	SW	W-SE	Y	na	na
No trade-off (yield benefit), small effect on recharge											
BB1	2001	<i>E. polybractea</i>	canola	WA	Med duplex	mid	W	W-SE	Y	na	na
BB2	2001	<i>E. polybractea</i>	canola	WA	Med duplex	mid	S	W-SE	Y	na	na
Pa1	2001	<i>E. wandoo</i>	wheat	WA	Heavy duplex	mid	N	E-NW	Y	na	na
H2	2001	<i>Pinus</i> spp.	wheat	NSW	Heavy duplex	low	E	E-NW	Y	na	na
M1	2001	<i>Eucalyptus</i> spp.	wheat	NSW	Heavy duplex	valley	E	E-NW	N	na	na
Positive trade-off											
Mc1	2001	<i>E. polybractea</i>	wheat	WA	Heavy duplex	low	N	E-NW	Y ^A	7.8	2.7 ^A
L1	2001	<i>Cham. proliferus</i>	barley	WA	Deep Sand	top	W	W-SE		6.0	
G1	2001	<i>Pinus radiata</i>	wheat	WA	Deep sand	valley	SE	W-SE	Y	5.2	0.9
C2	2001	<i>E. leucoxylon</i>	barley	WA	Light duplex	mid	SW	W-SE	N	3.1	4.8
G3	2001	<i>Cham. proliferus</i>	wheat	WA	Deep sand	mid	E	E-NW	Y	2.6	0.1
G3b	2002	<i>Cham. proliferus</i>	wheat	WA	Deep sand	mid	E	E-NW	Y ^B	2.0	0.1 ^B
Pa3	2001	<i>E. camaldulensis</i>	wheat	WA	Light duplex	low	SE	W-SE		1.9	
Mc2	2001	<i>Eucalyptus</i> spp.	wheat	WA	Heavy duplex	low	W	W-SE	^A	1.2	^A
P2	2001	<i>E. populnea</i>	wheat	WA	Heavy duplex	valley	NE	E-NW	Y	1.0	0.2
Negative trade-off											
Pa1b	2002	<i>E. wandoo</i>	barley	WA	Heavy duplex	mid	N	E-NW	Y	0.9	0.3
Pa2b	2002	<i>E. camaldulensis</i>	barley	WA	Heavy duplex	mid	N	E-NW	Y	0.9	0.4
Pa2	2001	<i>E. camaldulensis</i>	wheat	WA	Heavy duplex	mid	N	E-NW	Y	0.7	0.3
H1	2001	<i>Pinus</i> spp	peas	NSW	Heavy duplex	valley	E	E-NW	Y	0.7	0.1
BB1b	2002	<i>E. polybractea</i>	wheat	WA	Med duplex	mid	W	W-SE	Y	0.6	0.3
C1	2001	<i>E. leucoxylon</i>	lupins	WA	Light duplex	mid	NE	E-NW	N	0.6	0.6
P1	2001	<i>E. sideroxylon</i>	wheat	WA	Light duplex	valley	NE	E-NW	N ^B	0.6	0.6 ^B
Pa3b	2002	<i>E. camaldulensis</i>	barley	WA	Light duplex	low	SE	W-SE		0.6	
H1b	2002	<i>Pinus</i> spp	canola	NSW	Heavy duplex	valley	E	E-NW	Y	0.5	0.1
P3	2001	<i>E. sideroxylon</i>	lupins	WA	Light duplex	valley	SW	W-SE	N	0.5	0.5 ^D
Pk1	2001	<i>E. microcarpa</i>	canola	NSW	Heavy duplex	valley	E	E-NW	N	0.4	
BB2b	2002	<i>E. polybractea</i>	wheat	WA	Heavy duplex	mid	S	W-SE	Y	0.3	0.1
C1b	2002	<i>E. leucoxylon</i>	wheat	WA	Light duplex	mid	NE	E-NW	N	0.2	0.3
M1b	2002	<i>Eucalyptus</i> spp.	wheat	NSW	Heavy duplex	valley	E	E-NW	N ^C		0.3
H3	2001	<i>E. sideroxylon</i>	canola	NSW	Heavy duplex	low	E	E-NW	N ^C		0

na = Complementarity Index is not applicable where the NYZ is negative (i.e. where trees effectively increase rather than decrease the area of cropped land)

Soil type: heavy duplex = loam over clay; light duplex = sand over light clay; medium duplex = sand over clay
Landscape position: valley and low = low in landscape, top and mid = high in landscape

^A trees had only two rows so cannot use the inner and outer tree calculations; ^B inner trees younger than outer trees; ^C LAI_{outer} < LAI_{native}; ^D LAI_{inner} > LAI_{outer}

5. Deconstructing the Complementarity Index (CI)

The Complementarity Index (CI) produced some insights into the range of trade-off situations likely to occur under different combinations of tree species, crop type and environment. However it did not satisfactorily identify some of the most favourable agroforestry designs as it is based on the assumption there will always be competition between trees and crops. For the eight sites at which yield was enhanced by the presence of trees, potentially the most favourable from a landholders perspective, a CI could not be calculated as the NYZ was negative (meaning the trees had effectively ‘added’ extra land). This suggests that the trade-off between water management and yield would be better expressed by keeping the two measures separate rather than combining them into an index. This section therefore examines the two components of the Complementarity Index, the NYZ and the NRZ. It looks first at the factors most likely to minimise competition between trees and crops and maximise water management by trees and then examines the compatibility of these factors.

5.1 Factors influencing the size of the No-Yield-Zone (NYZ)

By grouping the measured NYZ's from the 32 sites into yield enhancement and yield loss classes (Figure 12), we see that more sites experienced a yield loss. A net yield loss occurred at 24 of the 32 sites with the majority in the range 0 to 30 m of land effectively lost from cropping. The sites with yield enhancement increased the effective area cropped by 0 to 15 m with two as high as 40 m. In the environments studied, there was clearly a greater likelihood of experiencing a net yield loss than a yield gain.

The difference between the CI and an examination of yield alone is the assumption that if the area of recharge control is greater than the area experiencing yield loss, alley farming becomes attractive. However, the promise of high recharge is unlikely to be sufficient incentive to persuade a landholder to take up alley farming where there is the prospect of losing 30 m of arable land every year for every belt of trees, in addition to the area occupied by the trees.

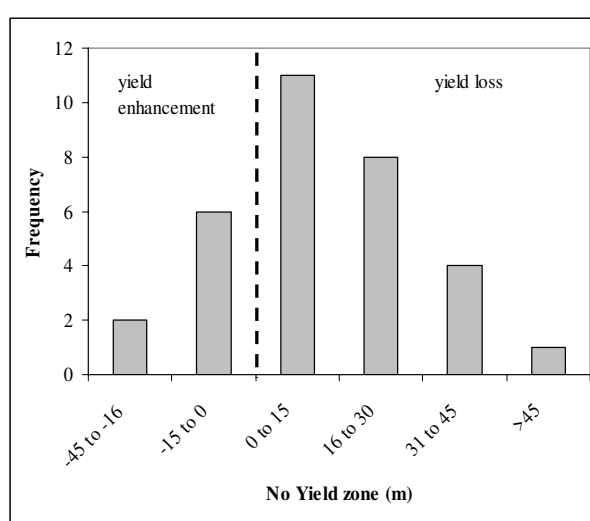


Figure 12. Number of sites which had a No-Yield-Zone corresponding to a net yield loss (NYZ of 0 to 15 m, 16 to 30 m, 31 to 45 m and >45 m) and yield enhancement (negative NYZ of 0m to -15 m, -15 m to -45 m).

To understand the relative influences of environmental and farming system characteristics on the size of the NYZ and the competition zone, the data were separated into the following groups and analysed statistically using ANOVA: a) All sites, b) WA vs NSW sites, c) Eucalypt vs non-Eucalypt sites, d) cereal vs non-cereal crops, e) aspect (east to north west (E, NE, N, NW) vs west to south east (W, SW, S, SE)), f) landscape position (high vs low), g) heavy vs light soils, h) water gaining sites, i) tree height (<8 m vs >8 m), j) age of tree (young <10 years vs old >10 years) and k) rainfall (>400 mm vs <400 mm) (Table 8).

Table 8. Average No-Yield-Zone (NYZ) for sites grouped by region, tree species, crop type, aspect, soil type, landscape position, access to water, tree height (H) and tree age (standard errors in brackets).

	Number of replicates	NYZ	
		m	H
All	32	11.0 (3.2)	1.5 (0.5)
WA	25	10.3 (3.8)	1.6 (0.5)
NSW	7	13.2 (7.0)	1.1 (0.9)
Eucalypts	26	11.9 (3.6)	1.6 (0.5)
Non-Eucalypts	6	6.9 (7.6)	1.3 (1.1)
Cereal	23	10.2 (3.9)	1.6 (0.6)
Non-cereal	9	13.0 (6.8)	1.3 (0.9)
Aspect – east, north east, north, north west	16	14.8 (4.6) [*]	2.1 (0.7)
Aspect – west, south west, south, south east	16	7.0 (4.7) [*]	1.0 (0.7)
Light soils (sand and sandy clays)	14	16.3 (4.7) ^{**}	2.6 (0.7) ^{***}
Heavy soils (heavy duplex clays)	18	6.8 (4.4) ^{**}	0.7 (0.6) ^{***}
High landscape position	18	11.3 (5.0)	1.3 (0.6)
Low landscape position	14	10.7 (5.4)	1.9 (0.7)
Water gaining sites ^a	18	6.7 (4.4) ^{**}	0.9 (0.6) ^{**}
Non water gaining sites	11	17.2 (5.7) ^{**}	2.4 (0.8) ^{**}
Short trees <8 m	21	8.6 (4.1)	1.5 (0.6)
Tall trees >8 m	11	15.4 (5.5)	1.6 (0.8)
Young trees <10 years	10	10.0 (4.1)	1.6 (0.8)
Old trees >10 years	22	11.4 (4.1)	1.4 (0.6)
High rainfall (>400 mm)	18	14.1 (4.1)	1.7 (0.6)
Low Rainfall (< 400 mm)	14	6.9 (4.9)	1.2 (0.7)

***P<0.1, **P<0.2, *P<0.25,

^aThe water gaining sites were determined in section 4.2, and do not include sites L1, Mc2 and P3 as they only had two rows of trees (i.e. no inner row).

Based on the analysis in Table 8, we can say that it is more likely to reduce competition between trees and crops if 1) trees are planted on water gaining sites, 2) trees are planted on heavier soils and 3) trees protect crops from winds from the south, south east, south west and west (particularly for WA).

Where trees were planted on water gaining sites such as over groundwater, in seeps or had access to through flow (as determined by $LAI_{outer} > LAI_{inner} > LAI_{native}$) then the NYZ was significantly lower than if they were planted elsewhere ($P=0.156$) (Table 8). Three sites were excluded from the analysis as

they did not have inner tree rows (L1, Mc2 and Pa3). The influence of water gaining sites was most noticeable at 1H (~8 m) where relative yield was slightly higher ($P=0.25$). There was no relationship between water gaining sites and landscape position, reflecting the fact that water gaining sites can occur in many landscape positions.

The heavier soils (heavy duplex clays) had a lower NYZ compared to the lighter soils (sands and sandy clays) ($P=0.153$). The relative yield at 16 m, 1 H and 2.5 H was slightly higher in the heavy soil class ($P=0.003$, 0.03, 0.05 respectively). The soil grouping of heavy and light was based on near surface features and may not indicate the soil process which affect the water holding capacity and root penetration.

Aspect was the third site factor to have a slight but significant influence on the NYZ. Crops which were protected from west, south, south west and south east winds had a smaller NYZ ($P=0.23$) (Table 9), particularly at 16 m or 2.5 H ($P=0.049$). However, aspect was not a significant factor on the width of the competition zone, as reduction in wind speed influences yield enhancement. Albertson *et al.* (2000) similarly found that aspect was significant in influencing pasture loss adjacent to bluegum (*Eucalyptus globulus*) plantations.

System characteristics had relatively small influences on the tree-crop interactions. The NYZ was lower for non-Eucalypts than Eucalypts, although the small number of data points and variation resulted in the lack of statistical difference. Non-Eucalypt species had a lower competition zone width ($P=0.096$), however the number of sites with non-Eucalypt species (6) was far lower than the number with Eucalypts (26) (Table 9). The relative yield at 8 m was lower for the Eucalypts than the non-Eucalypt tree species ($P=0.082$) which may indicate greater competition for resources by Eucalypts close to the trees. In contrast, Sudmeyer *et al.* (2002c) suggested that *P. pinaster*, *P. radiata* and *E. globulus* might have similar potential to compete with crops given that the lateral extent of their roots is similar, and all three have their greatest root density within 0.5 m of the soil surface where crop and pasture roots are concentrated.

The yield benefit of shelter on non-cereals such as lupins, peas and canola as commonly reported in the northern hemisphere literature (Kort 1988, Brandle *et al.* 1992) was not observed in this study, but the small number of non-cereal sites compared to cereal sites may be responsible. The relative yield at one tree height was slightly higher for the non-cereal crops than the cereal crops which indicates the slight benefit to non-cereals close to the trees ($P=0.136$). Regional differences (WA vs NSW) were not significant for the NYZ. However, the relative yield at one tree height at the WA sites was significantly higher than at the NSW sites ($P=0.016$).

The effect of season on the width of the competition zone was observed with the difference in the NYZ at the 11 sites measured in both 2001 and 2002. The NYZ was lower in 2001 than 2002 for nine of these sites (BB1, BB2, Pa1, M1, Pa3, C1, G3 and Pa2). This may be the result of lower rainfall in 2002 which also had a patchy distribution (Figures 5 and 6). Two sites had a decrease in the NYZ from positive in 2001 to negative in 2002 (P3 and P4). The crop response to the trees was seasonally dependant as 2002 was generally a drier year with higher NYZ and patchier crop yield across the paddock. A drier year will increase the competition between the trees and crops for the small available water (Ssekabembe *et al.* 1994, Jose *et al.* 2000).

In summary, the site and systems features likely to reduce the size of the NYZ or result in yield enhancement are possibly one or more of the following:

1. Water gaining site
2. Crop protection from the west through to the south east (particularly for WA)
3. Heavier soils.

5.2 Factors influencing the No-Recharge-Zone (NRZ)

The No-Recharge-Zone (NRZ), predicted from LAI, ranged from a very small predicted lateral influence on recharge (0.6 m) to highly effective recharge control (30 m). The difference between the LAI_{outer} , LAI_{inner} and LAI_{native} provided insight into the potential of water gaining sites. The results of this study indicate that of the environmental factors, soil type, water availability, tree species and tree age had the more significant influence on the size of the NRZ (Table 9).

Eucalyptus species had higher $NRZ_{outer/inner}$ than tagasaste and pine species ($P=0.06$). This may be due to root exploration but could also be correlated with soil type as tagasaste and pine tended to be planted on lighter soils. However the small number of sites with non-Eucalypts makes this conclusion fairly tenuous.

The lighter soils had a greater $NRZ_{outer/inner}$ than heavier soils ($P=0.045$) suggesting a greater lateral exploration of the roots in sandier soils. The $NRZ_{outer/native}$ was significantly lower on the western side of a tree belt than the eastern side ($P=0.028$) but only slightly different when the NRZ in tree heights were compared ($P=0.177$).

The high rainfall sites had the lowest $NRZ_{outer/inner}$ and $NRZ_{outer/native}$ ($P=0.046$, 0.001 respectively). The likely cause for this was less competition between the inner and outer trees for water due to high rainfall. The $NRZ_{outer/native}$ was significantly lower in WA than NSW ($P<0.001$) which may reflect the generally heavier soil types found in NSW sites. Crops which were protected from west, south, south west and south east winds also had a larger NRZ ($P=0.028$). Landscape position did not have a significant influence on the NRZ.

In summary, older trees planted on heavier soils in low rainfall areas in the lee of winds from the south, south west and south east were more likely to provide greater recharge control than other site and system features.

5.3 Factors optimising yield and water management

The factors most likely to minimise competition *and* maximise recharge management at a site are one or more of the following:

1. Water gaining sites
2. Crop protection from the west, south west, south or south east
3. Older trees (>10 years)
4. Lower rainfall (<400 mm)

Table 9. Average No-Recharge-Zone in metres and tree heights, determined from the ratio of LAI_{outer} and LAI_{inner} and the ratio of LAI_{outer} and LAI_{native}.

	NRZ (outer/inner) (m)	NRZ (outer/native) (m)
All	7.3 (1.3)	12.7 (1.6)
WA	5.5 (2.8)	4.3 (2.8) ***
NSW	7.7 (1.6)	16.0 (1.5) ***
Eucalypts	8.4 (1.5) ***	12.9 (1.7)
Other	1.6 (3.1) ***	16.1 (3.6)
Cereal	<i>na</i>	<i>na</i>
Non-cereal	<i>na</i>	<i>na</i>
Aspect – east, north east, north, north west	5.9 (1.8)	10.1 (2.1) ***
Aspect – west, south west, south, south east	8.9 (2.1)	16.8 (2.1) ***
Light soils (sand and sandy clays)	10.8 (1.6) ***	17.3 (2.2) ***
Heavy soils (heavy duplex clays)	5.1 (2.2) ***	10.5 (2.1) ***
High landscape position	5.8 (1.8)	11.4 (2.4)
Low landscape position	7.9 (1.7)	14.5 (2.2)
Water gaining sites	<i>na</i>	<i>na</i>
Non water gaining sites	<i>na</i>	<i>na</i>
Short trees <8 m	8.2 (1.7)	14.5 (1.9)
Tall trees >8 m	5.0 (2.4)	11.6 (2.7)
Young trees <10 years	3.5 (2.4) ***	12.3 (2.9)
Old trees >10 years	9.1 (1.6) ***	13.8 (2.0)
High rainfall (>400 mm)	4.6 (1.8) ***	<i>na</i>
Low rainfall (<400 mm)	10.1 (1.9) ***	<i>na</i>

***P<0.1 ** P<0.2 *P<0.25

na. LAI for native vegetation is used to define water gaining sites. Rainfall is used in the calculation of the LAI for native vegetation

6. Improving the Complementarity Index

6.1 Can we predict the NYZ from the tree height?

Carberry *et al.* (2002b) found a strong relationship between their visually determined NYZ and tree height ($r^2=0.86$, $n=23$) for Eucalypts on the Darling Downs. Windbreak research also uses tree heights to measure the influence of the trees on the crops, however in this study there was no clear relationship between tree height (H) and the width of the competition zone or the width of the NYZ (Figure 13). Normalising the distance data by H removes some of the scatter in the actual yield (Figure 4) indicating some relationship but insufficient on which to base any prediction of the NYZ.

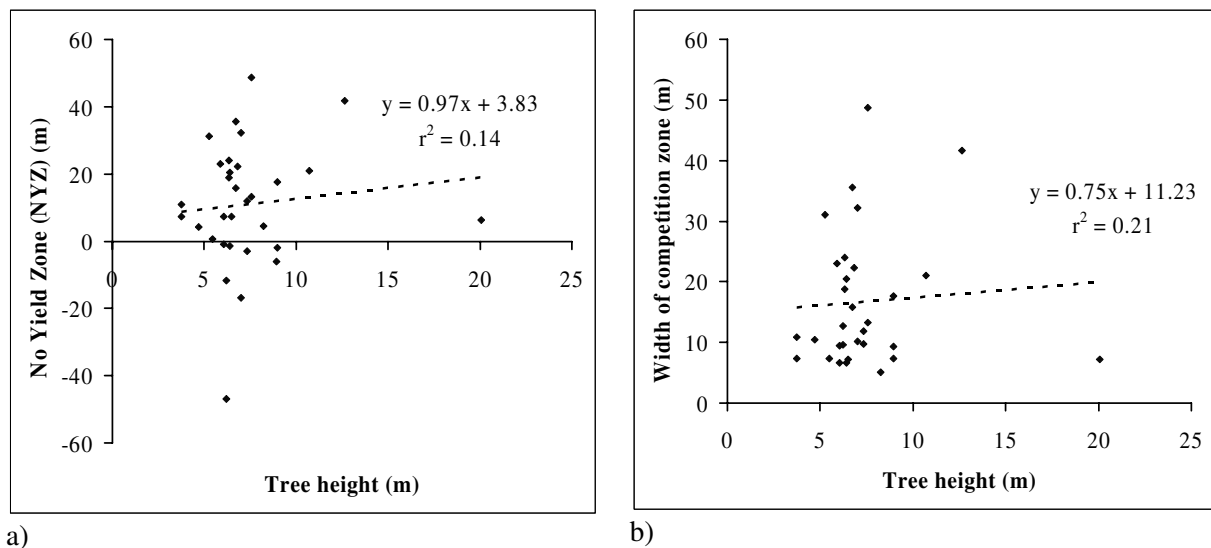


Figure 13. The relationship between tree height and (a) width of the competition zone determined from the NYZ and (b) width of the competition zone determined from the percentage yield loss.

6.2 Does Harvest Index provide any insight into the NYZ?

The harvest index (yield/biomass) may indicate how the windbreak affects crop growth and grain production. A high harvest index indicates the crop has put more energy into seed production while a low harvest index indicates more energy has been used for leaf production. The harvest index and relative grain yield away from the tree belts had similar trends (Figure 14). A harvest index of 0.5 or greater is considered acceptable in grain cropping.

The harvest index was normalised for the different crops by dividing by the open paddock harvest index. Where the relative harvest index is greater than 1, grain yield was higher than in the open paddock situation. Where the relative harvest index is less than 1, it indicates higher biomass than grain production compared to the open paddock situation. Low relative harvest index was commonly found in the competition zone, which related to the crop using the available energy and water for growth and survival rather than seed production.

Relative harvest index presents a similar picture to the measured NYZ with the lowest values (<0.6) all clustered between 1 and 2 tree heights, compared with the mean NYZ across the sites (1.5 ± 0.5). However it also indicates that the competition zone, indicated by a relative harvest index less than 1, extended as far as 10 H.

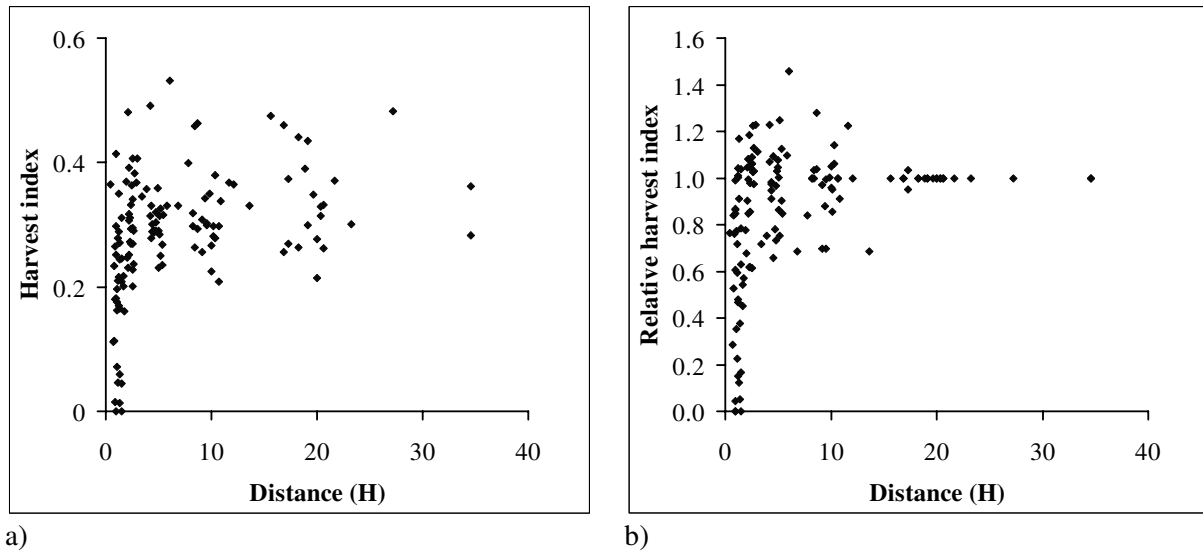


Figure 14. Harvest index (a) and relative harvest index (b) (harvest index/harvest index at 128 m) at distances away from the tree in tree heights (H).

6.3 Do the types of yield curve provide insight into the NYZ?

The sites were grouped into three classes according to their relative yield, with representative yield curves shown in Figure 15. The grouped yield curves are given in Appendix A.

1. Yield enhanced in the sheltered zone (2.5 to 10 H) – this yield enhancement may be greater than the yield loss in the competition zone
2. Yield peaks at close to 10 H, with no yield enhancement in the sheltered zone, which means there is an overall yield loss
3. Yield still increasing at the limit of measurement, indicating the open paddock yield may not have been reached

Significant yield enhancement (Type 1) occurred in 12 of 32 sites with yield enhancement in the sheltered zone resulting in a net yield increase in eight of the 32 sites. These included P4, BB1, BB2, Pa1, M1 and H2 in 2001, and P3b and P4b in 2002 (Table 4). A yield increase in the sheltered zone was offset by yield loss in the competition zone resulting in a net yield loss at L1, Pk1 and Mc1 in 2001 and BB1b in 2002.

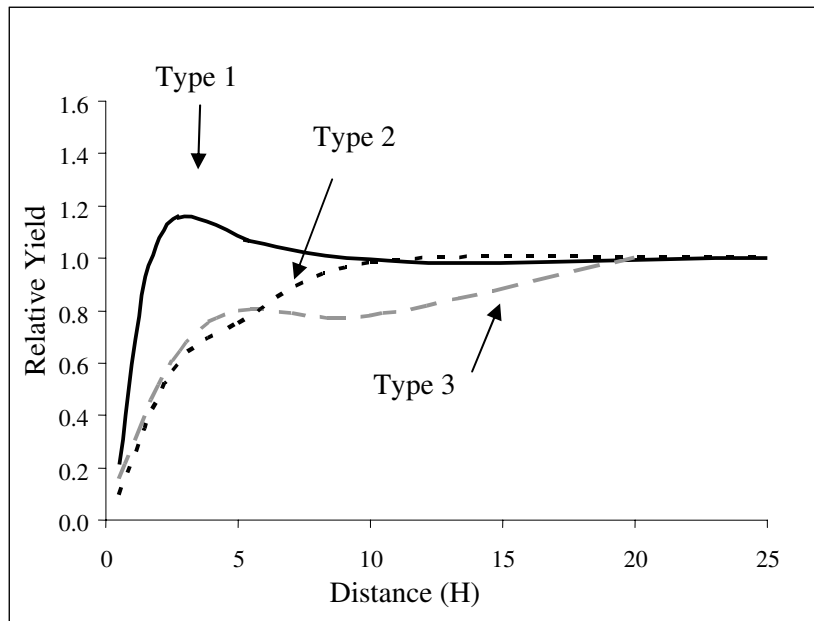


Figure 15. Representative yield curves for Types 1, 2 and 3.

Where there was yield enhancement in the sheltered zone between 2.5 and 10 H (Type 1 in Figure 15) the aspects were more often W, SW and S (Table 10). This indicated the trees were effectively able to shelter the crop from winds from the west, south west and southerly directions to enable some yield enhancement in the sheltered zone. A greater proportion of non-cereal crops sites (5 out of 9 sites with lupins and canola) had yield enhancement in the 2 to 10 H zone (Table 8). However, there was no clear trend with landscape positions, tree species or soil type.

The normal yield curves (or Type 2 in Figure 15), with a peak at around 10 H, which had an overall yield loss were: G3, Pa1, Pa3, C1, Mc2, P2 and Pa2 in 2001 and G3b, Pa2b and H1b in 2002. The majority of these sites were in the less favourable aspect class (sheltered from the east, north and north east).

The sites where the yield appeared to be still increasing (Type 3 in Figure 15) required more points at greater distances away from the tree belt to determine the yield pattern. At some sites the paddock width was less than 20 H due to a road or another tree which made it difficult to determine the open paddock yield. The normalised yield graphs, where the yield is divided by the yield at 128 m, reached 1 for the Type 3 curves but it is not possible to establish if it was the real open paddock yield.

The average NYZ increased from Type 1 to Type 3 yield curves. The Type 1 yield curve (enhanced yield) had an average NYZ of -5.5 m but had a wide range of -46.8 to 7.3 m. Type 2 (normal curves with a yield peak at 10 H) had an average NYZ of 16.8 m (ranging from 7.3 to 24 m). The Type 3 yield curve had the highest average NYZ of 25.3 m, ranging from 4.4 to 48.6 m.

Grouping the sites by their yield response curve gave some insight into the influences on the NYZ. For example, enhanced yield (Type 1 curve) was more likely if the aspect was south, south west, west or south east while the normal yield curves (Type 2) with a larger NYZ tended to be from sites with less favourable aspect.

Table 10. Sites classed by yield response curves.

Code	Origin	Year	Tree species	Position		Aspect ¹		Crop Species	Crop Type ²	Soil type	NYZ
Type 1 -Yield enhanced in the sheltered zone											
P4b	WA	2002	<i>E. populnea</i>	valley	low	SW	b	wheat	c	heavy duplex	-46.8
P3b	WA	2002	<i>E. sideroxylon</i>	valley	low	SW	b	wheat	c	light duplex	-16.9
P4	WA	2001	<i>E. populnea</i>	valley	low	SW	b	lupins	nc	heavy duplex	-11.6
H2	NSW	2001	<i>Pinus radiata</i>	lowslope	low	E	a	wheat	c	heavy duplex	-6.2
Pa1	WA	2001	<i>E. wandoo</i>	midslope	high	N	a	wheat	c	light duplex	-3.0
M1	NSW	2001	<i>Euc. spp.</i>	valley	low	E	a	wheat	c	heavy duplex	-1.9
BB2	WA	2001	<i>E. polybractea</i>	midslope	high	S	b	canola	nc	medium duplex	-1.5
BB1	WA	2001	<i>E. polybractea</i>	midslope	high	W	b	canola	nc	medium duplex	-0.9
Mc1	WA	2001	<i>E. polybractea</i>	lowslope	low	N	a	wheat	c	heavy duplex	0.7
L1	WA	2001	<i>C. proliferus</i>	midslope	high	W	b	barley	c	deep sand	4.24
Pk1	NSW	2001	<i>E. microcarpa</i>	valley	low	NE	a	canola	nc	heavy duplex	6.3
BB1b	WA	2002	<i>E. polybractea</i>	midslope	high	W	b	wheat	c	medium duplex	7.3
Average											-5.9
Type 2 - Yield peak at close to 10 tree heights											
G3	WA	2001	<i>C. proliferus</i>	midslope	high	E	a	wheat	c	deep sand	7.3
G3b	WA	2002	<i>C. proliferus</i>	midslope	high	E	a	wheat	c	deep sand	10.8
Pa1b	WA	2002	<i>E. wandoo</i>	midslope	high	N	a	barley	c	light duplex	11.9
Pa3	WA	2001	<i>E. camaldulensis</i>	lowslope	low	SE	b	wheat	c	light duplex	13.3
C1	WA	2001	<i>E. leucoxylon</i>	midslope	high	NE	a	lupins	nc	light duplex	15.8
Pa2b	WA	2002	<i>E. camaldulensis</i>	midslope	high	N	a	barley	c	heavy duplex	18.8
H1b	NSW	2002	<i>Pinus radiata</i>	valley	low	E	a	canola	nc	heavy duplex	21.0
Mc2	WA	2001	<i>Euc. spp.</i>	lowslope	low	W	b	wheat	c	heavy duplex	22.3
P2	WA	2001	<i>E. populnea</i>	valley	low	NE	a	wheat	c	heavy duplex	23
Pa2	WA	2001	<i>E. camaldulensis</i>	midslope	high	N	a	wheat	c	heavy duplex	24.0
Average											16.8
Type 3 - Yield still increasing at the limit of measurement											
G1	WA	2001	<i>Pinus radiata</i>	valley	low	SE	b	wheat	C	deep sand	4.4
C2	WA	2001	<i>E. leucoxylon</i>	midslope	high	SW	b	barley	C	light duplex	7.2
H1	NSW	2001	<i>Pinus radiata</i>	valley	low	E	a	pea	nc	heavy duplex	14.1
M1b	NSW	2002	<i>Euc. spp.</i>	valley	low	E	a	wheat	C	heavy duplex	17.6
BB2b	WA	2002	<i>E. polybractea</i>	midslope	high	S	b	wheat	C	medium duplex	20.5
P1	WA	2001	<i>E. sideroxylon</i>	valley	low	NE	a	wheat	C	light duplex	31.1
P3	WA	2001	<i>E. sideroxylon</i>	valley	low	SW	b	lupins	nc	light duplex	32.1
C1b	WA	2002	<i>E. leucoxylon</i>	midslope	high	NE	a	wheat	C	light duplex	35.5
H3	NSW	2001	<i>E. sideroxylon</i>	lowslope	low	E	a	canola	nc	heavy duplex	41.7
Pa3b	WA	2002	<i>E. camaldulensis</i>	lowslope	low	SE	b	barley	C	light duplex	48.6
Average											25.3

¹Aspect group: a = N, NW, NE, E; b = S, SW, SE, W²Crop Type: c = cereal; nc = non-cereal

6.4 Can we improve the estimated NRZ?

The measurement of LAI is time consuming and difficult, and a surrogate measure that could provide a rapid prediction of LAI is required to make the NRZ determination simpler. However, in this study there was not a strong relationship between the LAI and the more easily measured diameter at breast height for most species, with the exception of outer trees for three species (Figure 16 and Figure 29 Appendix C). Ellis *et al.* (1999, 2001) also found a weak relationship between the stem diameters and leaf area of the *Eucalyptus* species in that study ($r^2=0.54$). There was also a weak relationship between the average LAI_{outer}/LAI_{inner} and the average diameter at breast height_{outer/inner} (Figure 16). Therefore it appears that the NRZ cannot be estimated readily from the simpler diameter at breast height measurement.

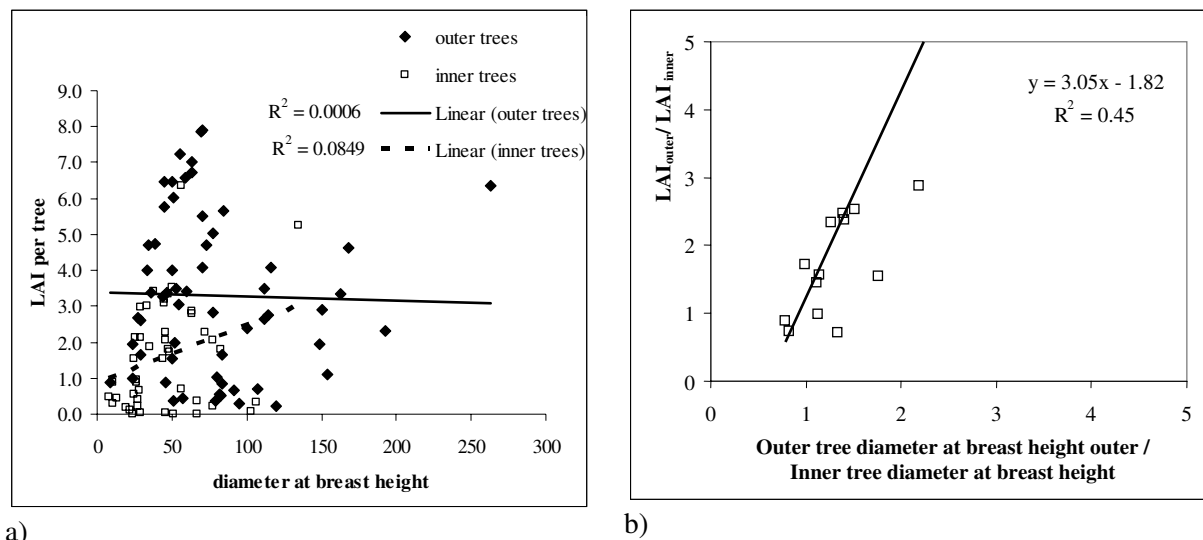


Figure 16. a) LAI per tree vs diameter at breast height for inner and outer trees, and b) The ratio of LAI for outer and inner belt vs the ratio of diameter at breast height for inner and outer trees.

The NRZ was also tested against EM38 readings of soil electrical conductivity for the WA sites, which has been suggested as an integrated measure of the environmental impact of the trees (Ellis pers comm.). A NRZ predicted from EM38 would assume that salinity is similar across the paddock, with possibly a higher concentration of salt near the trees, and any other changes in EM38 reading being due to changes in water content. However, a confusing range of EM38 responses were found at the WA sites. These have been grouped as low conductivity (Figure 17a), conductivity increasing away from the trees (Figure 17b), a small increase then decrease in conductivity away from trees (Figure 17c) and decreasing then increasing away from trees (Figure 17d).

The zone of influence of the trees can be visually estimated as extending 20 to 30 m (3 to 5 H) from the plateau in conductivity readings at four sites (Figure 17b). However, no clear patterns emerged from the other sites.

The high conductivity reading near the trees may be associated with higher accumulated salts due to transpiration by the trees, as the trees are between 14 and 16 years old, indicating the area which the trees are influencing recharge. It may also indicate the presence of a saline drainage line. The low conductivity readings are associated with lighter textured soil which included the deep sands, sand over sandy clay loam and sand over clay.

A further complication with this approach is that the two approaches to estimate the NRZ are based on methods that use data from different time scales. The LAI of the trees is an expression of adaptation to rainfall and environment over the past few years, whereas the electrical conductivity is influenced by the water content on the day, and the long term salinisation processes of the trees.

In short, it appears that the LAI will still have to be measured to enable prediction of the NRZ.

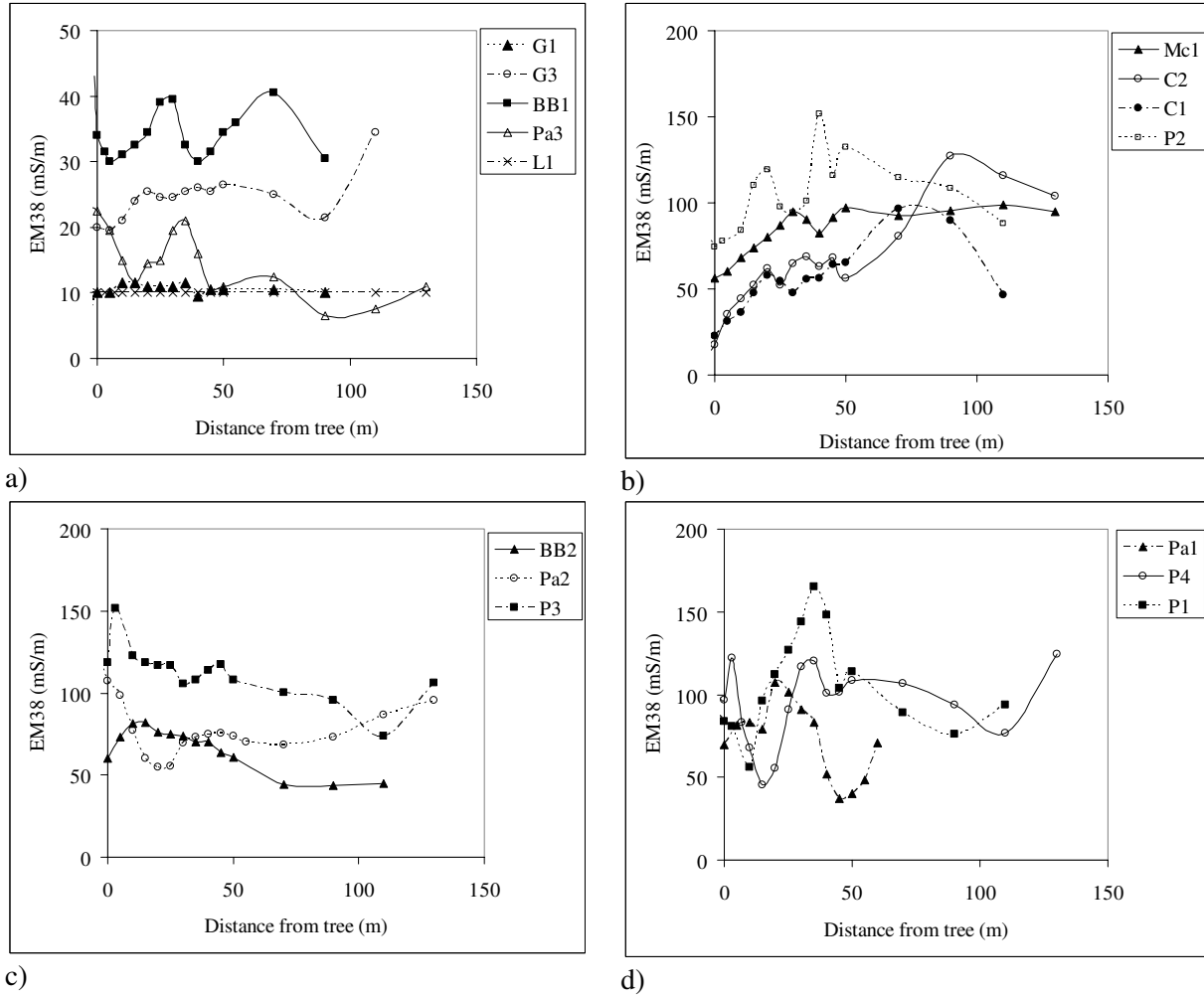


Figure 17. The soil electrical conductivity (mS/m) measured by EM38 vertical mode at distances away from the tree belts for (a) low conductivity, (b) conductivity increasing away from the trees, (c) small increasing in conductivity then decrease away from trees and (d) decreasing then increasing away from trees.

6.5 Introducing opportunity cost into the Complementarity Index

A weakness of the Complementarity Index (CI) is that it combines two very different effects of trees, their influence on crop growth and on subsoil water, but does not reflect the fact that these effects are valued very differently. While the impact of trees on the value of crop production is fairly easily determined, it is very difficult to place a value on their role in managing recharge. Apart from a few case studies in NSW testing the payment for ecosystem services, landholders are not rewarded for managing recharge. While the CI expresses the relative influence of trees on crops and water in terms of the area of land affected, landholders making decisions about agroforestry will be influenced to a far greater extent by the absolute impact of trees on their income.

To give an indication of the opportunity cost of using trees for water management, this section presents estimated gross margin change and recharge reduction for the 32 sites. The assumptions used in calculating gross margins and recharge reduction were as follows. Tree belts were assumed to be part of an alley system with belts 15 m wide-spaced 100 m apart, leaving 85 m of arable land. The gross margin calculations used on-farm prices of \$180/t for barley, \$190/t for wheat, \$195/t for lupins, \$210/t for peas and \$385/t for canola with variable costs of \$180/ha. Recharge reduction and net yield were based on Equations 11 and 12 below. The NYZ and NRZ were doubled to incorporate the impact of tree belts on either side of the arable land between two tree belts.

$$\% \text{ recharge reduction} = \frac{(2 \times \text{NRZ} + \text{belt width})}{\text{tree spacing}} \quad (11)$$

$$\text{adjusted yield} = \frac{[\text{tree spacing} - (2 \times \text{NYZ} + \text{belt width})] \times \text{open paddock yield}}{\text{tree spacing}} \quad (12)$$

The results are presented in three classes based on the degree of trade-off required to achieve particular recharge reduction target (Figure 18 and Table 11). The first class (Group A) consists of the four sites at which the gross margin increased in the presence of trees and recharge was estimated to be reduced by more than 30%. The average for these sites was a 60% reduction in recharge with a gross margin increase of \$40/ha. This varied from an increase of \$7/ha in 2001 to \$70/ha in 2002, with the recharge reduction being similar in both years.

The second class (Group B) consisted of nine sites at which the gross margin fell by less than \$120 and recharge was estimated to be reduced by more than 30%. The average for these sites was a 50% reduction in recharge at an opportunity cost of \$73/ha, varying from \$72 in 2001 to \$77 in 2002. The majority of sites (19) fell into the least favourable class (Group C) where either the gross margin fell by more than \$100 or recharge was estimated to be reduced by less than 30%. The average for these sites was a 37% reduction in recharge at a cost of \$198/ha.

Across all sites, the average trade-off was -\$133/ha reduction in gross margin for a 42% reduction in recharge, with the results proved relatively insensitive to changes in variable costs.

The factors identified in Part 5 as most likely to produce a favourable yield-recharge trade-off on an area basis also featured strongly when the impact was expressed in economic terms (Group A, Table 11.) In other words, the integration of trees into cropping systems for water management is more likely to be profitable where trees are older (>10 years), planted on water gaining sites with heavier soils in low rainfall areas (<400 mm); and in Western Australia where crops are protected from the west to south east.

While this study examined a range of tree-crop interfaces over a wide geographical area, the data only covers two years, one of which was a drought at virtually all sites. When making decisions about the adoption of agroforestry however, it is important to have some idea of the likely impact of trees over a

range of seasonal conditions given the inflexible nature of the technology. Carberry *et al.* (2002a) modelled grain yield and gross margin for 11 sites over 30 years based on experimental data on crop production in the lee of windbreaks from a smaller number of experimental sites around Australia. In comparison with this study, their modelling suggested a far narrower range in gross margin change as a result of adding trees to a cropping paddock ($\pm \$20/\text{ha}$) with a mean change of only $-\$2.50/\text{ha}$.

This was primarily due to the assumptions involved in their modelling. As only one side of a tree belt was considered to a distance of 100 m, this equated to having tree belts 200 m apart. In addition the belts were assumed to occupy one tree height on the paddock (equivalent to 10 m for our sites, compared to 15 m in our economic analysis), competition was assumed to result in a set 20% yield loss in the first 3.5 H (with up to 40% yield loss extending over a larger distance in this study), and a set 4.6% yield gain at 5 H was assumed for all sites in all years (compared to a mean 2% yield loss in this study). In other words the modelling was more favourable for crop production but the agroforestry systems would have had a smaller hydrological impact due to the wider spacing between belts.

In summary, while only four of the 32 sites showed an improvement in estimated returns from better water management, those sites tended to share some common features: older trees (>10 years), water gaining sites, heavier soils, low rainfall areas (<400 mm); and in Western Australia with crop protection from the west to south east. The addition of trees to these sites all produced a negative NYZ of approximately 1 H or better (0.7-7.5), indicating the effective area of extra land contributed by the yield enhancement effect of the trees.

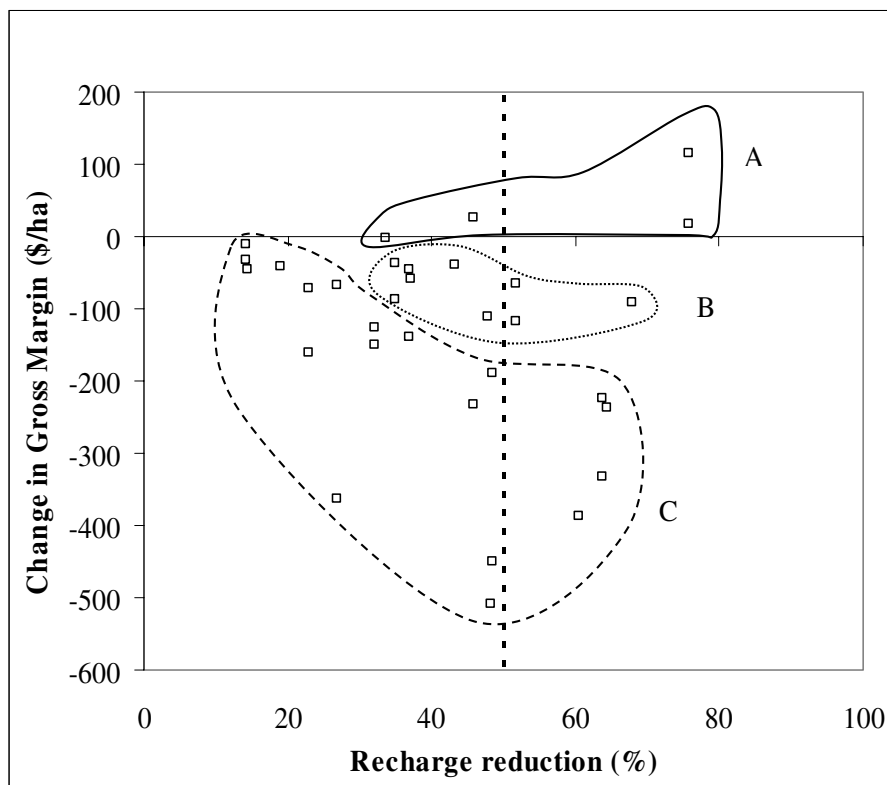


Figure 18. Change in crop Gross Margin (\$/ha) for a given level of recharge reduction (%) for 32 tree-crop interfaces. Group A are those sites with a Gross Margin increase *and* greater than 30% reduction in recharge; Group B are those sites with a Gross Margin loss of less than \$120/ha *and* greater than 30% reduction in recharge; Group C are those sites with a Gross Margin loss of greater than \$100/ha *or* less than 30% reduction in recharge.

Table 11. Sites ranked by Gross Margin and % recharge reduction showing their status with respect to the five factors most likely to produce a favourable yield-recharge relationship (water gaining sites, W-SE aspect, older trees and low rainfall).

Code	Gross Margin difference (\$)	% recharge reduction	Water gaining sites	W-SE aspect	Older trees	Low rainfall
Gross margin increase <i>and</i> >30% drainage reduction						
P4b	114.5	75.8	✓	✓	✓	✓
P3b	25.2	45.9		✓	✓	✓
P4	17.4	75.8	✓	✓	✓	✓
H2	-2.9	33.8	✓		✓	
Gross Margin loss <\$120 <i>and</i> >30% drainage reduction						
H1	-36.2	35.0			✓	
L1	-38.0	43.3	-	✓		✓
Pa1	-45.6	37.0	✓		✓	
Mc1	-59.2	37.0	✓			✓
G3b	-66.2	51.8	✓			✓
H1b	-87.8	35.0			✓	
G1	-90.7	67.9	✓	✓		✓
C2	-111.1	47.7		✓	✓	✓
G3	-118.2	51.8	✓			✓
Gross margin loss >\$120 <i>or</i> <30% recharge reduction						
M1b	-10.0	14.1			✓	
M1	-31.6	14.1			✓	
H3	-44.9	14.3	✓		✓	
BB2	-66.6	26.9	✓	✓		
Pk1	-42.4	19.0			✓	
BB1	-71.0	22.9	✓	✓		
C1b	-125.0	32.0			✓	✓
Pa1b	-139.5	37.0	✓		✓	
C1	-149.7	32.0			✓	✓
BB1b	-161.3	22.9	✓	✓		
Pa2b	-189.3	48.4	✓		✓	
Pa3	-224.5	63.7	-	✓	✓	
P3	-231.9	45.9		✓	✓	✓
Mc2	-237.5	64.4	-	✓		
Pa3b	-333.6	63.7	-	✓	✓	
BB2b	-363.6	26.9	✓	✓		
P2	-386.2	60.4	✓		✓	✓
Pa2	-449.3	48.4	✓		✓	
P1	-509.2	48.2			✓	✓



4 out of 4 attributes



3 out of 4 attributes

-

Could not determine the water gaining site attribute as no inner tree row

7. Modelling the tree-crop interactions with APSIM

The APSIM agricultural systems model (McCown et al, 1996) has recently been adapted to investigate the seasonal variation in crop yield adjacent to trees. APSIM's component-based design allows individual models to communicate via a common communications engine. At present, over twenty individual crop and pasture models are available within APSIM for use in simulating diverse farming systems. These crop modules communicate with existing modules for simulating soil processes such as carbon, nitrogen and phosphorous cycling, surface residue dynamics, water and solute fluxes, soil temperature, and soil acidity. Recent developments in the capability of the APSIM model allow for the simulation of tree growth, resource use (Huth et al, 2001) and competition with neighbouring crops (Carberry et al, 2002, Huth et al 2002). In the following case study, APSIM was configured for a hypothetical tree-crop farming system based on data from the Broomehill site in Western Australia.

7.1 Configuring the APSIM model

A simple agroforestry system was simulated for the Broomehill site in WA. (-33.85oS, 117.64oE) in which a winter wheat crop is grown adjacent to a belt of trees each year between 1957 and 2002. Each wheat crop was planted after 12 mm rainfall had been recorded over a 3 day period between the 1st of May and 30th of June. A split application of fertilizer was added (55 kg/ha at sowing, 30 kg/ha in mid-July) to reflect the amount of nitrogen likely to be supplied or available to the crop through mineralisation of residues from legume crops or pasture phases in a preceding season.

A duplex soil was used with 30 cm of sand overlying a heavy clay with approximately 67 mm of plant available water to the maximum wheat rooting depth of 0.6 m. The sand had a bulk density was 1.7 g/cm³, a drainage upper limit of 0.14 cm³/cm³ and a 15 bar moisture content of 0.04 cm³/cm³. The clay had a bulk density was 1.3 g/cm³, a drainage upper limit of 0.35 cm³/cm³ and a 15 bar moisture content of 0.18 cm³/cm³. Climatic data from 1/1/1957 to 31/12/2002 for this location was obtained from Patched-point Meteorological Data (Queensland Department of Natural Resources, 1999. <http://www.dnr.qld.gov.au/silo>). The leaf area and height of the trees were assumed to remain static through time to enable comparisons to be made with the field data over the full simulation period. The trees were set at 6m in height and the leaf area index of outer and inner trees at 4.0 and 2.0 respectively. The No-Yield-Zone (NYZ) was set at 3 tree heights (or 18 m).

The model structure employed in this analysis follows that described by Huth et al (2002). APSIM was set up to consist of a main driving system with an array of subsystems representing points along a two-dimensional transect away from the trees. The two dimensions being simultaneously simulated were (i) the horizontal flows of wind, water and nitrogen between adjacent points represented by an inner tree block, an outer tree area and a series of points in the cropped area, and (ii) the vertical flows of water, nitrogen and carbon between plants and the soil at each point along the transect. Seventeen points were included in the analysis representing inner trees, outer trees and fifteen in the cropping area lying within 75m of the tree belt. Seven of these were in the first three tree heights and a further eight between three and twelve tree heights.

7.2 Simulation results

Transects of simulated grain yield out to 75 m from the trees are shown for each season from 1957 to 2002 in Figure 19. The pronounced depression in grain production next to the trees (within three tree heights) is due to competition for water and nitrogen by the trees. While the level of competition varies seasonally according to the amount and timing of resource availability, the relative yield loss is fairly constant at 48% within the first three tree heights. This corresponds to a 7 % yield loss over the

128m transect used in the field study, or a NYZ of 9 m. This compares with an average 15% yield loss and an average NYZ of 19 m recorded in the two years of the field study at the Broomehill sites.

As average daily wind speed information was not available for the site, a simple representative value was used for each day in the simulation to capture variation in wind speed and direction, however this produced no significant enhancement of growth in the sheltered zone near the trees due to a modified microclimate.

The lack of any yield enhancement due to shelter effects does however enable a comparison to be made of crop yield with and without trees by examining production within the competition zone. With trees 6 m in height and competition set to a distance of 3 tree heights, we can compare the probability distribution for open paddock yield with average yield values within the first 18m from the trees. Figure 20 shows cumulative probability functions for the open paddock yield and the average yield within the tree's competition zone.

The competition for resources by the trees constrains production in the tree-crop system to a much smaller range of between 0.5 and 2.5 t/ha compared to a range of 1 to 5 t/ha without trees. The divergence in the two yield functions indicates the high penalty paid for having trees in the more favourable seasons.

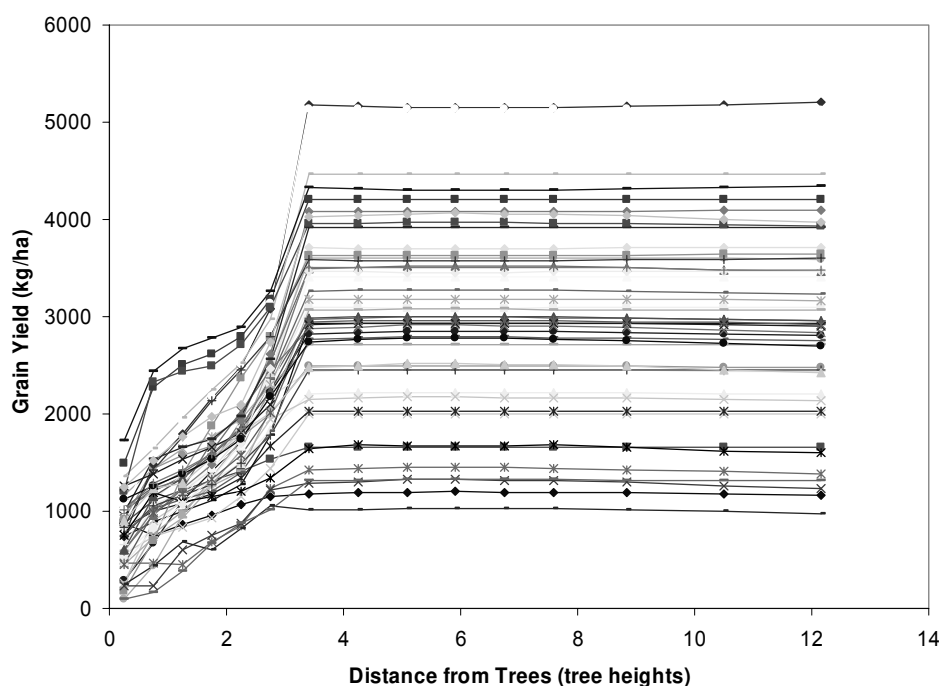


Figure 19. Transects of grain yield for 1957-2002.

It is interesting to compare the results of this simulation with those obtained in previously published analyses of tree-crop systems. Simulation of agroforestry systems in SE Queensland (Huth et al, 2001, 2002 and Carberry et al, 2002) indicated the importance of soil water uptake by trees during the fallow periods preceding a winter crop. Features of agricultural systems in SE Queensland are deep clay soils and summer dominant rainfall. As a result, large amounts (up to 300mm) can be stored in a soil profile during a summer fallow period and be available for use by a subsequent winter crop. This simulation in contrast involves a shallow duplex soil and winter dominant rainfall, with much lower soil water storage during the summer.

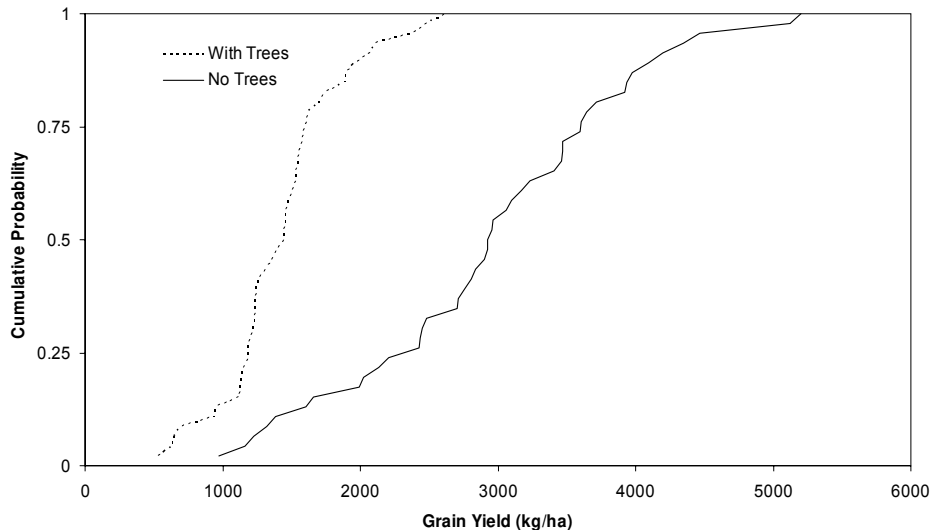


Figure 20. Cumulative probability distribution functions for the open paddock and competition zone for 1957 to 2002.

This difference can be seen in Figure 21 which shows the variation in stored soil water. Whereas Huth et al (2001) indicated differences due to soil water storage over summer of up to 300mm in a simulation of tree-crop systems in SE Queensland, the variation in this Western Australian example is in the order of 20-30mm. As the Western Australian cropping system features excess water during the early part of the growing system, the effects of trees on pre-season on water balance may not be as important as their influence on nutrient availability.

Periods of high soil water content can lead to losses of nitrate in the soil due to leaching or denitrification. Previous analyses with the APSIM framework for *Eucalyptus globulus* trees adjacent to winter crops in the Esperance area of Western Australia (Carberry et al, 2002) showed that competition for nitrogen by the fast-growing Eucalypts was often more important on the nutrient-poor deep sands in that area than competition for water. If paddock yields are limited by low levels of nutrients, the availability of water may become less important. A simple analysis was performed with APSIM to evaluate the importance of modifications of the water balance by trees on the subsequent nitrogen balance. The APSIM simulation was configured as described above but with nitrogen uptake by the trees removed from the calculations. The results can be seen in Figure 22.

This shows the effect of drier soil conditions near the trees on the subsequent nitrogen balance and crop production. Reducing the amount of nitrate lost through leaching and denitrification enhances the crop yield to various degrees depending on the nature of the individual season. Whereas the average effective No-Yield-Zone was 9 m for the first simulation, it was reduced to about 2.4 m in this simulation due to a reduction in nitrogen competition between trees and crops in those seasons in those years in which significant nitrogen losses would otherwise have occurred. This simulation highlights the complex interactions that are likely to underlie the patterns of competition observed in the field.

7.3 Summary

A limitation of this modelling approach apparent in this case study was the assumption that the competition zone invariably extends 3 tree heights from the tree belt. This assumption was based on a study of tree-crop interactions on the Darling Downs that was used to calibrate the APSIM tree module. While the APSIM model was capable of predicting the yield loss in the competition zone and the yield maximum outside the competition zone, it could not account for variability in the No-Yield-Zone observed in the field. In summary, APSIM in its present form is not capable of reflecting the

complex interactions between annual and perennial components in an agroforestry system, in particular simulating the yield increases observed within the sheltered zone.

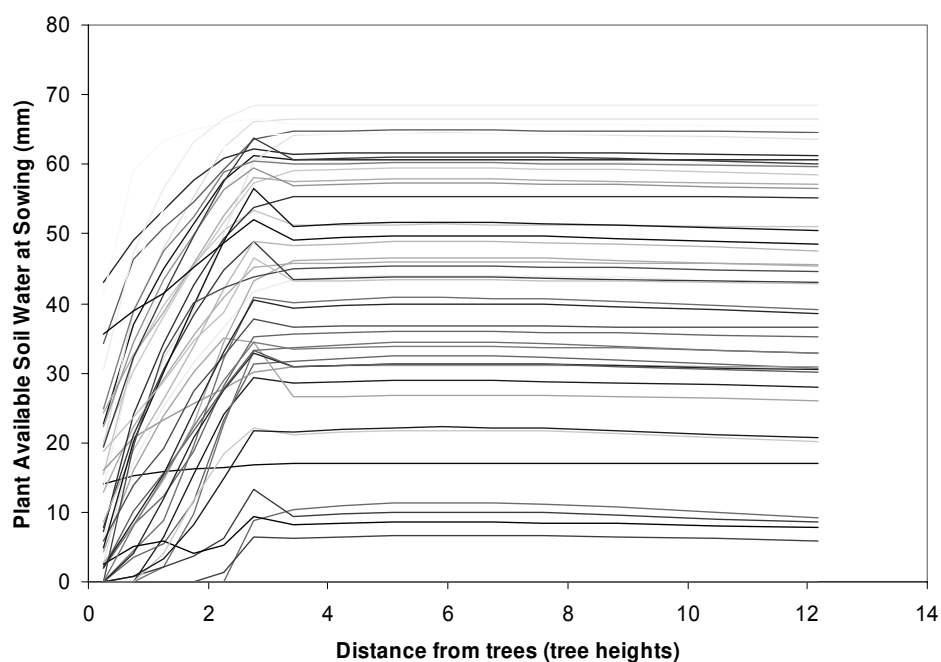


Figure 21. Transects of plant available soil water content at sowing for 1957 to 2002.

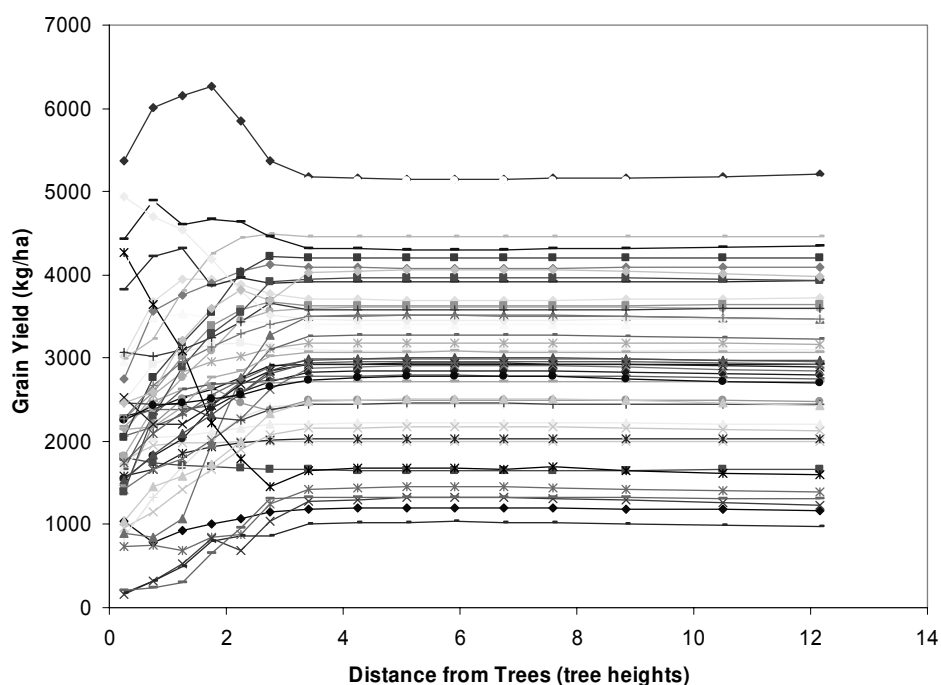


Figure 22. Transects of crop yields from 1957 to 2002 with nitrogen uptake by trees removed from the calculations.

8. Discussion

This project started out with the aim of applying a simple index to quantitatively express the trade-off between loss of crop yield and gains in water management resulting from the addition of trees to cropping systems. This index, proposed by Stirzaker *et al* (2002) is the ratio of two integrals, the distance over which trees reduce drainage and crop yield to zero. The approach of using these integrals, the No-Yield and No-Recharge Zones, was proposed as a means of overcoming the problem of dealing with the immense number of potential interactions between the large number of site and system characteristics that influence tree and crop growth. In applying this index to 32 case studies of tree-crop interactions across Southern Australia, we came to the conclusions that the trade-off between production and resource conservation is best represented by keeping the two integrals separate rather than deriving a single index, and that crop production is most meaningfully expressed in terms of value rather than physical yield in determining trade-offs between production and conservation. We also set out to identify short hand measures of system functioning that integrate resource use and productivity over time and space that could be easily measured. This section sets out how we came to these conclusion and recommends an approach to assessing trade-off in integrated agroforestry systems.

8.1 The Complementarity Index

The idea of a Complementarity Index was based on the observation that competition at the tree crop interface tended to be the norm, but in certain circumstances depending on the tree species, crop type, site characteristics, or climatic conditions, complementarity between tree and crop could occur. In these situations there is a win-win opportunity to improve the management of soil water using trees and either increase or at least maintain the same crop yield as the open paddock situation. This project therefore set out to observe where such complementarity occurs, to quantify the degree of complementarity, and use the particular features of those sites to predict under what circumstances it is more likely to occur and how to capture complementarity in agroforestry designs. Hence the idea of a complementarity index based on the ratio of the lateral distance over which trees effectively reduce recharge to zero to the distance over which they reduce yield to zero.

Ironically however, the very act of combining these two measures of the influence of trees into a single index removed the ability to identify those situations where complementarity occurred. This is because the Complementarity Index cannot be calculated for those sites where there is a net yield increase as it is based on the assumption that competition always exists, and becomes meaningless where the No-Yield-Zone is negative (i.e., where the trees improve crop yield, see Table 7).

Where the Complementarity Index is greater than one, trees are preventing recharge over a greater area of land than they are reducing yield and a positive trade-off between water management and yield occurs (Table 7, Figure 11). This was found to be the case at 9 of the 32 sites in this study. Where the Complementarity Index is less than one, trees are preventing recharge over a smaller area of land than they are causing a yield penalty and a negative trade-off occurs between water management and yield (Table 7, Figure 11). This situation occurred at 15 sites. At the remaining 8 of the 32 sites, crop yield increased in response to the presence of trees. These are potentially the most interesting sites, but as a yield increase produces a negative No-Yield-Zone, the Complementarity Index could not be calculated and therefore the degree of complementarity at these sites cannot be expressed.

One of the major flaws in the concept of a Complementarity Index is the fact that the distance (or area) over which trees influence crop yield does not reflect the value of that influence, value being a function of crop type and price.

To overcome this problem, we identified the degree of complementarity occurring between the objectives of profitable crop yield and sustainable water management by plotting the economic impact of the trees against their estimated hydrologic influence (Figure 18). This showed that of the 32 tree-crop interfaces studied, the win-win situation of a gross margin increase *and* a reduction in recharge occurred at only 4 sites. At a further 9 sites, a better than 30% reduction in recharge was achieved at a cost of a gross margin loss of under \$120/ha, while at the majority of sites (19) there was a less than 30% reduction in recharge at the cost of a gross margin loss of over \$100/ha ha.

A further problem with the Complementarity Index is that the time scales over which the two components of the ratio are measured are very different. The influence of the trees on crops is based on yield data measured annually and is subject primarily to climatic variation, while the influence of the trees on recharge is based on measurement of leaf area which integrates growth over several seasons. This problem affects any comparison of yield and recharge effects of trees, but is compounded when the two measures are combined in one index.

In short, a more effective assessment can be made of complementarity in an agroforestry system by keeping measures of the yield and recharge effects separate than by combining them in an index either as the No-Recharge-Zone or percent reduction in recharge and the % change in yield or change in gross margin.

8.2 The No-Recharge-Zone

The concept of a No-Recharge-Zone is based on the hypothesis by Ellis that the difference in LAI between inner and outer trees in a belt provides a measure of the hydrologic impact of that tree belt, based on the assumption that the outer row has access to soil water beneath adjacent crops or pastures. While this concept has been empirically tested by Ellis *et al.* (1999) and Robinson *et al.* (2002), there was no empirical test used in this study which was a survey of a large number of sites aimed to provide generalisations and design guidelines for alley cropping and other closely integrated agroforestry systems.

In this study, the site and system characteristics associated with a large No-Recharge-Zone were found to be (in order of significance)

1. Older trees (< 10 years)
2. Heavier soils
3. Lower rainfall (<400 mm)
4. Crops protected from the West, South West, South, and South East.

The major weakness encountered with the No-Recharge-Zone approach was the difficulty of finding surrogate measures of leaf area.

8.3 The No-Yield-Zone

In comparison with the No-Recharge-Zone, the No-Yield-Zone is easy to measure, but again we encountered difficulty in finding a simple and effective surrogate measure. Tree height proved to be a poor predictor of the size of the No-Yield-Zone in this study with an R^2 of 0.14, whereas Carberry *et al.* (2002) reported an R^2 of 0.86 in their study of tree belts on the Darling Downs. This may reflect soil type and other regional differences given that this study included a highly variable collection of sites from the grain belts of Western Australia and NSW.

The site and systems features likely to reduce the size of the No-Yield-Zone or result in yield enhancement were found to be (in order of significance)

1. Water gaining sites (access to perched water tables or run-on water)
2. Crops protected from the West, South West, South or South East (particularly for WA)
3. Heavier soil types

8.4 Conclusions

Complementarity between the goals of water management and profit in an agroforestry system is best expressed through comparison of gross margin and estimated recharge reduction rather than the use of a ratio or index that combines these two effects of trees on cropping systems.

The search for simply measured integrals of system functioning still has some way to go. In this study we found that tree height was a poor predictor of crop yield. Similarly tree basal area, which is simply measured and often found to be a good predictor leaf area within a species, was a poor predictor of leaf area across the wide range of species involved in this study.

Seasonal conditions had a strong influence on the complementarity between water management and yield, with some sites being in positive trade-off in one year and negative trade-off in the other. As agroforestry systems are long lived and therefore relatively inflexible to management, further modelling work would be required to produce a probabilistic prediction of trade-off over time. Despite the strong influence of seasonal conditions, the combination of factors found to most likely minimise competition with crops and maximise recharge management were found to be (in order of significance).

1. Water gaining sites (access to perched water tables or run-on water)
2. Protection of crops from the West, South West, South or South East
3. Tree age (> 10 years)
4. Lower rainfall (<400 mm),

9. Appendices

Appendix A. Type 1, Type 2 and Type 3 yield curves.

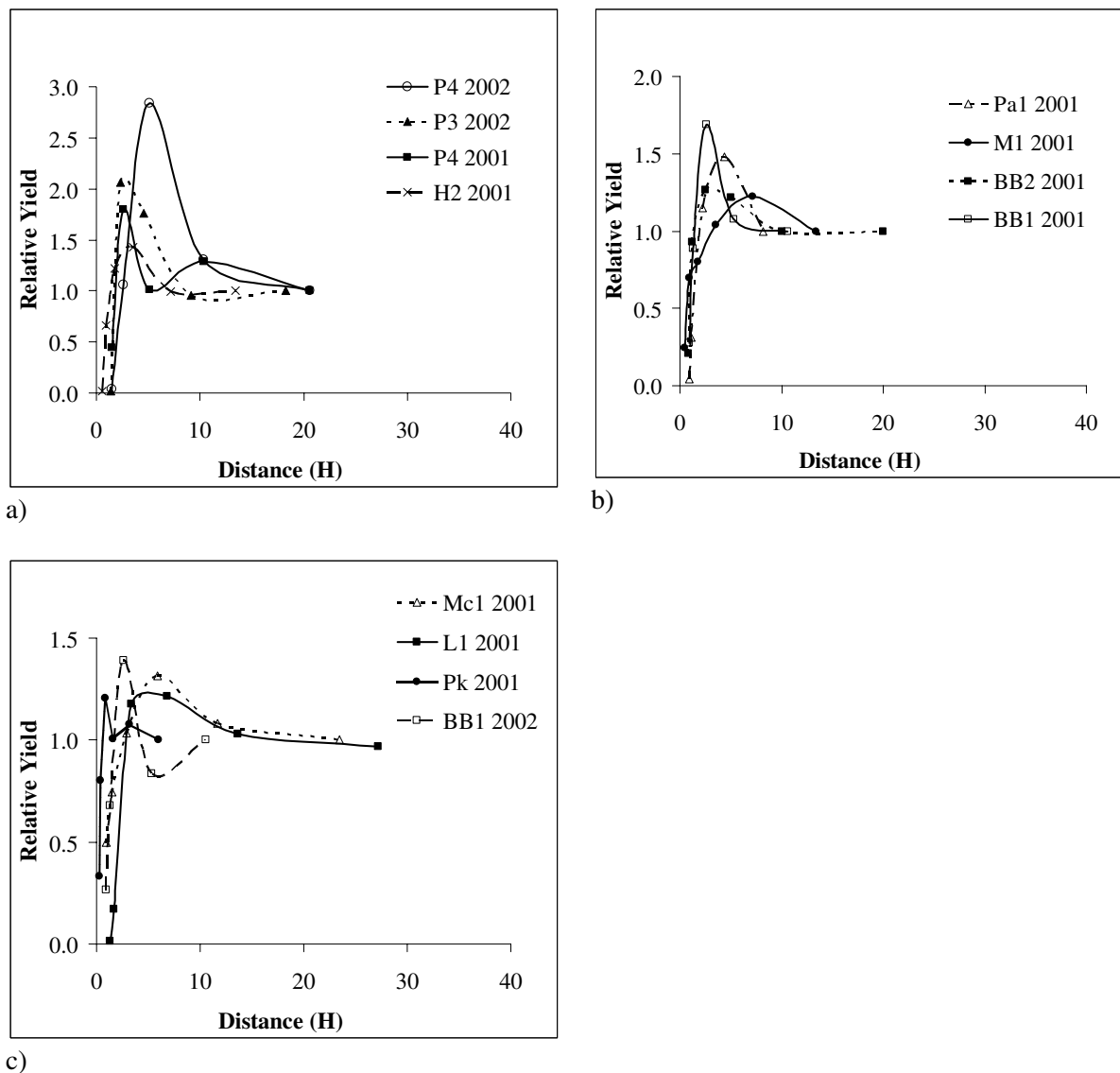


Figure 23. Relative yield at distances away from the tree belt (in tree heights) for Type 1 yield curves, with yield enhancement in the sheltered zone (2.5 to 10 H). The sites were split into three graphs for visual ease.

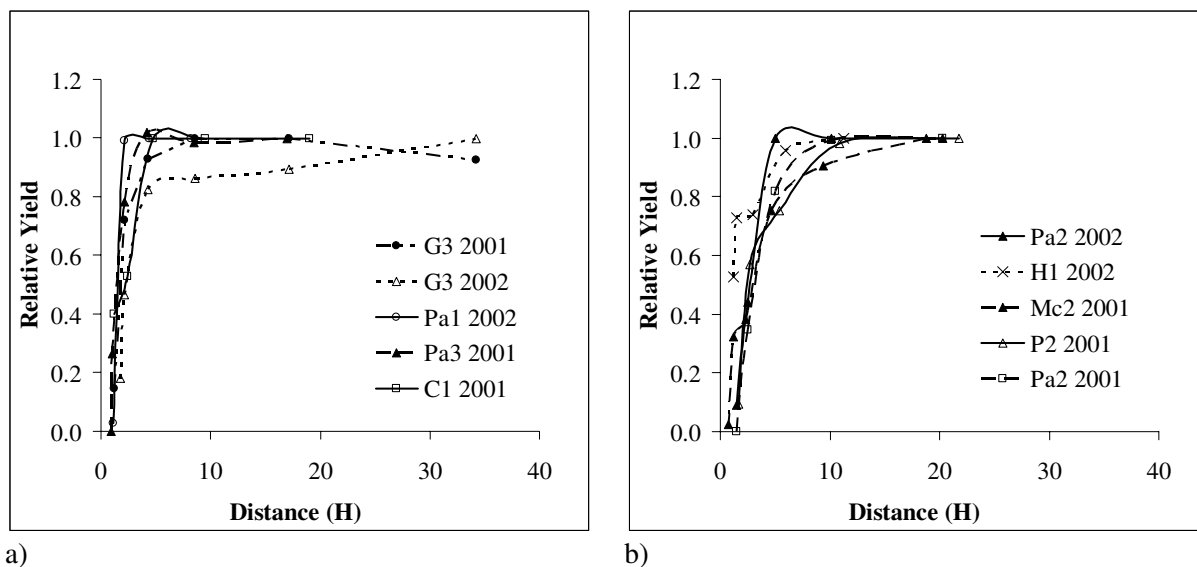


Figure 24. Relative yield at distances away from the tree belt (in tree heights) for Type 2 yield curves, with a yield maximum at 10 H, yield loss in the competition zone and no yield enhancement in the sheltered zone.

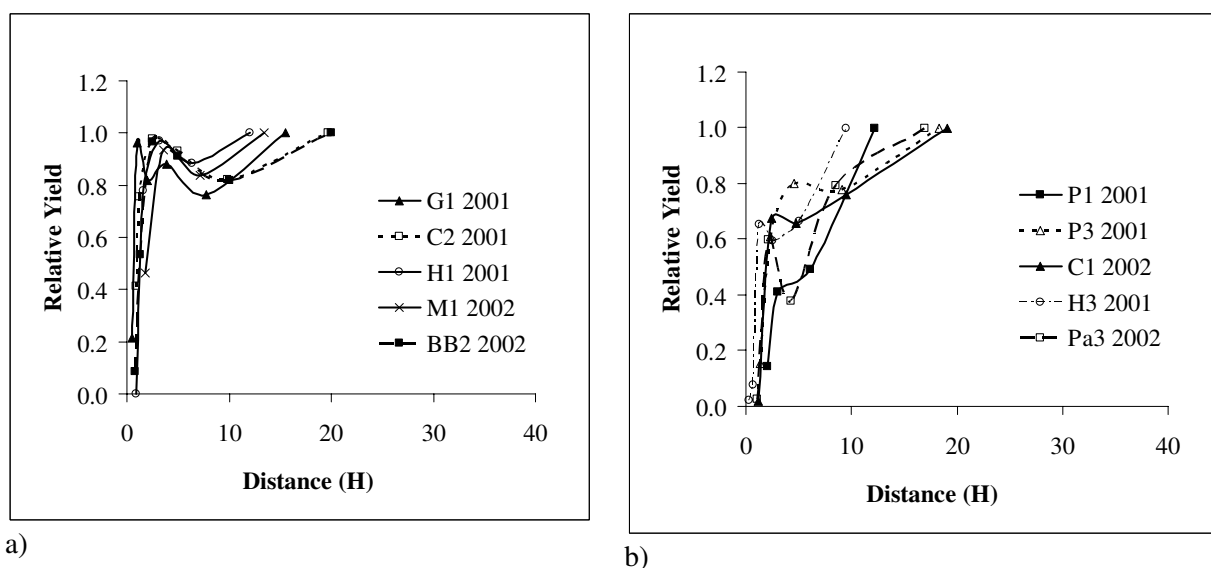


Figure 25. Relative yield at distances away from the tree belt (in tree heights) for Type 3 yield curves, where yield is increasing and has not reached a plateau.

Appendix B. Average yield graphs.

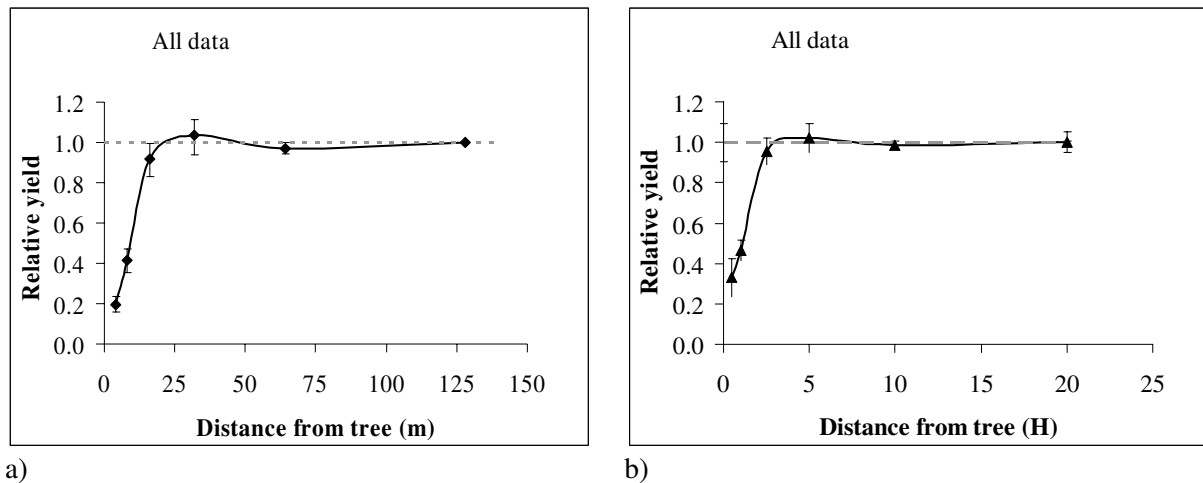


Figure 26. The average relative yield for all sites in 2001 and 2002 at distances away from the trees in (a) metres and (b) tree heights.

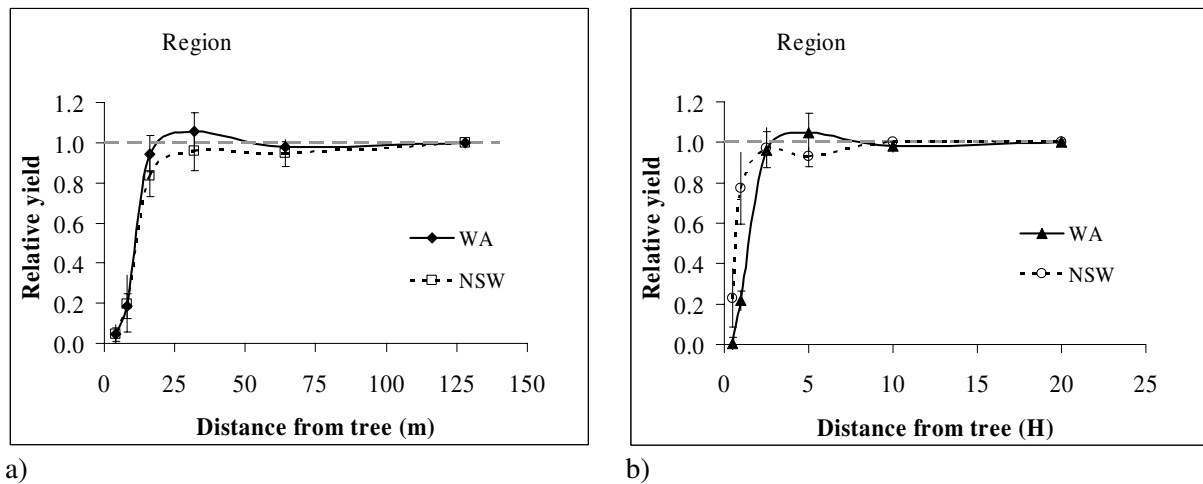


Figure 27. The average relative yield for WA sites and NSW sites at distances away from the trees in (a) metres and (b) tree heights.

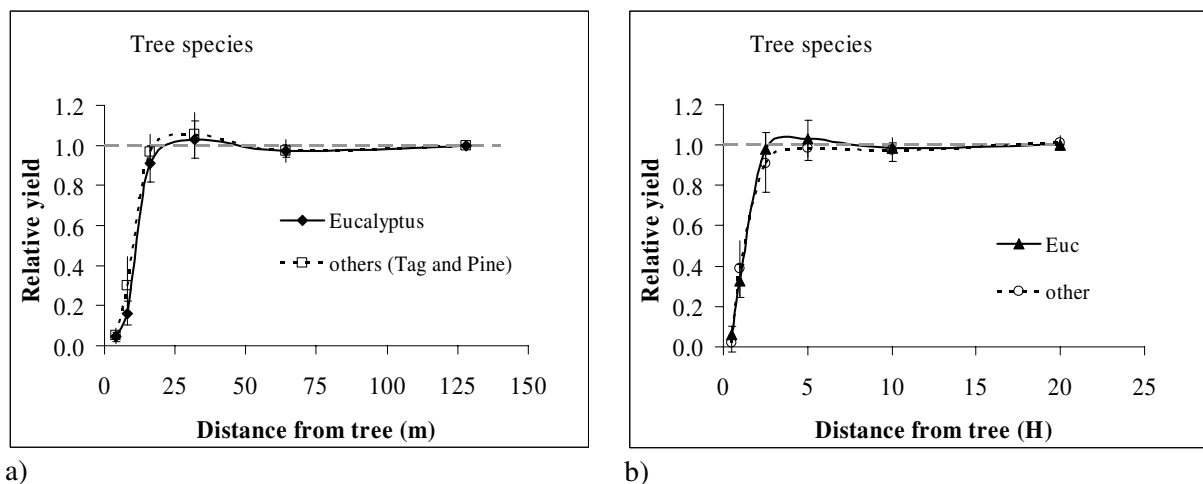


Figure 28. The average relative yield for Eucalypt and other tree species (tagasaste and pine) at distances away from the trees in (a) metres and (b) tree heights.

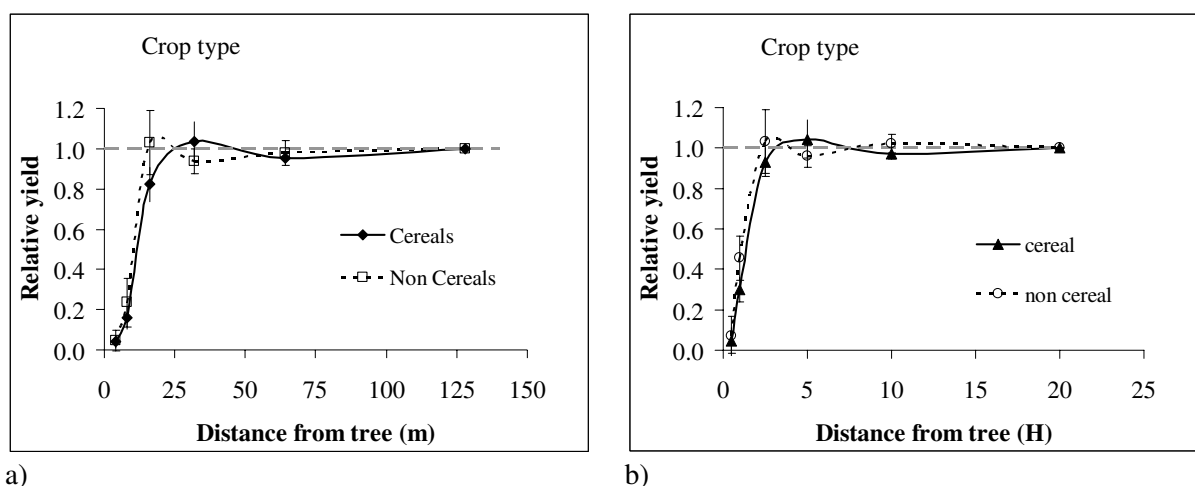


Figure 29. The average relative yield for cereals (wheat and barley) and non-cereals (lupins, canola, pea) at distances away from the trees in (a) metres and (b) tree heights.

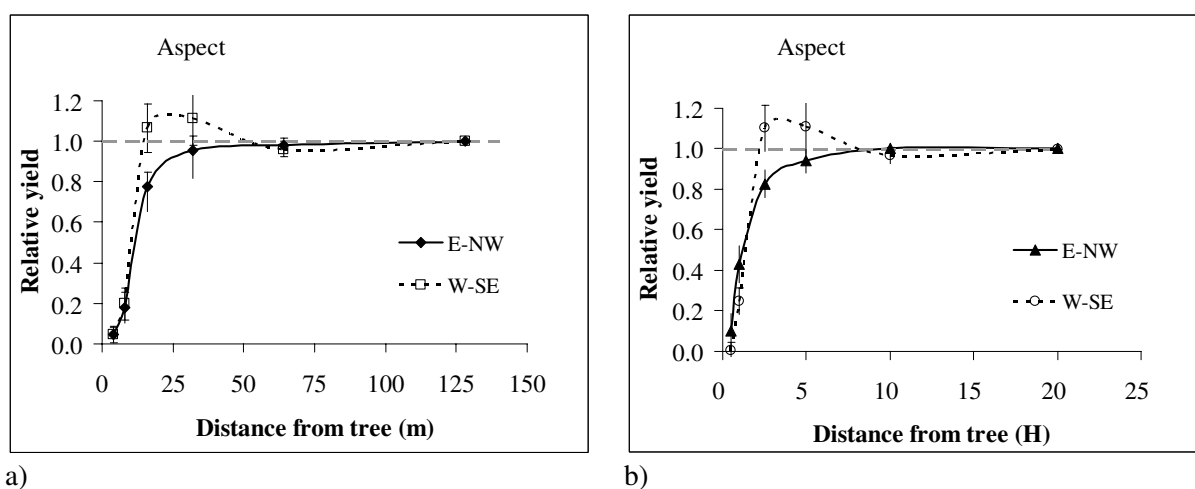


Figure 30. The average relative yield for aspect class (E-NW) protecting from the east, north east, north or north west and (W-SE) protecting from the west, south west, south or south east at distances away from the trees in (a) metres and (b) tree heights.

Appendix C. Relationships between measured tree parameters.

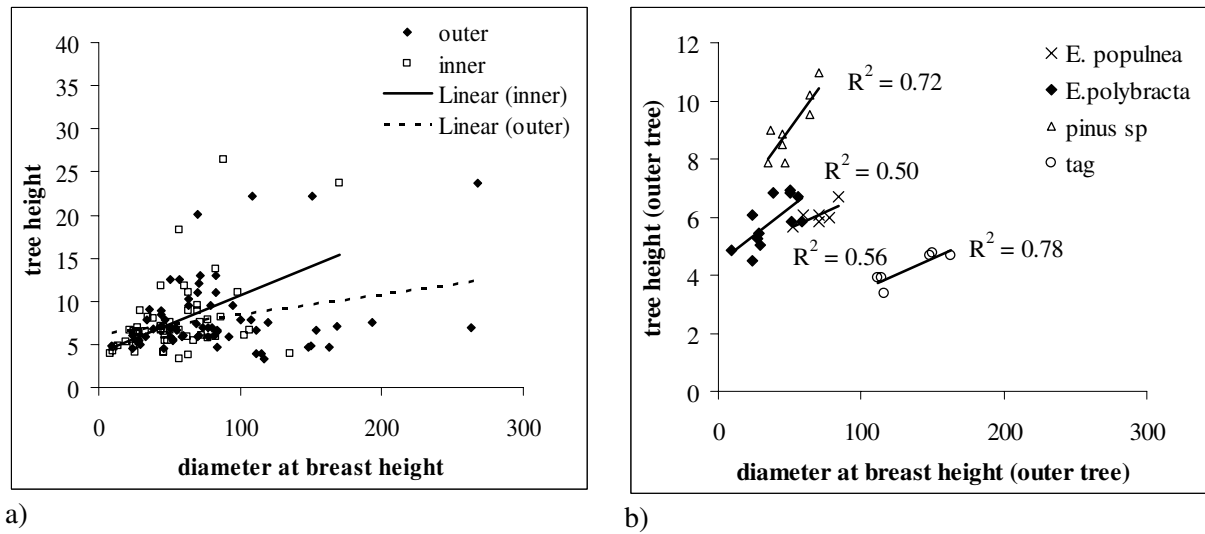


Figure 31. Diameter at breast height vs tree height for (a) all the sites and (b) trends within four selected species.

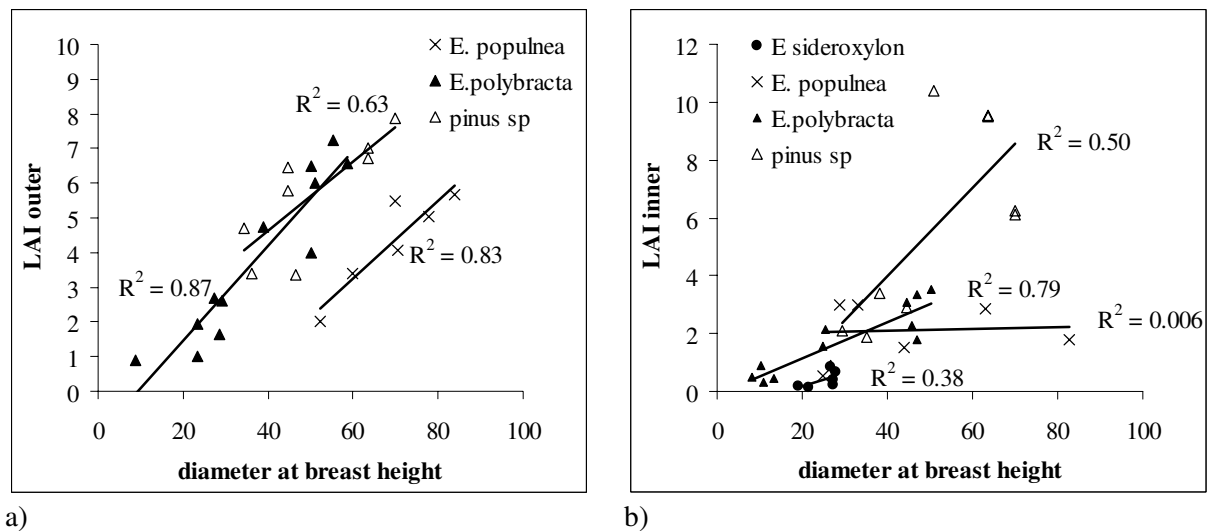
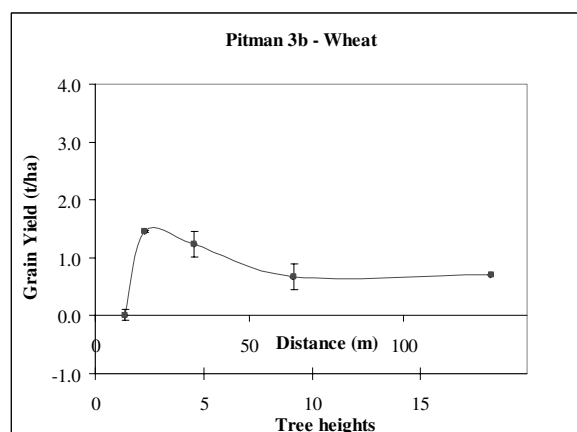
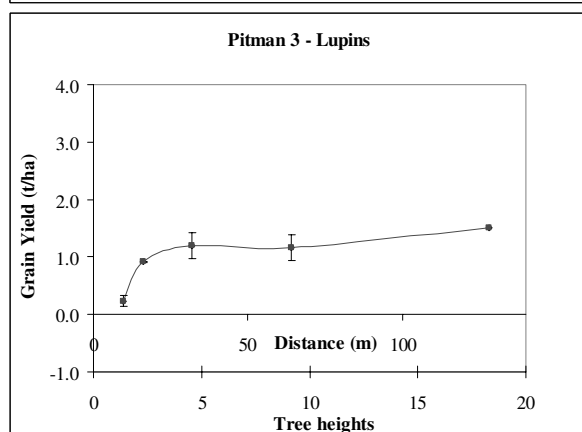
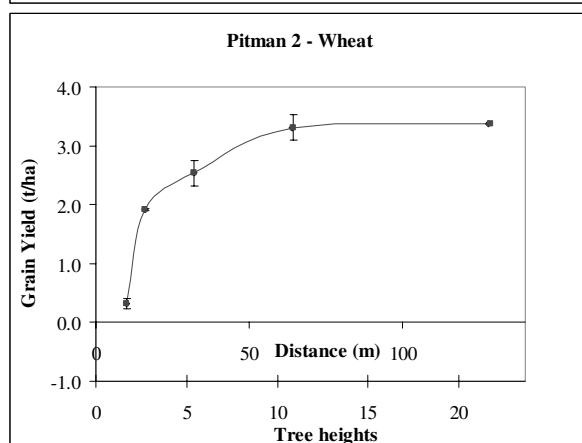
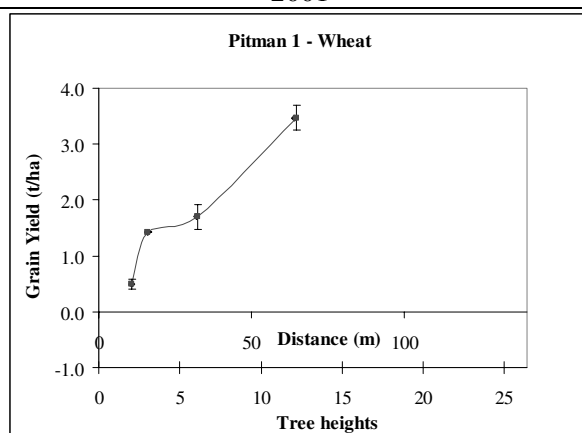


Figure 32. LAI per tree vs diameter and breast height for (a) outer row LAI for three species and (b) for inner row LAI for four species.

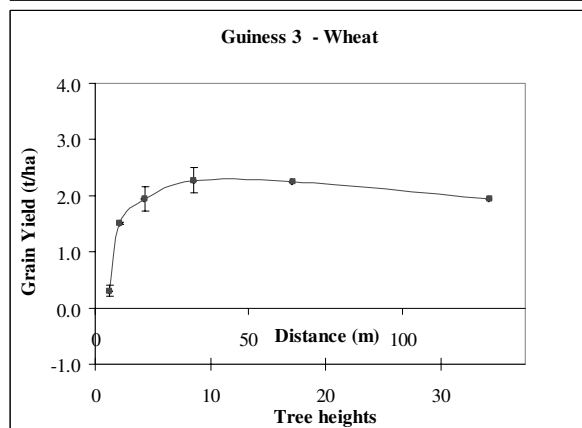
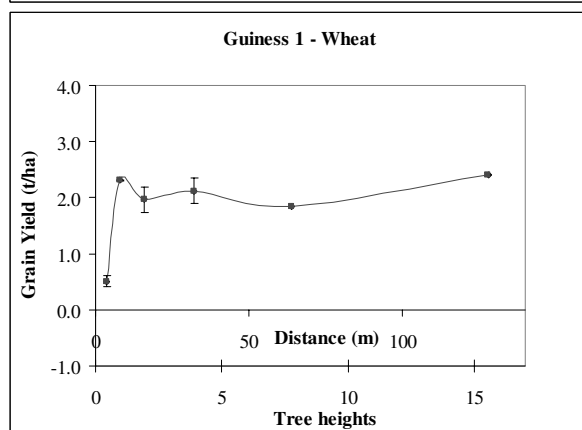
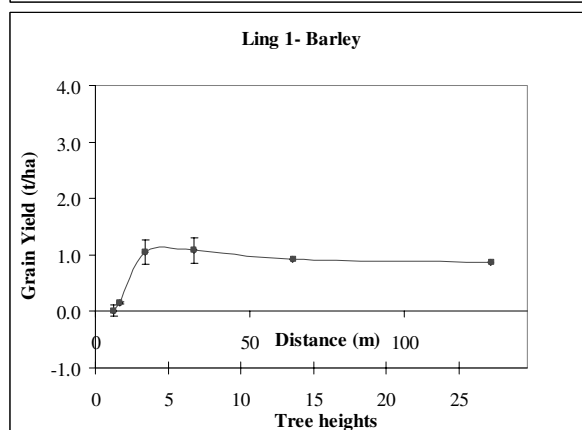
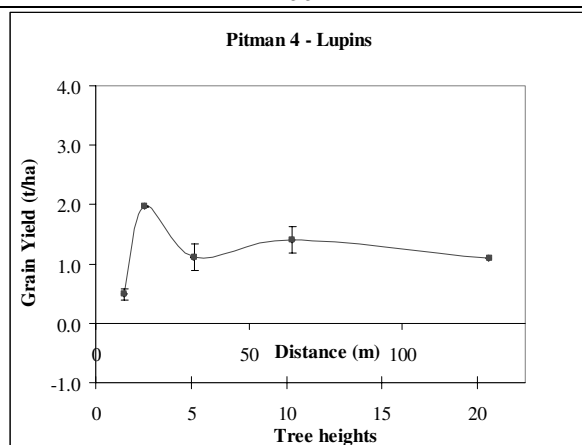
Appendix D. The average grain yield at each distance measured from the tree belt in metres and tree heights for each site 2001 and 2002.

2001

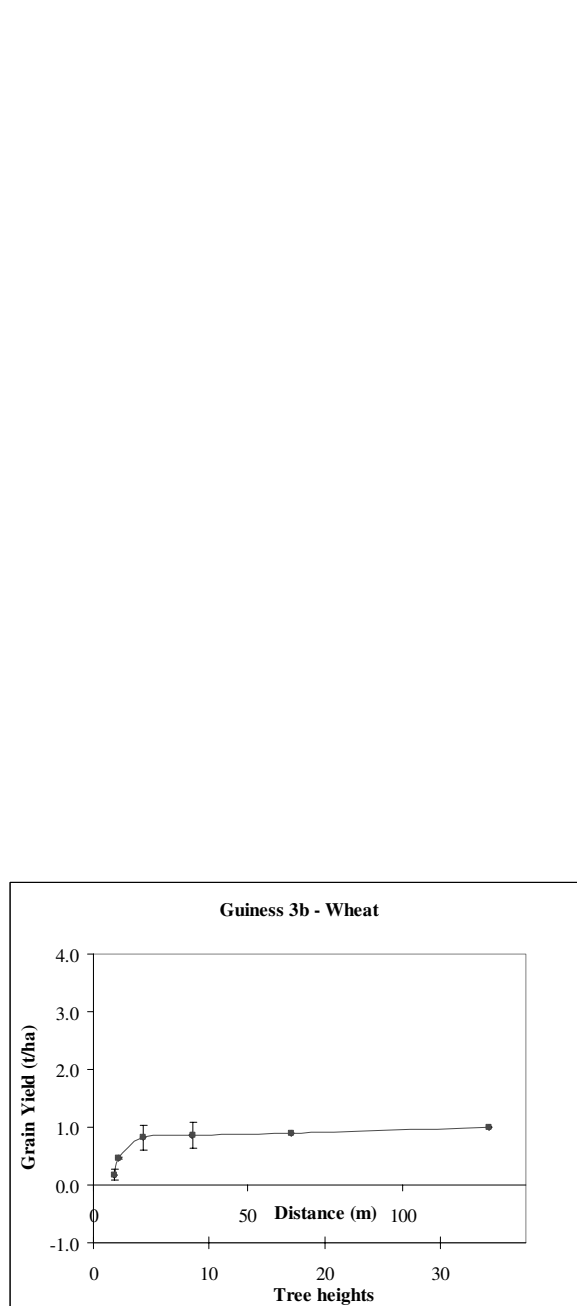
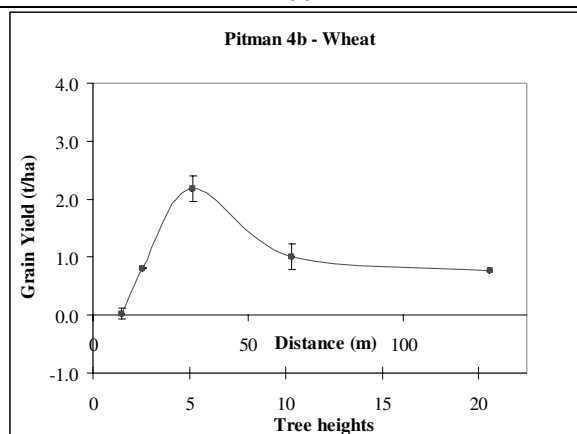
2002



2001

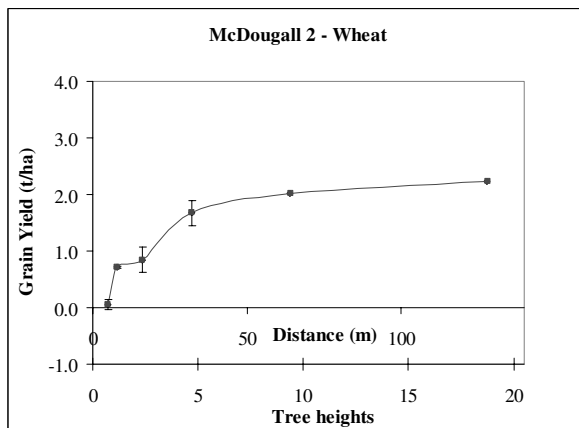
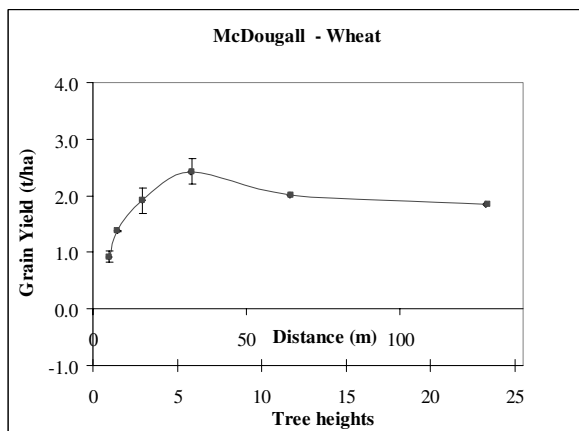
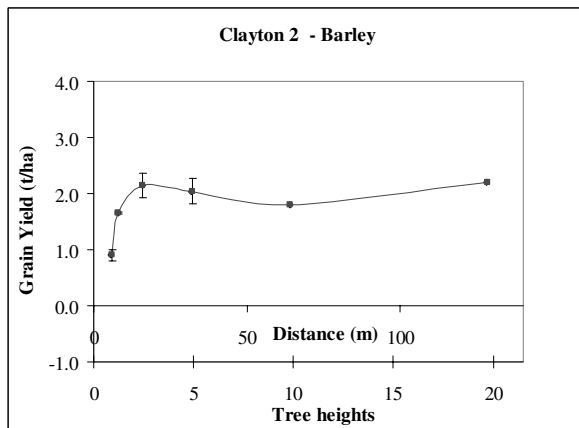
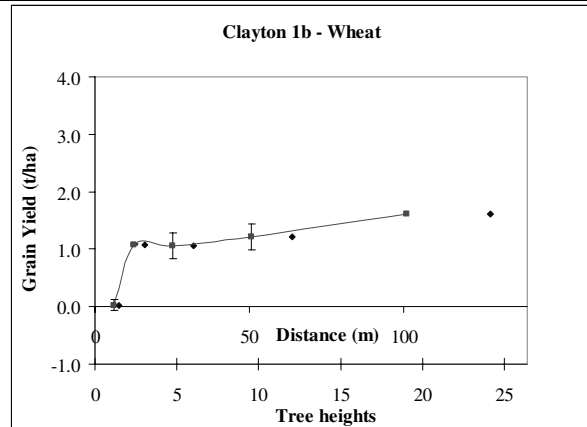
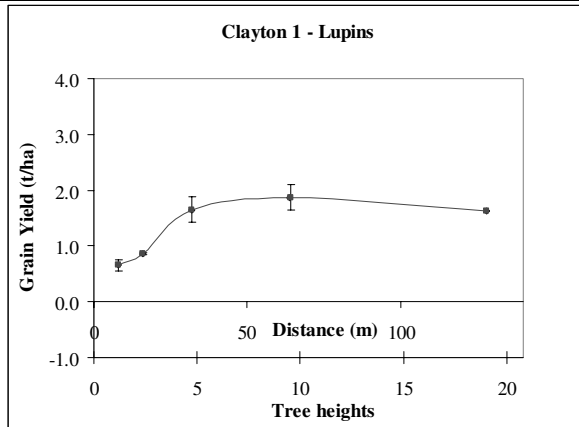


2002

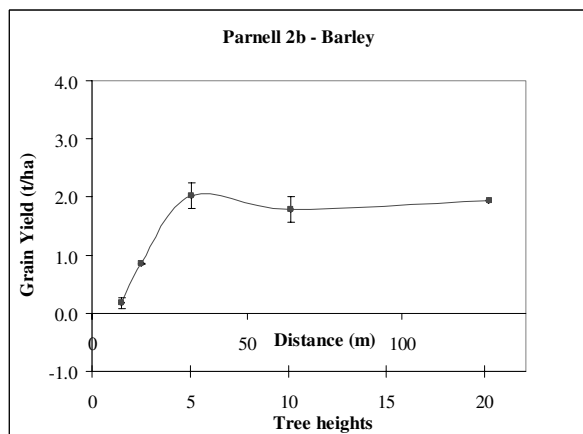
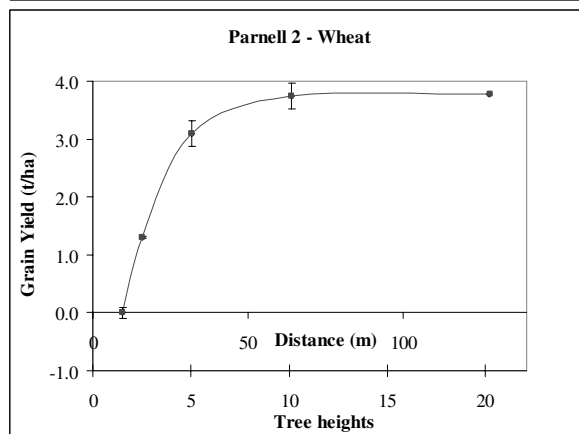
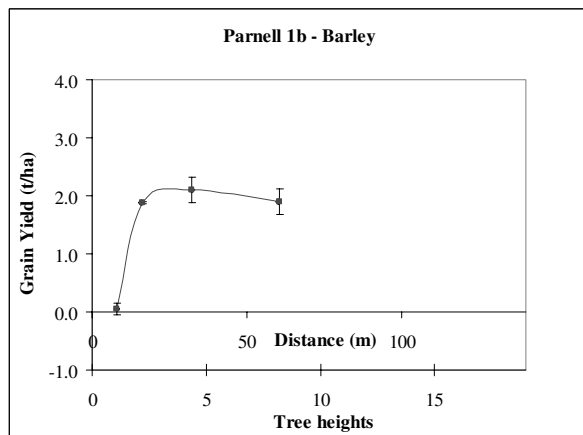
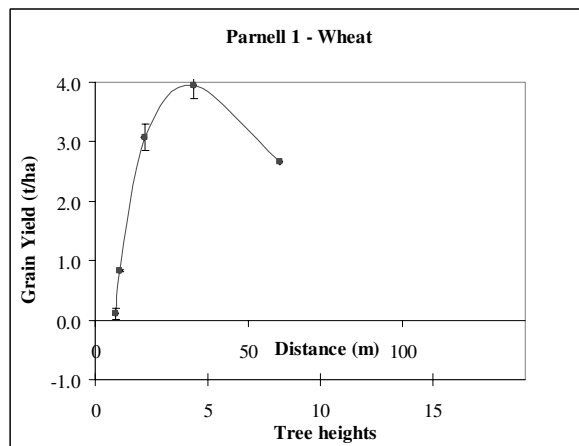
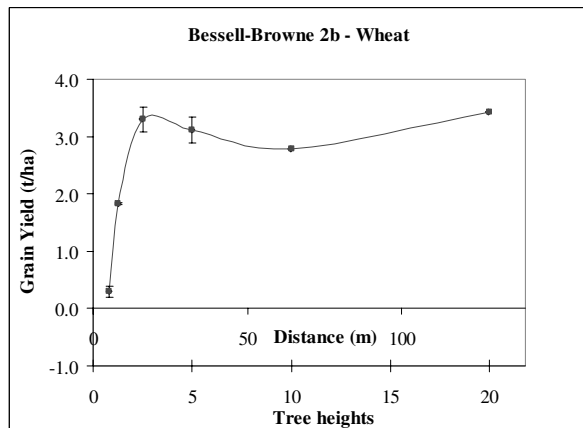
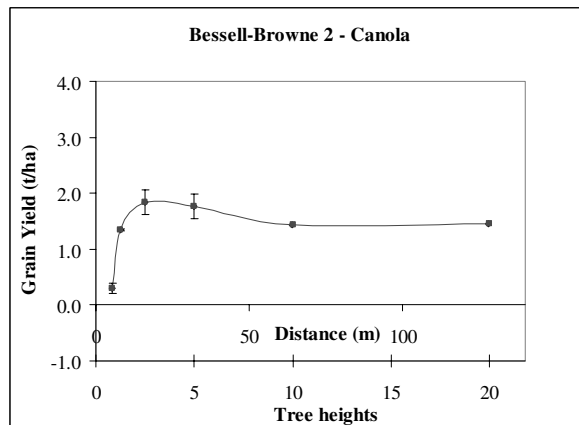
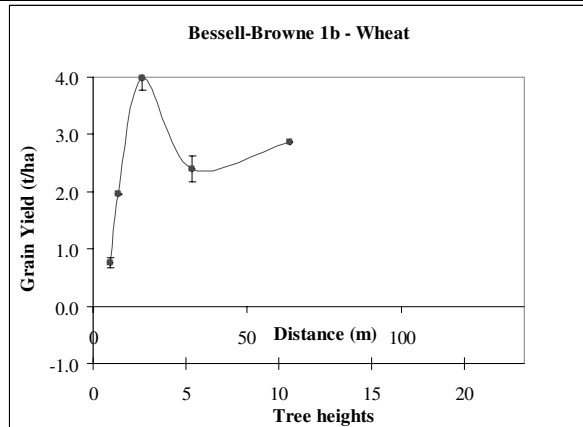
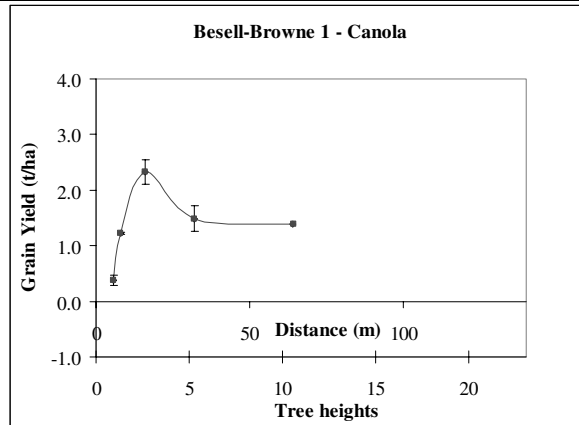


2001

2002

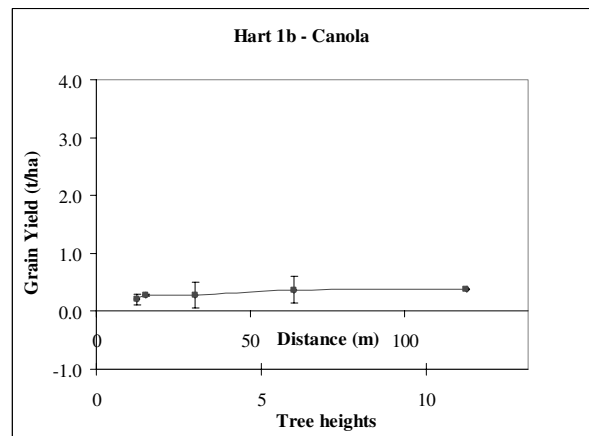
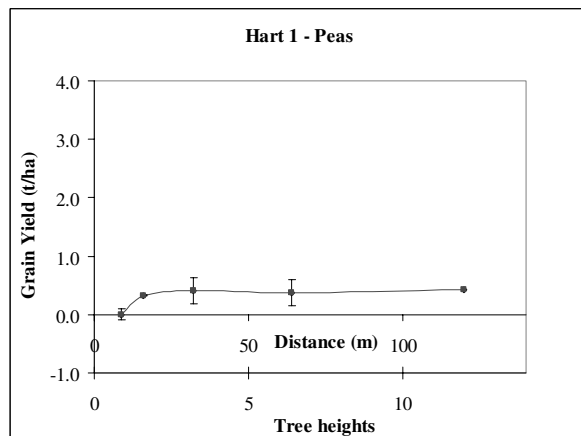
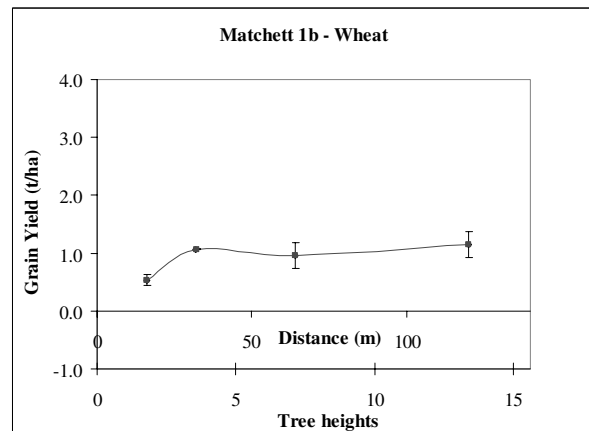
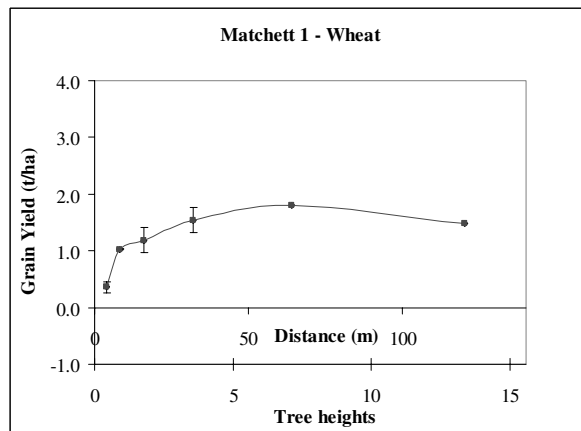
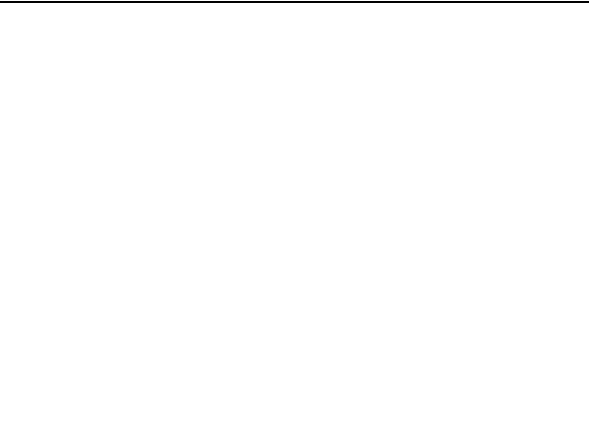
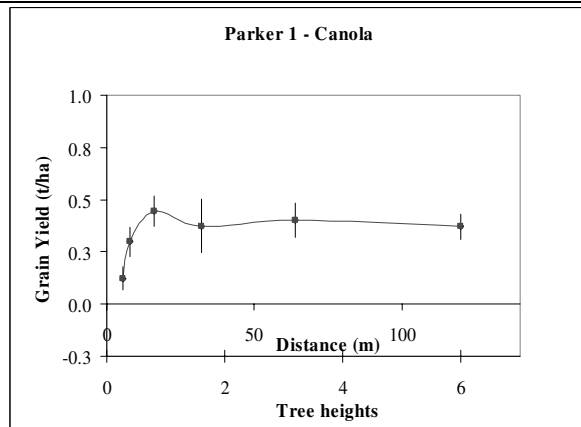
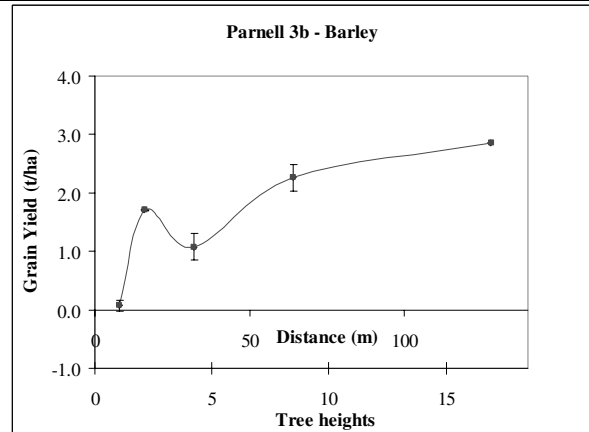
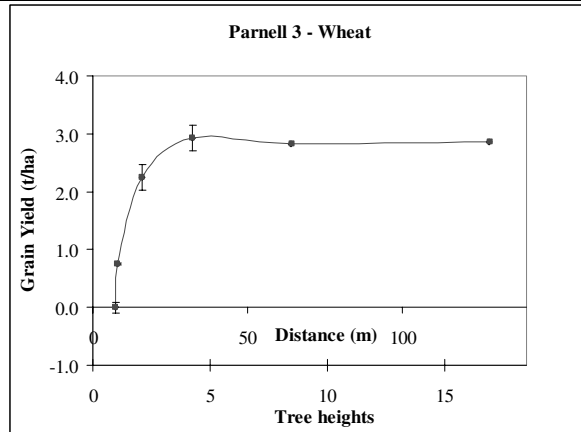


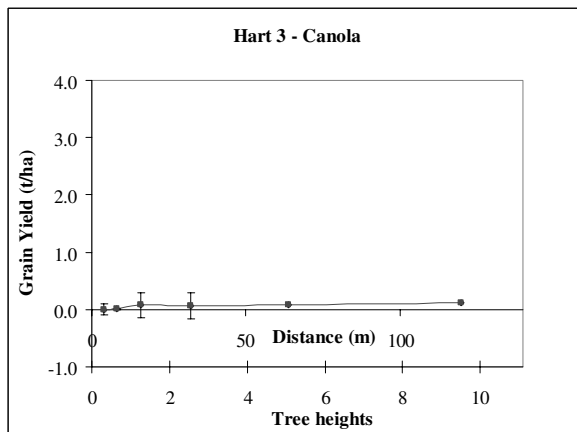
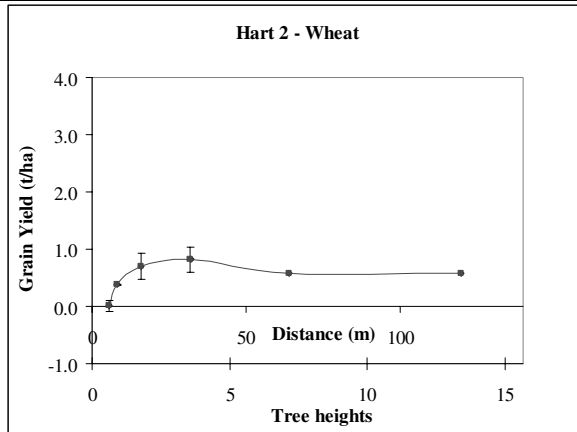
2001



2001

2002





Appendix E. Photographs of the sites.

Separate document available from the authors

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