Agroforestry Systems **32**: 185–204, 1995.

Process studies in a *Pinus radiata*–pasture agroforestry system in a subhumid temperature environment. II. Analysis of dry matter yields in the third year

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Key words: competition, water use efficiency, radiation use efficiency, land equivalent ratio

Abstract. In this paper we analyzed the dry matter yields (DM) produced in an agroforestry trial consisting of pine trees grown over (1) Control (bare ground), (2) ryegrass/clovers (*Lolium perene/Trifolium* spp.), (3) ryegrass only, and (4) lucerne (*Medicago sativa*) during the third growing season between 1992 and 1993. In addition these pastures were grown alone in separate plots in the open. The results show that:

1. Pasture yields during the one-year period in the agroforestry plots were little affected by the presence of trees although there were seasonal trends: yields were generally unaffected or increased in summer, but reduced in spring as a result of tree shade. Total pasture yield during the one-year period was in the following order: lucerne > ryegrass/clovers > ryegrass. This trend was the exact opposite of that shown by the above-ground tree weight which was reduced in the pasture ground covers by between 16 and 52%. The reduction in tree weights was associated with reduced soil moisture availability arising from competition with the pasture species. Thus the relationship between the yields of trees and pasture species in the agroforestry plots was reciprocal.
2. The combined DM for both the trees and pastures in the agroforestry plots during the one-year period was in the following order: lucerne (20 t ha^{-1}) > ryegrass/clovers (16 t) > ryegrass (11 t) > control (6 t) which was consistent with the total water used and photosynthetically active radiation (PAR) intercepted. The trees accounted for 55, 44, 34 and 24% of water used respectively in control, ryegrass, ryegrass/clovers and lucerne ground covers. The balance was largely accounted for by pasture transpiration, except in the control where soil evaporation was significant. The fraction of intercepted PAR accounted for by the trees followed a similar trend to that of the water used.
3. The crop coefficient for water use efficiency (k) (Pa) was 2.3 for radiata pine, 3.6 for ryegrass/clovers, 2.8 for ryegrass and 4.8 for lucerne. The DM produced per unit of water used (kg mm^{-1} ha^{-1}) during the one-year period was 24.5 for radiata pine, 41.1 for lucerne, 30.0 for ryegrass/clovers and 23.1 for ryegrass. Radiation use efficiency (g DM MJ^{-1} m^{-2}) was 1.33 for pine, 1.83 for ryegrass/clovers, 1.49 for ryegrass and 2.34 for lucerne.
4. The land equivalent ratio (LER), i.e. the sum of ratios of DM produced by the plant species in the agroforestry plots to those produced in the sole plots, was 1.95 for ryegrass, 1.71 for ryegrass/clovers and 1.45 for lucerne ground covers.
5. These results indicate the susceptibility of pasture species to shading and interception of rainfall by the tree crowns (aboveground interactions), and the trees to competition for soil moisture (underground interaction).

Nomenclature

DM	=	dry matter produced in the shoots (g m^{-2} or kg ha^{-1} or t ha^{-1})
E_p	=	transpiration through the pasture canopies (mm)
ET	=	evapotranspiration from the agroforestry plots (mm)

Et	=	transpiration through the radiata pine canopies (mm)
GAI	=	green area index, area of green surfaces produced by the pasture species per unit land area (dimensionless)
k	=	crop constant for water use efficiency (Pa)
LER	=	land equivalent ratio, sum of ratios of DM produced in the agroforestry plots to those in the sole plots
PAR	=	photosynthetically active radiation (400 to 700 nm)
RUE	=	radiation use efficiency, DM produced per unit PAR intercepted (g MJ m^{-1})
T	=	transpiration by the plant species (mm)
TE	=	transpiration efficiency, DM produced per water transpired (kg mm^{-1} ha^{-1})
VPD	=	vapour pressure deficit (kPa)
WUE	=	water use efficiency, DM produced per ET (kg mm^{-1} ha^{-1})

1. Introduction

Most agroforestry systems aim to improve the productivity of the land through increased capture of the biophysical resources (solar radiation, soil moisture and nutrients) by two or more plants species. However, competition between the species for the limited resources may be detrimental to the growth of some or all the species in a mixture. An earlier study [Mead and Mansur, 1993] in the trial reported in the preceding paper, using vector analysis, indicated that variability in the growth of pine trees planted over pasture species could be explained on the basis of the ability of the component species to capture nutrients and soil moisture, although the limited physical data in that study [Mead and Mansur, 1993] did not permit a comprehensive analysis of the partitioning of biophysical resources amongst the species.

Land productivity due to growing a community of different plant species together on same piece of land concurrently is often evaluated by calculating the land equivalent ratio (LER). LER may be defined, after Mead and Willey [1980], as the land needed to produce in pure stands the same yields of the crops in an agroforestry system at the same level of management. When LER is greater than one, agroforestry is beneficial. However, the plant dry matter yield does not depend entirely on the quantities of nutrient, radiation and water used alone, but also on the efficiency with which these resources are used. For water use, the ratio of dry matter yield (DM) to the quantity of water transpired by the plant, i.e. transpiration efficiency (TE), is given by Tanner and Sinclair [1983] as:

$$TE = k/(VPD) \tag{1}$$

where k is the crop specific constant and VPD is the vapour pressure deficit. Thus agroforestry system consisting of species with high k should be more productive than systems of species with low crop constant. Furthermore, for any species in the agroforestry system, if its k is known, its water use can be estimated from its DM yield and the seasonal VPD. A similar analysis can be applied to the use of radiant energy in agroforestry systems once the crop constants, in this case 'radiation use efficiency' (RUE), of the individual species are known.

In the proceeding paper [Yunusa et al., 1995] we showed that there were significant differences in the interception of radiation and evapotranspiration (ET) by the combined canopies of trees and pastures species in the agroforestry plots. In the present paper we analyse the dry matter yields of both trees and pasture species in relation to availability and use of soil moisture and solar radiation. The objectives were to (1) evaluate the respective effects of trees and pasture species on each other's growth, (2) determine water and radiation use efficiency, (3) partition the use of these biophysical resources between the trees and pastures, and (4) analyse the productivity of the various tree – pasture combinations described in the preceding paper.

2. Procedures

The details of the site characteristics, experimental design and field layout were briefly presented in part 1 of this study [Yunusa et al., 1995]. The experiment reported here consisted of two parts – the agroforestry section, already described [Yunusa et al., 1995], and the open pastures. In the agroforestry section, we used four ground covers as main treatments: (1) control, bare ground, (2) ryegrass/clovers, (3) lucerne and (4) ryegrass. Pine seedlings were transplanted over these ground covers in July 1990. There were five subtreatments consisting of positions in the transects between the tree rows at which the measurements of plant and soil variables were centred:

1. 0.9 m south of tree rows (0.9 mS).
2. 1.8 m south of tree rows (1.8 mS).
3. Midway (3.5 m) between the adjacent tree rows, i.e. centre of transect (CT).
4. 1.8 m north of tree rows (1.8 mN).
5. 0.9 m north of tree rows (0.9 mN).

These positions are indicated in Fig. 1 of the preceding paper [Yunusa et al., 1995].

The open pasture section of the experiment consisted of 18 × 20 m plots, and was located to the immediate east of the agroforestry section. The pasture species were assigned to plots in a randomized complete block design with three replications. The pasture species in both sections were planted at same time and managed similarly.

2.1. *Measurements and observations*

2.1.1. *Pasture growth*

Seasonal dry matter (DM) produced by the pasture during the 1992/93 season was determined in spring (22 October 1992 and 9 December 1992), summer

(1 February 1993) and autumn (20 April 1993). Additional sampling for the spring season was made in the following growing season on 29 September 1993, since pasture growth variables were not measured during the previous season. Before February, plants were sampled by cutting at 50 mm height using secateur mowers, and the DM was determined by weighing all the cut herbage fresh in the field, and then taking sub-samples which were oven dried and weighed. From February, DM was monitored in situ using a pasture probe (Mosaic Systems Ltd, New Zealand). The probe was calibrated by taking several plant samples from 0.25 m^2 quadrat which were oven dried and weighed. In the agroforestry plots, the monitoring was carried out along 0.3 wide strips centred along the five positions and running parallel to the tree rows. Thus the DM data presented in this paper for February and for later sampling dates represented standing herbage in contrast to the herbage harvested and removed from the plots [Pollock et al., 1994].

The green area index (GAI), i.e. the total green surface areas produced per unit land area, was determined with a plant canopy analyser (LAI 2000, LI-COR Inc., USA) commencing from mid-January 1993 and thereafter at four-weekly intervals. Measurements were made at the five positions as with the DM determination. The sensor was calibrated with data obtained from destructive sampling at the start of the measurements.

The measurement of photosynthetically active radiation (PAR) intercepted by the pasture canopies was described previousely [Yunusa et al., 1995]. The fraction of ground surface area covered by the green pastures was determined with a modified point quadrat [Cackett, 1964; Yunusa et al., 1992]. Because of poor growth by the pure ryegrass species during dry periods, the linear sensor could not be placed beneath the canopy to determine light interception, which in this case was taken to be similar to the fraction of ground cover [Firman and Allen, 1989; Yunusa et al., 1992].

In the open pastures, all measurements were made at several positions randomly chosen to cover as much of the plots as possible.

2.1.2. *Tree growth*

Tree height and stem diameter near the base at the root collar (height of 50 mm) were measured for all the trees during winter in 1992 and 1993. On the same occasions, two trees were randomly selected and felled by cutting at the base in all the plots except those for ryegrass ground cover. The samples were oven dried at 70 °C to obtain their dry weights. The plot means for the tree weights were determined using the base area ratio [Madgwick, 1981]. For ryegrass ground cover, the tree weight was determined indirectly from their stem diameters and the base area ratios obtained in the ryegrass/clovers ground cover. The mean tree weights were multiplied by the stocking rate, in this case 800, to calculate DM yields per unit land area.

2.1.3. *Plant water potential and stomatal resistance*
Plant water potential at midday was monitored in lucerne in both the agroforestry and open pasture plots with a pressure chamber. Measurements were made on shoot tops above the third upper fully expanded leaf. Measurements commenced in mid-March and thereafter at weekly intervals until the end of April when the pasture started dying out. Similar measurements were made on pine trees using the previous season's fascicles from the branches in the third uppermost whorls. Stomatal resistance was measured in lucerne at the same time as leaf water potential measurements using a porometer (AP4, Delta T Devices, UK). The porometer also measured the leaf temperature. The procedures for measuring both the water potential and stomatal resistance followed those described by Turner [1981].

2.1.4. *Land equivalent ratio (LER)*
The LER was calculated as the sum of the ratios of total dry matter yields produced by the component species in the agroforestry plots to their yields in the sole plots [Mead and Willey, 1980]:

$$LER = DM_{tpc}/DM_{tc} + DM_{pf}/DM_{po} \quad (2)$$

subscripts tpc refer to trees in pasture ground covers, tc trees in the control, pf pasture in the agroforestry plots, and po pastures plots.

2.1.5. *Determination of k for the pastures and partitioning of water use between pastures and trees*
The k was determined from DM, transpiration by the pasture species (E_p), and VPD data measured for selected periods. E_p was determined as described earlier in part one [Yunusa et al., 1995], while VPD was obtained from a nearby weather station. The k was taken as the slope of regression of DM vs. E_p/(VPD) with the line forced through the origin [Walker, 1986], and was used in Eq. (1) to calculate E_p for the whole growing season. Transpiration by the trees (Et) was obtained from the difference between evapotranspiration (ET) for the whole plots, presented previously [Yunusa et al., 1995], and E_p, after making allowance for soil evaporation. For the period between July 1992 and June 1993 soil evaporation was taken to constitute 10% of ET in ryegrass/clovers and 8% in lucerne. For the control, in which there was no pasture cover, and ryegrass, for which there were no soil moisture data, Et was determined from tree DM data and mean DM/Et ratios from the other two pasture ground covers. Soil evaporation in ryegrass was taken to be similar to that in the ryegrass/clovers ground cover.

2.1.6. *Statistical analysis*
All tree data were analysed using a randomized complete block model. Pasture data from the agroforestry plots were analysed using the split plot model with the three pasture types as the main treatments and the five positions as sub-

treatments. Data from the open pastures were analysed using the randomized complete block model. The analysis was performed using the repeated measurement option of GLM SAS (SAS Users Guide, 1987). Means were compared using the appropriate standard errors of difference (SED). Data from plant water potential, stomatal resistance and leaf temperature were compared using their standard errors of means (SEM). No statistical comparison between the agroforestry and open pasture plots was intended.

3. Results

3.1. *Tree growth*

There were no significant effects of ground cover on tree height in 1993 (Table 1). The tree weight (Table 1) was highest in the control and least in the lucerne ground cover. Over the one-year period, increment in tree weight was reduced by between 16 and 52% by the pasture ground covers. Amongst the pasture ground covers tree weight was in the following order: ryegrass > ryegrass/clovers > lucerne.

Table 1. Effects of ground covers on the heights and dry weights of radiata pine trees measured in winters of 1992 and 1993.

Ground covers	Height (m) (1993)	Increase in height (m)[a]	Dry weight per tree (kg)	Increase in tree weight (kg)[a,b]
Control	2.77	1.26	11.29	7.31
Ryegrass/clovers	2.91	1.36	9.66	5.53 (0.76)
Ryegrass	2.69	1.21	9.91	6.17 (0.84)
Lucerne	2.73	1.30	8.69	3.53 (0.48)
SED	0.129	0.047	0.256	0.538

[a] Increments over the values measured in July 1992.
[b] Numerals in parentheses are the ratios of tree weight for the pasture ground covers to that for control.

3.2. *Pasture growth and yield*

In the agroforestry plots, the DM produced in early spring (22 October 1992) (Table 2) was greater for lucerne than for ryegrass/clovers by 62%; ryegrass was not sampled at this time due to its poor growth. In late spring (9 December), DM was similar for lucerne and ryegrass/clovers, both of which produced more than twice the yield of ryegrass species. In summer (February), the DM for lucerne was 68% more than for ryegrass/clovers and more than double the yield for ryegrass. In autumn (April), ryegrass/clovers produced the least yield, while both lucerne and ryegrass had similar yields. The follow-up sampling for spring in September 1993 showed that lucerne produced

Table 2. Periodic dry matter yields produced by the pasture species in the agroforestry plots and in the open plots during the 1992–1993 study period at Lincoln, New Zealand.

Pasture types	Sampling dates					Totals	
	22 Oct 92	9 Dec 92	1 Feb 93	20 April 93	29 Sept 93	Up to April	Up to Sept
Agroforestry plots (t ha^{-1})							
Ryegrass/clovers	2.99	3.82	3.07	1.72	2.05	11.85	13.64
Ryegrass	na	1.46	2.41	2.53	2.23	6.00	8.64
Lucerne	4.86	4.00	5.16	2.82	3.47	16.84	20.31
SED	0.169	0.230	0.087	0.086	0.045	0.859	0.952
Open pasture plots (t ha^{-1})							
Ryegrass/clovers	3.29	4.06	2.85	2.09	5.00	12.28	17.29
Ryegrass	na	1.83	1.18	2.46	4.55	5.47	10.10
Lucerne	5.01	4.30	4.78	3.32	6.80	17.41	24.21
SED	0.121	0.457	0.236	0.238	0.142	0.391	0.572

significantly ($p < 0.05$) more yield than the other two pastures, both of which had similar yields. The total yields by the pastures during the 1992/93 growing season was obtained by summing the DM data for the first four samplings up to April 1993; lucerne DM yield totalled 16.8 t ha^{-1}, which was 42% and 180% more than the yields by ryegrass/clovers and ryegrass respectively (Table 2). A similar trend was observed with the total yield over the entire study period (July 1992 to September 1993).

In the open pasture plots (Table 2), the differences in DM yields amongst the pasture species were similar to those observed in the agroforestry plots. Lucerne produced the most yields and ryegrass the least at all sampling dates, except in December when both lucerne and ryegrass/clovers produced similar yields, and in April when ryegrass appreciably outyielded ryegrass/clovers.

Relative to the DM yields in the open pasture plots, yields in the agroforestry plots were severely reduced during spring, especially in September 1993 (Table 2) when DM produced by all the pastures was at least halved in the agroforestry plots compared to the open plots. In summer (February), yields were increased for all pastures in the agroforestry plots, especially for ryegrass species in which the increase was 104%. During the main growing season (up to April), pasture yields in the agroforestry plots were reduced by less than 4% for ryegrass/clovers and lucerne, but remained largely unaffected in the ryegrass species. However, total yields over the five sampling dates were reduced by between 14 and 21% in the agroforestry plots compared to the open pastures.

Both the maximum GAI and fraction of PAR intercepted (Table 3) by the pasture species in the agroforestry plots were mostly in the following order: lucerne > ryegrass/clovers > ryegrass, except in February when GAI was similar for ryegrass/clovers and lucerne. Compared to the open pastures, GAI

Table 3. Seasonal trends in the growth attributes for the pasture species in the agroforestry and open pasture plots, measured just before dry matter samplings, during the 1992–1993 study period at Lincoln, New Zealand.

Pasutre types	Agroforestry plots			Open pasture plots		
	1 Feb 93	20 Apr 93	29 Sept 93	1 Feb 93	20 Apr 93	29 Sep 93
Green area index (GAI)						
Ryegrass/clovers	2.74	1.66	1.70	3.04	1.79	3.30
Ryegrass	1.83	1.02	1.43	1.79	1.29	2.21
Lucerne	2.74	2.30	1.92	2.46	2.22	2.59
SED	0.279	0.453	0.127	0.140	0.213	0.258
Fraction of PAR intercepted						
Ryegrass/clovers	0.75	0.36	0.53	0.76	0.52	0.92
Ryegrass	0.54	0.38	0.47	0.67	0.64	0.96
Lucerne	0.82	0.68	0.59	0.87	0.93	0.76
SED	0.098	0.027	0.060	0.171	0.007	0.033

was generally reduced in the agroforestry plots by between 7 and 49% with the largest reductions occurring in spring (Table 3); although lucerne and ryegrass showed occasional small increases in their GAI in the agroforestry plots especially in summer. PAR intercepted by the pastures was reduced by between 2% and 39% in the agroforestry plots compared to the open plots; the least reductions occurred in summer and the most in spring (Table 3).

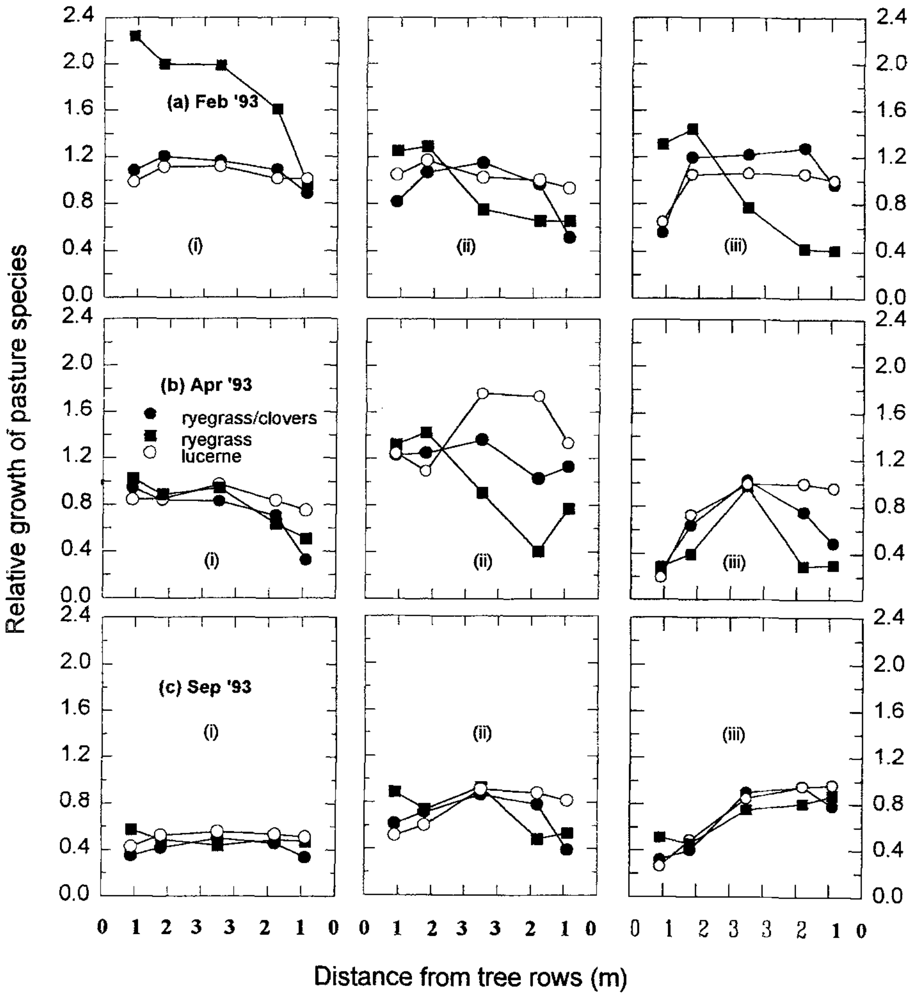

Fig. 1. The ratios of values for the pasture growth variables measured in the agroforestry plots to those measured in open pasture plots in (a) February (Summer), (b) April (Autumn), and (c) September (Spring) at Lincoln, New Zealand: (i) DM yields, (ii) GAI, and (iii) fraction of PAR intercepted. In all graphs the left hand side represents the south of the tree rows, and the right hand side north of tree rows.

3.3. *Effects of distance from tree rows on relative pasture growth*

In summer (February) (Fig. 1(a)(i)) the relative DM produced by the pastures in the agroforestry, compared to the open pastures, was equal to, or greater than, one at all positions in the transect between the tree rows. The highest value was produced by ryegrass at 0.9 mS. The relative GAI (Fig. 1(a)(ii)) was more than 1.6 at 0.9 mS and 1.8 mS for ryegrass, but was between 0.75 and 1.25 mS at other positions for all pasture species except for the value of 0.5 produced by ryegrass/clovers at 0.9 mN. The relative PAR intercepted by the pasture species was more than one for both ryegrass/clovers and lucerne, except at 0.9 mS; this value was less than one for in ryegrass at all positions except at 0.9 mS and 1.8 mS, where it averaged 1.25. In autumn (April) (Fig. 1(b)) the relative DM yields were generally less than unity especially in the southern half (north of the tree rows) of the transects. In contrast to relative DM, the relative GAI was generally more than one for all pasture species at all positions except for ryegrass in the southern half of the transect. The relative PAR intercepted was less than unity at all positions except at mid-transect for all pasture species, and for lucerne at both 0.9 mN and 1.8 mN. In spring (September) (Fig. 1(c)), when the sun was at low zenith angle, the relative DM was less than 0.6 for all pasture species at all positions. Similarly the relative GAI was less than unity at all positions for all pastures. The relative PAR intercepted by the pasture species in the agroforestry plots was around 0.4 at 0.9 mS and 0.18 mS, increasing to around one at mid-transect; in the southern half of the transect only lucerne had relative interception above one.

3.4. *Radiation use efficiency*

The tree dry weights presented in Table 1 were expressed as DM yield per land area and regressed on the PAR intercepted by the tree crowns during the one-year period (August 1992 to July 1993) (Fig. 2(a)). The slope shows that for every MJ m^{-2} of PAR intercepted, *Pinus radiata* trees produced 1.33 g of assimilates in their shoots. For the pastures, the DM produced and PAR intercepted at mid-transect (CT position) during four sampling intervals were used to determine RUE (g DM MJ^{-1} m^{2}) which was 1.83 for ryegrass/clovers, 1.49 for ryegrass and 2.34 for lucerne (Fig. 2(b)). Thus for every MJ of PAR intercepted lucerne produced at least 28% more DM than the other two pastures. These RUE values were used along with the DM yields (up to April) to estimate the quantity of PAR intercepted by the pasture species during the one-year period (July 92–June 93); PAR intercepted by the pasture species (Table 4) was highest for lucerne, which was 55% more than that for ryegrass.

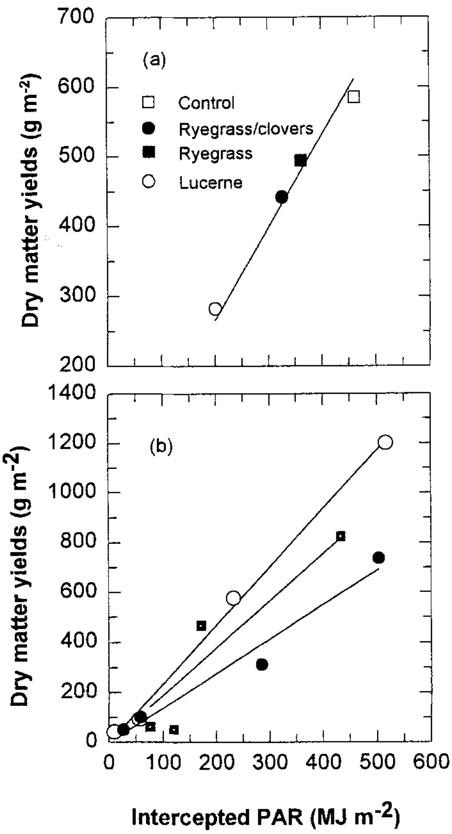

Fig. 2. The relationships between dry matter yields and photosynthetically active radiation (PAR) intercepted by (a) the pine trees and (b) the pastures species. The regressions were forced through the origin and the equations are:

Radiata pine:	$y = 1.34x$	$r^2 = 0.997$
Ryegrass/clovers:	$y = 1.83x$	$r^2 = 0.969$
Ryegrass:	$y = 1.59x$	$r^2 = 0.886$
Lucerne:	$y = 2.34x$	$r^2 = 0.997$

3.5. *Total radiation use, water use, radiation and waster use efficiency, and land equivalent ratio*

The combined total PAR intercepted by the pasture species and the pine trees (from part 1, Table 2) were 481, 1006, 804 and 920 MJ M^{-2} respectively in the control, ryegrass/clovers, ryegrass and lucerne ground covers; thus total PAR intercepted by the control was less than half that by ryegrass/clovers ground over. Of the combined total PAR intercepted, the trees accounted for 100% in control, compared to 42% in ryegrass ground cover and only 22% in lucerne ground cover (Table 4).

Table 4. The total PAR intercepted by the pastures and partitioning of evapotranspiration in the agroforestry plots (ET) between the pastures (E_p) and pine trees (Et) during the 1992/93 growing season.

Ground covers	PAR intercepted (MJ m^{-2})[a]		E_p (mm)	Et (mm)[b]	Et/ET[a]
	Pastures	Trees/Total			
Control[c]	na	1.00	na	295	0.55
Ryegrass/clovers	680	0.32	395	210	0.34
Ryegrass	464	0.42	260	249	0.44
Lucerne	720	0.22	410	153	0.24

[a] Both PAR intercepted by the tree and total evapotranspirtation (ET) were taken from Table 2 (part 1, Yunusa et al. [1995]).
[b] For ryegrass, Et was estimated from the tree DM yield and mean tree WUE for the other ground covers.
[c] Data not applicable.

The determination of *k* for the pasture species is presented in Fig. 3; the values were 4.8 Pa for lucerne, 3.6 Pa for ryegrass/clovers and 2.8 Pa for ryegrass. This indicated that lucerne produced more DM per unit of water used than the other pastures. Transpiration by the pastures (E_p) (Table 4) was highest for lucerne pasture, which was only 4% greater than that for ryegrass/clovers, but 58% greater than that for ryegrass. By contrast to E_p, transpiration by the tree (Et) was 295 mm for control which was almost double that for lucerne ground cover. The trees accounted for 55% of the ET in the control, compared to only 24% in lucerne (Table 4).

A regression of the tree DM against E_t data pooled from all the ground covers produced a linear relationship (Fig. 4). The slope gave a mean transpiration efficiency (TE) of 24.5 kg ha^{-1} mm^{-1} for radiata pine. When the regression was repeated, but with the E_t divided by VPD, the slope produced a *k* value of 2.3 Pa for radiata pine. The ratio of total DM produced by the pastures (up to April) to E_p, gave TE of 41.1 kg ha^{-1} mm^{-1} for lucerne, which was 37% higher than that for ryegrass/clovers (30.0 kg ha^{-1} mm^{-1}) and 78% higher than that for ryegrass (23.3 kg ha^{-1} mm^{-1}).

The combined DM yields by both the trees and pasture species in the various ground cover treatments (Table 5) were highest for lucerne which produced 22% more yield than ryegrass/clovers, 82% more than ryegrass and more than three times than control ground covers. The RUE for the combined tree and pasture DM yield was highest in lucerne ground cover (Table 5), which produced 33% more DM for every MJ PAR intercepted than ryegrass/clovers and 59% more than ryegrasss ground covers. RUE was lowest in the control which had no pasture component. When the combined DM yields were expressed per unit of ET, water use efficiency (WUE) was in the following order: lucerne > ryegrass/clovers > ryegrass > control (Table 5). The LER was highest for ryegrass ground cover, which was 14% more than that for ryegrass/

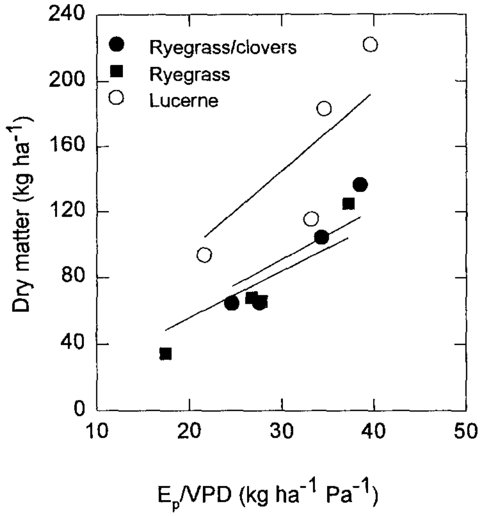

Fig. 3. The relationships between dry matter produced by the pastures and the ratios of E_p: vapour pressure deficits (VPD). The regressions were forced through the origin and the slopes give the values for k (Eq. (2)); the equations are:

Ryegrass/clovers:	$y = 3.63x$	$r^2 = 0.948$
Ryegrass:	$y = 2.80x$	$r^2 = 0.956$
Lucerne:	$y = 4.84x$	$r^2 = 0.750$

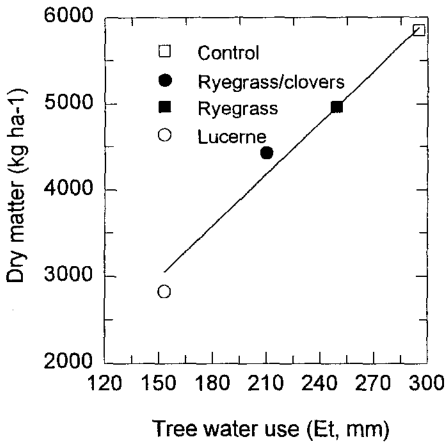

Fig. 4. The relationship between dry matter produced and water used by the pine trees during a one year period. The regression was forced through the origin:
$y = 0.0245$ x $\qquad r^2 = 0.95$

Table 5. Total dry matter (DM), radiation use efficiency (RUE), water use efficiency (WUE) and land equivalent ratio (LER) for main agroforestry plots during the period July 1992 to June 1993, at Lincoln, New Zealand.

Ground covers	Total DM ($t\ ha^{-1}$	RUE ($g\ DM\ MJ^{-1}\ m^{-2}$)	WUE ($kg\ DM\ ha^{-1}\ mm^{-1}$)	LER
Control	5.85	1.32	10.5	na
Ryegrass/clovers	16.29	1.62	26.1	1.71
Ryegrass	10.89	1.32	19.3	1.95
Lucerne	19.86	2.15	31.1	1.45
SED	1.093	–	–	0.088

na = data not applicable.

clovers and 34% more than for lucerne. Thus all the pasture ground covers increased the productivity of the land compared to the control (Table 5).

3.6. *Plant water potential and stomatal resistance*

For brevity, only the data taken on 6 April 1993, when the plants were most stressed, are presented here (Table 6). The water potential in the pine fascicle was reduced by 70% in the lucerne ground cover compared to the control. The lucerne plants were generally more stressed in the agroforestry plots than they were in the open pastures; the leaf potential was reduced by 28%, whereas stomatal resistance was increased by 80%, in the agroforestry plots compared to the open pastures. The leaf temperature for lucerne was similar in both the agroforestry and open pasture plots (Table 6). In the transect between tree rows, the plants were more stressed in the southern half (north of tree rows) than they were in the northern half (Fig. 5). The large SE for the stomatal resistance at 0.9 mN was a result of the large different between the adaxial (526 $s\ m^{-1}$) and abaxial (1323) surfaces of the leaf. The leaf temperature for

Table 6. Plant water potential for lucerne and pine trees, and stomatal resistance and leaf temperature for lucerne, measured at mid-day on 6 April 1993 at Lincoln, New Zealand.

Treatments	Water potential[a] (MPa)	Stomatal resistance ($s\ m^{-1}$)[a]			Leaf temperature (°C)
		Adaxial	Abaxial	Mean	
Pine trees					
Control	−1.43 (0.213)	na	na	na	na
Lucerne ground cover	−2.43 (0.332)	na	na	na	na
Lucerne					
Open pasture plots	−1.56 (0.124)	250 (28.1)	201 (45.8)	226 (26.6)	25.2 (0.71)
Agroforestry plots	−2.00 (0.319)	381 (49.3)	432 (45.8)	407 (31.9)	24.3 (0.63)

[a] Numerals in parentheses are SE of means.
na = data not available.

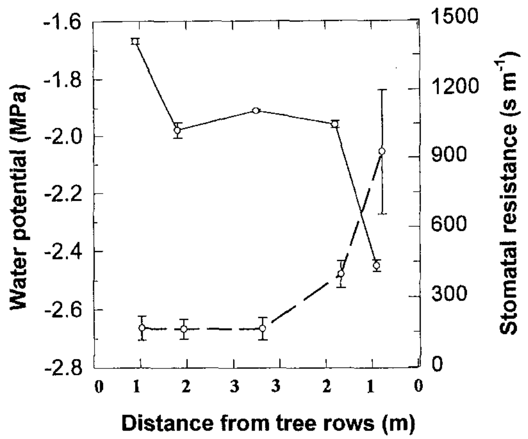

Fig. 5. Plant water potential (solid curve) and stomatal resistance (dashed curve) for lucerne pasture in the agroforestry plots measured at mid-day on 6 April 1993. Graph orientation as in Fig. 1.

lucerne in the northern half averaged 23.1 °C compared to the southern half where it was 24.8 °C at 1.8 mN and 26.3 °C at 0.9 mN.

4. Discussion

4.1. *Effects of trees on pasture growth*

To evaluate the effects of tree rows on the performance of the pasture species in the agroforestry plots, pasture growth between the tree rows should be related to that observed in the open. Most of the adverse effects of 2-to-3-year-old pine trees on the pasture species were due to direct above-ground interactions rather than to competition for soil moisture. Interception of rainfall and PAR by the tree reduced the availability of both soil moisture and energy to the pasture understorey. If trees imposed severe direct competition for soil moisture on the pastures, this would be most apparent in the pasture yields measured in April (autumn), when soil moisture storage was lowest [Yunusa et al., 1995]. However, most reductions in the pasture yields in the agroforestry plots in autumn were marginal – averaging 16% for ryegrass/clovers and lucerne (Table 2), and occurred mostly at positions in the southern half of the transect (north of tree rows) (Fig. 1). These positions of low yields were located in the rainshadow where interception of precipitation by the tree crown was highest (see Fig. 3 [Yunusa et al., 1995]), and is consistent with the low water potential and high stomatal resistance in the lucerne pastures at 0.9 mN (Fig. 5).

The trees also interfered with pasture growth by intercepting a good fraction of the incident radiant energy, especially in early spring when, due to the low solar angle, most of the transect was shaded [Yunusa et al., 1995]. For instance, while GAI for the pasture species in the agroforestry plots was reduced by only 7%, the fraction of PAR intercepted fell by 30%, compared to the open plots (Table 3). This led to reductions of about 50% in the DM produced by the pasture species in agroforestry plots compared to the open plots (Table 2). However, in summer (February), when solar angle was high, the adverse effect of tree shade on pasture growth was limited to positions to the immediate south of the tree rows, where the relative DM yields were reduced in lucerne and ryegrass/clovers (Fig. 1(a)); ryegrass, by being shade tolerant [Blackman, 1938], did not suffer yield reductions at this section.

Further evidence that the trees imposed limited water stress, through competition, on the pasture species is given by the water relations for lucerne during periods of low soil moisture storage in autumn (April). The lucerne leaf water potential of −1.67 MPa at 0.9 mS (Fig. 5) was significantly higher than −2.0 MPa at mid-transect and similar to −1.56 MPa in the open pastures (Table 5). Therefore, the possibility of water stress being the cause of the relatively low pasture yields at this position, due to proximity to tree rows, could be discounted. Also, despite the increase in the stomatal resistance in the agroforestry plots, lucerne yield was only marginally reduced in the agroforestry plots (Table 2 and Fig. 1). Although, no water relations data were obtained for the other pasture species, their yield response in autumn was similar to that of lucerne (Fig. 1); their smaller relative yields in the southern half of the transect were consistent with their shallow root systems compared to the lucerne as indicated by the depths of extraction of soil moisture [Yunusa et al., 1995].

Reasons for the increase in the yields of the pasture species, particularly ryegrass, during summer (Table 2) are not quite clear, but a similar trend was observed in a related study in which the accumulation of DM by the pastures species was higher in the agroforestry plots than in the open plots between cutting intervals [Pollock et al., 1994]. Since wind speeds could be reduced by as much as 75% in agroforestry systems [Hawke and Wedderburn, 1994; Monteith et al., 1991]; it was possible that in the present study the calmer conditions in the transects reduced the adverse mechanical and physiological effects of strong winds on the pasture plants. Wind runs of 294 km day^{-1} were found to damage leaves and reduce photosynthesis by as much as 50% in tall fescue (*Festuca arundinacea*) [Grace and Thomson, 1973]. Other factors that could have contributed to the increased yields in the agroforestry plots may include improved stomatal conductance and gas exchange [Caldwell, 1970; Grace, 1981], during this period when soil moisture was still readily available [Yunusa et al., 1995].

The determination of k (Fig. 3) and RUE (Fig. 2(b)) for the pasture species allowed us to quantify the water used and PAR intercepted by the species in the agroforestry plots. The yields of the pasture species in the agroforestry plots were proportional to the fractions of ET and PAR used by these species during the one-year period (Table 4). However, the differences in yields between the pasture species were also associated with their k and RUE. Although the total E_p (Table 4) for ryegrass/clovers was only 96%, and intercepted PAR 94%, of that for lucerne, the latter's yield (up to April) was only 70% that of the former. The k of 2.8 for ryegrass is within the range reported for several temperate cereals [Gregory et al., 1992; Yunusa et al., 1993], while 4.8 Pa for lucerne is similar to that calculated for this crop [Tanner and Sinclair, 1983]. However, the use of k in this type of analysis should be approached with caution, since the foliage and air temperatures may not always be at par, especially during periods of stress. In the present study, the maximum difference between the ambient and leaf temperatures was less than 1.5 °C even at the peak of stress when the data in Table 6 were measured.

The main conclusion drawn from the growth of understorey species is that the pasture species used in this study were less susceptible to the adverse effects of competition for soil moisture with radiata pine than they were to shading by the tree crowns. The adverse effects of shading on pasture growth between widely spaced (6.7 × 1.3 m) four-year-old pine trees have been reported in the northern hemisphere (31°00′ N, 95°45′ W) [Ziehm et al., 1992]. Our conclusion is also consistent with that reached in the study of a 15-year-old pine-clover agroforestry system in a medium rainfall district of Western Australia (31°57′ S, 115°52′ E) [Anderson and Batini, 1979].

4.2. *Tree growth over pasture ground covers*

In contrast to the reductions in pasture yields that were associated with above-ground interactions, reductions in the growth of trees in the pasture ground covers were a result of underground competition for soil moisture. The tree, by its morphology, always had the first call on the incoming solar radiation [Yunusa et al., 1995], and, therefore, was not subjected to competition for PAR with the pastures species. The 70% fall in water potential for the trees in the lucerne ground cover compared to those in the control in autumn (Table 6) showed that the trees were stressed in the pasture ground covers. Needle growth was reported to cease once predawn needle water potential fell to −1.5 MPa [Sands and Correll, 1976]. Our unpublished data showed predawn fascicle water potential to range between −2.0 to −1.5 MPa when the midday water potential was around the −2.5 MPa found in the present study (Table 5). Several other studies have attributed reduced photosynthesis and biomass yields in radiata pine to adverse water relations [Linder et al., 1987; Whitehead, 1985].

Hence, it is concluded that the reduced DM yields by the trees in the pasture ground covers (Table 1) were the result of competition for soil moisture with the pasture species. Furthermore, the large differences in tree weights between pasture ground covers (Table 1) reflected, to almost the same degree, the differences in the fractions of water and radiation used by the trees (Table 4).

4.3. *Overall dry matter yield, WUE, RUE and LER*

The advantage of the agroforestry plots, in terms of total DM yields (Table 5), was a result of the greater quantities of resources used in these plots compared to the sole plots of control and open pastures. Only 55% of the total ET in the control was due to Et (Table 4), suggesting that almost half of the water used in this treatment was wasted through evaporation from the exposed soil surfaces and transpiration by the occasional weeds that infested the plots. Similarly, only 29% of the total incident PAR was intercepted by the trees in the control [Yunusa et al., 1995]. The amounts of resource used in the agroforestry plots were also greater than those in the open pastures. To provide initial comparisons in the resource use between the sole and agroforestry plots, approximations of water use and PAR intercepted by the pasture species in the open plots could be made from their DM yields using the appropriate *k* and RUE values. Using equation (1) and assuming 8% soil evaporation for lucerne and 10% for the other two pastures, ET in the open pastures could be about 316 mm for ryegrass/clovers, 244 mm for ryegrass and 449 mm for lucerne; these values were 51%, 43%, and 71% of the total ET from respective agroforestry ground covers during the 1992/93 growing season. Also, using the RUE (Fig. 2(b)) and total DM yields (Table 2), approximates PAR intercepted (MJ M^{-2}) by pasture species in the open plots as 670 for ryegrass/clovers, 367 for ryegrass and 744 for lucerne; these were 67%, 46% and 81% of the combined PAR intercepted by both the trees and pasture species in the corresponding agroforestry ground covers.

The advantage of agroforestry in terms of yield outputs is evident in the high LER produced (Table 5). These LER values indicated that to produce in separate plots of trees and pastures the equivalent yields obtained in the agroforestry plots would require increases in the land area of between 45 and 95%. That the ryegrass ground cover produced the highest LER is consistent with the poor yields of this pasture species in the open plots, which cover the one-year period was only 5.5 t ha^{-1} (Table 2). Although the use of LER is yet to a gain wide adoption in agroforestry studies, the values obtained in this study are far higher than those reported for field crop mixtures which are often between less unity and 1.20 [Fisher et al., 1987; Yunusa, 1989].

5. Summary and conclusions

In the third year of growing trees over pastures, an inverse relationship between pasture DM yield and tree growth was observed during a one-year period. Reductions in tree growth was highest for lucerne ground cover (52%) which produced the most pasture yields (17 t ha^{-1}), and lowest for ryegrass ground cover (14%) which yielded the least pasture DM (6 t). Over the same period, total yields for the pasture species in the agroforestry plots were reduced by an average of 3.5% in lucerne and ryegrass/clovers species compared to their yields in the open plots; whereas ryegrass species did not suffer any yield reduction in the agroforestry plots. DM reductions in the trees in the pasture ground covers were associated with water stress arising from competition for soil moisture with the understorey species. Reductions in the yields of pasture species occurred in spring when the transect was shaded, and to a lesser extend in autumn due to the effects of rainshadow to the immediate north of the tree rows. However, during the windy summer, the shelter provided by the trees marginally increased the yields of the pasture species in the agroforestry plots, especially in ryegrass where understorey yield was doubled. The total combined yields by the trees and the pastures in the agroforestry were greater than the individual yields of the trees and pasture species grown separately. Agroforestry, therefore, increased the productivity of the land by between 51 and 95%.

These results also showed that at age 2–3 years radiata pine is a weak competitor for soil moisture when grown in association with pastures. At this stage, therefore, underground competition is more critical for pine growth than aboveground interactions. The trees accounted for less than 60% of the total ET and PAR intercepted in the agroforestry plots over a one-year period. Controlling pasture growth along tree rows up to drip line, i.e. effective rooting zone for the pine [Clinton and Mead, 1990], either by heavy grazing or use of herbicide in summer should reduce the competitive pressure for soil moisture on the pine in late spring and autumn. This measure would not be necessary in spring, when moisture supply is abundant and if not used could be lost through evaporation and/or drainage. In contrast to trees, the pasture species appeared to have an advantage over the pine in competing for soil moisture, but the former were disadvantaged by their morphology in capturing solar energy. To promote pasture growth in spring would involve pruning the trees at the end of winter to increase transmission of solar radiation to the understorey during the following spring.

Acknowledgements

We thank Dr David Whitehead for helpful suggestions during the preparation of this and the preceding papers, and Dr Karl Sommer and Jenny Guy for going through the manuscripts. George Love, Phillipa Masters and Ayalsew Alemayehu are acknowledged for their assistance with statistical analysis. We also thank the anonymous referees for their helpful comments.

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