Submission No. 69

Submission on forestry

Thank you for the opportunity to submit a comment to the Inquiry into the Australian forestry industry. My comments are made after working as a forester for 35 years in Queensland with the Queensland Dept. of Forestry and in the Northern Territory and Queensland with the Forest Research Institute and CSIRO Division of Forest Research. In addition to that, I spent 6 years working in South-East Asia for the Swedish International Development Authority and the Food and Agriculture Organization of the United Nations Organization.

My submission covers aspects that fit within focus points listed in your advice on the Inquiry. These are 'opportunities for and constraints to production', 'opportunities for diversification, value adding and product innovation', as well as partly within other focus points. Specifically they cover the need for long-term research, conservation, logging in native forests and the interaction between agriculture and forestry.

Long-term research

Consideration needs to be given into how long-term forest research can be funded consistently and adequately and experiments protected in such a way that they can be managed and maintained for many years. The following is an example of the need for long-term research.

Twenty years ago I secured funds from the National Afforestation Programme for installation of an experiment to examine the competition between two valuable Australian timber species hoop pine and Queensland maple. This followed the observation in a 50-year old plantation of apparently better form, individual stem volume and health of the maple when grown in alternate rows with hoop pine compared with when grown as a monoculture. The Nelder design used gave a range of tree densities from about 3000 per hectare to about 40 per hectare as well as comparisons between combinations of the two species. Funding was provided to Greening Australia (Qld) at a time when I was employed as a Research Scientist with CSIRO. Two years after establishment, I left CSIRO but the experiment was managed and measured by staff of the University of Queensland. Data from the experiment has been analysed by Prof Vanclay of Southern Cross University to assess competition between the two species. This is an important consideration as there is increasing community pressure to move away from monocultural plantations towards mixed species plantations. Mixtures that provide synergies between species could be attractive economically and environmentally. Measurements of the effects of one species on another in a mixture will be essential to provide a sound basis for establishing mixtures in future. In this experiment after 20 years, the hoop pine has suffered from competition by the maple but not the converse. The original observations of enhanced volume, form and health of the Queensland maple have not as yet been measured. The reasons for this could be that the experiment is not yet old enough to exhibit these factors and that other parameters need to be measured such as bole measurements at a range of positions up the stem, crown depth, lowest live branch, lowest whorl and branch lengths. It must be appreciated that the rotation length for both species would be in excess of 50 years and there could be economic and environmental benefits for longer rotations of 70-80 years. So after 20 years a further period of 20-30 years may be necessary to more fully evaluate the impact of each species on the other

Another concern regarding long-term research is described below. At the time of planning the experiment referred to above, the Queensland Department of Forestry was approached for land but none was available close to Brisbane and our CSIRO Headquarters. However a dairy farmer at Mt Mee (north of Samford) was prepared to have the experiment on his land. Without his very generous offer the experiment would not have been established. I understand that recently the plantation resources of the Queensland Government have been sold, so if the experiment had been established on crown land, it may well have been cleared for other plantations. This is the sort of action that follows the takeover of land as happened to another large CSIRO-Qld Forestry Dept cooperative experiment on Melville Is. in the Northern Territory in which I was involved. That experiment would now be about 35 years old but I understand it was cleared when rights to the plantations were acquired by a MIS company and sold as pulpwood with all surrounding plantations!

These two examples illustrate the need to have long-term experiments very well planned, well established and managed throughout their life but they also need security. How can Governments supervise or sponsor long-term forest research when Government terms are either 3 or 4 years? Furthermore Governments are not committed to long-term policies regarding forestry as is illustrated by decisions in the last three years to terminate the CSIRO Division of Forest Research after an existence in its various forms of over 60 years. This decision was followed by terminating the Plantation Committees set up around the country to assist in forest establishment, management and harvesting. Those Committees provided landholders with a reliable and knowledgeable basis for assisting in supporting new plantations on private land. This was a very necessary development following reduction in support for virtually all forest services by all State Governments.

Recommendation.

- It is suggested that long-term forest research be supported by all Australian Governments and that it be scientifically planned, well managed, thoroughly measured and regularly reported.
- A register of such experiments be maintained and adequately funded to provide the necessary outputs to ensure the country has readily available the best directions in forestry nationally.

Conservation

I was a member of the Northern Territory Environmental Council very shortly after it was established and remember discussing with another member the need to conserve unique vegetation types as national parks. To this I agreed but when we started to discuss the many small ecological differences in the vegetation, it indicated to him the need to conserve each different ecotype. In effect he really wanted to see the whole of the broader vegetation type protected as national park and insisted that none should be used for any other purpose! This approach is unfortunate as it has applied to quite a few decisions on new national parks throughout the country. In my time in south-east Asia, I was often asked how Australia managed its wet tropical rainforests and what and how the sustainable logging limits had been decided. I had to admit that in Australia, we had in effect locked up all of our wet tropical rainforest as a National Heritage Park.

One wonders what would have been the result if a different approach had been taken with regard to the wet tropical rainforests. Would it have been possible to transfer all parts of the rainforest that had never been logged into national parks and then administer the remainder as follows. Select about 10% of the total remaining area that had been logged over many coups in which there were very good records of volumes removed by species within compartments within the logging program. Areas with long-term inventory plots would also be needed to provide growth data, stocking by species and stand tables. The area would also have to be relatively contiguous to allow for efficient management. The next step would be to request the Forest Deptartment to manage the area in a manner similar to that prior to the declaration of National Heritage status and continue to aim at setting and monitoring long-term sustainable logging yields. A Supervising Authority comprising foresters from the Forest Department, ecologists from National Parks and CSIRO, economists and conservationists would need to be set up with terms of reference requiring regular meetings to monitor the Department's management including logging yields by species and size classes. Other aspects would have to be monitored including impacts on the ecology as well as impacts on plant and animal biodiversity. It would be appropriate to have the timber processed at a local sawmill using the best available processing machinery. Parameters monitored in the logged area would have to be replicated in the Heritage area to assess changes between the two types of management. This monitoring would have to continue for at least 20 years with reports to Government 5-yearly. After 20 years, a decision could be made on whether the trial should continue and whether any other aspects needed to be incorporated into the monitoring program. It is likely that there would be international interest in such an approach and perhaps involvement by the International Union of Forest Research Organizations.

This approach would ensure that the long-term management by the Queensland Department of Forestry of the wet tropical rainforest could be maintained for at least 20 years. The Department's records extend back for about 50-80 years and this information could have been made available to all other countries with wet tropical rainforests. It could have been a very valuable gift to tropical countries on a challenging topic -'How can the wet tropical rainforests be managed to provide sustainable timber production'? Australian assistance on management of wet tropical rainforests would have been in demand around the world.

Other vegetation types in Australia have been converted from state forest into national parks often without adequate scientific examination. In future it could be worthwhile considering ensuring a minimum of 10% be managed in the manner suggested above, to prove whether it is possible to have sustainable production. Again representatives of the forest authority, ecologists, economists and environmentalists should be on a monitoring panel. After 20 years and with good records of logging and a thorough range of ecological measurements, a more comprehensive assessment of what should happen to the vegetation type would be available.

This approach could have application in other vegetation types such as the Murray River red gum forests or the western cypress.

Logging in native forests

There has been pressure throughout Australia to stop logging in the native forests. I have no difficulty in accepting that some of the rare and unique native forest stands should be transferred into National Parks control but that does not apply to the large areas of native forest found in Queensland, New South Wales, Western Australia and Victoria. These forests contain a range of eucalypts with timber properties of interest to the Australian community at large. These species differ in colour, figure, strength, density and durability and provide Australia with a large enough volume, if managed correctly, to satisfy national demand in perpetuity. Australian foresters have managed these forests since the early 1900's and through their efforts, there are healthy well-stocked stands scattered throughout the country. However over the last 30 years, the impact of 'green' demands have seen large areas of these forests converted to National Parks and remaining areas in private ownership provided with particularly strict management requirements that in effect exclude about 70% of the forest from timber production. Private landholders have been forced, in attempting to have an economic logging on their land, to take progressively the best trees in the harvesting process. This process called 'high grading' removes the best trees in the stand with each harvest. Farmers can fully understand the impact of this approach when likened to similar management of their cattle herd. After about 20 years, their herd would have greatly reduced value. The forest is left as a genetically inferior stand as the best genes will have been removed with the best trees. Some stands in northern NSW are so poor with recruit stems are of such poor form and vigour, that the best approach is to clear the forest and plant with genetically better stock.

Those that propose conserving the native forest in total must accept that the alternative is to use only plantation timbers. Australian timber plantations comprise exotic conifers established from the early 1900's and eucalypts established over the last 30 or so years. There is not enough production from the plantations at this stage to replace the timber from native forests. The alternative is to continue to import timber from countries, sometimes with inadequate certification schemes. This policy continues to press poorer tropical countries to go beyond their own levels of timber sustainability and often in a manner that leads to destruction of ecosystems. The other problem is that if we are to rely totally on plantations, the Australian community will be left with timber of really just a few species – pale timber of the exotic conifers and a few eucalypts of pale red and yellow timbers from fast-growing plantations. The community and industry are used to having slow-growing dense, durable, strong timbers from a range of species from the native forest.

Agriculture and forestry

Much is made about the competition between agriculture and forestry for land but there is a solution. That is to look at how land management can be modified to support both activities on the one piece of land or in adjoining parts of the same property. This approach is termed ***agroforestry*** and I believe that it can help to provide landholders with the confidence that both tree growth and pasture growth can be achieved off the same piece of land or adjoining paddocks and in a manner that has an economic benefit. In this discussion, agriculture is restricted in effect to grazing. The old adage that ‘if it moves, shoot it and if not cut it down’ is well known in rural Australia. It is a difficult belief to overcome but I was given this chance while based in Brisbane with CSIRO during the 1980’s to examine the interaction and competition between trees and pasture for water, nutrients and light. I approached the problem not really knowing how the two components of the plant system would compete and what the result would be. Like most Australians, I was probably of the opinion then that any stand of trees in a pasture would be likely to reduce pasture production and I was well aware of the impact of a healthy grass sward in reducing tree health and production.

We found after 3.5 years, that pasture production was reduced with tree densities over 300 stems/ha but that tree density was associated with optimum tree growth, form, taper, crown dimensions and health. Pasture production and health under trees during periods of stress (frost, dry westerly winds and high temperatures) was better than in the exposed areas of the paddock. Water was extracted by the trees at age 1 year from a depth of 1.5m, at age 2 years from 3 m and at 3 years from 5.5 m which was the limit of detection of extraction. Some of the results of this research are in the attached paper from Australian Journal of Agricultural Research.

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Project STAG: An Experimental Study in Agroforestry

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Abstract

An agroforestry study to identify problems in the development of stable silvopastoral systems in a subtropical environment was run over 4·6 years.

Eucalyptus grandis was planted in a Nelder fan design with tree stand densities ranging from 42 to 3580 stems ha^{-1} into a *Setaria*-dominated pasture. Growth of trees improved with increasing stand density until competition for water and light outweighed the benefits of mutual protection. For most parameters measured, there was a change in magnitude with time away from the centre of the wheel like ripples in a pond. At 1·5 years the maximum above-ground individual tree biomass was at a stocking of 3580 stems ha^{-1}. At 2, 2·5, 3, 3·5 and 4·6 years the maxima were at 1140, 595, 305, 158 and 82 stems ha^{-1} respectively. Trees interacted with each other, even at low stand densities.

Pasture production also showed a ripple effect, being little affected by the trees at age 0·5 years, but was substantially reduced after 1·5 years at stand densities over 1000 stems ha^{-1}. By age 3·5 years, pasture production was reduced at stand densities over 300 stems ha^{-1}. At this age and stocking, tree growth, taper, crown dimensions and health were also optimal.

Trees and pasture can be successfully grown together to provide substantial production from each. A thinning regime would be required to maintain an optimum balance between the two components of this agroforestry system.

Introduction

Agroforestry is the term applied to the growing of trees on the same land used for agricultural crops and/or grazing animals and requires a combination of skills in forestry, agriculture and/or animal husbandry. It may have a role in conservation, in reducing the quantity of timber imports, and in avoiding and reversing some of the problems of land degradation. Agroforestry comes in many forms and has been little studied or practised in tropical and subtropical Australia (Cameron 1984*a*). There is increasing evidence from temperate Australia and New Zealand that agroforestry has a real and important role in providing shelter for stock in periods of wet, cold, windy weather and for certain crops (Lynch and Donnelly 1980). Production systems have been developed in New Zealand for pastures (Reid and Wilson 1985), with either sheep or cattle, often using *Pinus radiata* as the tree species (Tustin *et al.* 1979). Tropical and subtropical information is limited (Briggs and Bacon 1986), but there are some studies which support the beneficial effects of shade in hot weather to improve survival and production for both sheep and cattle (Roberts 1984; Daly 1984; Ryan *et al*, 1986; Silver 1987).

To enable an objective assessment of the biological value of an agroforestry system, it is essential to know the limiting environmental factors and how they interrelate to determine productivity of each component in the system. Usually trees and their associated understorey will compete for light, water and mineral nutrients, and livestock and fauna will have an impact on both the trees and pasture.

There are many land use problems in Australia related to the lack of trees. Their removal

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has had obvious effects in land degradation through land-slip, sheet and gully erosion, and salinization.

There are growing pressures, both within Australia and overseas, to retain all existing natural forests and woodlands in their present condition, since many represent the best remaining stands of important vegetation types and their associated fauna (Breckwoldt 1986). There is also growing concern for global environmental changes thought to be caused by large-scale deforestation (Simon 1986).

The cost of timber and wood products imported into Australia was about $1·4 billion in 1984–85, roughly equivalent to the export value of meat or the combined export value of sugar, fruit and dairy products (Castles 1986). This contrasts with other major primary products of which Australia is a net exporter. Although forest trees are an important crop, when grown as plantations they are usually relegated to land unsuitable for growing agricultural and/or horticultural crops. Scope for increasing tree production lies mainly in the private sector on farms, using agroforestry systems.

Project STAG (the acronym stands for Soil, Trees and Grass) was established to investigate competition between trees and pasture at a range of tree densities. In this paper we report on the experimental design and methodology used to estimate tree and pasture production and some of the interactions which became evident during the first four years of the experiment.

Materials and Methods

Site Description

The experiment was established on a 10 ha site at the Samford Pasture Research Station, 23 km west–north–west of Brisbane (Q, 27°22'S., 152°53'E.). The site is typical of much of the coastal grazing land in the humid Australian subtropics. The original dry sclerophyll forest containing *Eucalyptus microcorys, E. propinqua, E. maculata* and *E. tereticornis* had been cleared and replaced by a mixed pasture which had been grazed by cattle for 20 years. The average annual rainfall is 1100 mm, two-thirds of which falls in the six warmest months (October–March).

The site is underlaid by metamorphic rocks of the Bunya Phyllite series (Stevens 1973; Anon. 1984). The site selected (Fig. 1) was a west-facing slope, falling approximately 30 m over a distance of 200 m from a ridge to a level valley floor. In an initial survey, six principal soil profiles were identified, a lithosol on the ridge, and red and yellow podzolics on the slopes. A wet depression with gleyed podzolics was further downslope leading to a valley floor with deep alluvial soils.

Experimental Design

As the small area available and the heterogeneity of the site precluded the use of traditional block plantings of trees, the experimental design chosen was a competition wheel of the type proposed by Nelder (1962). Trees were planted in concentric circles with increasing stand density toward the centre. Nelder (1962) suggested using several replicate wheels to help deal with systematic trends in soil or microclimate, but for our purposes we considered that one intensively monitored wheel was adequate. The design requires regression analysis techniques to identify the principal effects of stand density upon tree and pasture performance. Asymmetry in tree or pasture growth at different positions around the wheel can be examined in relation to site heterogeneity.

The wheel consisted of trees in eight circles with radii of 4·4, 6·2, 8·6, 11·9, 16·5, 23·0, 31·9 and 44·3 m (Fig. 2). An outer guard ring of trees was planted with a radius of 61·6 m, and the centre in-filled with approximately 1 tree per 2 m^2. The angle between the spokes of the wheel was 20°, giving 18 trees around any circumference. Because of constraints imposed by the size and topography of the site, successive radii of the circles within the wheel increase by 39%, which is more than the recommended 10–15% for these designs. Within the wheel, trees were planted at densities approximating 3580 trees ha^{-1} in circle 1, decreasing to 2150, 1140, 595, 305, 158, 82, 42 respectively in circles 2 to 8, and a nominal 22 trees ha^{-1} in the guard circle (number 9).

Four separate blocks of trees were also planted at constant spacings on square grids of 1·8, 3·3, 6·5 and 12·5 m. These densities (3086, 918, 237 and 64 trees ha^{-1}) approximate to those intermediate between the first and second, third and fourth, fifth and sixth, and seventh and eighth circles of the competition wheel. A view of the wheel and block plantings about one year after planting is shown in Fig. 1(*b*).

Fig. 1. A view of the experimental site before planting (*a*) and the *E. grandis* competition wheel and biomass plots looking north-east about one year after the trees were planted (*b*).

Site Preparation and Establishment of Pastures and Trees

The site was surveyed on a 30 m grid. Physical, chemical and morphological properties of soil cores taken at each of the 123 grid reference points on the site were determined and 39 principal profile forms identified (Roberts and McBratney 1984). Subsequent planning, tree planting and installation of monitoring equipment were made with reference to this grid.

The main species present in the original pasture were *Axonopus affinis* (carpet grass), *Setaria sphacelata* cv. Nandi (setaria) and *Digitaria didactyla* (blue couch). To prepare the site for the experiment with minimum soil disturbance, existing pasture was slashed and then burnt to encourage regrowth. When actively regrowing it was sprayed with herbicide (glyphosate at a rate of 3 l ha^{-1}), and a few days later oversown with seed of *Setaria sphacelata* cv. Kazungula at a rate of 4·5 kg ha^{-1}. This initial phase of pasture preparation occurred in December 1982, 11 months before the trees were planted. The pasture was subsequently fertilized, and where necessary, both irrigated and resown to establish a reasonably uniform sward of *Setaria*. Details of fertilizer applications are given in Table 1. Whilst the pasture was dominated by *Setaria*, about 80 other pasture species were identified in a botanical survey.

A fast-growing native tree species of commercial importance, *Eucalyptus grandis*, was chosen for the study. Seed for the experiment was collected from ten widely separated, high quality mother trees near Coffs Harbour in northern New South Wales. Stands originating from this provenance have generally performed well in trials and plantings in the subtropics of Africa and South America. Seedlings were raised in a glasshouse for 16 weeks and then hardened in full sunlight for about 6 weeks. Pasture in a 0·5 m diameter circle around each tree position was killed by herbicide (glyphosate) before the seedlings were planted. A tree planting auger, developed as part of the project (Anon. 1986), was used to cultivate the soil to 0·5 m deep and 0·5 m diameter. The seedlings (about 0·6 m high) were planted, watered in and fertilized in November 1983. Further applications of fertilizer were made 3 and 6 months after planting (Table 1). When necessary, trees were sprayed with acephate and/or white oil to eliminate leaf-eating insects and scale (on 10 occasions). Wood borers were removed manually.

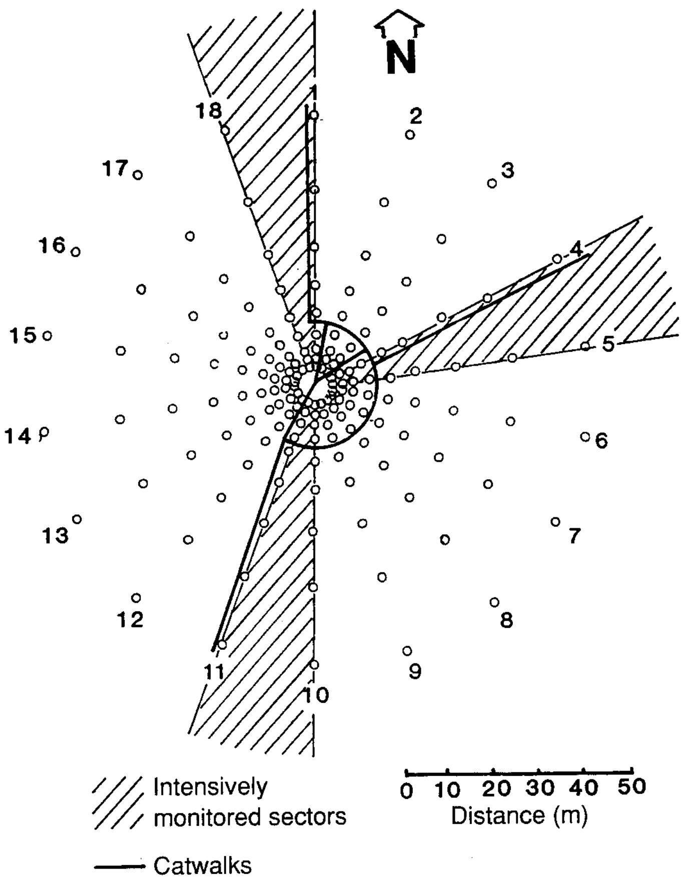

Fig. 2. Layout of the Nelder competition wheel. Estimates of the production and species composition of the pasture were made in the shaded sectors, access being provided by a series of catwalks to prevent undue trampling.

Table 1. Fertilizer application rates

(*a*) Broadcast applications across the site

Months after pasture seeding	Fertilizer form	Elemental rate (kg/ha) N	P	K
1	Urea, superphosphate, KCl	46	18·2	30
10	Superphosphate, KCL	—	22·8	25
13	Urea	46	—	—
15	Urea	46	—	—

(*b*) Pocket application 20 cm from tree base

Months after planting	Fertilizer and rate (g/tree)
1	Diammonium phosphate (D.A.P., 100)
3	D.A.P. (50)
6	D.A.P. (150), K_2SO_4 (40), combined minor trace elements (20)

Total applications per tree (g) were: P = 61, N = 58·8, K = 23·5, S = 17·7, Ca = 0·45, Mg = 0·23, Mn = 0·02, B = 0·015, Zn = 0·005, Cu = 0·004, Co = 0·0008

Measurements

During the first 4·6 years of the experiment all trees within the competition wheel were measured at approximately six-weekly intervals for total height, and stem diameter at several heights. Similar measurements were made twice-yearly on the trees in each of the four block plantings. Trees from these 'biomass plots' were destructively harvested periodically to obtain data for calibration of the non-destructive measurements made on trees within the competition wheel. Harvested trees were severed at ground level and measurements of height, diameter at intervals along the stem, and crown dimensions were made. They were then separated into the components stem wood, stem bark, branches and leaves, dried to constant weight at 105°C and weighed. During the first year of the experiment roots of some of the harvested trees were also recovered.

Standing biomass, species composition, pasture height and per cent bare ground of the pasture was estimated to 1 cm above the soil surface in each spring (October) and autumn (May) using BOTANAL sampling procedures (Tothill *et al.* 1978). Measurements were made on a grid with 72 quadrats in each of three monitored sectors (see Fig. 2). The quadrat positions were about 1 m apart near the hub of the competition wheel and 6 m apart near the edge. In addition, similar pasture measurements were made at 2, 4, 6 and 8 m from isolated trees at the edge of the wheel. After the BOTANAL measurements had been made, the pasture was slashed to a height of 0·15 m, with an additional slashing in mid-summer depending upon pasture growth. Just before the pasture was slashed, measurements were made of pasture biomass above the cutting height of 0·15 m. Herbage samples from each arc within four different sectors, not used for routine yield measurements, were cut to 1 cm above ground level in February 1986 and 1987. They were separated into green leaf, green stem and dead material and analysed for nitrogen, phosphorus, potassium and *in vitro* digestibility.

Long-term monthly averages of rainfall, temperature and radiation for Samford (Cook and Russell 1983) are given in Table 2. During the first four years of Project STAG the Samford Pasture Research Station experienced lower-than-average rainfall. Monthly means of the daily radiation integral and average daily temperatures were not markedly different from the long-term values.

Data Analysis

The reduced major axis regression (Till 1978) was used for all linear regression analyses reported here. Simple analysis of variance was not appropriate for examination of data collected in this experiment. In the present paper, only the mean values of the parameters measured on the 18 trees growing at each density within the wheel, and their standard errors are presented.

Non-destructive estimation of above-ground biomass of a tree depends upon an estimate of stem volume which in turn is reliant on measurements of tree height and diameter (Husch 1963; Carron 1968). Tree trunks taper from the base to the top and as a first approximation, can be considered to be conical. The conical volume of the stem, V_c (m^3) is then

$$V_c = \pi R^2 H/3 \qquad (1)$$

where R is stem radius at ground level (m) and H is total height (m). If the mainstem radius, r (m), is measured at some height h (m), equation (1) can be rewritten as

$$V_c = \pi[Hr/H-h)]^2 H/3. \qquad (2)$$

Estimates of V_c for harvested trees calculated from their stem radii measured at both 0·3 m and breast height (1·3 m) were highly correlated, with a slope of 1·0 and a correlation coefficient of 0·967. All subsequent estimates of stem volume reported here are based on the assumption that the stems of the trees are cones.

The total dry weight of live, above-ground parts of the destructively harvested trees (W) was linearly correlated to the equivalent conical stem volume, V_c. No significant differences were observed in the separate linear regressions of W upon V_c for trees harvested from each of the four biomass plots. The pooled data for the 86 trees harvested from all four biomass plots gave the regression equation

$$W\,(\mathrm{kg}) = 875\,(\pm 54)V_c - 0{\cdot}03\,(\pm 1{\cdot}35), \qquad r^2 = 0{\cdot}965. \qquad (3)$$

Results

As the trees grew they had an increasing influence on each other and on the pasture, and these effects radiated out with time from the higher tree densities at the centre of the wheel like ripples in a pond. A 'ripple effect' was observed in most of the parameters that were measured. Only part of the data set is presented here.

Pasture Growth and Botanical Composition

Pasture growth responded to rainfall, which was appreciably lower than average from 1984 to 1986 (Table 2). Growth was also affected by tree density, being depressed at high densities. The degree of depression increased with time as tree height and crown spread

Table 2. Long-term climatic data[A] for Samford Research Station (after Cook and Russell 1983)

Month	Mean radiation (MJ m² day)	Max.[B] temp. (°C)	Min.[B] temp. (°C)	Relative[B] humidity at 0900 hours (%)	Wind run (km day−1)	Mean rainfall (mm)	Rainfall (mm) 1984	1985	1986	1987	1988
Jan.	21·6	29·3	18·0	71	99	163	66·1	95·2	45·3	257·6	85·6
Feb.	18·5	28·9	18·4	73	98	160	51·5	91·0	41·0	50·2	116·3
Mar.	18·3	28·1	16·7	74	90	139	25·4	150·0	38·3	174·0	87·0
Apr.	15·9	26·2	13·3	70	79	81	200·2	78·7	16·3	39·4	538·1
May	12·4	23·2	9·7	72	86	66	34·7	52·2	74·3	113·5	9·7
June	12·1	21·0	7·3	72	102	60	58·8	43·6	5·7	37·6	156·9
July	12·9	20·3	4·9	69	102	55	131·7	102·7	49·2	41·9	132·7
Aug.	15·8	21·9	5·6	65	99	32	21·5	52·0	46·1	77·4	61·5
Sept.	18·6	24·1	7·8	62	106	46	32·5	53·0	35·5	5·5	58·8
Oct.	20·2	26·3	11·5	64	107	85	101·8	136·9	120·7	171·3	13·7
Nov.	23·2	28·0	14·6	64	102	91	100·3	26·2	145·6	30·4	
Dec.	24·6	29·1	16·7	65	100	122	58·7	81·6	120·5	90·5	
Total						1100	883·2	963·1	738·5	1089·3	
Mean											
Daily	18·6	25·5	11·9	69	99						

[A]Rainfall was recorded for 65 years, radiation for 10 years, and temperatures, relative humidity and wind run for 25 years.
[B]Measured in screen 1·5 m above ground.

increased. As growth was not significantly influenced by tree densities less than 158 stems ha^{-1}, yields have been expressed as a fraction of that obtained at this density or less (Table 3). The effect of very high tree densities on pasture biomass became increasingly more severe with time, and pasture biomass was depressed at progressively lower tree densities. There was also a 'ripple effect' on pasture height which peaked at 3580 trees ha^{-1} after 1·0 years and at 305 trees ha^{-1} after 4·0 years.

Table 3. Pasture standing biomass at the end of the growing seasons (May) expressed as a percentage of the biomass at tree densities of 158 stems ha^{-1} or less

The mean pasture biomass at tree densities of 158 stems ha^{-1} or less is given for each sampling date

Circle No.	Tree density (stems ha^{-1})	Relative yield (%) at tree ages (years)			
		0·5	1·5	2·5	3·5
1	3580	81	15	1	2
2	2150	75	42	9	7
3	1140	75	105	60	22
4	595	87	102	94	34
5	305	97	92	115	73
6,7,8	≤ 158	100	100	100	100
Pasture yields (kg ha^{-1})	≤ 158	5795	6185	4395	6699
Significance[A]		**	*	***	***

[A]Significance of regression relationships between $\log_{10}$ tree density and measured pasture biomass at each sampling (*, **, *** = $P<0·05$, $P<0·01$ and $P<0·001$).

At the times of assessment, there was no effect of tree density on the estimated percentage of bare ground as eucalypt litter covered the soil surface in the centre of the wheel where the pasture had largely died out. However, there were periods when the ground was exposed following decomposition of leaf litter. Where pasture biomass was markedly depressed by tree competition, the percentage of green leaf in the pasture increased, the percentage of dead material decreased, but the percentage of green stem was not affected (Table 4).

The nitrogen and potassium concentrations of green leaf, green stem and dead material increased with increasing tree density. The *in vitro* digestibility of the pasture components was not affected by shading in 1986, although there was a trend to higher digestibilities at the highest tree densities in 1987. However, despite these trends in nutrient concentrations, the impact of shading on reducing pasture biomass was such that the total nitrogen yields in either green matter or total biomass of pasture were depressed by tree densities above 595 trees ha^{-1} in 1986 and 305 trees ha^{-1} in 1987.

Although 80 different herbaceous species were present in the pasture, most were of little consequence. In May 1988, setaria comprised 78% of live pasture, followed by *Paspalum notatum* (13%), *D. didactyla* (4%) and *A. affinis* (1%). There were only minor changes in species frequency with tree density. The percentage frequency of most species tended to decrease with time, a few species showed little change (e.g. setaria), and the frequency of *P. notatum* increased irrespective of tree density. Four years after planting, the percentage of setaria in live pasture was highest in the intermediate tree densities (*c.* 90% of pasture biomass) falling to *c.* 60% at the two highest and three lowest tree densities. There was a negligible effect of tree canopy cover of the isolated trees (42 stems ha^{-1}) on pasture yield or botanical composition beneath the canopy compared with the inter-tree areas.

Table 4. Pasture standing biomass in February 1986 and 1987, and the proportions of green leaf and dead material, and the nitrogen, phosphorus and potassium concentrations of green leaf, green stem and dead material in response to tree density (mean of 1986 and 1987 analyses)

Tree density (stems ha^{-1})	Pasture biomass (kg dry matter/ha) 1986	Pasture biomass (kg dry matter/ha) 1987	Percentage of biomass (%) Green leaf	Percentage of biomass (%) Dead	Green leaf (%) N	Green leaf (%) P	Green leaf (%) K	Green stem (%) N	Green stem (%) P	Green stem (%) K	Dead material (%) N	Dead material (%) P	Dead material (%) K
3580	150	263	52	19	1·66	0·17	3·27	0·75	0·20	3·18	0·67	0·071	0·56
2150	380	675	50	15	1·53	0·18	3·22	0·74	0·22	3·03	0·79	0·075	0·52
1140	1400	1237	41	24	1·45	0·16	3·34	0·67	0·20	2·87	0·72	0·073	0·40
595	3260	1813	27	39	1·48	0·18	3·13	0·63	0·21	2·85	0·80	0·077	0·39
305	3780	3286	26	45	1·23	0·19	2·66	0·58	0·23	2·41	0·69	0·068	0·31
158	5150	4381	22	49	1·21	0·22	2·67	0·57	0·24	2·55	0·75	0·081	0·31
82	4660	4640	25	42	1·09	0·22	2·75	0·48	0·23	2·56	0·57	0·077	0·39
42	4580	5225	19	48	1·04	0·18	2·21	0·44	0·21	2·24	0·55	0·064	0·32
Significance[A]	***	***	***	**	***	—	**	***		***	*	—	**

[A]Significance of regression relationships between $\log_{10}$ tree density and each attribute (*, **, *** = $P<0{\cdot}05$, $P<0{\cdot}01$ and $P<0{\cdot}001$).

Tree Growth

Trees around any circumference within the competition wheel and within the rectangular block plantings were relatively uniform in height and diameter. Mean heights and diameters for the four biomass plots at age 1·5 years (May 1985) are shown in Figs 3 and 4. Until age 2·0 years, all 18 trees in each circle were similar, the standard error for each set of trees being approximately 5% of the mean, with no systematic variation associated with tree location around the wheel. Observable asymmetry in the growth of trees on the site, primarily in crown shape, was attributed to chilling effects of strong winds during winter on the south-western side of the crown. Trees on the uphill part of the wheel did not grow as quickly as those lower down the slope during a particularly dry season in the third year (1986: Table 2). This was attributed to greater water stress on those shallower soils.

Tree height was influenced by stand density. At age 0·5 year (May 1984, Fig. 3), there was little difference in height at different densities, but by 1·5 years (May 1985), heights ranged from 3·8 m at 42 stems ha^{-1} to 6·2 m at 3580 stems ha^{-1}. By age 2·5 years, height increased between stand densities of 42 to 1140 stems ha^{1}, with little change at higher densities, and the pattern was similar at age 3·5 and 4·6 years but with reduced increments at the higher densities (2150 and 3580 stems ha^{-1}).

Diameter growth also varied in relation to stand density (Fig. 4). At age 1·5 years, mean diameter at breast height over bark (dbhob) was 4·3 cm at 42 stems ha^{-1}, and there was a steady increase with density to 5·9 cm at 3580 stems ha^{-1}. One year later the trend was different, with the trees of largest diameter occurring at 305 stems ha^{-1}. This 'ripple effect' continued with the largest trees occurring at 82 stems ha^{-1} at 3·5 and 4·6 years.

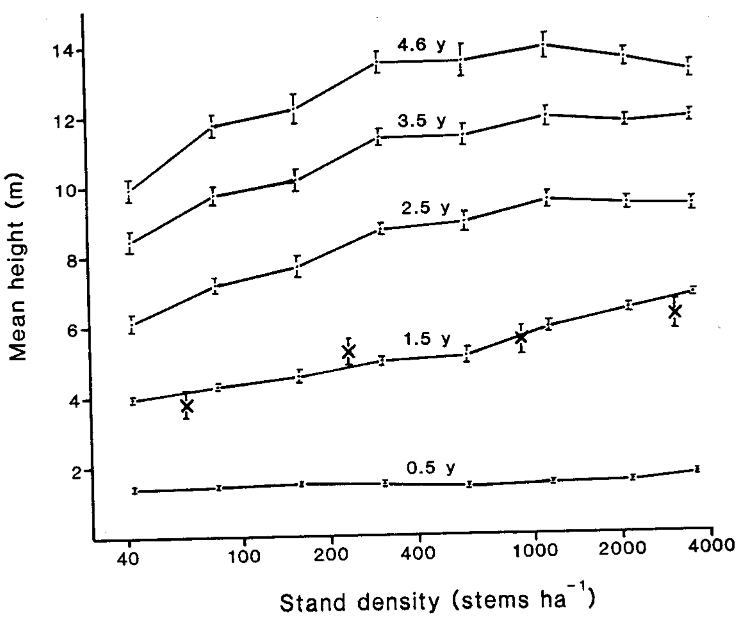

Fig. 3. Mean tree heights in relation to stand density at the end of the growing season (May) for the years 1984 to 1988 (age 0·5–4·6 years). Standard errors are shown as vertical bars. Mean heights of trees in the four biomass plots are shown at age 1·5 years (x).

Tree Form and Taper

The early development of stem taper was measured by examining the ratio height:diameter 0·3 m above ground level ($H{:}d_{0\cdot3}$ (m:cm)). The ratio increased with time at the higher stockings as the trees competed increasingly with each other for light, while that of trees at wider spacings remained relatively constant (Fig. 5). The ratio in the most exposed trees (42 stems ha^{-1}) decreased slightly with time.

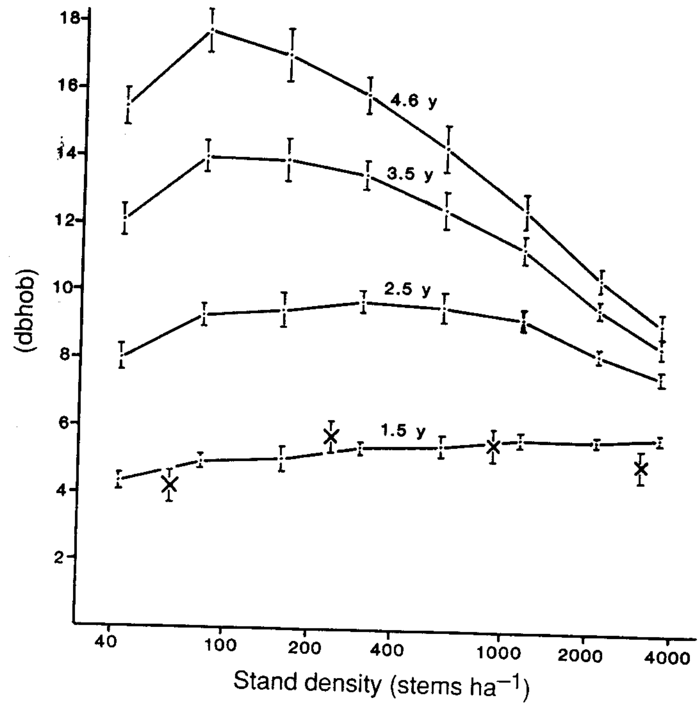

Fig. 4. Mean diameters of trees at breast height over bark (dbhob) in relation to stand density at the end of the growing season (May) for the years 1985–1988 (age 1·5–4·6 y). Standard errors are shown as vertical bars. Means for the four biomass plots are shown at age 1·5 years (*x*).

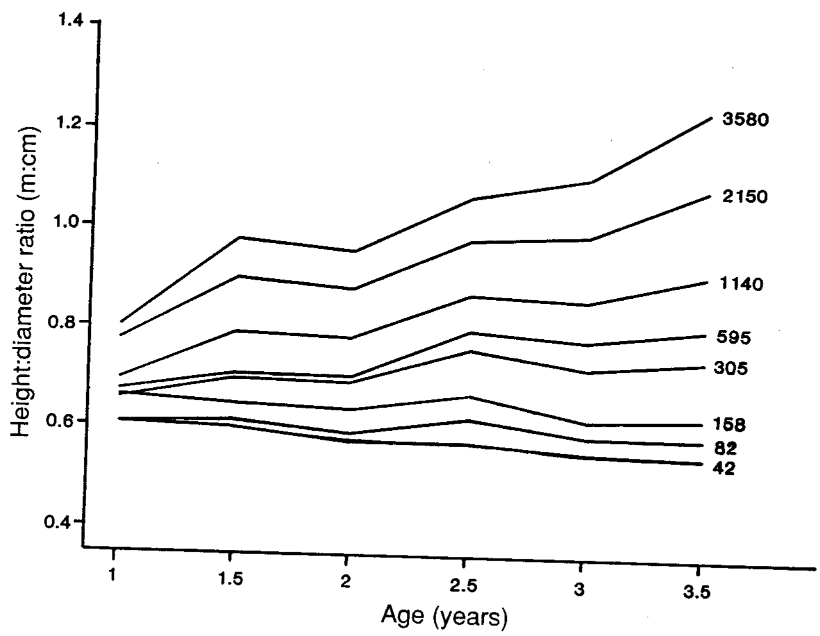

Fig. 5. Mean tree height: diameter over bark at 0·3 m ratio (H:$d_{0\cdot3}$) for stand densities of 42 to 3580 stems ha^{-1} for ages 1·0–3·5 years.

Table 5. Regression parameters for the function $H{:}d_{0\cdot3}$ (m:cm) = a(stems ha^{-1})$^{1/2}$ + b fitted to the data from all 162 trees in the Nelder wheel

Age (years)	Mean height range (m)	*a*	*b*	r^2
1·5	4·0–6·7	0·0072 (± 0·0007)	0·554 (± 0·022)	0·86
2·5	6·1–9·5	0·0094 (± 0·0008)	0·555 (± 0·025)	0·89
3·5	8·4–11·9	0·0130 (± 0·0008)	0·479 (± 0·023)	0·95
4·6	8·9–13·9	0·0147 (± 0·0008)	0·457 (±0·024)	0·95

The height:diameter ratio also responded to seasonal effects. Height increments were smaller during periods of water stress and during the winter months, while diameter increments through the year were more uniform. As a result, $H{:}d_{0\cdot3}$ ratios tended to be higher in autumn.

$H{:}d_{0\cdot3}$ ratios varied as a function of spacing and tree height. Regressions of the form

$$H{:}d_{0\cdot3} = a(\text{stems ha}^{-1})^{1/2} + b$$

were fitted to height:diameter ratios for all trees in the wheel and values for a, b and r^2 are shown in Table 5. Slope of the regressions increased with time as the trees at high stand densities became more spindly.

Mean Tree Biomass

Estimates of above-ground mean tree biomass are shown in Fig. 6. After 1·3 years, trees at the highest density (3580 stems ha^{-1}) had the greatest mass. At age 2·0 years the heaviest trees were at a stocking of 1140 stems ha^{-1} and at age 2·5 years at a stocking of 595 stems ha^{-1}. This 'ripple effect' moved further out from the centre with the heaviest trees at a stocking of 82 stems ha^{-1} at 4·6 years. Trees at low stand densities (42 stems ha^{-1}), were significantly smaller than those at 82–305 stems ha^{-1}. These data represent measurements made at the end of summer–autumn growth (May) and the start of spring growth (October).

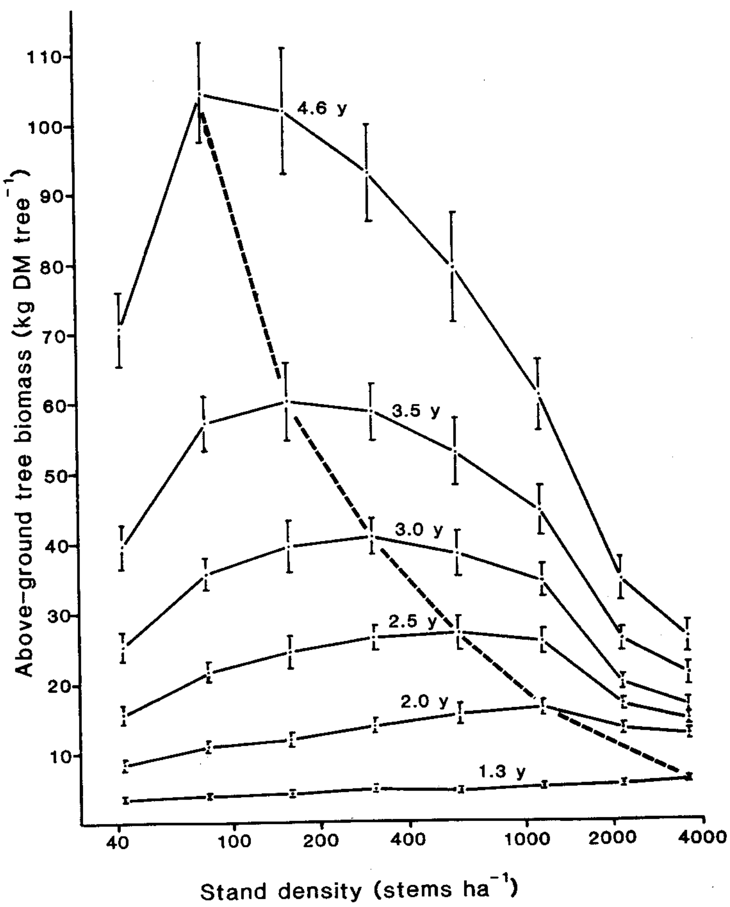

Fig. 6. Mean tree above-ground biomass in relation to stand density from age 1·3–4·6 years. The 'ripple effect' is marked by the dotted line joining trees of maximum biomass.

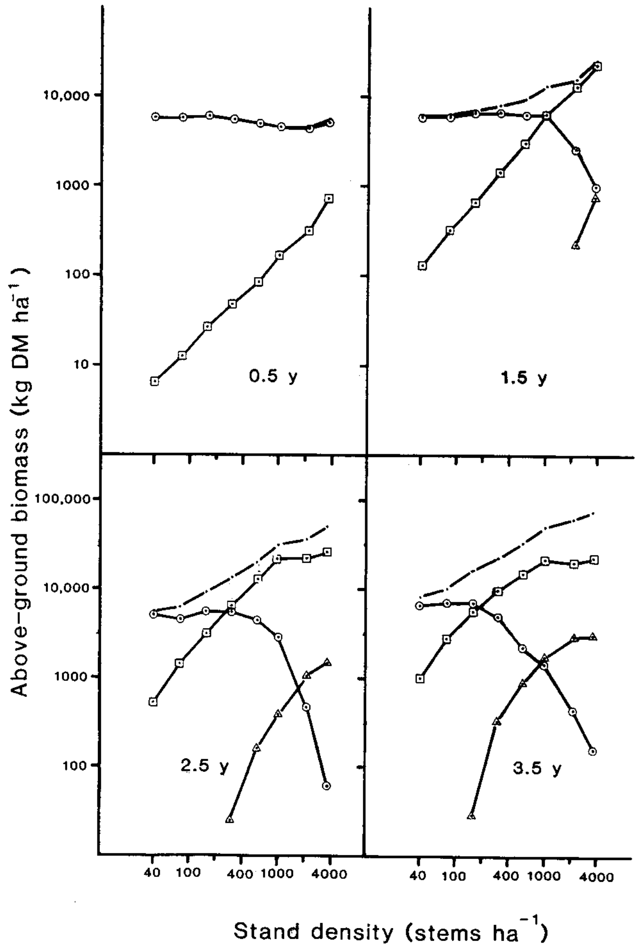

Fig. 7. Above-ground annual pasture (○), total accumulated biomass of trees (□), and eucalypt litter (△) and total standing biomass (·) in relation to stocking at tree ages 0·5–3·5 years.

Tree and Pasture Production

Above-ground biomass of trees, pasture and eucalypt litter in relation to spacing and time are shown in Fig. 7. In May 1984 (when the pasture had been established for 1·4 years and the trees 0·5 year), pasture biomass was relatively even throughout the wheel and tree biomass increased directly with stand density. At age 1·5 years, tree biomass was greater than annual pasture biomass increment at tree densities of 1140 stems ha^{-1} or more, and eucalypt litter was starting to accumulate at 2150 and 3580 stems ha^{-1}. By age 2·5 years, tree biomass exceeded annual pasture biomass increment at 305 stems ha^{-1} or more, and there was a substantial drop in pasture production at tree densities of 1140 stems ha^{-1} or more. These trends have continued.

Mean growth rates (kg DM ha^{-1} day^{-1}) of trees and pasture for the period November 1985 to May 1986 are shown in Fig. 8. Trees contributed very little to the total production at wider spacings, but increased to around 80 kg DM ha^{-1} day^{-1} at the highest densities. Pasture production was around 20 kg DM ha^{-1} day^{-1} at the lower tree densities, with the suggestion of a slight increase at a density of 305 stems ha^{-1}, and then a rapid decline at higher tree densities.

Discussion

An underlying objective of agroforestry systems is that an optimum combination of overstorey and understorey crops can be found which will give greater total production than would be the case if each crop were grown separately on the same area of land. In Project STAG, a tree crop was introduced into a mixed species pasture dominated by a tall

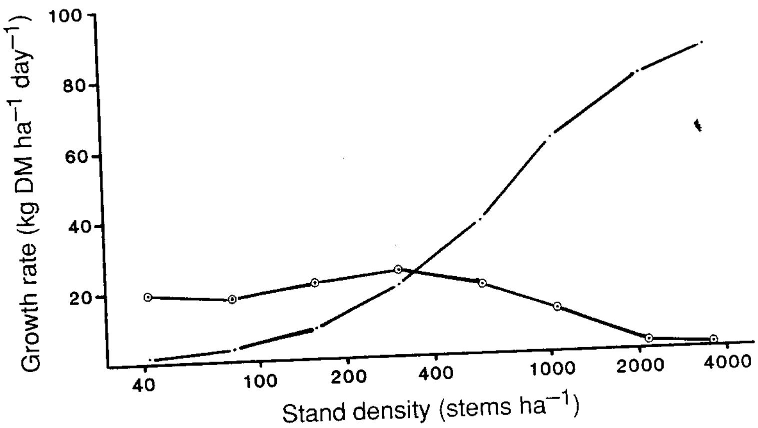

Fig. 8. Mean growth rates (kg DM ha^{-1} day^{-1}) of pasture (○) and trees (•) in relation to stocking for the 6-month period November 1985 to May 1986 when the trees were 2, and 2·5 years old respectively.

grass. A ripple effect was observed in most of the parameters measured. This occurred in tree heights (Fig. 3), tree diameters (Fig. 4), tree above-ground biomass (Fig. 6), pasture biomass and tree litterfall (Fig. 7).

Pasture production between the trees at wider spacings was not reduced by the presence of the trees (Fig. 8). The growth rate of about 20 kg DM ha^{-1} day^{-1} was comparable with that of other unirrigated pastures in the region not fertilized with nitrogen (Henzell 1963). There is a suggestion that pasture growth was enhanced slightly in a zone near the optimum spacing for tree growth. This was most apparent during the winter months when the pasture between widely spaced trees was frosted, while that between trees at high density remained green (data not presented). There was evidence that pasture quality was also improved by shading, as a higher portion of the yield was allocated to green leaf with a higher nitrogen content than in more exposed pasture (Table 4). These effects may have been a consequence of the method of fertilizing the trees, which resulted in application rates of nitrogen varying from 2·5 kg ha^{-1} at low density (42 stems ha^{-1}), to 210 kg ha^{-1} at high density (3580 stems ha^{-1}). However, these high rates of application of nitrogen under trees had little effect on pasture yield over the first growing season when competition from trees was minimal (Fig. 8). Furthermore, there was no change in the phosphorus content of the green leaf, although phosphorus application was also greater at 3580 stems ha^{-1} (218 kg ha^{-1}) than at 42 stems ha^{-1} (2·6 kg ha^{-1}) (Table 4). It could also have been a consequence of nutrient cycling through litter fall and break-down. While there was a substantial increase in the quantity of eucalypt litter under the dense trees (Fig. 7), most of this was woody litter from fallen branches. Leaf litter decomposed quite rapidly, usually within 6–10 weeks after falling. Higher nitrogen concentrations in the pasture near the centre of the wheel could also be due to considerably lower total pasture yields and hence to less dilution of nitrogen. Increases in nitrogen and potassium concentrations in shaded pasture plants have been measured by other workers (Wilson 1982; Samarakoon 1987).

Grime (1979) discussed relationships between herbage species diversity, dominance, stress and productivity. The data reported here show that the dominance of setaria increases in the zone of least stress. Stress would have been greater at the centre of the wheel where there was considerable shading of the pasture and competition for water, and at the edge of the wheel where plants experienced a higher radiation load in summer and frosting in winter. Setaria, potentially the highest yielding of the species present, was more dominant at the intermediate tree densities which included the maximum mean tree biomass in a zone presumed to be subjected to less stress.

Pasture growth rates declined at the higher tree densities to almost nil (Fig. 8), while the trees at those densities were growing at about 80 kg DM ha^{-1} day^{-1}, comparable to well-watered pasture in the region which had been regularly fertilized with nitrogen (Henzell and Stirk 1963; Bryan and Sharpe 1965; Strickland 1978). This growth was achieved during a 6-month period when rainfall was only 39% of the average (Table 2) by exploiting water stored in the soil profile. By age 3·0 years, trees at 2150 stems ha^{-1} had depleted the soil water in the profile to wilting point to a depth of at least 5·6 m in soils with a bulk density of 1·7–1·9 g cm^{-3} (Eastham *et al.* 1988). Even in the relatively mild climate of south-eastern Queensland, the availability of soil water was a major constraint to growth. Trees established at about 1000 to 2000 stems ha^{-1} could be used as biological pumps to lower water tables and stabilize land slips. Species and stand density would have to be selected with care after considering such factors as soil type and salinity, and climate. It is expected that tree growth will decline in time, initially in the inner circles, as soil water resources are further depleted. Pasture production in the inner circle is expected to continue to be suppressed by the trees. It is likely that the 'ripple effect' of density on pasture growth will continue to expand outwards, although at a slower rate.

Growth of *E. grandis* was typical of the species in this area (Clarke 1975; Borough *et al.* 1978; Cameron 1984*b*), although higher growth rates have been recorded overseas (Rockwood and Geary 1982; Darrow 1984; Campinhos 1987). Planting density affected the growth and morphology of trees. Height growth was markedly reduced at low stand densities. Similar results were found by Cremer *et al.* (1982) working with *P. radiata*. They attributed the growth reduction to increased exposure to wind. At high densities mainstems tapered gently, primary branches were slender and the crown base began to lift by age 1·5 years. In contrast, at low densities primary branches were thick and remained active in the lower crown, and taper was rapid, features associated with high wastage when logs were squared off for sawing or peeling.

From the tree growth data there appeared to be an optimum size–spacing relationship, whereby closely-spaced trees benefited from a 'mutual protection effect' while wider-spaced trees often appeared to be stressed even when reserves of soil water were adequate. The optimum occurred where trees were near their neighbours but did not shade them for more than an hour or two each day. Even the most widely–spaced trees in this experiment appeared to interact with each other. Figs 3 and 4 suggest smooth changes in height and diameter even at the very wide spacings. For instance, by age 1·5 years, the mean heights of trees at stockings of 158, 82 and 42 stems ha^{-1} were 4·54, 4·28 and 3·97 m respectively. The trees in circles 6 and 7 (158 and 82 stems ha^{-1} respectively) were 8·9 m apart and those in circles 7 and 8 (82 and 42 stems ha^{-1}) were 12·4 m apart. By age 2·5 years the differences were even more striking.

An optimum stocking for tree production depends on the end use of the tree crop. High stand densities (> 1000 stems ha^{-1}) yield maximum wood biomass in small–sized stems and virtually no pasture. Strip plantings at these densities could be used to lower water tables and be harvested for charcoal or biomass. Trees established at medium densities (300–600 stems ha^{-1}) could be managed to yield round timber for pulpwood, poles and posts, and sawlogs. Pasture growth could be maintained at a high level through tree thinnings at earlier schedules than used in forest practice. A final stand density of 20–50 stems ha^{-1} could be expected following a number of thinnings. Plantings of lower densities (< 100 stems ha^{-1}) could be used for stock shelter without seriously affecting pasture production. Heavy branching and rapid taper will limit log recovery from some species but may be an advantage with some fruit and nut trees. Other tree species may be more tolerant of exposure than *E. grandis.*

The compact Nelder (1962) design allowed trees to be established at a wide range of densities and provided an opportunity for direct visual assessment of the main effects. In traditional 'block' planting, such comparisons are possible only along block boundaries of adjacent treatments.

Nelder (1962) designs have been infrequently used for tree crops (Freeman 1964; Smith 1978; Lemoine 1980; Rockwood and Geary 1982; Dippel 1982; Van Mieghem *et al.* 1983). Faber (1985) used a wheel of 9 circles and 20 spokes, with spacings varying from 83 to 6450 stems ha^{-1} of a black balsam hybrid poplar in Germany. His data showed similar 'ripple effects' in height and diameter to those found in STAG and suggest similar silvicultural characteristics for these two species growing in very different climatic zones.

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