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The role of shelter in Australia for protecting soils, plants and livestock

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Abstract. The purpose of this review is to examine the current knowledge of the role of trees in providing shelter for pastures, crops, and livestock, for controlling erosion of soils and improving productivity and sustainability of agricultural production in Australia — and the extent to which this knowledge has been applied.

Land degradation — tree loss and associated soil salinity, water and wind erosion, soil acidification, soil structural decline and nutrient degradation — is evidence that our primary production systems are not sustainable. We have sought increased production without proper consideration of the ecological context of that system. About half of Victoria's crop and pasture lands are affected or at risk, and in Western Australia about 25% of the cleared agricultural land is wind-eroded and 60% is potentially susceptible, salinity affects 0.43 m ha and half of the divertible surface water is affected by salinity. Similar problems occur in other States. At least 43 m ha or 13% of our rangelands are seriously degraded by wind erosion caused by overgrazing, often coinciding with drought or a run of drier years.

'Minimum tillage' and stubble management for erosion control in cropping has been a major extension and research activity in Australian agriculture. Severe weather, combined with imperfect adoption of appropriate grazing and crop management systems, shows the weakness of complete reliance on these methods of erosion control. An effective system must accommodate the impact of extreme events, which are the most damaging. However, the complementary use of windbreaks to reduce soil erosion is rare, and their establishment has not been promoted, despite the wide-spread adoption of this technology by other countries.

In the cropping and higher rainfall grazing areas, the systematic planting of 10% of the land in a net of shelterbelts/timberbelts/clusters could achieve a 50% windspeed reduction; this would substantially improve livestock and pasture production in the short and long-term. Wind erosion could be dramatically reduced and crop production probably increased by the use of windbreaks. Wheat and oat yield at Rutherglen (Victoria), and lupin yield at Esperance (Western Australia), were increased in the sheltered zone by 22% and 47%, and 30%, respectively.

In semi-arid and dry temperate areas, planting of 5% of the land to shelter could reduce windspeed by 30–50% and soil loss by up to 80%. This planting would also contribute substantially to achieving other objectives of sustainable agriculture. Agroforestry — particu-

larly timberbelts applications — will be important in the long-term strategy for achieving revegetation. If some of the trees yield a marketable product then the adoption of the system will be more readily achieved.

In the arid (pastoral) areas there is an urgent need to promote the ethic that preservation and improvement of the perennial grass and shrub vegetation is critical for the protection of the soil and maintenance of land capability. Control of animal grazing remains the sole means of preventing erosion in much of this zone. While satellite imagery allows us to assess the condition of leasehold lands, we have failed to achieve stocking policies that will halt the degradation of our rangelands.

1. Introduction

The purpose of this review is to examine the current knowledge of the role of trees in providing shelter for pastures, crops, and livestock, for controlling erosion of soils and improving productivity and sustainability of agricultural production in Australia — and the extent to which this knowledge has been applied. An attempt has been made, for each of the major regions in Australia, to determine:

a) the adequacy of existing shade/shelter for soil, plant and animal production
b) improvements in productivity and/or sustainability that can be achieved using trees/shrubs

and to identify crucial areas for further research or demonstration.

2. Tree cover — land degradation — sustainable agriculture

Two hundred years ago our forests covered 10% and woodlands 23% of the continent. Now 50% of those forests and 35% of the woodlands have been cleared or severely modified. Many of the remaining woodland trees are in decline and losses outstrip gains through planting [26].

Tree loss has been associated with almost every aspect of land degradation in Australia [36]; tree clearing for agriculture, and soil disturbance associated with grazing and cultivation, has produced massive soil erosion. This is most visible on steep slopes associated with sub-tropical horticulture or cropping where a tonne of crop product can result in the loss of 380 tonnes of topsoil [67]. In the wheatlands of Queensland the soil loss may exceed 50 t ha^{-1} y^{-1} (i.e. >4 mm y^{-1}), which is 50 times the most optimistic estimate of the rate of soil formation [27].

Retention of trees — and the re-establishment of more trees, assisted by appropriate farm planning is critical to the long-term objective of sustainable soils [18, 19, 24].

Tree clearing restrictions on freehold or leasehold land are currently in force in South Australia, Victoria and in a few water catchment areas in

Western Australia. In the latter state, remnant vegetation on 13 shires in the 300—600 mm rainfall zone ranges from 8 to 16% of farmland [5]. In New South Wales there are restrictions on clearing of trees in environmentally sensitive areas (as mapped by the Soil Conservation Service) on leasehold land in the Western Division, along water courses, and on land with slope >18 degrees east of the divide. No restrictions have been introduced in Queensland or Tasmania or the Northern Territory. The area cleared of trees in the Northern Territory is fairly small and largely the result of development of settlements, roads and services, firewood harvesting and concentration of stock around watering points [62]. Tree clearance in Queensland has not reached the extent of the southern states, although the pressure to do so is rising and there are significant areas of salinity and erosion. Mooted partial clearance of up to 50 m ha of poplar-box woodlands in Queensland may have serious adverse consequences resulting from the loss of an estimated 5 billion trees [26, 54]. Pasture development in that area, without further tree clearing, may be a better solution to the problem of long-term viability of cattle stations [54].

Land degradation — dryland salinity, water and wind erosion, soil acidification, soil structural decline, soil nutrient degradation — is Australia's major environmental problem [36]. About half of Victoria's crop and pasture lands are affected or at risk. Five million ha of land are affected by declining soil structure, 4 m ha are affected by declining soil fertility, over 0.2 m ha are salt affected and 25,000 km of gullies are actively eroding. The costs in terms of lost production and off-site effects are substantial. While these costs can only be generalised they already exceed $100 m per year and could be as high as $200 m per year [60].

The situation in Western Australia is no better: about 25% (4 m ha) of the cleared agricultural land is wind-eroded and 60% is potentially susceptible; water erosion affects 0.75 m ha; salinity affects 0.43 m ha and over 50% of the divertible surface water is affected by salinity; soil structure decline occurs on 3.5 m ha, sub-soil compaction on 8.5 m ha, acidification on 0.5 m ha and water repellence on 5 m ha [20, 55, 65]. The annual cost could be as high as $600 m.

Conservative estimates suggest that 43 m ha or 13% of our pastoral land is seriously degraded, with soil losses exceeding 20 t ha^{-1} y^{-1}. Compared with erosion of cropping lands or salinised areas the degradation of our rangelands is massive. The basic cause is overgrazing, often coinciding with major droughts or a run of drier years, and a reduced incidence of fire resulting in proliferation of woody shrubs at the expense of native forbs and grasses [67]. In spite of the best intentions, practices adopted in the past have not been adequate to contend with combined pressures of grazing and climatic variation of our pastoral dryland regions and degradation is continuing virtually unabated [32].

Management decisions taken to maximise output, such as the introduction to our harsh tropical rangelands of better adapted *Bos indicus* cattle, use of mineral and nitrogen supplements, and improved transportation have been cited as reasons for the present-day increased impact of grazing on our rangelands. We can also see politically inspired large-scale clearing of semi-arid land in the last thirty years, and a reluctance either to enforce compliance with current pastoral leasehold provisions or to review them and assist graziers to cope or leave.

Land degradation should be seen as a consequence of an inadequate agricultural or pastoral production system — a testimony to the fact that our systems are not sustainable — that we make decisions to improve primary production without proper consideration of the ecological context of that system [67].

3. Soil erosion

Most of our soils are based on very old weathered surfaces, without fresh additions of minerals from volcanic or glacial activity. Consequently, they are generally low in nutrients and erosion further depletes such impoverished material. Most of the nutrients are held in the organic matter of plants or in the top few centimetres of soil which is vulnerable to degradation following cultivation, or erosion by wind and water. Cropping and livestock production further depletes the nutrient pool as a result of export of minerals from the system in grain, meat and wool; losses for phosphorus, nitrogen or potassium are invariably not offset by fertiliser inputs or from weathering of rock [43, 67].

Tree replacement will be essential if we are to re-develop the fertility of many of our degraded soils and maintain sustainable systems of agriculture [36]. Agroforestry systems have an important role in conserving soil fertility [71]. Trees intercept rain and litter also reduces raindrop pounding of soils; surface litter increases soil organic matter, increases the water-holding capacity of the soil, promotes water absorption and decreases the rate of runoff; roots also bind the soil [47, 36, 71, 34].

3.1. *Soil erosion by water*

In Australia, more than 2.6 m km^2 (almost two thirds of the land used for grazing or cropping) needs treatment for land degradation [26]. Water erosion accounts for about 70% of the total Australia-wide [22].

Control of water erosion requires solutions based on whole catchment planning, incorporating pastures, cropping technology, grazing control, trees and physical structures such as contour banks. Trees alone are often insufficient to protect soil from sheet and rill erosion, since ground cover plants are also required to protect the soil surface [47, 71, 34]. In some circumstances shrub growth may prevent the growth of ground cover species and promote runoff. However, tree establishment in association with mulching or pasture is a practical means of controlling tunnel erosion on land with dispersible sub-soil, landslip on steep slopes and gully erosion [47, 24].

3.2. *Soil erosion by wind*

Wind erosion of agricultural or pastoral lands is a severe problem world-wide. Our dryland agricultural ecosystems are vulnerable to both natural and human impact.

The following examples from Western Australia are used to indicate the extent of wind erosion and the likely consequences to productivity [47]. Sheep grazing an 'average' sandy paddock in summer loosened 41 t of soil per ha and a wind storm removed 5 t of dust of the 28 t of topsoil lost per ha. A badly overgrazed paddock lost 30 t of dust in the 200 t of topsoil blown from each hectare of land. A clover pasture harvested for seed lost 18 t of dust in the 110 t of soil lost from the top 8 mm of each hectare. Losing the dust from the top 8 mm of soil reduced the yield of the next crop by 12–25%. It was also estimated that summer grazing on the same paddock for 7 years would reduce productivity by 50%.

Each soil has a particular propensity to erode — and sandy soils are particularly prone to wind erosion. The 'starting velocity' where sand flux begins is a function of soil type, pasture or trash cover, surface crusting from rain, soil particle aggregation (reduced by hoof pounding or cultivation) and moisture. Sand flux on a sandy soil may only begin when the windspeed at the surface exceeds around 9 m sec^{-1} but the rate of flux increases steeply thereafter as windspeed increases [6]. However, the fine fraction (clay, silt) has been removed from the surface long before the sand moves — the effect of the sand movement is to destabilise the new soil surface to allow further loss of 'fines' [53]. Loss of dust in smaller amounts is usually not regarded by the public as being soil erosion — yet the particles of clay and silt (<50 microns) contain the bulk of the soil nutrients and organic matter and these are the first to move on windy days. Where cultivation or soil disturbance associated with grazing (hoof pounding/plant uprooting) reduces the aggregation of particles then loam or clay soils are also at risk.

We believe that the problem in Australia is as critical as in other continents and if we want sustainable farming systems then we should accept that the problem can not be overcome without reforestation. Current approaches in North America, the USSR and China are given below to indicate how other countries are dealing with soil erosion through revegetation — and to emphasise, by comparison, our neglect.

3.2.1. *Experience in North America, USSR and China.* In the Great Plains of America topsoil is being lost twice as fast as it was during the 'dust bowl' years [61]. Current USDA estimates are that 159 m acres of cropland are either environmentally sensitive or economically marginal for cropping; agroforestry options for this land would relieve the problem. The Center For

Semiarid Agroforestry is establishing a program of research, demonstration and technology transfer to integrate agroforestry and sustainable land-use systems. A major objective is to minimise loss of topsoil [61]. A windbreak model has been developed to assess alternatives for cropland protection in North America [39, 40].

In southern Ontario, Canada, sandy soils of glacial origin once devoted to dairy and beef cattle are now cultivated for soybeans, peas, tobacco, sweet corn and other field and processing crops; many single and double-row windbreaks of Cedar and Spruce have now been planted, despite extremely slow growth in this environment, to prevent wind erosion of the exposed soil. Others growing cash-crops on erodible sands are using a permanent-bed system with tall wheatgrass or cereal rye in beds about 12 m apart (8% of the area) to shelter the crop and soil.

Field shelterbelts in the USSR (2—4 row belts placed around 30 heights apart) reduce the windspeed in the protected fields by 30—40% and are regarded as an 'integral part of the agro-landscape' and 'the solution to the major task of rational utilisation and conservation of natural resources' [56].

In the European portion of the USSR there are 227 m ha of arable land (200—500 mm precipitation) and of this 90 m ha are subject to wind erosion. About 40 m ha of cropped land are protected by 2 m ha of shelterbelts and 3 m ha of woodlots; the combined effects of improved soil cultivation technology and shelterbelts have reduced average soil losses to around 20% of previous rates and in some regions very prone to erosion 0.8 m ha of two or three-row belts have eliminated wind erosion [56, 41]. The long-term target is for protective afforestation with shelterbelts of 2—2.5% of the arable lands in the forest-steppe, 3—4% in the steppe regions and 5—7% on light sandy soils and slopes — this will entail about 5 m ha of shelterbelts and 13 m ha of woodlots. Aerial and satellite photography are used to provide an inventory of shelterbelts, to study their effectiveness, to map and classify pastures and soils, and to plan protective works for erodible soils [41].

Trees were planted around cropping land in China to prevent wind erosion as early as 550 BC [59]. A return to that practice in the People's Republic of China began in 1950, with the planting of 4,000 km of forest belts to control sand movement on the 13% of China's land considered desert. Planting began in the 1960s of narrow forest belts along roads, canals and ditches, and small network grids on the farmlands. In 1978 the 'Three North' shelter-forest system was initiated to protect 12 provinces in semi-arid northern China extending 7,000 km east to west. The shelter-forest belts are mostly of 2—4 rows; the area within the grid varies with the climate but is 13—16 ha in the warm-temperate area of the sub-tropical zone. Within the grid there may be rows of deep-rooted small-crowned timber trees (e.g. Paulonia) planted 30—50 m apart to further protect crops.

After 40 years 30 m ha of shelter-forest has been established in China and the forest coverage on the agricultural plains regions (a fifth of China's cropland) has increased from 1.1% in 1950 to 7.8% [59].

3.2.2. *Wind erosion in Australia.* Wind erosion has been substantial across the Australian continent and particularly in the semi-arid lands in south-western New South Wales, South Australia, Victoria and Western Australia [53, 32]. However, the use of windbreaks to reduce soil erosion is rare and their establishment has not been actively promoted by any state or federal agency.

New South Wales. In the lease-hold Crown lands of south-western New South Wales the soils range from sand to clay and support vegetation ranging from mallee eucalypts to saltbush and spear grass. There is an embargo on clearing in the Murray geological basin and soils more sandy than sandy-loam may not be cropped. Loamy-textured soils may be at risk if cultivated or grazed bare. Wind erosion is not a major constraint to landuse for soils with a high clay content [53].

Victoria. Wind erosion in the Victorian Mallee has been very severe; large dust storms persisted into the 1950s [53]. After that period 'conservation farming' methods developed by the Department of Agriculture and promoted by the former Soil Conservation Authority and other bodies have reduced but not eliminated the problem [45]. Some 0.7 m ha of land are affected in the Mallee and Wimmera [60]. Predicted greenhouse effects on the Mallee and Wimmera areas of Victoria are increased windspeed and lower winter rainfall — both will increase erosion [53].

Despite conservation farming methods (stubble retention, minimum tillage, stock control) soil erosion by wind is still expanding [44] and in Victoria is still significant in drought years [60]. Spectacular events, like the day in February 1983 when an estimated 1—3 m tonnes of dust passed over Melbourne, are obvious effects of drought, combined with cultivation or over-stocking of erodible soils. The dust came from areas of southern Victoria and South Australia not usually associated with wind erosion. Ordovician sediments in the Wickliffe-Mortlake-Hexham area experienced topsoil and sand movement reminiscent of the Mallee in the 1930s.

The 1982 drought in southern Victoria was due to a shortage of rain between July and November inclusive (159 mm at Hamilton compared with the long-term mean of 369 mm), with a subsequent shortage of pasture growth that spring. Some of the damage in the summer and autumn of 1983 could have been avoided had farmers removed stock from the loam and sandy soils and confined them to clay soils. Where windbreaks were present the damage was reduced, but much sand was deposited to the windward and through the belt. There were insufficient belts to prevent the windspeed from recovering in the intervening space — and early failure to remove sheep from the paddocks left the soil in an erodible state.

Tasmania. Historically in coastal Tasmania and the islands, there has been actual or potential encroachment of sand-dunes onto agricultural land. A more recent development, however, has taken active erosion by wind into the north midlands, where clouds of soil are increasingly a feature of the spring scene.

The erodible soils are naturally occurring wind-blown sands in the extensive valley of the South Esk river. The economic imperative of the last few years, coupled with irrigation possibilities, has made this area more attractive for cropping of potatoes, cereals, peas and poppies. These soils have a like appeal for the processors, as an offset to the traditional vegetable growing krasnozem soils of the north-west, and through their prospects of clean root-crops and winter harvesting.

With recent annual precipitations much below the mean of about 625 mm and typically frequent high winds in spring and early summer, a multi-million dollar industry and a large soil resource are in jeopardy through over-exploitation and through inadequate protection by means of conservation cropping practices and appropriate shelter systems.

Western Australia. Most of the soils in the agricultural regions are susceptible to wind erosion; it was estimated in 1983 that about 25% of the 16 m ha of cleared agricultural land needed special attention and another 40% some management to control wind and water erosion [20]. Another report indicated that, in 1986, 0.5 m ha was actually affected by wind erosion, and another 10 m ha were susceptible [55]. 'Sandplain' soils (approximately 11.7 m ha, or 27% of the South West Agricultural Region) are particularly prone to wind erosion.

Anecdotal evidence of dust erosion in the central wheatbelt is widespread. Instances in 1991 include severe wind erosion in the north-eastern, central and south-eastern wheatbelt. The latter area, north of Esperance, was put at risk by the driest spring and summer on record. The central wheatbelt was affected by a decaying cyclonic low pressure system in May 1991, when many paddocks had been cultivated for crop establishment, and pastures were mostly bare.

Jerramungup, cleared mostly since the 1950s, has had significant wind erosion since 1969 and particularly in 1980, 1981, 1983 and 1984. About 0.44 m ha in 1980 and more than 0.64 m ha in 1981 were estimated to have been seriously affected by wind erosion [65]. This was about 7.3% of cleared land, and 18.3% of the cropped area showed evidence of sand-blasting.

Conditions leading to wind erosion are very similar in the Esperance agricultural region, about 300 km further east from Jerramungup, and based on the coast. Farming conditions, soils and winds experienced at times of high risk on the Esperance sandplain, have led to widespread and severe erosion.

'Minimum tillage' and stubble management in cropping have been a major extension and research activity of the Western Australian Department of Agriculture for nearly a decade. However, severe weather and/or economic factors, combined with imperfect adoption of appropriate grazing and crop management systems, show the weakness of relying on management systems developed for the 'normal' year. An effective system must accommodate the impact of extreme events — shelterbelts are a complementary erosion control aid.

4. Shrubs and trees for rangelands and low rainfall farmland

The greatest wind erosion occurs in the arid and semi-arid lands, where the pastoral industry exists entirely by a precarious exploitation of the natural vegetation [32]. The maintenance of this vegetation by animal management is the sole means of preventing erosion, but during drought when erosion is potentially the greatest this vegetation is regarded as a drought fodder reserve. The loss of perennial shrubs (including the saltbush species) mitigates against control of erosion, and soil losses are certain when arid lands are overgrazed. The drier the climate the greater the difficulty in matching livestock numbers to the vagaries of seasonal production. A single episode of mismanagement may cause serious deterioration from which recovery may be almost impossible [32]. Most of the arid and semi-arid lands are severely eroded as a consequence of the loss of vegetation. Only 10% of shrublands and 30% of the grasslands have been retained in a condition approximating the original state; 65% of the shrublands and 15% of the grasslands have degenerated to less than 60% of their pristine condition [32].

The pastoralist has, in the past, been encouraged by drought relief and subsidy arrangements to pursue a stocking policy based on the best years. Drought feed or transport subsidies have hitherto encouraged producers in semi-arid and higher rainfall areas alike to maintain these stock numbers during drought when the land is most susceptible to erosion. In contrast, prudent land managers did not benefit as much from their conservatism. The Federal government has recently reviewed its policy on drought, now recognising that it is a normal event and should be largely catered for by the producer.

In time we will show more interest in the growing of trees for timber on farms in the lower rainfall areas (<600 mm). We suffer from the belief that forestry is only an option for high-rainfall regions and for short-rotation species. This myopia effectively limits our vision to 5—10% of the country and does nothing to promote the revegetation of the degraded remainder. For this attitude to change we should look again at forestry practises in Europe where one generation plants trees for the next to manage — and harvests those planted by previous generations. We need to adopt that tradition — but pioneers seldom reap the reward of their enterprise.

It is possible to incorporate eucalypts (firewood, posts, poles), acacia (posts, decking, furniture), callitris (decking, furniture), casuarina (shingles, furniture), melaleuca (brushwood), sandlewood (scented wood), quandong or carobs (fruit) and other species in cluster planting or timberbelts. Whilst the trees are relatively slow-growing under low-rainfall conditions, many yield high value products and their inclusion in shelter networks will be of long-term benefit, particularly where they are managed to permit regeneration. In Portugal the evergreen oak *Quercus suber* is grown for shade, to improve grass production (through shelter, increased soil organic matter from leaf fall, and leaf drip), to reduce soil erosion (largely from storm runoff) and to produce cork [37]. Cork is stripped after 30—40 years then perhaps every 10 years thereafter.

Despite slow growth rates, we could argue that in many cases forestry provides a better option for sustainable multiple-use of leasehold lands than the current pastoral activities which have caused such devastation.

5. Wide-spaced trees and clusters of trees for farmlands

Isolated groups or individuals lend a pleasing park-like appearance to the landscape (for example, the river red gum (*E. camaldulensis*) country of western Victoria, or the white gum (*E. wandoo*)/red gum (*E. marri*) country of SW Western Australia) and these provide much needed shelter. Mature river red gums (17 trees/ha) in a paddock at Vasey (western Victoria) showed that the trees reduced the wind speed at 1.5 m above ground to 50—60% of that in an adjacent open paddock [38].

Trees obviously reduce the paddock area that can be cropped. Estimates of this for both *E. wandoo* and *E. marri* near Arthur River in Western Australia, are 0.006% per tree per ha, with a further 1.8—2.4% reduction per tree per hectare due to competition with the crop within 20 m of the tree (T.R. Negus, pers. comm.). However, estimated yield losses such as the latter are difficult to substantiate because they take no account of the effect of trees in modifying the microclimate across the paddock (increasing crop yields in areas away from the trees) or effects on the site fertility (nutrient cycling and root-soil interactions). The long-term effect of clearing the trees on that site may be to depress crop yield.

Oliver Guthrie, a wheat farmer near Donald in the eastern Wimmera of Victoria, has retained about 70% of his original bulloaks (*Allocasuarina luehmannii*) and river red gums, with clumps and scattered trees averaging about 2—3 trees per ha. He has intensively cropped the area since 1950 and believes that the gain from trees in sheltering the crop and field from erosion outweighs the loss around each tree [70].

We do not have good data in Australia of the effects of tree species and spacing on pasture growth. There is anecdotal evidence that certain species are particularly competitive (e.g. *E. sideroxylon*) whilst other species, such as *E. camaldulensis* and *Casuarina cunninghamiana*, allow good growth up to the base. This effect is very noticeable around old river red gums on old or newly sown pasture in the 600—750 mm rainfall area of western Victoria — the pasture remains greener for a longer period and may be more vigorous.

Data for several species will be forthcoming from spacing-design projects at Hamilton in the next few years.

Cluster planting (small fenced woodlots dispersed over the landscape) is an economical means of providing shelter for livestock whilst preserving the open woodland character of the property and indigenous elements of the flora and fauna. Without such protection it will be virtually impossible to maintain the existing biotic elements; most of our grazed farmlands have only sparse mature trees, without any seedling regeneration, and the price of planting and protecting individuals from livestock is so high as to be prohibitive.

6. Shelterbelts for farmlands

Many of the farmlands have been extensively cleared and the most economical and practical option for revegetation, particularly in cropping country, is to provide trees and shrubs in belts which may include timber species for future harvest.

6.1. *Effect on windspeed*

Research in Victoria [11] has confirmed very extensive overseas research [3, 16, 29, 57, 58] that a variety of shelterbelts afford significant protection from wind. Some data are given in Table 1.

Some observations from this study are:

1. Despite significant differences in tree density all belts give a substantial degree of protection across the paddock, actual distance protected being proportional to tree height. Thus, taller belts give greatest distance protection — almost 500 m for a 20 m tall belt of *Pinus radiata* (No. 7) compared with about 250 m for a 10 m tall belt of *Cupressus macrocarpa* (No. 4). This is an important practical consideration — belts planted for soil protection should include species that are long-lived and will attain a substantial mature height. Retention of isolated mallee strips will provide some landscape protection, and preserve elements of the regions flora, but complementary planting of a taller species adjacent to the mallee would improve the shelter.
2. As indicated in Table 1, even a single row of tuart (*E. gomphocephala*) can make a large impact, despite the sparseness of foliage and the 4 m gap between foliage and ground. Fencing and including shrubs in the belt would eliminate wind gaps and improve the effectiveness of the belt, but in many instances this is not achievable. Too much attention has been paid to density aspects — we strive to achieve the impossible and yet the structure that we can achieve provides a significant wind protection to soil, plant and livestock. Our main objective must be to encourage the

Table 1. Effect of windbreaks on windspeed reduction in south western Victoria. Windrun was measured at 0.5 m and/or 1.5 m above ground (G) and the result expressed as % of values at the respective levels (G) in the open.

Species	Belt type and width	Height (m)	Trees/m of belt	G	Windspeed (% of open values) at various distances (H) from the belt									
					Windward			Mid belt	Leeward					
					−3H	−H	0		0	H	3H	6H	12H	24H
1. Sugar gum	Sown, 20 m, nfd	18	7	1.5	78	72	73	–	74	66	47	37	55	76
2. Sugar gum	Sown, 28 m, 4 rows, nfd	19	4	0.5	85	106	97	–	130	86	49	43	73	100
				1.5	85	76	76	–	107	76	49	39	72	91
3. Tuart gum	Single row, nfd	15	0.43	0.5	96	72	–	114	–	92	53	52	62	98
				1.5	95	81	–	108	–	110	73	61	77	100
4. Monterey cypress	Single row, fd, 4.5 m	10	0.29	1.5	89	80	–	56	–	58	37	30	54	82
5. Monterey cypress	Single row, nfd	15	0.17	0.5	85	58	–	133	–	102	49	29	(78)	(100)
				1.5	86	61	–	92	–	80	50	27	54	(84)
6. Monterey cypress	Single row, fd	9	0.25	0.5	89	78	–	81	–	68	37	33	71	100
				1.5	88	66	–	55	–	(49)	45	24	52	97
7. Monterey pine	Two rows, 6 m, nfd	20	0.33	0.5	85	66	123	–	116	90	65	48	54	82
				1.5	62	47	45	–	45	40	37	45	74	95
8. Young acacias	Four rows, 7 m, fd	3	2	0.5	100	–	–	–	–	20	42	68	89	–
				1.5	100	100	95	–	26	23	46	66	83	(91)

fd = fenced; nfd = not fenced; H = height of belt; ( ) = values by extrapolation.

planting of those species that will survive and grow in some very stressful environments.

3. Gaps beneath windbreak trees result in acceleration of windspeed at that point (No. 3, 5). With the unfenced cypress (No. 5) cattle had browsed the lower 2 m of foliage and the windspeed measured 50 cm above ground was 33% greater than in the open. Clearly this could create a significant unseen hazard (e.g. erosion, exposure of sheltering stock, accelerated passage of a fire front). A similar effect has been shown by others to occur at the ends of belts [29] and this should be countered by tapering off the ends with shrubs and grass. Belts should be fenced to retain lower foliage and shrubs.
4. Maximum wind protection for the wind-permeable belts occurred at around 6H to lee. There was still substantial protection at 12H (windspeed 50—80% of open values). Note that the impermeable belt (No. 8) which consisted largely of acacia species with sheoaks (*Allocasuarina verticillata*) and phalaris 2 years after planting, had maximum protection at 1H from the belt. However, at age 7 this belt has now become more permeable as the wattles and sheoaks developed and would conform more with the others. For some purposes, such as protection of freshly shorn sheep from rain and wind, a small area of dense shelterbelt is desirable [12].
5. It is apparent that belt profile is not of great importance. A myth has been perpetuated in the extension literature that a sloping profile is required and obtained by planting shorter species on outside rows. Evidence from the sugar gum (*E. cladocalyx*) and pine belts (Table 1) and shelterbelts in New Zealand [57, 58] confirm early work that a uniformly permeable vertical face is a desirable structure [16].

For practical purposes it may be necessary to site shelterbelts at around 10—15H apart (at maturity) to obtain the most economic response in terms of pasture and animal production [10]. Shelterbelts spaced at about 12.5H would also greatly reduce soil erosion, since windspeed in the area between the belts would be reduced by an average of about 50%. Siting belts at intervals of around 25H could also reduce windspeed by an average of about 33% in the sheltered gap.

6.2. *Control of soil erosion*

Wind erosion (E) is proportional to the wind speed (W) cubed for loose sandy soils, when wind velocity is above that required to initiate erosion [2, 42].

$$E \propto W^3$$

Small reductions in wind speed would, therefore, result in large soil erosion control benefits — this is an important point that is largely unrecognised by our agricultural advisers and land managers. For example, windspeed 0.5 m above the ground at 12H beyond the seemingly inadequate single-row tuart shelterbelt (Table 1) is reduced to 62% of open windspeed, but the estimated erosive force of the wind is reduced to 24% of open values. This situation is illustrated in Fig. 1. This model also shows the effect of the large gap in the foliage beneath the tree crowns — on susceptible soils wind erosion in this zone will occur unless ground cover is maintained by fencing to exclude livestock.

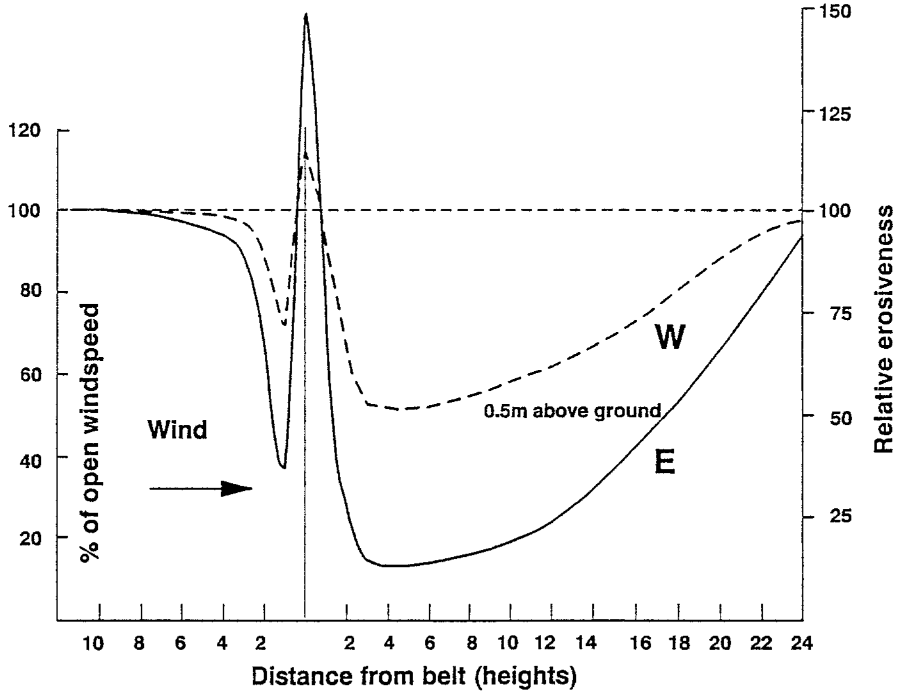

Fig. 1. Effect of a single row of Tuart trees (15 m tall, 2.3 m apart) on windspeed (W) at 0.5 m above ground and predicted relative erosiveness (E) of wind at varying distances from the belt.

Soil flux increases with windspeed and the area protected by the windbreak is less at higher windspeed [42]. The area protected also decreases as the wind approach angle becomes more acute to the windbreak [30, 31]. When the wind is parallel to the windbreak there is some erosion protection but maximum soil fluxes can be expected to occur beyond 8H (Fig. 2a).

When the wind is at 45 degrees to the windbreak (Fig. 2b), only the highest windspeed, 21.5 m s^{-1}, results in maximum soil flux at 24H. All other wind velocities have lower than maximum soil fluxes and erosion control (< 5 g^{-1} m^{-1} s^{-1}) was maintained to 24H for all winds less than 14 m s^{-1}.

With the wind at 90 degrees to the windbreak, erosion control is main-

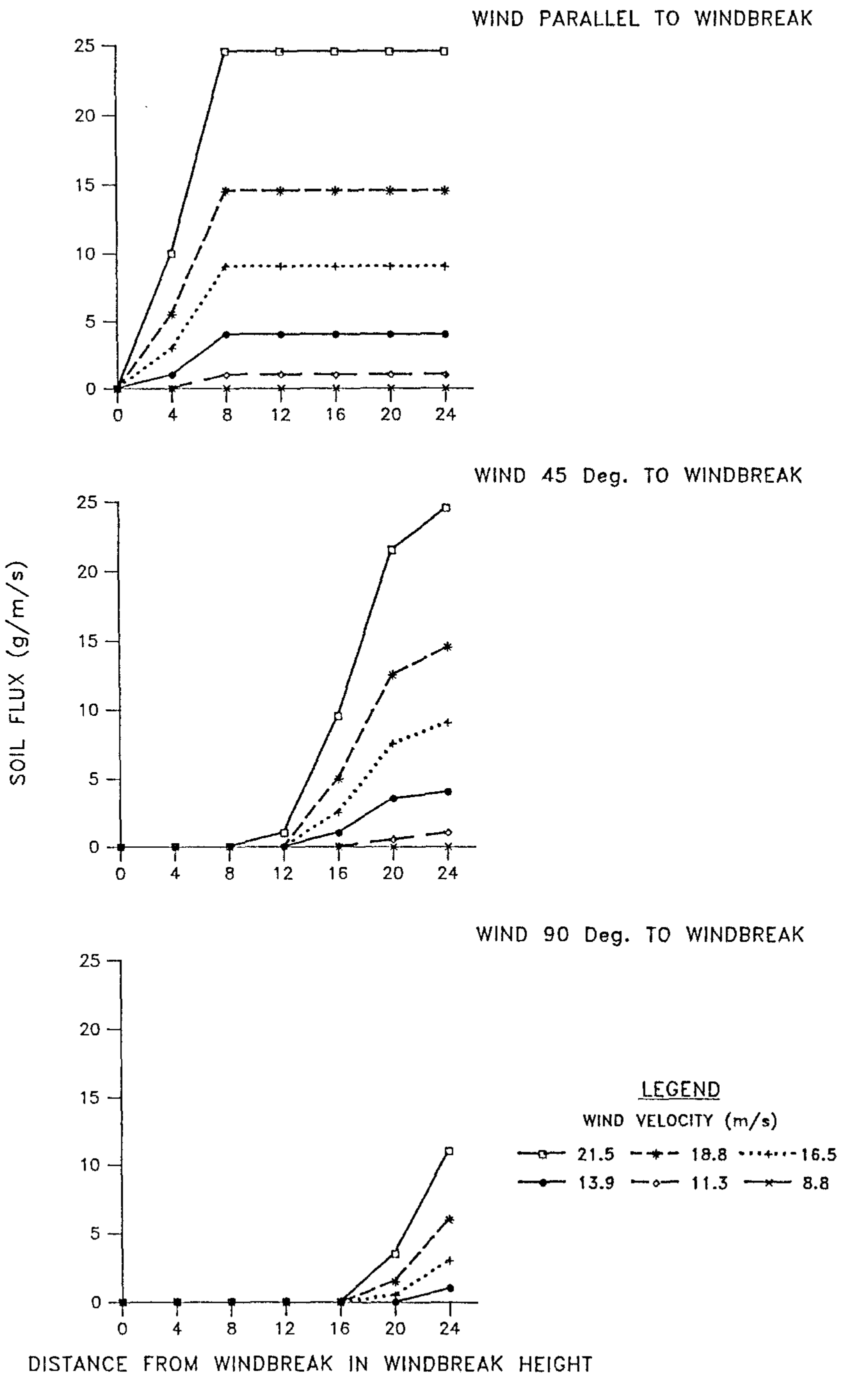

Fig. 2. Predicted soil flux to windward of a 40% porous windbreak.

tained to 24H for winds up to 18 m s^{-1} (Fig. 2c). Extrapolation of the data indicates that maximum soil flux rates would not occur until approximately 30H.

Tree windbreaks for the prevention of wind erosion would overcome deficiencies in current short-term agronomic management for protection during severe conditions. Combinations of tree and agronomic management systems are likely to be the most effective over the entire range of risk conditions.

Shelterbelts to reduce windspeed over vulnerable paddocks would substantially reduce wind erosion and loss of fertility, but what are the practicalities?

The main determinants of windbreak network development are the likely mature height of the windbreak, the distance apart of belts, the positioning of gaps, and the width of belt needed to achieve satisfactory shelter [29]. Only 2% of land would be occupied by belts that were 20 m tall at maturity, 10 m wide and spaced 25H (500 m) apart. If trees are planted in rows 3 m apart, with outside rows 2 m from the fence, 3 rows could be planted in a 10 m belt. In areas of southern Australia where annual rainfall exceeds 400 mm this could be achieved with belts of *E. cladocalyx* (sugar gum), *E. occidentalis* (flat-topped yate), *E. camaldulensis* (river red gum), *E. microcarpa* (grey box), pinus or other species suited to the site. Conversely, for mallee belts only 5 m tall, 7.4% of land would be used if the 10 m wide belts were spaced 25H (125 m) apart [11]. Belts wider than 10 m are required when 4 or more rows are planted; when the spacing between rows is 4—5 m (this may be necessary in semi-arid areas); when strips of remnant vegetation are to be retained in a viable condition; when more than 2 m is left between the fence and the outside rows of trees. For 20 m wide belts the percentage of land devoted to trees in the above cases is 4 or 15%.

We consider that appropriately positioned windbreaks offer major advantages for reducing wind erosion. This conclusion is supported by results and widespread adoption of windbreak technology in the USSR [56], USA [30, 61] and China [59]. We believe that further research in Australia will show that windbreaks for soil erosion control should not be considered 'impractical on most rural properties' [47]; on the contrary, they will be regarded as a necessary adjunct to sound pasture, stock and crop management practice on most rural properties [1].

7. Shelter effects on plants and animals

The many effects of trees on plant and animal physiology and production have been extensively reviewed in recent years [6, 7, 9, 10, 13, 51]. A summary of the important effects of shelter are presented below.

7.1. *Trees, shelter and plant production*

Trees may affect pasture or crop production in the following ways:

1. by reducing water loss, as a result of reduced windspeed and/or shading — this can also prolong pasture growth in summer [7, 51]. Pasture growth may also be increased by provision of shelter in the irrigation areas, with added benefits of a reduced loss of applied water and increased crop water use efficiency [7, 13, 51].
2. by retaining the heat of soil and air in the sheltered areas in autumn-winter-spring [29, 56, 72], and preventing overheating from dry hot winds during summer [59], crop yields are increased or the growing range extended.
3. by reducing inward radiation during the day and decreasing outward radiation at night [29] — it is a common observation that trees afford ground plants protection from frost. This has been observed experimentally in the sub-tropics where the grass remained green in winter under the trees [17]. Frosting may occur on the up-slope side of a belt on hillsides, unless some air drainage is provided [29].
4. by protecting soil by leaf or twig litter and/or reduced windspeed at the soil surface — reducing erosion of soil nutrients by wind and water runoff [71].
5. by competing with pastures or crops for light or soil moisture [6, 17, 50]. Photosynthetic rates of corn are maximised 10H from shelter but are low immediately adjacent to the trees [72]. Shading affects pasture species differentially. Thus, growth of Nangeela cultivar of sub clover and Berseem clover is reduced by only about 10% but other legumes by 40% under 50% shade [50]. Maku lotus also appears to cope with reduced light. Inevitably there is a point at which increasing density of trees completely excludes pasture. This point, and the shape of the response curve, will probably vary for different tree and pasture species. With some combinations it is possible that pasture production could be greater with a certain density of trees than without trees. We do not have good data on these interactions.
6. by reducing mechanical damage to plant tissue arising from flexion or sandblasting of seedlings [6, 7, 13, 51, 72].
7. by promoting mineralisation of soil nitrogen as a result of shading pasture or soil — and thereby increasing pasture growth [17, 68].
8. by contributing to soil organic matter (leaf and twig litter forming humus) and improved soil moisture retention [48, 56, 71, 72].
9. by improving soil physical properties, associated with soil root mass [71].
10. by trapping or recycling nutrients — these attributes may permit sustained yields from land where cropping rapidly depletes the soil nutrients in the absence of fertiliser applications [71]. Nitrogen fixation by acacias,

casuarina and other shrubs; trapping of dust on foliage and deposition of nutrients to ground with rain; accessing nutrients by root-induced rock weathering in the B and C horizons; recycling of minerals leached beyond the A horizon are all possible modes [4, 6, 48, 56, 71, 72].

11. by reducing or preventing soil acidification — acidification is a particular problem on soils having a low initial base status and where cropping and/or grazing with legumes is practised. Most pasture and crop species grow poorly on acid soil — some minerals are rendered unavailable (e.g. P), or too soluble, leading to Al or Mn toxicity or loss of N, Ca, Mg and K through leaching [33]. Such acidification is aggravated when the N produced from pasture or crop legumes (e.g. sub. clover) is converted to NO_3^- and leached from the root zone before it can be re-converted to plant or microbial protein. This is more likely to happen when there are few perennial plants. A challenge for the future is to develop production systems that efficiently recycle nutrients released from weathering or applied as fertiliser, and that minimise nitrate leaching [33]. The role of trees has still to be widely recognised, but there is evidence that trees in pastures have prevented soil acidity increasing [21], possibly through their trapping of nitrate and by their substantial additions of Ca in leaf drip and litter return [6].
12. by reducing deep infiltration of water to groundwater systems — and thereby preventing the rise of saline watertables which would otherwise result in deposition of sodium and other salts at the surface, with consequent depression of pasture and crop growth [35, 56, 59, 60, 64].

Windbreaks may assist horticultural production in following ways:

1. by preventing rubbing damage to fruit — e.g. citrus, stone-fruits and tropical fruits such as mangoes — the damage is largely cosmetic but may lead to the down-grading of 30% of crops in some areas of Queensland [63].
2. by preventing mechanical damage to orchards — e.g. protection of macadamia plantations in Queensland [63].
3. by controlling disease and insects — windbreaks may assist in the control of anthracnose outbreaks in mangoes [63] and as alternative hosts for leaf-feeding red shoulder beetles (*Monolepta*). These beetles are attracted by *E. torelliana* trees and can then be treated with insecticide away from the fruit trees. Windbreak trees also afford habitat for predatory birds and insects which may help control some insect pests.
4. by improving pollination efficiency — e.g. fruit set of cucurbit crops in Queensland may be increased 30% in some years [63].
5. by controlling spray drift — shelterbelts may be used to reduce the drift of chemical sprays from cotton fields; the windbreaks also extend the opportunities for spraying in otherwise unsuitable weather conditions [63].
6. by improved production from shelter — some varieties of apples and

cherries are tolerant of wind but other stone-fruits are very responsive to shelter [65].

7.2. *Trees and effects on animal production*

Trees may affect animals in the following ways:

1. by indirect effects on animals through effects on pasture production (see 7.1)
2. by providing foliage or fruit which supplement their intake from pasture. Examples of indigenous vegetation used for this purpose include mulga (*Acacia aneura*), saltbush (*Atriplex spp.*) and kurrajong (*Brachychiton spp.*) [32]. Useful introduced species include tagasaste (*Cytisus polmensis*) to provide green leaf in the summer, paulownia (*Paulownia spp.*) and poplar (*Populus spp.*) which provide edible leaves, sub-tropical shrubs such as leucaena (*Leucaena leucocephala*) which provide browse or cut foliage, and carob (*Ceratonia siliqua*) or honey locust (*Gleditsia triacanthos*) which produce edible pods [52].
3. by reducing livestock maintenance requirements due to shelter, as energy expenditure is increased by excessive heat or cold. This diverts energy from productive purposes into maintenance functions. It may also alter grazing behaviour and thereby reduce intake. Experiments with penned sheep and cattle indicate that strong wind and rain can double the requirement of energy for maintenance. A 33% reduction in windspeed from 3 m s^{-1} (10 km h^{-1}) to 2 m s^{-1} can result in a 10% saving in energy; a 55% reduction on windspeed would increase that value to 17.5% [6, 7, 51].

   Cattle appear to be particularly sensitive to hot humid conditions and the provision of shade on rangeland or dairy farms improves their tolerance and level of production [6, 23]. Shade also improves utilisation of pasture on rangeland. Provision of shade to cattle in feedlots in Queensland has improved feed conversion efficiency and survival [63]. Recent well publicised incidents where hundreds of cattle perished in unshaded feedlots in Queensland have resulted in prosecution of the operators. Cattle in unshaded saleyards in Victoria have also perished during very hot weather.

   It is unlikely that sheep with fleeces suffer significantly from heat stress in temperate regions.
4. by shelter effects on fertility. Heat stress can reduce ram fertility and, particularly with shorn sheep, affect ovulation, oestrus, conception and embryo survival. Heat stressed cows produce smaller calves and have longer intervals between calving. These effects with ewes and cattle are more pronounced in the tropics and sub-tropics but ram infertility as a consequence of heat stress is not uncommon in temperate regions [51]. The foliage of some tree species may cause abortion in cattle (e.g. *Cupres-*

sus spp.) while death may result from ingestion of foliage of sugar gum shortly after lopping.

5. by shelter effects on newborn animals. Published studies in SE Australia show that lamb mortality is decreased by an average of 50% when adequate shelter is provided [7]. Losses are worst in windy, wet and cold weather — perhaps all lambs born in such a bout will die. However, if wind speed can be reduced by 50% (e.g. from 3 m s^{-1} to 1.5 m s^{-1}) during such weather the predicted effect is a 50% increase in lamb survival [25]. On average, lamb losses can be reduced from around 20% to 10% of those born alive [7]. Since ewes will not always seek shelter prior to lambing, the shelter must either be dispersed (e.g. woodland with logs, tussocks etc.) or the sheep need to be confined to a sheltered area for maximum effect [12, 69].

   Provision of shade can improve the survival prospects of calves and lambs. On shadeless rangelands most of the 5—10% calves that die in the first week do so from heat stress [23]. Provision of shade in lambing paddocks in the sub tropics also improves lamb survival and subsequent growth and wool production [6, 7, 51].
6. by shelter effects on newly shorn sheep. Losses of shorn sheep following cold, wet and windy weather in southern Australia can be catastrophic [6, 9, 12, 51]. The conditions leading to the losses — and the use of shelterbelts and havens to reduce or eliminate them — have been discussed in the above papers. Regrettably, while most farmers are well aware of the danger, many have not made an effort to rectify the problem. A shelter haven can be created inexpensively by direct-seeding of trees of mixed species — and will be effective within two years of sowing, as evident from blocks established by the Department of Agriculture around Hamilton, Victoria. A brochure is available which illustrates several options for havens [69].

7.3. *Shelter effects on agricultural production*

Substantial effects of shelter on agricultural production have been claimed by those countries in which extensive shelter networks have been developed. Over a 25 year period from 1955—1980 in the USSR the average yield response of crops to shelter (allowing for land occupied by the belts) was: cereals 18—23%, industrial crops 20—26%, forage crops 29—41%, citrus 20—26% [56]. In China, protective effects are seen up to 20H from belts. Crop yields in 500 m × 500 m shelter networks in north-east China, during the years 1986—90, increased by 9—32% [72]. Another report of long-term effects of shelter in China shows increases for wheat, barley, rice and corn of 10—25%, 6—14%, 5—15% and 20%, respectively [59].

A case has been made for the deployment in the higher rainfall (>600 mm) grazing areas of southern Australia of 10% of the land in a shelter network [9, 10]. The model predicted that, for discount rates less than about

7% real interest, it was better to have 10% of the farm in a network of close-spaced belts (12.5H apart) rather than 5% of the farm in wide-spaced belts. The economics of the system would be further improved by the incorporation of timber species and management of the timberbelts [8]. While the simple models above give support to the economic feasibility of a farm revegetation program we need to use a sophisticated model, such as the Farmtree model [28], when considering a particular species, site and layout for a chosen option.

'Farmtree' [28] is an agroforestry simulation model for micro-computers in which details of site, layout, species, intended harvest age, proposed management and other data are entered and likely costs, effects on agriculture, tree growth, timber value and direct effects on farm income and net rate of return are estimated.

A preliminary model for a lower rainfall area in South Australia (450 mm) suggests that tree establishment to provide shelter or control salinity would also be profitable in the long term. With this model it is possible to make an allowance for land protection values as well as short-term agricultural production factors [14].

We require substantive evidence to verify the assumptions made in the models, particularly in relation to the effects of shelter on plant production (crops and pastures) for a wide range of Australian conditions. However, we now have evidence from Rutherglen, Victoria [15] that shelter provided by eucalypts can increase wheat and oat crop yields in the sheltered zone (1.5—

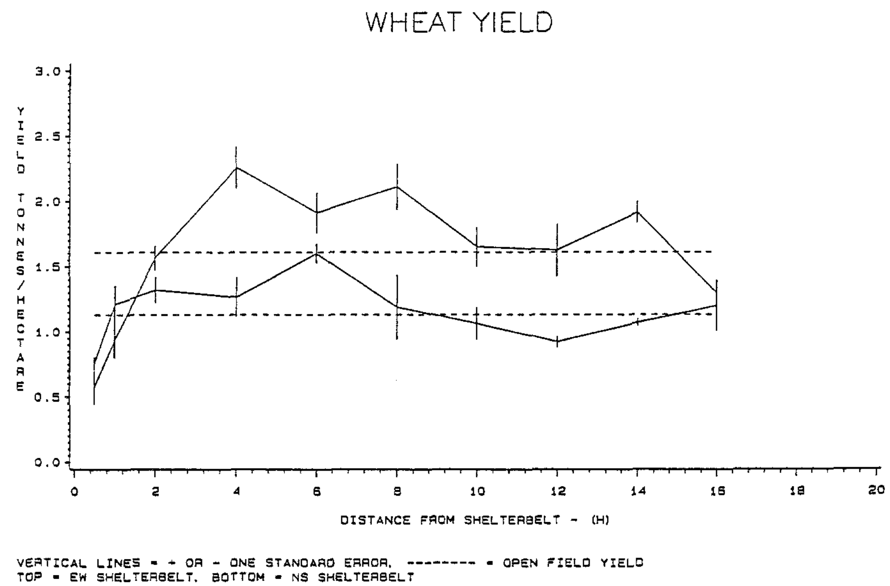

Fig. 3. Effect of shelter from east-west (EW) and north-south (NS) orientated belts on wheat grain yield at Rutherglen, Victoria.

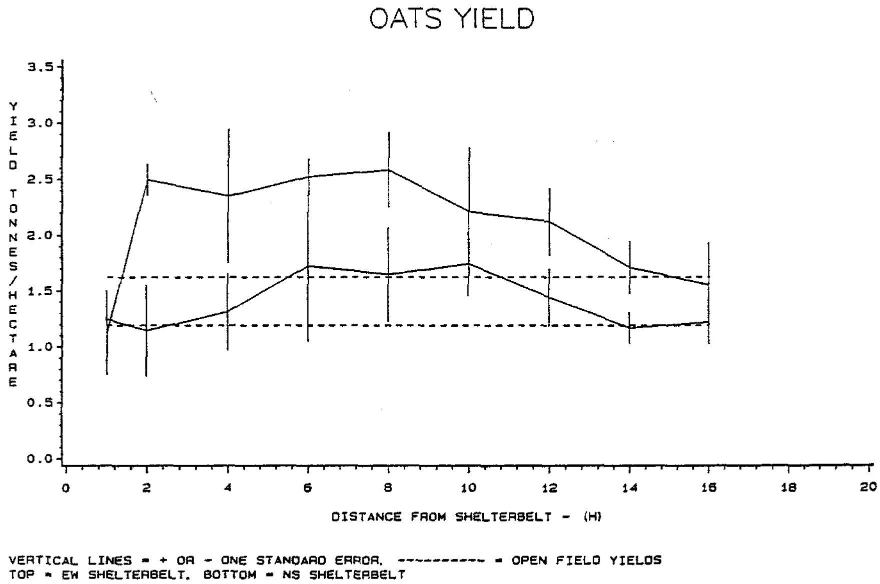

Fig. 4. Effect of shelter from east-west (EW) and north-south (NS) orientated belts on oat grain yield at Rutherglen, Victoria.

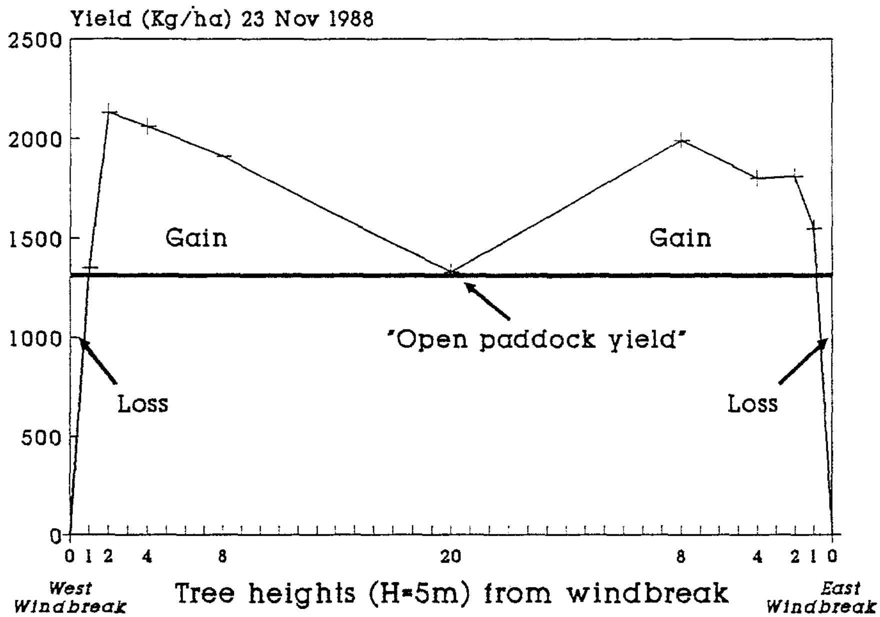

Fig. 5. Lupin grain yield between parallel pine windbreaks at Esperance, Western Australia, 1988 (property of G & J English).

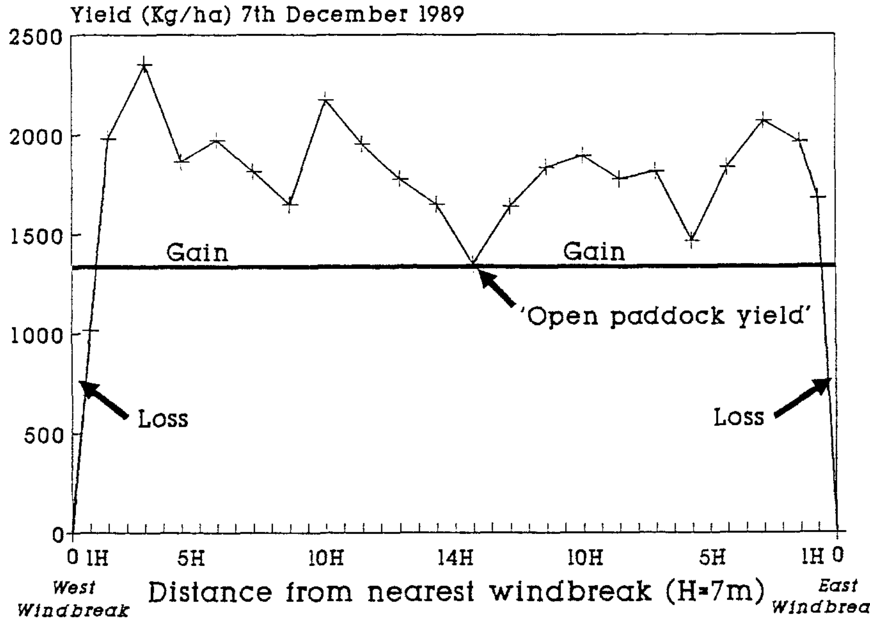

Fig. 6. Lupin grain yield between parallel pine windbreaks at Esperance, Western Australia, 1989 (property of G & J English).

9H) by 22% and 47%, respectively (Figs 3 and 4). Also, work at Esperance in W.A. [5] shows that lupin yields have increased by up to 30% when sheltered by *Pinus radiata* windbreaks (Figs 5 and 6). These data confirm experimental results world-wide [3, 6, 9, 13, 16, 29, 56] and we should procrastinate no further in our advocacy of the use of shelterbelts in Australia.

8. Conclusion

In the cropping and higher rainfall grazing areas, the systematic planting of 5—10% of the land in a net of shelterbelts/timberbelts/clusters could achieve a 50% windspeed reduction; this would substantially improve livestock and pasture production in the short and long-term. Wind erosion could be dramatically reduced and crop production probably increased by the use of windbreaks.

In semi-arid and dry temperate areas, planting of 2—5% of the land to shelter could reduce windspeed by 30—50% and soil loss by up to 80%. This planting would also contribute substantially to achieving other objectives of sustainable agriculture. It has been estimated, for example, that around 25% of the 300—700 mm rainfall belt in Western Australia will need to be reforested in order to prevent salinity from increasing ten-fold to 2.5 m hectares within 20 years [66].

In the arid (pastoral) areas there is an urgent need to promote the ethic that preservation and improvement of the perennial grass and shrub vegetation is critical for the protection of the soil and maintenance of land capability [32]. Control of animal grazing (introduced and native) remains the sole means of preventing erosion in much of this zone. While satellite imagery allows us to assess the condition of leasehold lands, we have failed to achieve stocking policies that will halt the degradation of our rangelands and revegetation strategies to restore them.

Agroforestry — particularly timberbelts (where timber and shelter are products) — will be important in the long-term strategy for achieving revegetation. Whilst trees are relatively slow growing under low-rainfall conditions, many yield high value products and their inclusion in shelter networks will be of immense long-term benefit. If some of the trees yield a marketable product then the adoption of the shelter system will be more readily achieved. Regrettably, forestry has only been considered an option for high-rainfall regions and for short-rotation species. We need to look at attitudes towards forestry in Europe, where one generation plants trees for the next to manage — and harvests those planted by previous generations.

We have the technical means of achieving goals of 10% or more of the land devoted to tree cover and the shelter and other benefits that follow. To that end, direct-seeding of trees and shrubs will increase the speed of revegetation and markedly reduce costs. This technology is well developed in Victoria, South Australia and Western Australia, and has gained much acceptance among farmers. What is required now is the political will to vest with some meaning the new bureaucratic jargon 'sustainable development'.

There are a number of areas in which research must be improved if we are to positively model biological and economic responses of soils, plants and animals to shelter:

- the effects of windbreaks in combating soil erosion should receive high priority in the arid, semi-arid and dry temperate zones — unlike other countries Australia has badly neglected this approach to land management
- demonstration/research is required on shelterbelts for the semi-arid and dry temperate zone — with emphasis on belt width and species composition in relation to their effectiveness in protecting fields; optimal spacing of belts across paddocks; overcoming competition with crops along the belt margins
- in all regions more data is needed on the relationship between shelter and agricultural response — particularly for crops — models such as 'Farmtree' [23] currently do not have an adequate base of data for tree and plant interactions
- in those pastoral regions where there is presently woodland there is an

urgent need to define the long-term effects of clearing on sustainable landuse — the present information is simply not adequate — and to develop alternatives to tree removal in order to attain or maintain a sustainable production system
— agroforestry options (woodlots and timberbelts) need to be investigated for all regions but particularly for the dryland areas where grazing and/or cropping activities have been ecologically destructive.

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