
http://researchrepository.murdoch.edu.au/14615/
How farming and forestry converge: enhancing the interface between agricultural production, and tree biomass/bioenergy systems to improve farm-scale productivity in Western Australia

Mark P McHenry 1 *
1 School of Energy and Information Technology, Murdoch University, Western, Australia

Abstract
Shifting government policies and degrading terms of trade are leading to a range of tree biomass related options competing with food production on agricultural lands, including bioenergy, forestry, conservation legislation, and carbon biosequestration markets. Tree bioenergy plantations need not be monocultural and homogenous, and can be successfully incorporated into existing agro-ecological systems to increase primary productivity and food security while providing cost-effective bioenergy resources. This work examines trees integration in relation to wind speed, turbulence, humidity, evaporation, transpiration, temperature, water competition, solar use efficiency, frost, erosion, and fodder. These effects are examined in terms of farm-scale limiting factors in agro-ecological systems (water, sunlight, wind, frosts, fodder, etc.), alongside research data on tree system integration with conventional livestock, horticultural and broadacre food production in southern Western Australia (WA).

Introduction
Agriculturalists require regionally-specific research demonstrating the physical costs and benefits of integrating new tree biomass industries with traditional primary production. New agroforestry opportunities and markets arising from climate change policies, natural resource management, and biodiversity conservation, promote a greater proportion of tree biomass cover in agricultural systems. While planting more trees on agricultural land seems to offer a simple solution to environmental and climate change objectives, agriculturalists must balance a range of options that compete for limited resources. It is unrealistic for large numbers of agriculturalists undertaking land-use change purely for environmental, carbon biosequestration, or biodiversity reasons (Fischer et al., 2008). Therefore, this paper explores cases where trees have successfully integrated into agricultural production systems to improve food production. By exploring cases where research shows simultaneous increases in farm productivity, and integrated tree-cover, progress can be made where macroeconomic environmental, social, and economic objectives overlap with the business of farming.

* Correspondence should be addressed to mpmchenry@gmail.com
Traditionally, trees supplied farmers with timber and fencing material at low cost (Gregory, 1995) and may have been a source of some net revenue from felled timber. As opposed to the commodity value of felled trees, their implicit value is revealed by their presence in agricultural landscapes worldwide (Manning et al., 2006). Trees clearly displace pasture and crops in the paddock. Yet one assumes there are economic reasons for this consistent pattern, especially as active replanting is labour intensive and land is at a premium.

Assessing integrated tree biomass return on investment is a complicated and cumbersome process, as the relative magnitudes of positive and negative effects of trees on a diverse range of primary crops, soils, rainfalls, and seasons, can generate a large range of current and future values. The recent upsurge in new biomass conversion technologies, carbon prices, and conservation policies add additional choices for diversification decision makers. This work recognises these uncertainties and focuses on the physical interactions between crops, animals and trees, to enable agriculturalists to adapt tree biomass systems for their particular climate, soil type, water resources, and business objectives. Due to the variability of agricultural land characteristics and the complexity and unpredictability of numerous natural cycles and their interactions, this work centres on research data derived from specific research plots over time (McNaughton et al., 1989; Sudmeyer and Speijers, 2007). The purpose of this work is to assist land allocation decision-making at the farm-scale, and critique the magnitude of both competition and synergies of tree system integration with cropping, livestock, and horticultural production systems.

Trees, Wind Speed, Microclimates, and Vegetative Competition

“Working trees” are most familiar to agriculturists as a windbreak to protect a primary crop (Perry et al., 2009). Single trees deflect wind around the tree, which reduces wind speeds near the tree, and correspondingly increases turbulence and wind speeds away from the tree (McNaughton et al., 1989; Lefroy et al., 2001). In simple terms, tree rows deflect winds upward to form a triangular zone of reduced wind speed from the crown of the windbreak line to the ground (Fig. 1) This deflection occurs at a horizontal distance roughly 2-5 times that of the windbreak height (H) windward, and 20-40 H in the lee, depending on the tree windbreak characteristics, wind speed, and the wind direction in relation to the tree-line. The effect on the wind changes when the wind direction changes relative to the tree-line (Sudmeyer and Scott, 2002). Sudmeyer and Scott (2002) found areas between 3 and 12 H leeward, the greatest wind speed reduction (almost 50%) occurred when the angle of incidence approached 90º, or perpendicular to the windbreak. However, when the angle of incidence of the wind was between 35 and 45° to the windbreak, the maximum wind speed reduction of almost 60%, occurred between 1 and 3 H in the lee of the tree row (Fig. 2). This demonstrates the variability of the magnitude of wind speed reduction in protected zones windward and leeward, with all possible angles of incidence (Sudmeyer and Scott, 2002) (Fig. 3). On a regional scale, the systematic planting of around 10% of land to shelterbelt trees could reduce local ground wind speeds by 50% (Bird et al., 1992).
Fig. 1 Two-dimensional tree schematic showing areas of increased wind speeds and windward and leeward in terms of windbreak height (H). The horizontal and vertical scales are not to scale.

Fig. 2 A stylised chart of 1996 results from Sudmeyer and Scott (2002) of wind speed and angles of incidence at positions windward and leeward of a windbreak at their Howick research site. Positive angles indicate leeward measurements. Negative angles represent windward data.
The porosity of a windbreak is an important determinant of the effect it will have on crops. Porosity is an optical measure defined as the ratio of open to total area, as seen from the wind direction (Judd et al., 1996). Windbreaks with porosities of between 70-30% (a porous windbreak), will lead to wind speed reductions that are inversely proportional to the windbreak density. For example, a windbreak with a porosity of 60% reduces wind speeds by around 40%, while a relatively dense windbreak of 30% porosity reduces wind speeds by around 70%. The higher the windbreak porosity, the smaller the effect on wind speed, air temperature, and humidity (Cleugh et al., 2002). However, at extremes of porosity, dense windbreak of porosities less than 20 can induce eddies in the immediate lee (0-10 H), which increases turbulence encountered by crops. The leeward wind speed reduction for very low porosity windbreaks is less than medium porosity windbreaks (Vigiak et al., 2003). Therefore, the most effective windbreak porosity is around 35%, as it provides the best shelter over long, intermediate and short distances, without creating excessive circulation and turbulence leeward of the windbreak (Santiago et al., 2007).

Designing a windbreak system with the optimum porosity is not a simple concept in practice, as the shape and density of individual trees vary from top to bottom, and between each tree in the line (McNaughton...
et al., 1989). The windbreak porosity also varies throughout the year due to seasonal leaf changes, especially with deciduous trees. Seasonal porosity changes may be either beneficial or detrimental to the primary crop, and the choice of windbreak design, and tree species, is crucial to achieve the required wind speeds for their production system. Windbreaks should ideally be consistent along the line to maximise wind protection, as the majority of the reduction in wind speed depends on tree height and porosity (McNaughton et al., 1989; Cleugh and Hughes, 2002). Gaps in windbreaks result in acceleration of wind speeds through these areas, and can cause erosion and damage to crops (Cleugh et al., 2002; Sudmeyer and Scott, 2002). Using multiple rows of trees together in a narrow design will reduce the likelihood of gaps appearing due to tree injury, death, or disease (Hennon and McClellan, 2003) (Fig. 4).

Reducing wind speeds alters heat and water vapour fluxes in the air (Cleugh, 2002). As turbulence carries heat and vapour, it can determine which parts of a paddock are warm, cool, humid, or dry (McNaughton et al., 1989). The use of windbreaks can also reduce sensible heat advection (the transfer of heat energy by means of horizontal mass motion), which reduces water evaporation, especially during irrigation, and in dry years (Bird, 1998). In the vast majority of cases, this is an advantage as the conservation of soil moisture improves plant growth. However, this can also contribute to a higher incidence of disease in a minority of crops when the evaporation from leaf surfaces is reduced alongside increased humidity. This is more likely to occur with irrigated crops (Brandle et al., 2004). Sudmeyer and Scott (2002) recorded a summer season of wind speed, relative humidity, and air temperature when the wind angle of incidence was 90º to the windbreak. They found that the leeward wind speed decreased between 11-48% within 20 H, with the greatest reduction in wind speed occurring between 3 and 6 H. The air temperature and relative humidity in areas within 6 H were both increased up to 7%, relative to unsheltered areas. Between 6 H and 12 H the air temperature and relative humidity increase was only 2%, compared to unsheltered areas beyond 12 H. While these changes in relative humidity and air temperature are small, the majority of the significant effects on the reduction in wind speed are largely confined to the quiet zone, which is generally between 2 and 8 H (Cleugh et al., 2002; Sudmeyer and Scott,
While much windbreak literature has slight differences in definitions of the quiet zone, alongside numerous micro-meteorological empirical and modelled data, much uncertainty remains in the net benefit to agricultural crop productivity (McNaughton et al., 1989).

An extensive Australian windbreak study (concluding in 2002) known as the Australian National Windbreak (ANW) program found only relatively small changes in the paddock microclimate due to windbreak integration. This was suggested to be due to experimental plots with single line windbreaks, which left crops exposed to day to day and seasonal variability of wind direction. The extensive analyses undertaken under the ANW program recommended either closely spaced windbreaks, or those that surround the perimeter of paddocks to create consistent protection over a greater number of wind directions (Cleugh et al., 2002). This advice came with a caveat that increased tree plantings may reduce yields in the competition zone, a very important factor in Australian wind break design (Oliver et al., 2005) (Fig. 5).

The zone of competition reduces crop yields due to the trees and crop competing for limited moisture, nutrients, light, and also allelopathic effects of some trees (Sudmeyer et al., 2002; Oliver et al., 2005). The type and magnitude of competition depends on the crop, windbreak species, the soil type, and the climate. Sudmeyer and Scott (2000) found that within 3 H of Maritime pine (*Pinus pinaster*) windbreaks in the WA
Howick research site, (100 km east of Esperance), the amount of stored soil water was reduced by 100-150 mm, up to 1.8 m of depth. This halved the water available for crop transpiration, compared to distances greater than 3 H from the pines. The negative effects on crops were more pronounced in drier years within 3 H. Sudmeyer et al. (2002) found that pruning tree roots reduced the expanse and magnitude of crop losses next to trees where roots are confined close to the surface. Competition between the primary crop and the windbreak can be minimised by selecting taller trees to be planted in narrow windbreaks (around 3 tree rows), positioned at least 30 H apart. The tree roots should be deepripped periodically to reduce the competition zone (Sudmeyer et al., 2002).

**Windbreaks, Crops, Energy, and Water Use Efficiency**

As evaporation is proportional to the square root of the wind speed, any reduction in wind speed will reduce evaporative water loss (Sudmeyer and Scott, 2002). Windbreaks that reduce wind speeds in the early growing season increase chances of seed germination, while at the end of the growing season the reduced water loss can increase water use efficiency, and prolong the season (Sudmeyer et al., 2002). Research undertaken by Campi et al. (2009) in a European Mediterranean region found wheat crop evapotranspiration reduced by up to 16% behind a Arizona cypress (Cupressus arizonica L.) windbreak, with a corresponding temperature increase of 9% in the areas of maximum wind protection (1.3 - 4.7 H). ANW studies by Sudmeyer and Scott in 2002 showed that at the Howick site, the average potential soil evaporation was 20% less than areas with no windbreak. The ANW program summary estimated that crop evapotranspiration was reduced by less than 3% in the lee of windbreaks, alongside decreased evaporation, suggesting increased crop transpiration (Sudmeyer and Scott, 2002). In areas of high turbulence, evaporation rates are greater than in areas within the quiet zone. When there are reduced levels of evaporation in wind protected areas, the stomata of some plants may remain open and maintain high transpiration rates from increased photosynthesis, potentially increasing evapotranspiration rates (Bird, 1998). The shelter provided by windbreaks can sometimes have little effect in practice on transpiration from crops, even when the levels of evaporation are reduced. This is because the amount of water transpired by plants depends on the availability of water in the soil and other factors, such as air humidity windward of the area (Cleugh, 2002; Sudmeyer and Scott, 2002). The interpretations of evaporation, transpiration and evapotranspiration processes in the lee of windbreaks are complex, and often simultaneously increase and decrease water loss and retention in the paddock. Crop surface tissue damage from wind increases transpiration, and windbreak protection can lead to circumstances of reduced crop transpiration. However, protection can also lead to increased transpiration levels due to plants growing larger leaves (Bird, 1998). Therefore, the measured levels of crop transpiration and evapotranspiration can be misinterpreted, unless the origins for such increases or decreases are known alongside yield.

An additional means of increasing water use efficiency is by using perennial plants to increase the physical infiltration of rainwater. Runoff is substantially reduced under trees and shrubs, due to decayed root channels, holes made by soil fauna, higher organic matter content, and general soil porosity (Cleugh et al., 2002). Nulsen et al. (1986) reported in a southwest Australian study that 25% of rain falling on the canopy of
mallee\(^1\) trees ran down the stem and was directed around the bole to soil root channels at depths of 28m, to apparently be used in the dry season. The reduction of groundwater salinity and water-logging to adjacent paddocks is a critical issue in Australian agriculture. However, there are very specific conditions required for trees to reduce groundwater levels. Trees are more effective at lowering the water table when the water is fresh, and aquifers are small/local, rather than regional. Groundwater reduction by trees rarely exceeds 30 m from their base (George et al., 1999; Hall et al., 2002). Therefore, planting rows at 60 m intervals would likely reduce the water table, albeit at the expense of yields with such proximal distances the tree-crop interface (Oliver et al., 2005). A study of 80 tree planting sites in the southwest of WA by George et al. (1999) on reducing groundwater levels and salinity encroachment, found that the trees will only make a significant difference in a large regional aquifer if there are considerable areas of the catchment (70-80%) planted to trees.

In addition to water use efficiency, the design of windbreak systems can increase the energy use efficiency of a farm. This can be achieved by dispersing trees with differing canopy characteristics with crops or pasture arranged and orientated to intercept solar energy at different canopy levels, in alternate seasons (Patabendige et al., 1992). This can increase the net primary production considerably from the difference in active growth periods between annuals and perennials. In the higher rainfall areas of southwest WA, annuals active growth periods are usually between five and seven months, whereas perennials can extend the growing season and take advantage of summer and opening rains (Patabendige et al., 1992; McDowall et al., 2003).

**Windbreak trees, Horticultural Farm Yields, and Frosts**

Fruits and vegetables are often more sensitive to wind stress and show yield and quality reductions in even moderate winds. Shelter and climate moderation for horticultural production contributes to increased marketable yield and individual fruit weight (Brandle et al., 2004). Protection at critical times, such as when seedlings are young, or during flowering periods, can increase plant survival and improve fruit set by reducing damage from abrasive winds (Cleugh et al., 2002; Brandle et al., 2004). Using windbreaks in high-value horticultural areas can reduce wind speeds for wind pollinated crops, provide floral species for maintenance of insect pollinator colonies throughout the year, as well as attract parasitic wasps, or other predatory insects and birds. However, providing some types of trees in shelterbelts can cause problems. Plants that produce heavy nectar can attract some birds that attack flowering crops, and by providing niches where smaller birds can peck fruits without corresponding niches for their predators (Yunusa et al., 2002).

Some crops grown in sheltered areas also tend to mature earlier than unsheltered crops. This is often due to the several degree increase in daytime temperatures for temperate regions from the reducing turbulent mixing, leading to a slight increase (1 or 2\(^\circ\)C) at night near ground level. In temperate regions these increases in temperature usually appear earlier in the growing season (Brandle et al., 2004). This can be an advantage for crops such as fruit and vegetables that receive premium prices at particular times of the year, in addition to potentially expanding the range of alternative crop cultivars. The regulation of soil temperatures by windbreaks may reduce the losses from winter and spring frosts in southwest WA. The common type of frost in the

---

\(^1\) a general term used to describe multi-stemmed, small species of Eucalypt.
southwest is called a radiation frost. On clear and calm nights, radiative heat losses by soil and vegetation can reduce the air temperature to below 0ºC, resulting in the condensation on plant surfaces freezing to produce a frost (Brandle et al., 2004). A slightly increased soil temperature will protect against some radiation frost, but this effect is likely to be small.

**Trees, Livestock, Fodder Tress and Perennial Pastures**

Altering the microclimate for stock protection is vital in many regions of the southwest of WA, especially during winter storms and on hot summer days (Pollard et al., 1999; Cleugh et al., 2002; Mader, 2003). Winter born lambs and shorn sheep are especially at risk from cold, wet and windy conditions (Gregory, 1995; Pollard et al., 1999). Exposure to high wind speeds increases the lower critical temperature for animals, which is wasteful in terms of energy utilization (Gregory, 1995). There are many documented benefits windbreaks can offer animal husbandry including: improved growth rates; increased ovulation rates in both sheep and cattle; increased wool growth rate; reduced lamb mortality, and; decreased abortions rates induced by hypothermia (Gregory, 1995). Research undertaken by Holmes et al. (1978) in New Zealand, found that 150 kg dairy heifers grew faster than control twins when they were provided access to shelter in their paddocks (Gregory, 1995). Windbreaks also offer protection from the sun in hot conditions, which has been shown to improve milk yield, milkfat yield, assist the prevention of mastitis, improve conception rates in dairy cattle, and increase growth rates in fattening cattle (Gregory, 1995; Mader, 2003).

Extremes of weather cause much animal discomfort in confined areas, and the provision of shelter allows livestock to self-regulate to improve their individual welfare. The design of windbreaks for livestock can also incorporate the preferences of the animals under critical periods (Pollard et al., 1999). For example, many ewes prefer to lamb in isolation from the rest of the flock, and also have a tendency to lamb at the perimeter of the paddock. In cold winter conditions when flocks huddle together behind windbreaks, lambing ewes may stray from the flock and increase their environmental exposure. Therefore, providing scattered blocks of trees in paddocks is more than thin windbreaks for lambing paddocks (Prinsley, 1992; Gregory, 1995).

In most regions, extreme weather events are unlikely to occur every year, but windbreaks can be justified as a form of stock insurance (Sudmeyer et al., 2002). It was suggested in a 1973 study by Sturrock in New Zealand that for optimum protection of livestock, a minimum of 5% of land under tree cover was required (Gregory, 1995). However, the farmer would realise that from a productive efficiency perspective, the reduced pasture available to animals with the introduction of inedible windbreaks may cancel out the benefits of shelter for animals (da Silva et al., 1993). Edible windbreaks can compensate for such pasture loss, especially as a summer source of fodder (Cleugh et al., 2002). The lack of additional green feed in late summer and autumn is a major constraint to livestock production in the southwest of WA, and importing feed is particularly expensive in years with region-wide feed shortages. The ability of some tree species to provide fodder and forage to supplement seasonal food shortages, defer the grazing of annual pastures, and reduce hand feeding, has generated much interest in finding suitable species for specific production systems and climates (Patabendige et al., 1992; Cleugh et al., 2002).
Two tree species that have received much attention for use as forage in WA are the tagasaste (Chamaecytisis palmensis) and saltbushes (Atriplex spp.). Tagasaste is suited to well-drained soils in areas of higher than 400mm of annual rainfall, and saltbushes are tolerant to moderately saline areas and occasional waterlogging, but is often used in dryer climates. Both are sometimes used as sheep feed in the autumn feed-gap and provide vegetative cover on erosion-prone sites (Patabendige et al., 1992; de Koning and Milthorpe, 2008). Research by de Koning and Milthorpe (2008) reviewed the use of various saltbush species as a fodder crop, and found that when grown in salty or moderately saline affected areas, the feed value of these species are poor without ample fresh drinking water. The study recommended the use of saltbush species for fodder only from areas with fresh groundwater, or solely for environmental reclamation of salt affected land (de Koning and Milthorpe, 2008). While tagasaste has proved itself as a high value fodder crop in areas of WA with lower rainfall, some tree designs create a level of pasture/crop competition that decreases farm productivity (Lefroy et al., 2001; de Koning and Milthorpe, 2008). Integrating fodder plantations into parallel rows in paddocks (also known as alley-cropping), have been a relatively popular design, although it requires quantification of various levels of competition between the tree alley, and the pasture/crop (Lefroy et al., 2001). An alley-cropping and water balance study on deep sand in Moora, by Lefroy et al. (2001), compared control yields with three integrated crops, using another species of tagasaste (C. proliferus). Trees were spaced at 30 m between rows, and 0.7 m between each tree. Experiments with the two lupin varieties (Lupinus angustifolius vars. Gungurr and Merrit)), and the oats (Avena sativa var. Toodyay) found that segregated monocultures performed better than alley cropping. In the first year, the Gungurr lupins provided a yield increase of 23%, including the land area under the four year old tagasaste trees pruned from 2 m to 0.6 m in year zero. However, the second year Toodyay oat and third-year Merrit lupin crops suffered significant losses of 8 and 32%, respectively. The oat crop losses were due solely to the trees displacing the crop aboveground, with no below-ground competition verified by pot trials. However, the continuing tagasaste tree growth both displaced and competed with the second variety of lupins, at a magnitude of 20 and 12%, respectively. Lefroy et al. (2001) offered a review and recommendation to agroforestry literature of segregating trees from crops, and targeting landscape niches when production is water-limited.

If alley cropping is a preferred option, such productivity losses may be offset in economic terms by the tagasaste fodder eaten by stock in the “feed gap” period (Lefroy et al., 2001). A study undertaken by Scott (1990) used tagasaste as a management strategy to improve the efficiency of sheep production on a Badgingarra property (30km northwest of Moora), over the summer and autumn feed-gap period, and compared it to grain and dry-fed animals. The research found that in addition to greater wool production over the summer period, the 8% discounted economic analysis suggested that feeding the sheep tagasaste over the summer feed-gap period would become cost effective in the sixth year after planting. This analysis included the lost production from a segregated paddock-style plantation, and the additional labour costs of establishing the plots.

Other trees that have received attention for forage value in the southwest are the golden wreath wattle (Acacia saligna), the mulga (Acacia aneura) the black sheoak (Casurina cristate), the swamp sheoak (Casurina obesa), carob (Ceretonia siliqua), honey locust (Gleditsia trichanthos), and leucaena (Leucaena leucocephala), in addition to various other wattles, poplars, tamarisks, and willows. However, some wattles have uncertain
palatability and digestibility for sheep and cattle, due to high leaf-tannin content (Patabendige et al., 1992; Lefroy et al., 2001). A significant issue with the introduction of some fodder tree species is their potential to become an invasive pest (Lefroy et al., 2001).

As an alternative to perennial tree fodder species, perennial pastures offer another option for farmers to supplement stock diets in the feed-gap period. A study by Sanford et al. (2003) focused on the importance of using perennial pastures to fill the feed-gap with non-fodder windbreaks on both Merino sheep and salinity. The study measured sheep carrying capacity, wool production and groundwater recharge in the southwest of WA near Albany. The study found that in the growing season, there was similar herbage in the annual pasture consisting mostly of subterranean clover (Trifolium subterraneum), and erodium (Erodium botrys), and the perennial kikuyu pasture (Pennisetum clandestinum), with small amounts of subterranean clover. He annual pasture stocking rate was 12 dry sheep equivalents per hectare (DSE ha\(^{-1}\)), and the kikuyu was 14 DSE ha\(^{-1}\). In spring, all stock rates were increased, and in autumn all paddocks were destocked. In summer and autumn, the kikuyu paddock contained between 350 and 4,900 kg more dry matter per hectare (DM ha\(^{-1}\)) than the annual pasture, mostly due to summer rains. Both the carrying capacity and clean wool production per hectare was significantly higher on kikuyu pasture in the years with summer rainfall (Sanford et al., 2003). These control paddocks were compared with paddocks with ten-year-old blue gum tree belts (Eucalyptus globulus), planted at 1250 ha\(^{-1}\), with 4 m between rows and 2 m tree spacing. The adjacent annual pasture suffered reduced herbage accumulation in the paddock with tree belts by 16%, while not affecting the perennial kikuyu herbage accumulation. The research found that the tree competition of the closely spaced native evergreen windbreaks reduced the carrying capacity of the annual and kikuyu pasture by an average of 10%, and the annual average clean wool production by 13%. The research concluded that there was less tree-pasture competition with kikuyu pastures than annual pastures. The research showed that kikuyu pasture, without trees produced significant increases in livestock production, in addition to substantial groundwater reductions, relative to the annual pastures. Sanford et al. (2003) recommended a combination of balancing kikuyu and trees to lower the water table, and to slightly lower livestock production.

**Trees and Broadache Yeilds**

There is considerable variation in response to shelter from common broadacre crops (Sudmeyer et al., 2002; Sudmeyer and Speijers, 2007). Much of this variation is due to the growth habits, and different positions of the shoot apex. If the shoot apex is carried at the top of the plant canopy, the plant is more likely to be sensitive to wind damage (Sudmeyer et al., 2002). In Australian agricultural systems, crop yields exhibit large annual variations. Significant yield differences occur between crop varieties, regions, and even across paddocks (Sudmeyer and Scott, 2002). Notwithstanding such difficulties, crop research in Esperance undertaken by Sudmeyer et al (2002), integrated various pine, Eucalypt timber belts, and remnant mallee vegetation with broadacre crops. The results suggested that the sheltered primary crop yield at 5-20 H was slightly greater than the unsheltered yield at 20-30 H, in similar soil and topographical conditions. These increases were only statistically significant at 9 H, and must be evaluated against significantly reduced yields within 4 H of the trees. These trials included crops of barley (Hordeum vulgare), wheat (Triticum aestivum), lupins (Lupinus angustifolius), canola (Brassica napus), and one trial of faba bean (Vicia faba) (Sudmeyer et al., 2002). Sudmeyer
et al. (2002) stated that the yields of the 37 windbreak sites on the south coast of WA in years with average or above-average rainfall between 4 and 20 H were generally similar to unsheltered yields. This contrasted with mean yields between 1 and 20 H reduced by 2-6%. In dry years, when crops received less than 50% of the average annual rainfall, the mean sheltered yield between 5 and 20 H was 11% greater than the unsheltered yield, although the mean yield between 1 and 20 H being similar to the unsheltered yield (Sudmeyer et al., 2002). The greatest improvements in crop yield were recorded in 1996 at Jerdacuttup (around 120km west of Esperance), where an estimated 20% of the cropping areas were severely effected by wind erosion. In this year the tree windbreaks increased the mean yield of wheat and barley between 1 and 20 H by 25% and reduced sandblasting damage as far as 40 H, beyond which some crops were completely destroyed (Sudmeyer et al., 2002). The research showed that within 4 H, yields decreased with increasing proximity to the trees, although this varied with the amount of rainfall received in the growing season. In years with average or above-average rainfall, the yield decreased out to 2-4 H from the trees, and the mean yield between 1 and 4 H was 17-26% less than the unsheltered yield. In the dry years, the yield was reduced out to 3-5 H from the trees, and the mean yield between 1 and 5 H was 35% less than unsheltered yield (Sudmeyer et al., 2002). The overall results from the study were that the windbreaks decreased sheltered (1-20 H) crop yields in areas that suffer severe wind erosion by 1% compared to unsheltered areas (20-30 H) in the 64 field-years of the study between 1994 and 1997. This compared against a decrease of 4% in areas that do not suffer severe wind erosion in 58 field-years over the same interval. Sudmeyer et al. (2002) concluded that the net yield between 1 and 20 H was similar to the yield of the unsheltered crops over time, due to sheltered zones improving relative yields in dry and windy years, which offset reduced yields in the competition zone.

An economic analysis undertaken by Jones and Sudmeyer (2002) on the data from the 37 sites found that windbreaks reduce net agricultural income when the primary crop does not suffer wind damage. However, productivity increases in the lee of windbreaks in this region of WA could offset yield losses and the cost of establishing trees if unsheltered crops were subject to 3 or 4 severe wind damage events over a 35 year interval. The analysis found that appropriately spaced windbreaks in the region were unlikely to reduce the net present value of crop production more than 6.5% over the long term. Any net financial benefits from windbreaks are dependent on the timing, and frequency of wind damage in relation to the age, size and distance between the windbreaks, the extent of damage that normally occurs due to wind, and whether or not the lateral roots of trees are pruned (Jones and Sudmeyer, 2002). The primacy of below-ground windbreakcrop root competition, and the benefits of wind protection, contrasts with the practice of orientating tree lines north-south to reduce tree shading impacts. Some crops such as wheat will benefit early in the season from north-south orientation, although other crops such as lupins will not. Therefore, depending on the crop, and whether wind, water or light is the yield limiting factor, windbreak orientations should generally be orientated to protect from the common direction of damaging winds at sensitive times of the year (Sudmeyer and Speijers, 2007; Campi et al., 2009) (See Fig. 6 and 7 for Albany wind frequency analyses (wind roses) for Summer, Autumn, Spring, and Winter at 9am, and 3pm, respectively).

The effects of windbreaks on broadacre crops have also been examined under climate scenarios to model the potential of windbreaks to protect dryland maize from the negative effects of climate change. A study
in the USA by Easterling et al. (1996) found that shelter increased dryland yields relative to unsheltered crop yields for almost all levels of climate change. This was due to the windbreak providing night-time cooling, relieving some water stress which compensated for a shorter growing season. The most positive effect of shelter was for the most severe cases of large losses in rainfall, and large wind speed increases (Easterling et al., 1996). These and other similar studies suggest a greater role for windbreaks in moderating future climatic changes in the vulnerable southwest of WA.

**Conclusion**

Appropriate agricultural windbreak configurations allow farmers to increase the productivity, and profitability of their farming enterprise. With carefully planned tree biomass systems, agriculturalists have the potential to increase yields, improve product quality, and reduce losses during extreme-wind conditions. Harnessing tree systems that protect crops, pastures and livestock in key seasons can be an inexpensive form of insurance for agriculturalists. However, when planting trees for either conventional, strategic, forestry, or ecological objectives, farm productivity may be inadvertently reduced with regionally and seasonally inappropriate tree systems.
Acknowledgements
Many thanks, once again, to Julia Anwar McHenry.

References


Scott, P.R. 1990. Agroforestry - Integration of trees into the agricultural landscape. Resource Management Technical Report No. 102, South Perth, Western Australia: Western Australian Department of Agriculture.


