Ecological aspects of Eucalyptus plantations

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ABSTRACT

This paper takes up a number of issues associated with the planting of eucalypt trees as exotics. Matters addressed include climate and microclimate, hydrology, soil erosion, soil nutrients, competition and other interactions with flora and fauna, allelopathy and fire. Additional emphasis is given to soil non-wettability under eucalypts and the ability of at least some eucalypts to mobilize and store soil nutrients in surface soils close to the trees on poor sites. Guidelines are given for reducing adverse ecological consequences of planting eucalypts.

Key words: *Eucalyptus*, ecology, plantations, climate, microclimate, hydrology, soil erosion, soil nutrients, competition, flora, fauna, allelopathy, hydrophobic soils, fire.

INTRODUCTION

Importance of Eucalypts

More and more people are placing ever greater demands on the world's forests for wood and non-wood products. Diminishing natural forest resources are being compensated by rapid expansion of the use of planted exotic trees worldwide. Trees of Australian origin are at the forefront of these developments, particularly three genera: *Eucalyptus*, *Acacia* and *Casuarina*, which, together, comprise well over 1,500 Australian species. *Eucalyptus*, by far, is the most important, representing over 80 percent of the area planted with these three genera.

The genus *Eucalyptus* now (August 1993) encompasses some 700 species. Almost 200 of these are relatively new, having been described in the six years since the last major published revision which was undertaken for the Flora of Australia (Chippendale 1988). Included then were all 513 species published to January 1987. Nearly 100 new species have been described in the last two years in just four papers: Brooker and Hopper 1991, 1993; Hill and Johnson 1991,1992. Most of the new species described are endemic to Western Australia and many have the "mallee" (multi-stemmed) habit. (Colour illustrations of many of these new species are to be found in Brooker and Kleinig (1990)).

All but two of the 700 species occur naturally in Australia. Of the two non-Australian species, one,*Eucalyptus urophylla*, has a limited range at the south-eastern end of the Sunda Archipelago, Indonesia. There are extensive stands of *E. urophylla* on the large island of Timor above 1,000 m and throughout Wetar Island. More scattered stands are found on five nearby islands: Adonara, Alor, Flores, Lomblen and Pantar. The other, *Eucalyptu*s *deglupta*, has a wide pantropic range, from New Britain in the east, through New Guinea (Irian Jaya (Indonesia) and Papua New Guinea), to Ceram and Sulawesi in the west, and north to Mindanao. Nine, and possibly more, of the northern Australian species (*E. alba*, *E. brassiana*, *E. confertiflora*, *E. leptophleba*, *E. papuana*, *E. pellita*, *E. polycarpa*, *E. tereticornis* and *E. tessellaris*) extend also into southern New Guinea and one of those,*E. alba*, is found on Timor below about 2,000 m and as far west as Sumbawa Island in the Sunda Archipelago of Indonesia. Taxonomy of of the extra-Australian species is under revision.

Despite the proliferation of species names, commercial and rural forestry based on*Eucalyptus* worldwide still depend on relatively few species. According to Eldridge *et al*. (1993), the ranking of the ten most important eucalypts, in terms of current annual increment of wood, would include: *E. grandis*, *E. camaldulensis*, *E. tereticornis*, *E. globulus*, *E. urophylla*, *E. viminalis*, *E. saligna*, *E. deglupta*, *E. exserta*, and then either *E. citriodora*, *E. paniculata* or *E. robusta*. Of these, the first four mentioned are by far the most important on a world basis. In the Asia - Pacific region, countries participating in the UNDP/FAO Regional Project on forest tree improvement and propagation (RAS/91/004) (Bangladesh, Bhutan, India, Indonesia, Nepal, Malaysia, Pakistan, Philippines, Sri Lanka and Thailand) ranked *E. camaldulensis* first, then *E. urophylla*, hybrids such as *E. urophylla* x *grandis* and *E. deglupta* x *pellita*, then *E. globulus*, *E. grandis* and *E. deglupta* in that order as regards regional importance (Davidson 1993).

There is a multitude of possible uses to which eucalypts can be put. A recent paper by a Chinese scientist to the 46th Annual General Conference of Appita in Launceston (Song Yongfang 1992) gave an insight into products derived from *Eucalyptus*. He mentioned construction timbers, furniture, farming tools, transmission poles, railroad sleepers, fuelwood, honey, pulp and paper, rayon, fibreboard and plywood. Then he went on to describe some less conventional uses such as essential oils, plant growth regulators, tannin extracts, industrial chemical additives, adhesives, fodder additives and fabrics (derivatives of rayon).

China began its *Eucalyptus* oil production in 1958. Since the 1970's oil production in China has been developing rapidly, now providing 1,000 tonnes/yr or 40 percent of the international essential oil market. In the eucalypt forests of China, oil production is very attractive since it can represent 20 percent of the total income obtained from the trees. By further processing the *Eucalyptus* oil, citronellol, menthol, thymol and roseol are obtained which are used wide-ly in the pharmaceutical industry for the manufacture of throat lozenges, candy for cough re-lief, oil balms, cooling ointments for burns, cold ointments, etc. They also are used in com-positions for tooth paste, perfume, toilet soap and prickly heat powder, as well as for flota-tion of metals, industrial solvents, insecticides and fungicides as additives in small amounts.

China started its research on preparation of plant growth regulators from eucalypt leaves in 1981 and has achieved some significant results according to Song Yongfang (1992). Facto-ries have been built for the production of the growth regulators (phytohormones). They have been applied experimentally in the field on large areas which confirmed their effect in increasing the growth rate and yield of vegetables, grapes, rape, cotton, as well as in the protection of the plants from insects and diseases (Zheng Haishui 1987, Song Yongfang 1992). As a product of natural origin, the growth regulator has great potential for decreasing chemical pollution and reducing residual toxicity in agriculture.

In the past, the residues left after distillation of oil from eucalypt leaves has been used as fuel or compost. In China now this residue is crushed, chemically treated and washed to produce an additional extract which when evaporated and dried contains 45 percent of mixed tannin with a purity of 48 percent. This product is used for decreasing the coagulation of drilling mud, for metal flotation and tanning of light leather. Cooking the leaf residue in the presence of NaOH and Na_2SO_3 produces another product used as a water reducing agent for cement, an additive in the ceramics industry for increasing anti-abrasion strength during ball milling, a thinner for drilling mud and a component of a boiler anti-scaling product.

Studies on the feasibility of manufacture of fodder additives from eucalypt leaves have been proceeding in China since 1986. To date (1992) the biochemical analysis and nutrition evaluation of 25 *Eucalyptus* species have been completed and many feeding experiments have been made on chickens and swine with eucalypt leaf powder and its extractives. The results show that the addition of this eucalypt fodder additive increases the weight of swine by 13 percent. Song Yongfang (1992) states that the varied antimicrobial substances in the eucalypt leaves promote vigorous growth and provide protection from disease in chickens and domestic animals.

To improve eucalypt bark utilization, attempts have been made to prepare adhesives from polyphenols extracted from the bark to be used as alternatives to existing phenol or phenol-aldehyde resins. The preliminary results show that the bark powder of *E. citriodora* has the most active reaction and can replace 40 percent of phenol.

Research has been undertaken on artificial fibre (rayon and derivatives) manufacture from*Eucalyptus globulus* in China for use in fabrics, felts, blankets and handicrafts.

Despite their many potential uses, as demonstrated by the Chinese experience, for more than a century eucalypts nearly everywhere have been planted mainly for production of poles or fuelwood. Farmers have appreciated the relatively low establishment cost, fast growth, and vigorous coppicing under often adverse site conditions. In the highlands and inter-Andean valleys of Bolivia, Peru, Ecuador and parts of Columbia and in the highlands of Ethiopia, eucalypts are by far the species most sought for fuelwood, often in combination with other uses such as mine props, poles and timber. "Rwanda is one big agroforestry plantation, they have a policy of only growing *Eucalyptus* and *Grevillea*" says a forester in Kenya. Millions of inhabitants of these regions, including a large proportion of tribal people, depend today exclusively on eucalypts for their fuel and wood needs. Planting rates in these countries continue to accelerate.

Industrial planting of eucalypts has accelerated too, especially to produce raw material for pulping. Eucalypt pulp from intensively managed plantations is currently less costly than that produced from other hardwoods like Birch, and, for the time being at least, has taken a large share of hardwood market pulp and has been displacing softwood pulps on world markets. The market has recognized that eucalypt pulp imparts a special strength and softness to the product for tissues and fine white papers such as those for offset and laser printing, photocopying and writing. The international eucalypt pulp market has been growing at more than 5 percent a year while the softwood pulp market has had an annual growth of 3.7 percent.

Over 13 million ha of eucalypts now are estimated to be under cultivation in plantations worldwide (Table 1). This latest estimate is almost double that made in 1985 (7 million ha: Davidson 1985a, 1988) and already exceeds the prediction made in 1988 of 10 million ha by the year 2000 (Davidson 1988). These new data mean that eucalypt planting worldwide has doubled each decade since 1960, and, if this trend continues, will exceed 16 million ha by the year 2000. Despite the continuing acceleration of planting *Eucalyptus*, the genus today still only represents 15 percent of all plantations worldwide (excluding most of Europe which comparatively has hardly any eucalypt plantations)(Table 1). Regionally, *Eucalyptus* represents 38 percent of African, 8 percent of Asian and 43 percent of American plantations (Table 1). After planting huge areas over the last two decades, India and Brazil have the largest areas of eucalypt plantations (estimated at 4.8 million and 3.6 million ha respectively; or, for both countries combined: 63 percent of the world's total)(Table 1). In the Asia - Pacific Region, other than India, planting of acacias is overtaking eucalypts, with nearly 750,000 ha established, mostly in the last decade, and principally comprising *Acacia mangium* in Indonesia (500,000 ha estimated to date) and Malaysia (100,000 ha estimated).

Several million ha of additional equivalent area is estimated to have been planted to eucalypts on farms and in other rural areas (roadsides, canal banks, railway embankments and on common lands) as single trees and in lines and small groups. This situation is most noticeable in China, Ethiopia and India. In China, it is estimated over 1,000 million eucalypt trees (equivalent to 1 million ha at 1,000 trees/ha) have been planted around fields, homes and villages and along roads, railways, streams and canals in almost all Provinces of China south of the Yangtze River (McKenney *et al.* 1992). In Ethiopia, the equivalent of over 200,000 ha of*E. globulus* and *E. camaldulensis* has been planted on farms. Between 1981 and 1988, farmers in India planted roughly 8,550 million trees on private lands, more than 80 percent of them *Eucalyptus tereticornis*, equivalent to about 2.5 million ha of plantations at the average spacings used (Saxena 1991).

Success of *Eucalyptus* as an Exotic

Rates of growth of eucalypt trees are often much faster in the exotic locations than are experienced at home, and usually very much faster than local indigenous species. The conventional wisdom for this was that insect pests which attacked the trees heavily and continuously in Australia were absent from the exotic location. Though this idea may play a part, it is now considered that, given the way the genus *Eucalyptus* evolved in response to declining soil fertility and, after a long interval, to a drying climate as well on the Australian continent, they are almost invariably planted in an exotic environment which affords them access to more nutrients and moisture than they would experience at home (Florence 1990). Though they grow fast, their evolutionary background still means they usually consume less nutrients and water than indigenous species for production of the same amount of biomass.

Table 1 Eucalypts in the forest plantations of the world

	Total area of plantations (ha)	Eucalypt plantations (ha)	Percent eucalypts (%)
Africa:			
Algeria		30,000*	
Angola	171,500	135,000	79
Burkina Faso	28,000	7,000	25
Burundi	132,000	40,000	30
Cameroon	23,000	13,000	57
Central African Republic	9,000	1,500	17
Congo	53,000	35,000	66
Comores	1,000	500	50
Ethiopia	270,000	95,000	35
Gabon	30,000	2,000	7
Ghana	75,000	14,000	19
Kenya	168,000	17,000	10
Libya		26,000*	
Madagascar	310,000	130,000	42
Malawi	180,000	30,000	17
Mali	20,000	5,000	25
Mauritius	11,900	3,000	25
Morocco		200,000**	
Mozambique	40,000	14,000	35
Niger	17,000	2,000	12
Nigeria	216,000	11,000	5
Rwanda	125,000	60,000	60
Senegal	160,000	40,000	25
South Africa	1,500,000	538,000	36
Sudan	290,000	23,000	8
Tanzania	220,000	25,000	9
Tcad	6,000	1,000	17
Togo	24,000	10,000	42
Tunesia		42,000*	
Uganda	28,000	10,000	36
Zaire	60,000	20,000	33
Zambia	68,000	26,000	38
Zimbabwe	120,000	30,000*	25
Sub-total Africa	**4,356,400**	**1,636,000**	**38**
Mediterranean:			
Israel	100,000	10,000*	10
Italy		40,000*	
Portugal		500,000**	
Spain		350,000**	
Turkey		20,000*	
Sub-total (Mediterranean)		**920,000**	
Asia:			

India	18,900,000	4,800,000	25
Indonesia	8,750,000	80,000*	1
Malaysia	115,000	8,000	7
Myanmar	334,000	25,000	7
Nepal	80,000	5,000	6
Pakistan	569,000	28,500	5
Philippines	500,000	10,000	2
PR China	38,300,000	670,000*	2
Sri Lanka	198,000	45,000	23
Taiwan	680,600	3,500	1
Thailand	755,000	62,000	8
Vietnam	2,100,000	245,000	12
Sub-total (Asia)	**71,281,000**	**5,982,000**	**8**
Pacific:			
Cook Islands	630	8	1
New Zealand	1,400,000	22,000	2
Papua New Guinea	42,000	10,000	24
Australia	1,050,000	75,000***	7
Sub-total (Pacific)	**2,492,630**	**107,008**	**4**
Sub-total (Asia - Pacific)	**73,774,230**	**6,089,008**	**8**
North America:			
USA		110,000*	
Sub-total (North America)		**110,000**	
Central America:			
Costa Rica	40,000	10,000	25
El Salvador	6,000	2,000	33
Guatemala	20,000	6,000	30
Honduras	4,000	500	13
Mexico	155,000	38,000	25
Nicaragua	20,000	5,500	28
Sub-total (Central America)	**245,000**	**62,000**	**25**
South America:			
Argentina	780,000	236,000	30
Brazil	7,000,000	3,617,000	52
Chile	1,600,000	180,000	11
Colombia	180,000	31,000	17
Ecuador	64,000	44,000	69
Paraguay	13,000	8,000	62
Uruguay	208,000	160,000	77
Peru	263,000	211,000	80
Venezuela	362,000	70,000	19
Sub-total (South America)	**10,470,000**	**4,557,000**	**44**
Caribbean:			
Cuba	350,000	35,000	10
Haiti	12,000	2,000	17
Jamaica	21,000	80	0
Sub-total (Caribbean)	**383,000**	**37,080**	**10**
Sub-total (America)	**11,098,000**	**4,766,080**	**43**
WORLD TOTAL (in 74 countries)	89,328,630+	13,411,088	15

Notes: This Table was compiled in the Australian Tree Seed Centre in August 1993, using data from FAO's global inventory programme with supplementary estimates by Midgley(*), Moncur(**) and Davidson(***). Europe is excluded from the Table. There are small areas of *Eucalyptus* plantations in some European countries, e.g. the United Kingdom and France. Blanks mean either data were unavailable at the time of compilation, or were considered of too doubtful accuracy, so were excluded. The majority of figures are approximate and reliability varies.

Successful domestication and breeding of *Eucalyptus*, including hybridization and mass clonal propagation, have led to large gains in wood production on a given area and quality of land (Eldridge *et al.* 1993). Clones now are being tailor-made for optimum performance on particular soils, including nutrient-poor and saline types.

Scope of This Presentation

Although planted trees such as the eucalypts are conspicuously successful in many places, some governments, organizations and individuals have raised concerns about alleged adverse impacts of exotic species, particularly eucalypts. Environmental and social costs have been perceived by them to be too high in relation to the benefits. In some instances, when the kinds of trees have been inappropriate for the environment, environmental problems have led to social problems. But, in the majority of instances, the criticisms are unfounded in that the eucalypt trees are blamed for social, cultural, planning and managerial problems that would have arisen with any species of tree grown in the same location and under the same conditions.

Numerous publications in recent years have provided detailed information on biogeography and ecology of the more commonly planted eucalypts. With such a large number of useful species coming from so many habitats, these digests represent an enormous body of literature. Reference can be made to the following introductory accounts: Pryor (1976), Florence (1981), Pryor and Johnson (1981) and Ovington and Pryor (1983). More detail can be found in the following books and major articles: Metro (1955), Jacobs (1955), Penfold and Willis (1961), Boland *et al.* (1980), Jacobs (1981), Chippendale and Wolf (1981), Hillis and Brown (1984), Boland *et al.* (1984) Lima (1984) and Chippendale (1988). Evans (1982), National Research Council (1980, 1983), Little (1983), Tiwari and Singh (1984), Commonwealth of Australia (1985), Turnbull (1986), FAO (1988), Australian Forest Development Institute (1988) and Boland (1989) give general information on eucalypts as exotics and/or discuss the ecology of the Australian environment. In connection with perhaps the most controversial aspect, that of hydrology, the general reviews by Hamilton and King (1983), Bruijnzeel (1990) and Calder *et al.* (1992) are essential background reading.

There are several regional accounts on the eucalypts, including those for Brazil (Andrade 1961 and Lima 1987, the latter concentrating on environmental impacts), Chile (Prado and Barros 1989), India (Tewari (1992), Portugal (Goes 1977), South Africa (Poynton 1979) and Spain (Guttierrez 1977).

Since the *Eucalyptus* controversy began, the scientific information coming out of India has been particularly prolific with a National Seminar held in 1984 (Sharma *et al.* 1984), several regional meetings held and five special issues published of the journal "Indian Forester": December 1983, January and February 1984 on *Eucalyptus* and August and September 1984 on "Biomass", which also included many articles on eucalypts.

In the mid-1980s, the FAO accepted an offer made to it by The Swedish International Development Agency to carry out a study on the ecological effects of *Eucalyptus*. The study was published in 1985 (Poore and Fries 1985), ahead of a rapidly growing list of other technical reports on the same subject (e.g., Davidson 1985b,c; Florence 1986, Eldridge and Cromer 1987, Florence 1990). Attempts have been made also to explain the scientific arguments in terms which could be understood by lay persons (e.g., FAO 1988, White 1988, Davidson 1989, House 1992).

To attempt to further clarify the position and also to serve as an information base for this Consultation, a number of ecological aspects of *Eucalyptus* plantations is taken up in this paper. Given time and space constraints not all of the issues can be covered here. Those that are covered include:

- climate and microclimate,
- hydrology,
- soil erosion,
- soil nutrients,
- competition and other interactions with flora and fauna,
- allelopathy, and,
- susceptibility to fire.

Additional emphasis is given to soil non-wettability under eucalypts and to the ability of at least some eucalypts to mobilize and store soil nutrients in surface soils close to the trees on poor sites, since these aspects previously have received little attention in the literature mentioned earlier.

Silvicultural and socio-economic aspects concerning *Eucalyptus* will be taken up respectively in two other papers presented at this Consultation.

ECOLOGICAL ASPECTS

Climate and Microclimate

There is nothing to distinguish, in particular, the eucalypts from plantations of any other tree or from different types of native forests in their effects on regional rainfall or on other regional climate parameters.

There are, however, effects of eucalypts on micro-climate at the local level. These effects depend on the amount of leaf surface carried by the trees in relation to the surface area of the ground covered. The greater the leaf area and the more horizontal are the leaves, the greater the shading effect and the greater the evapotranspiration. In the shaded area, average air temperatures are lower, extremes of air and surface soil temperatures are reduced and there is a higher surface air humidity compared to areas with no trees. Eucalypts cast less shade, on average, than other broadleaved trees, but there are big differences in the amount of shade cast by different species because they have different leaf sizes and orientations. The Australian phyllodinous acacias, on average, cast more shade than the eucalypts or casuarinas or the bi-pinnate acacias of the African continent. The heavy shading effect of species like *Acacia mangium* explains why they are favoured for reforestation of *Imperata* grasslands, the grass dies out once the tree canopies close. A similar effect is found under close-spaced *E. torelliana* or some provenances of *E. urophylla* which have a dense canopy of broad leaves held almost horizontally. In contrast, if one of the objectives is grazing under the trees or to provide a living ground cover to protect the soil against erosion, species which cast less shade need to be chosen. The influences which are the result of shading are reduced if the trees are widely spaced. There is no reason to distinguish the eucalypts from other genera with similar crown architecture.

Hydrology

The dominating causal factor of interception loss is evaporation of rainwater from leaves. Interception is, therefore, somewhat species dependent, because the surface area of leaves varies with species. The greater the leaf area per square metre of ground covered, the greater the interception loss. Wider spaced trees usually will intercept less rain. Comparisons between species can only be generalized, because interception is also controlled by periodicity and intensity of rainfall events. There is more interception during a succession of light falls with dry spells in between than during one heavy fall of the same total amount. *Pinus* spp and *Casuarina* spp have some of the highest interception rates, followed in descending order by compound leaved genera with small leaflets such as *Albizia* spp and true-leaved *Acacia* spp, then come broadleaved genera (non-eucalypts, but including the Australian acacias), then eucalypts, followed by scrub and grassland. The majority of eucalypt values fall between 10 and 25 percent under a wide range of conditions. Higher interception means less throughfall and stemflow from a given rainfall event and therefore less rainwater reaching the soil.

Throughfall and stemflow, taken together, reach their highest values among some species of eucalypts (from about 75 to 90 percent of precipitation). Ranking of other genera and species is difficult because of lack of information, but the reverse of the order given for interception is an approximation: eucalypts, other broad-leaved genera, then small-leaved genera, followed by *Casuarina* and *Pinus* spp. The higher the throughfall and stemflow, the greater the potential for soil erosion under the trees.

Runoff rate depends more on ground surface conditions, i.e., on slope, on soil porosity and moisture conditions of the soil and litter just before rain falls. Impervious and/or highly erodible soils will be washed away more easily than porous soils. One of the factors which can make soils under eucalypts impervious is a non-wettable or water repellent property which is found in both natural stands in Australia (Bond 1964, Hamilton 1964, Davidson 1967, McGhie and Posner 1980, Burch *et al.* 1989) and under exotic plantations, e.g., in South Africa (Scott 1991, Scott and Schulz 1991). Water repellent soils are abnormal soils which resist wetting by water (Figs 1 and 2), a behaviour which is caused by a hydrophobic coating of organic origin on the soil particles (De Bano 1971). Common sources of these organic coatings are soil microbes and fungal mycelia (Bond 1960, 1962, 1964, Bond and Harris 1964, Davidson 1967, De Bano 1981, Jex *et al.* 1985) (Fig. 3). Water repellent soils cause impeded infiltration and percolation, resulting in water moving along preferred paths over and through the soil (Davidson 1967, Bishay and Bakhati 1976, Van Dam *et al.* 1990), causing patchy wetting of the upper soil horizons (Fig. 4). Blocks of soil near the surface may remain dry after considerable rainfall (Davidson 1967, Adams *et al.* 1969, Van Dam *et al.* 1990) (Figs 3 and 5).

FIGURE 1. A drop of water placed on a non-wettable soil taken from beneath a natural eucalypt stand at Kowen in the Australian Capital Territory. The water-solid contact angle (Letey *et al.* 1962a,b) is well over 180°. (Photograph from Davidson (1967).)

FIGURE 2. Soil taken from within a non-wettable body under a eucalypt stand is so hydrophobic it will float in a beaker of water while a similar size aggregate of normal soil sinks to the bottom. (Photograph from Davidson (1967).)

FIGURE 3. A soil aggregate (about 4X magnification) showing the boundary between normal (bottom) and non-wettable soil sampled under *Eucalyptus* just after rain. Fungal hyphae are associated with the hydrophobic portion (top) but are absent from the wet soil. (photograph from Davidson (1967).)

FIGURE 4. Moisture pattern in a eucalypt soil observed after removal of the litter layers and the surface 2cm of mineral soil. Locations of samples taken for soil moisture determination are shown with a figure for moisture content, in percent, alongside. Patches which appeared "wet" to the eye are cross-hatched. Scale: 1:12. (Source: Davidson (1967)).

FIGURE 5. Moisture distribution in a profile of eucalyt soil containing non-wettable bodies. The moist sandy-loam "A" horizons are represented by stippling and dry bodies by un-marked areas. The moist, clayey "B" horizon is represented by cross-hatching. (Scale: 1:12) (Source: Davidson (1967)).

Coarse textured soils more readily develop the water repellent phenomenon, e.g., in Florida (Jamison 1946), Australia (Bond 1964, Bond and Harris 1964, Anonymous 1965, Roberts and Carbon 1972, King 1981), New Zealand (Van't Woudt 1959), Egypt (Bishay and Bakhati 1976), Netherlands (Ruyten and Goede-Hiensch 1988) and Zululand and Cape Flats, South Africa (Scott 1991).

Other factors positively related to the degree of water repellency are the amount of organic matter in the soil (Van't Woudt 1959, Hamilton 1964, Scholl 1971), the age of the vegetation (correlated with the build-up of organic matter in the soil) (Teramura 1980) and the dryness of the soil before a rainfall event (Gilmour 1968, Singer and Ugolini 1976, Grelewicz and Plichta 1983).

Water repellency is not restricted to soils under eucalypts. It is also commonly associated with certain other species and vegetation types such as citrus orchards (Jamison 1942, 1945, 1946, Wander 1949a, 1949b, Bishay and Bakhati 1976), some Californian desert plants where repellency is confined to the drip zone of the plants (Adams *et al.* 1969), under juniper in Utah (Scholl 1971), with chaparral vegetation in southern California (De Bano 1966, De Bano *et al.* 1967, Osborn *et al.* 1967, Holzhey 1969) and under monoao heath in New Zealand (Van't Woudt 1954, 1959).

Australian studies (Hamilton 1964,1965, Davidson 1967) showed soils still under eucalypts were more water repellent than adjacent similar soil after conversion to *Pinus radiata* 23 years previously. In the South African study (Scott 1991), a generalized ranking of the repellency developed under different vegetation types was that grassland soils were wettable, pine soils somewhat repellant, wattle soils somewhat repellent to repellant and eucalypt soils repellant.

Abnormally dry soil may inhibit seed germination and may reduce seedling survival, preventing colonization of water-repellent soil by native plants or establishment of agricultural crops (Osborn *et al.* 1967, Adams *et al.* 1969). This effect may be observable under eucalypts in some instances and may persist in soil for a time after their removal. Thus, in some situations, soil water repellency has the same ecological effect as allelopathy in tending to reduce competition from other plants. Water repellency may not be a problem until the canopy and/or the ground cover are removed. Removal of the eucalypt litter and exposure of the surface mineral soil to direct sunlight increases the chance that difficult-to-reverse soil drying may occur.

Gullying, resulting from increased overland flow may be associated with vegetation types causing water repellent soils (Osborn *et al.* 1964, McGhie 1981).

Surfactants can remove successfully the resistance to wetting of water repellent soils, thereby improving seedling germination and growth and reducing erosion (Letey *et al.* 1962a,b, Pelishek *et al.* 1962). However, these chemicals are expensive. Good results can be obtained with cultivation which breaks up and mixes the water-repellent bodies with normal surrounding soil, thus improving the ability of water to penetrate. Deep ripping on the contour is also beneficial in increasing rainwater infiltration and storage deep in the soil profile, thus reducing overland flow.

Litters under pines, casuarina and acacia probably impede runoff more than litter under eucalypts in high runoff situations. Under low runoff conditions there are no differences between species.

Collection of litter for animal bedding and fuel and compaction of surface soil by animal and foot traffic lead to greatly increased runoff and to a heightened potential for erosion of soils under eucalypt trees on steep slopes.

Trees may have to be planted farther apart on sloping ground to allow live ground covers of grasses and/or legumes to develop. On very steep slopes, physical measures, such as earth bunds and rock walls, may be required as well to distribute runoff so that it cannot cause soil erosion.

Most forests, no matter what type, reduce greatly peak flood flows and buffer the influence of flood flows by increasing dry season flows and decreasing wet season flows. Forested catchments yield less water than grassed catchments, because trees normally use more water than grass.

Table 2 Water use by plants through evapotranspiration
(litres/kg of total biomass or harvested commodity produced)

Plant	Water use per total biomass (litres/kg)	Harvest index	Water use per harvested biomass (litres/kg)
Cotton/Coffee/Bananas	3200	0.25	800
Pongomia (T)	2600	0.50	1300
Sunflower	2400	0.25	600
Field Pea	2000	0.30	600
Paddy Rice	2000	0.30	600
Horse Bean	1714	0.35	600
Cow Pea	1667	0.30	500
Conifers (T)	1538	0.65	1000
Dalbergia (T)	1483	0.60	890
Soybean	1430	0.35	500
Acacia (T)	1323	0.65	860
Syzygium (T)	1017	0.60	610
Potato	1000	0.60	600
Sorghum	1000	0.25	250
Albizia (T)	967	0.60	580
Eucalyptus (T)	785	0.65	510
Finger Millet	592	0.40	225

(T) = Tree genus

Source: Davidson (1989)

Eucalypts appear to use less water per unit weight of biomass produced than other kinds of trees and many agricultural crops (Table 2), but their potentially high biomass production under low rainfall conditions may reduce streamflow more than slower growing kinds of trees. Water consumption by eucalypts can be reduced by planting trees farther apart or by thinning existing plantations.

The faster trees grow because of their natural or artificially improved genetic makeup, or are encouraged to grow by addition of fertilizer and use of other cultural techniques such as soil cultivation, and thus the greater the accumulating living biomass per unit area occupied, the more the water reserves of an area will be drawn down, no matter what the species. The decision has to be made on how quickly the benefits from trees are required. In many cases products such as poles and fuelwood are chronically short in supply, while water resources for all competing uses, including food production and consumption by humans and livestock, usually are limiting also. A balance has to be struck between growing a large biomass quickly or, alternatively, growing a lesser biomass over a much longer period of time. Rate of biomass production (and thus water consumption) can be adjusted through species choice, degree of fertilization, or withholding fertilizer, or application of other cultural practices, or by planting fast-growing trees farther apart, thus lowering water consumption per unit area of land. Given proper planning and management, there is no need to exclude the eucalypts because of their perceived high rate of water consumption.

Results concerning ground water and catchment management show many inconsistencies. Site influences seem to be greater than species' influences. Soil water balance and height of the water table at a particular site also can be influenced by factors far away from the site because water is mobile in underground aquifers. Drawing water from shallow and deep tube wells for high water demanding crops such as paddy rice, sunflower and cotton (Table 2) often has a greater effect on drawing down regional water tables than plantations of fast-growing trees. But many times the trees are blamed when the underlying cause is an expanding population which has to be fed by growing more food and provided with water for drinking and washing. One method of increasing food production is to construct more wells for irrigation to extend cropping into, or even throughout, the dry season.

Soil Erosion

In regard to soil erosion by water under trees, there is no evidence to single out eucalypts for special criticism. Erodibility (physical characteristics) of soils is more important than crop management and crop management is more important than the type of tree crop.

Erosive energy of rain under tree crowns depends much on the surface area of individual leaves, large leaves produce larger size droplets which have a greater impact energy on the ground. Erosive energy of rain under the crowns would be least for *Casuarina* spp, with the acacias (e.g., *A. auriculiformis*) and narrow-leaved eucalypts (e.g., *E. camaldulensis*) occupying the mid-range and the broad-leaved eucalypts (e.g., *E. globulus*) at the top of the range for eucalypts, but even these have much smaller leaves than *Anthocephalus* spp and very much smaller leaves than *Tectona grandis* (Teak), the latter of which has been widely planted in tropical plantations, particularly in Asia.

Since, in nearly every example where the litter is removed, erosion increases substantially, it is important to focus more on ground cover and ground level activities (cultivation, compaction by foot traffic, livestock grazing and trampling, harvesting/logging damage, i.e., the crop management component of the Universal Soil Loss Equation) rather than on the species of trees planted. On erosion-prone slopes it is better to use a periodic, partial harvesting system based on cutting of trees on lines around the contour or on removal of small patches in a mosaic pattern. Better still, whole trees should not be harvested, rather only branches lopped, or leaves harvested, or the stands managed for honey production. Litter should not be removed, nor should it be disturbed during harvesting. If whole trees are removed, manual or animal transport methods usually cause less damage than machines. Some machines and logging methods because of their specific design cause less damage than others, e.g., aerial cable versus ground cable, large, balloon-like rubber tires versus steel tracks.

In the more arid areas of Asia and Africa, planting of eucalypts to provide windbreaks to protect crops and slow down the movement of soil and sand has been carried on for over a century. They have been found superior to other tree species based more on their ability to survive and grow under harsh conditions, rather than for any physical attribute. Effectiveness of a windbreak depends mostly on its design (spacing, pattern of planting, mixtures of trees and shrubs of different heights) rather than on particular species, i.e., on physical rather than on biological characteristics.

Tree root systems act like tacks in a carpet on a slippery floor in preventing the slippage of soil down steep slopes. If the species of tree, when cut, does not coppice, i.e., its root system dies, the result can be a lower shear strength of slip-prone soils. The ability of many *Eucalyptus* species to coppice vigorously has led to them being used widely throughout the world for stabilization of soils on steep slopes. Reforesting slip-prone soils can help prevent shallow landslips (Figs 6 and 7), but not the kinds of mass-wasting which are normal geological processes in mountainous terrain.

There is nothing unusual about the root systems of the eucalypts vis-a-vis erosion compared to other species in general. There are both shallow and deep rooting species within *Eucalyptus*. Lateral roots may be dense and near the surface or more diffuse and at greater depths. Soil depth and texture and soil water relations/aeration often determine root architecture to a greater degree than genetic makeup of the trees.

Soil Nutrients

When compared with a range of crops, the eucalypts can achieve a high biomass production on a low nutrient uptake, as little as one-half to one-tenth that of most agricultural and estate tree crops (Table 3), i.e., they can be successful on poor soils without fertilizer. The formation of ectomycorrhizae on the roots plays a major role in nutrient uptake in eucalypts (Grove *et al.* 1991). Given the importance of ectomycorrhizae in the nutrient cycle for the genus *Eucalyptus* care should be taken to ensure that inocula are supplied to the young plants if they are unlikely to pick up local strains at a new location.

FIGURE 6. *E. globulus* plantations on steep land in Ethiopia. Animals graze the grass under the trees. Note in the foreground the erosion and slumping where there are no trees. (J. Davidson)

FIGURE 7. The same locality as in Fig. 6.*E. globulus* has been used to reforest steep slopes to give some measure of protection from landslides to the town below. Above the road on the far side of the town, about half of the stand has been harvested nearest to the road and allowed to coppice. (J. Davidson)

Table 3 Uptake and removal at harvest of nutrients for fast-grown *Eucalyptus* in relation to an *Acacia* and other crops

Crop	Uptake			Removal		
	N	P	K	N	P	K
	(kg/ha/yr)			(kg/ha/yr)		
Lowland Rice	110	24	170	33	7	51
Upland Rice	48	12	60	14	4	18
Maize	160	30	150	40	8	38
Sorghum	120	21	95	30	5	24
Cassava	120	22	170	40	4	50
Sweet Potato	90	17	187	54	12	110
White Potato	80	14	120	50	11	80
Yam	105	12	150	80	10	100
Soybean	(190)	20	65	(135)	13	32
Groundnut	(130)	12	60	(100)	10	25
Phaseolus bean	(75)	5	43	(55)	4	17
Cotton	135	20	90	75	12	22
Sugarcane	150	30	210	67	12	115
Coffee	110	9	120	40	3	48
Tea	240	20	100	120	10	52
Cacao	100	12	50	30	5	50
Rubber	312	33	163	16	3	12
Oil Palm	118	16	166	68	8	105
Banana	130	12	450	45	6	130
Coconut	90	14	150	40	7	100
Eucalyptus urophylla hybrids (Brazil 7yrs)	76	6	43	11	1	12[1]
				15	1.5	18[2]
				26	2	23[3]
Acacia mangium (China 2.5yrs)	(307)	10	110	(50)	3	18[4]
				(101)	4	55[3]

Notes:

(1) Main stem wood, without bark, above ground up to 7.5 cm small end diameter

(2) Main stem wood as in (1), with bark on

(3) Whole tree above ground

(4) Wood plus bark

Other figures in brackets are for N which has been supplemented by atmospheric Nitrogen fixation by legumes.

Table 4 Nutrients in the litter of a fast-growing plantation of *Eucalyptus*

Age (yrs)	Litter (t/ha)	Nutrients					
		N	P	K (kg/ha)	Ca (kg/ha)	Mg	S
1	1.3	13.0	0.9	4.9	19.3	3.1	2.7
2	4.0	39.0	3.4	11.9	54.7	8.8	7.5
3	5.5	48.8	3.2	16.1	65.5	10.3	10.6
4	8.3	54.4	2.0	27.5	61.3	12.2	18.5
5	11.0	59.1	2.3	27.3	77.1	12.9	14.9
6	10.0	85.9	7.2	32.8	88.8	14.2	15.5
7	7.4	55.8	4.6	19.3	74.3	14.6	10.9
Total	**47.5**	**355.0**	**23.7**	**139.9**	**441.1**	**76.2**	**80.7**

Note: Data are for a seedling-based rotation of seven years at Aracruz. Standing biomass at age seven was about 180 tonnes/ha. E. Campinhos pers. comm. (1993).

Table 5 Comparison of nutrients in litterfall under plantations of*Eucalyptus* and *Acacia*

Species	Litterfall (t/ha/yr)	Nutrients				
		N	P	K (kg/ha)	Ca	Mg
Eucalyptus urophylla (Brazil 2.5 yrs)	5.5	48.8	3.2	16.1	65.5	8.8
(Brazil 5.5 yrs)	10.0	85.9	7.2	32.8	88.8	14.2
Acacia mangium (China 2.5 yrs)	12.8	204.2	3.0	24.2	54.0	28.0

Data from Xu Daping *et al.* (1992) (*Acacia*) and E. Campinhos pers. comm. (1993).

Table 6 Soil nutrients balance after a seven-year rotation for Eucalypt pulpwood in Brazil

Nutrient	Input[1] (kg/ha)	Accumulation[2] (kg/ha)	Output[3] (kg/ha)	Left on site[4] (kg/ha)	Balance[5] (kg/ha)
N	455	179	77 (17)	102	378 (83)
P	60	15	8 (13)	7	52 (87)
K	235	164	87 (37)	77	148 (63)
Ca	607	381	104 (17)	277	504 (83)
Mg	96	56	17 (18)	39	79 (82)

Notes:

1. From rain, fertilizer and litterfall

2. In above ground biomass

3. In stemwood without bark, percent of input in brackets

4. In leaves, branches and top of the crown and bark

5. Remaining on site after harvest, percent of input in brackets.

Source: Raw data from E. Campinhos pers. comm. (1993).

A substantial proportion of the nutrients in a tree crop is held in the foliage which is returned periodically to the soil (Tables 4 and 5). This nutrient turnover is responsible for improvement of soil fertility by plantations established on previously cleared sites. Maintenance of the nutrient cycle is critical to the long term productivity of soils and it is essential foliage and leaf litter are not removed from the site. Even greater benefits accrue if bark is also left behind (see piechart Figures in Davidson 1985b for an illustration of the relative amounts of nutrients in different parts of the biomass of *E. tereticornis* in India).

The site nutritional balance for one of the most recent eucalypt pulpwood crops at Aracruz has been studied (E. Campinhos pers. comm. 1993) (Table 6). If bark is left on site, the balance of nutrients remaining is 83, 87, 63, 83, and 82 percent of inputs for N, P, K, Ca and Mg respectively. This reserve is enough to last 34, 42, 14, 35, and 28 years respectively, without considering the original nutrients still available in the soil, new and continuing inputs from natural processes of mineralization and from accretion in rainfall or addition of more fertilizer over several subsequent crops of trees on a seven-year cycle.

Once trees pass the age of about seven years, inert heartwood begins to form and as much as 90 percent of the nutrients in the wood are withdrawn to be kept in the mobile shell of sapwood and phloem. This means as the trees grow older beyond about seven years, the amount of nutrients present per unit volume of wood becomes progressively less since the relative proportion of sapwood becomes less. Therefore harvest of more mature trees will lead to even less nutrient drain on the site.

Sufficient fertilizer or mulch should be applied to more than compensate for the loss of nutrients in the harvest, as is the practice in agriculture. An excess of added nutrients usually is required over removals because of the inefficiencies of nutrient uptake by plants and losses through leaching or fixation in some types of soil, also as is the case in agriculture.

Fast growing tree species adapted to particularly harsh sites have an important function in rehabilitation and conservation of land. Tree cover has value in sustaining and improving beneficial physical and chemical properties of the soil. The improvement of soil conditions under all tree species is due to the presence of a litter layer.

Competition and Other Interactions with Flora and Fauna

There are documented instances where eucalypts have been used in an inappropriate environmental context because of a poor planning or management decision. Criticisms directed at planted trees which replace natural forest are proper, since a monoculture cannot replace the varied range of products and benefits which come from most indigenous forests. However there is also a case for supporting plantations to stabilize or recover land which has been degraded by inappropriate agricultural practices or extractive industries. In that context, plantations are able to replace some, perhaps most, but not all, of the products and functions that would have been provided by intact natural forest.

Neither a eucalypt, nor any other fast growing tree for that matter, is able to create biomass without using soil moisture and nutrients. It has to be recognized that some eucalypts in certain situations of relatively dry climates and nutrient-poor soils can be very competitive with other vegetation, including juveniles of the same eucalypt species. In a study in an *E. rossii* community and under other eucalypts in the Pilliga region of western NSW, Australia, Davidson (1965) found the association was maintained in a woodland form (open spaces between the tree canopies) because the eucalypts were very efficient in gathering nutrients from the soils in the open spaces and storing them in the litter and surface soils under the trees. Since annual rainfall was low and nutrients were inherently scarce in these sandy soils, this is a further example of another form of competition, analogous to allelopathy, evolved to ensure the survival of the eucalypt in that locality.

In the case of planted trees, the actual situation has to be examined on each individual site. What is a competitive weed in one place may be a saviour in another. The ability of a eucalypt to survive harsh conditions and sprout rapidly from a cut stump without replanting, may be advantageous for fuelwood production in chronically deficit areas, for control of landslips, or for windbreaks.

An important question is one of scale, a 20 ha woodlot, a 2,000 ha pole plantation and a 200,000 ha pulpwood plantation of the same species have markedly different effects on local flora and fauna, with the largest plantation having potentially the greatest adverse impact. In the latter case the impact can be reduced by spreading the plantation over a larger gross area (say 50 percent more) and planting the trees in a mosaic fashion in irregularly shaped compartments of 50-100 ha separated by patches and corridors of natural forest which can help conserve native flora and fauna and protect streams (as in the examples of Aracruz in Brazil and at Pointe Noire in the Congo). If native forest has long since been cleared, mixed planting of native species can be undertaken in the areas among the eucalypts, following the Aracruz example.

Many eucalypt species can compete vigorously for water and nutrients where these are scarce. Eucalypts are tall plants and, because of their faster growth, will tend to shade out native vegetation of the same age regenerating beneath them. Nearby crops can also be affected in this way, resulting in reduced yields. However, not all eucalypts cast shade which is heavy enough to discourage ground vegetation or understorey shrubs, and shading can be adjusted by varying the density of the trees. There are complex interactions between light and water requirements of different trees that make generalizations difficult. Certainly there are several species of trees with larger leaves than the eucalypts, thus they cast more shade. Closely spaced pines cause even greater reductions in understorey development.

Under certain circumstances, eucalypts can be grown in silviculturally compatible mixtures with other trees. If the other trees are leguminous, the mixture may be more productive than any of the individual species growing alone. There are good examples from Hawaii of silviculturally compatible mixtures of about two-thirds *E. saligna* and one-third *Albizia falcataria*.

Planted stands of any tree type generally will contain lower numbers of animal species than more diverse natural forests. Introduced species of trees will not have a local fauna adapted to them. Native eucalypt forests have a rich diversity of wildlife which has evolved in parallel with them and adapted to them in special ways that non-Australian fauna have not. Replacing indigenous vegetation with plantations of *Eucalyptus* species is almost certain to have an affect on native fauna, but the results are often difficult to predict, and varies from species to species and with the size of plots and compartments and with kind of native vegetation that is found adjacent to the planted stands. In Ethiopia, where native forests have been reduced to less than 3 percent of the land area, extensively planted eucalypts have high animal populations.

After two hundred years of export of eucalypts, mistakes have been made with quarantine. Australian insects such as stem borers and defoliators have appeared in overseas plantations. In some localities these have built up to epidemic proportions. Treatment with chemicals is possible, but usually these have environmental side effects. Biological control is always an option and tree breeding can be used to propagate naturally resistant individuals. Growing trees in small blocks of different species, different varieties, or different clones can be a useful strategy to prevent the buildup and spread of insects and disease. A block of maximum size 50 ha usually is suggested.

Allelopathy

Allelopathy is highly selective. Much of the work mentioned in the literature suffers from the lack of experimental precision, particularly the lack of proper controls and insufficient replication. Others do not duplicate natural conditions. Most of the studies put forward as "evidence" for eucalypts being strongly allelopathic involve laboratory studies of artificial extracts on germination of seeds *in vitro* or early growth of potted plants which provide conditions probably far removed from those found in the field.

Examples of inappropriate experimental design include the use of solvents such as methyl alcohol, petroleum ether and benzene for preparation of leachates, and soil disturbance when moving soil from the field and placing it in small pots. Often, in the discussion of results, alternative reasons for the effects observed are not reviewed. In the field, the effect observed on understoreys or adjacent intercropped food crops is, more often than not, the result of extreme competitiveness for water and nutrients. The result varies across a wide spectrum of conditions from humid, fertile sites to dry, infertile ones. Eucalypts can be extremely difficult to establish on humid, fertile sites because of competition from weed growth, implying that allelopathic effects, if present, are masked by good climatic and soil conditions and/or the trees are less competitive than the weeds under such conditions. Towards the other end of the spectrum often no understorey develops under eucalypts on infertile soils in dry climates where probably both extreme competition for soil water and nutrients, soil non-wettability and allelopathy are operating together.

Allelopathy may influence the choice of species when erosion control and grazing are intended to be important functions of the plantation. Wider spacing of the trees, mixed planting and deliberate planting of a compatible understorey may help. Soil working and, in appropriate situations, fertilization and irrigation will alleviate the effect of allelopathy.

Susceptibility to Fire

Virtually all planted forests are susceptible to fire damage and more so at less than five years of age. Planted eucalypts are particularly vulnerable because they are often planted on land which is covered with grass, weeds or brush which is highly flammable in dry weather. Peasants often set fire to such lands to hunt game, improve palatability of grass for stock, or to clear fallows for subsistence food gardens. Without expensive protection measures these fires easily enter planted forests and are a major cause of losses in forest plantations irrespective of the species planted.

Much is often written about the alleged extreme flammability of *Eucalyptus* plantations. Under similar fire hazard conditions widely planted genera such as *Cupressus*, *Juniperus* and *Pinus* are equally or more flammable. In the tropics and sub-tropics, a greater area of *Pinus* than *Eucalyptus* plantations has been lost to fire.

Most thick barked eucalypts above about three years of age are resistant to permanent damage by fire. All eucalypts have a dormant bud system which enables sprouting and renewal of the canopy in a short time. Some eucalypts have lignotubers which are fire resistant organs containing copious dormant buds. Very hot fires may damage the wood causing it to be downgraded from sawn timber use.

High intensity fires through catchments planted with eucalypts can markedly increase stormflows and cause high soil losses off forested slopes (see Scott and Schulze (1991) for an example in an *E. fastigata* plantation in the foothills of the Natal Drakensberg, South Africa). In this example water repellent soils in the plantation contributed to the increased overland flow.

The only acceptable way out in terms of cost-effective investment to maximize the productivity of trees is to exclude fire as is the practice in agriculture. There are a number of ways the fire hazard can be reduced in stands of planted trees. These include a purpose designed system of roads and firebreaks in industrial plantations, weed and grass removal by several means (hand, chemical, mechanical) elsewhere and, under certain circumstances, intercropping with food or fodder plants. In cases of extreme fire hazard, fuel management programmes (prescribed burning) should be implemented to prevent extreme soil heating by any fire event that enters the plantation (Scott and Schulze 1991).

CONCLUSIONS AND GUIDELINES

Eucalypts can provide many benefits very quickly, ranging from industrial wood and fibre, poles and posts, through fuelwood and timber for household use, to nectar, oils, tannins and many other products. Several species are used for windbreaks and shelter.

On the debit side, fast growth and high biomass production of eucalypts require the consumption of much water and this consumption, though efficient in terms of biomass produced and one-half to one third of that used by many agricultural crops, must be balanced with other requirements of finite water supplies such as for agriculture, livestock and human consumption. Although the trees take up as little as one-half to one-tenth of the nutrients than do most agricultural crops, the soil nutrient reserve of a site also is finite and there is a nutrient cost for high biomass production of the trees *vis a vis* agriculture. The eucalypts, like many other tall trees, by themselves, may not protect the soil from erosion perfectly. They may not provide ideal habitats for the native wildlife and they may upset local traditions and values, if projects are not carefully planned. Nevertheless, in most respects, the eucalypts cannot be singled out as being always bad or as being uniquely different from other kinds of fast-growing trees under the same management conditions.

Planted *Eucalyptus* trees will be successful only if they can grow well in the local conditions of climate and soil and only if they can provide the benefits required, either for industry or rural people in a sound land-use and environmental management programme. The tree planting project must be accepted by, and bring benefit to, the people both directly and indirectly affected.

In regard to competition with crops for moisture and nutrients and for other competitive effects, including allelopathy, it seems possible to draw up some general guidelines. If annual rainfall is less than 400 mm, food crops should not be grown in mixture with or adjacent to eucalypts, as the risk of adverse competition and allelopathy are high, especially where the trees are grown in blocks rather than as scattered trees and where the soils are nutrient-poor and coarse textured. Under dry conditions, extreme desiccation of the soil and allelopathic condition may be difficult to reverse following a crop of *Eucalyptus*, unless the soil is cultivated and given a mulch or fallow period. If annual rainfall is between 400 and 1200mm, the eucalypts can be grown in mixtures with food crops and other trees, but available water has to be assessed carefully and planting density adjusted to achieve the desired balance of water use between trees and crops and to leave enough surplus for humans and livestock. Any adverse effects caused by eucalypts, including allelopathy and hydrophobic soil properties, usually do not linger under these rainfall conditions. If rainfall is over 1200 mm per annum, no special precautions are required.

The reason for choosing the 400mm and 1200mm annual rainfall change points is that an examination of the literature has shown that under 400mm annual rainfall, evapotranspiration is approximately equal to rainfall in a well-stocked (> 1,000 stems/ha) eucalypt forest about 5 years old for the eucalypt species (the majority) which have some control over their rate of transpiration (Fig. 8). Between 400 and 1200mm annual rainfall there is a surplus of up to about 200mm of rain which is sufficient to support the growth of other vegetation as well as the trees, more so if the tree stocking rate is reduced below 1,000 trees/ha. Above 1200mm, the surplus of water over average evapotranspiration increases rapidly. For an annual rainfall of about 4,000mm, evapotranspiration is about 1,500mm, leaving a surplus of 2,500mm (Fig. 8). This means that planting density of the trees can be increased with increasing rainfall. These average figures must be treated as guidelines only, since evapotranspiration is governed by other climatic variables in addition to rainfall.

In addition to these general guidelines, there is now available a range of computerized techniques for achieving a good match between climate and species (e.g., "Bioclim" Busby 1991, also see Booth 1985, 1990, 1991a,b, Booth and Pryor 1991, Booth *et al.* 1987, 1988, 1989) and for matching sites and species (e.g., Hackett 1988 and "Plantgro", Hackett 1991). The Australian International Development Assistance Bureau has commissioned a literature review and preparation of detailed guidelines and checklists on the planning, design and implementation of tree planting projects using Australian tree species (Davidson, in manuscript). A book on domestication and breeding of eucalypts (Eldridge *et al.* 1993) has just been released. It remains for foresters and planners to ensure that these tools are put to good use in the better design of future eucalypt planting projects.

FIGURE 8. Average catchment evapotranspiration of a well stocked (>1,000 stems/ha) eucalypt plantation about 5 years old over a range of annual average rainfall for the eucalypt species (the majority) which have some control over their rate of transpiration.

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Eucalyptus plantations (mainly of Eucalyptus camaldulensis and some E. globulus) were also removed, with exception of those trees growing in riparian areas with difficult access. The wide distribution of E. camaldulensis trees within the Guadiamar valley, in a variety of soil types and with different levels of contamination, made that species suitable for studying plant-soil relationships.Â 24. Davidson J. Ecological aspects of Eucalyptus plantations. In: Proceedings of the regional expert consultation on Eucalyptus. FAO.