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# Process studies in a *Pinus radiata*–pasture agroforestry system in a subhumid temperate environment. I. Water use and light interception in the third year

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**Abstract.** In this study we determined soil moisture storage, evapotranspiration (ET) and light interception in an agroforestry trial consisting of pine trees grown over (1) control (bare ground), (2) ryegrass/clovers (*Lolium perene/Trifolium* spp.), (3) lucerne (*Medicago sativa*), and (4) ryegrass only during the third growing season between 1992 and 1993. The results show that:

1. In the period when rainfall was frequent and exceeded the evaporative demand ($E_{pot}$), ET and depletion of soil moisture were not affected by the ground cover treatments. During summer when rainfall was less frequent, but with moisture readily available in the soil profile, ET was associated with plant canopy, and was significantly higher for the pasture ground covers than for the control. Therefore, the more rapid growth by lucerne caused higher ET in this ground cover than in the ryegrass/clovers ground cover in which the pasture was slow growing. At the end of the study period, total ET was in the following order: lucerne (757 mm) > ryegrass/clovers (729 mm) > Control (618 mm).
2. ET was dominated by pasture transpiration ($E_p$) during most of the growing season, but by tree transpiration ($E_t$) in winter when large parts of the pasture canopy was shaded. $E_p$ was always at least 16% higher for lucerne than for ryegrass/clovers species as a result of a greater radiation intercepted by the former.
3. Fraction of incoming radiation intercepted by the tree crowns was in the following order: control > ryegrass > ryegrass/clovers > lucerne. At the end of the one-year period, fraction of intercepted radiation was 140% greater for control than for lucerne ground cover.
4. The control produced the largest tree crowns, which were almost twice the tree crowns in the lucerne ground cover which produced the smallest trees. Accordingly, the trees in the control intercepted more radiation and rainfall, with the former being lost to evaporation, than the trees in the pasture.
5. The fractions of radiation intercepted and ET accounted for by the trees and pastures were associated with the proportion of the plot area they occupied.

## Nomenclature

| | | |
|---|---|---|
| $E_p$ | = | transpiration through the pasture canopies (mm) |
| $E_{pot}$ | = | potential evapotranspiration using Penman equation (mm) |
| $E_{PT}$ | = | potential evaportranspiration using Priestley-Taylor equation (mm) |
| ET | = | evaportranspiration from the agroforestry plots (mm) |
| Et | = | transpiration through the radiata pine canopies (mm) |
| PAR | = | photosynthetically active radiation (400 to 700 nm) |
| Q | = | fractions of incident radiation intercepted by the pasture canopies ($Q_p$) soil surface ($Q_s$) and tree crowns ($Q_t$) |
| *S* | = | moistured stored in the soil profile (mm) |

## 1. Introduction

In New Zealand, widely spaced trees are being planted into pastures as a means of diversification and to provide shelter for livestock. This has led to the establishment of several agroforestry trials to evaluate the silvopastoral systems, and these have provided insights in to the socioeconomic benefits and gross biological yields of this mixed cropping system [Knowles et al., 1992; Mead et al., 1993]. However, information on the plant biological processes associated with the increased biomass yields of trees and perennial pastures grown together is still limited [Clinton and Mead, 1990].

The principal aim of agroforestry systems, like mixed cropping, is to increase the plants' capture of the biophysical resources, principally soil moisture, solar radiation and nutrients. The relationship between these factors and plant yield is often represented as [Ong, 1990]:

$$\text{yield} = cF \tag{1}$$

where $c$ is a plant constant, which is a measure of the efficiency with which the biophysical resource is used by the plant to produce yield, and $F$ is the quantity of the resource used. However, the presence of two or more species on the same piece of land reduces the quantities of the resources available to each of the component species. Since agroforestry often contains species of vastly different morphology, interference both above and below the soil surface can be intense. The above-ground interference entails mainly the interception of radiant energy and rainfall by the trees, whose presence also modifies the microclimate such as wind speed and rainfall distribution in the agroforestry stand [Hawk and Wedderbum, 1994; Monteith et al., 1991].

Interception of rainfall by the trees would be expected to reduce the supply of soil moisture to the accompanying understorey species which benefit little from any possible stem flows down the trees. Where rainfall is accompanied by winds, rainfall interception by the trees may create a 'rainshadow', where little rainfall reaches the soil surface, on the leeward side of the trees and a wet 'drip zone' on the windward side, where most interception and subsequent dripping of rainfall occur. This phenomenon may modify the distribution of soil moisture between the tree rows and underground competition for water. Thus, above-ground interactions may have strong impact on subterranean processes.

Previous studies [Eastham and Rose, 1985; Whitehead et al., 1994b] have shown that a significant fraction of evapotranspiration (ET) from agroforestry is accounted for by transpiration from the understorey in proportion to the fraction of solar energy transmitted through the tree crowns [Black and Kelliher, 1989; Eastham and Rose, 1988; Whithead et al., 1994b]. Where trees are widely spaced, this transpiration may constitute at least half of the total ET from the forest stand [Whitehead et al., 1994b]. However, the dependence of understorey transpiration on solar radiation will be to the extent that soil moisture is not in limited supply. Furthermore, since nutrient uptake by the plant is dependent on availability of soil moisture [Chinton and Mead, 1990; Ong, 1990], it then follows that variability in the yields of the component species in mixed communities could be explained, to a large extent, by the partitioning of ET between overstorey and understorey species.

In the present study we evaluated water use, light interception and biomass yields of an agroforestry system consisting of widely spaced trees of *Pinus radiata* associated with several pasture species. In part one (this paper), we present data on the interception of radiation and water use by the trees and pastures. In part two, the following paper [Yunusa et al., 1995], the productivity of the various tree-pasture combinations is analysed on the basis of water use and light interception.

## 2. Materials and methods

### 2.1. *Site*

This study was conducted between July 1992 and September 1993 in an agroforestry trial located about 2 km from Lincoln (43°38′ S, 172°30′ E; 11 m altitude) in the South Island of New Zealand. The climate is temperate subhumid with cold winters (June, July, August) when daily temperature averages 10.1 °C and frosts are common. The summer months (December, January, February) are warm with daily mean temperatures around 27 °C. Autumn and spring are generally mild. Annual rainfall averages 700 mm and is fairly uniformly distributed throughout the year, but with a tendency towards a slight maximum in winter. Table 1 shows that the winter of 1992 was cooler than normal. The winter experienced several snow falls in June and September, the heaviest being 60 mm in late September. However, the winter of 1993 was generally warmer and drier than usual, except for August when 10 mm snow fell, and the occurrence of several frosty nights. The intervening summer period between the two winters was cooler than normal, and autumn (March, April and May) was also cooler and wetter than usual. Rainfall and evaporation for spring (September, October and November) were close to normal.

The soil is silt loam locally referred to as Templeton Silt Loam; it is free draining with moderate water-holding capacity, and hardens when dry. The profile consists of 1 to 2 m of fine alluvial sediments with the thickness determined by the depths of the underlying stones and gravels [Kear et al., 1967]. The depth of the gravel at the trial site ranges between 0.9 and 1.6 m. The nutrient levels are high and the soil is considered the most productive in the region. Prior to the establishment of the agroforestry, the land was under peas (*Pisum sativa*).

*Table 1.* Summary of some key weather variables during the study period in 1992/93 at Lincoln, New Zealand.[a]

| Months | Temperatures (°C) | | No. of frost days | Precipitation (mm) | Potential evaporation (mm) |
|---|---|---|---|---|---|
| | Min. | Max. | | | |
| July | 2.5 (1.4) | 11.3 (10.1) | 12 (10) | 63 (68) | 39 (38) |
| August | 2.2 (2.7) | 9.8 (11.4) | 11 (7) | 167 (162) | 39 (38) |
| September | 3.3 (4.6) | 10.6 (14.2) | 9 (3) | 74 (47) | 51 (72) |
| October | 6.6 (6.7) | 14.5 (116.8) | 2 (1) | 81 (49) | 106 (103) |
| November | 9.2 (8.1) | 18.5 (18.8) | 0 (0) | 46 (53) | 119 (120) |
| December | 9.6 (10.4) | 18.2 (20.4) | 0 (0) | 55 (57) | 130 (132) |
| January | 10.0 (11.5) | 21.0 (21.3) | 0 (0) | 61 (60) | 149 (137) |
| February | 10.1 (11.5) | 20.2 (21.3) | 1 (0) | 44 (54) | 113 (116) |
| March | 8.4 (9.8) | 18.2 (20.1) | 1 (1) | 63 (56) | 88 (108) |
| April | 6.3 (7.4) | 15.4 (16.7) | 3 (1) | 72 (56) | 55 (63) |
| May | 4.2 (4.2) | 13.7 (13.3) | 7 (4) | 92 (71) | 37 (44) |
| June | 3.4 (1.9) | 13.2 (10.7) | 10 (9) | 46 (61) | 31 (34) |
| July | 0.7 (1.4) | 11.4 (10.1) | 15 (10) | 14 (68) | 25 (38) |
| August | 0.6 (2.7) | 11.3 (11.4) | 17 (7) | 17 (62) | 47 (51) |
| September | 8.5 (4.6) | 12.9 (14.2) | 6 (3) | 133 (47) | 64 (72) |

[a] *Source:* Climate Research Unit, Lincoln University, New Zealand; numerals in parentheses are long-term averages.

## 2.2. *Treatments and experimental design*

The treatments used here formed part of a large trial described in detail by Mead et al. (1993). Briefly, pine seedlings, raised from either seeds or tissue culture, were planted in July 1990 at $7.0 \times 1.4$ m spacing (1,000 stems $ha^{-1}$) into six ground covers consisting of pasture species and bare ground plots of $42 \times 46.2$ $m^2$. To aid tree establishment in the pasture ground covers, 1 m wide strips were carefully sprayed with a hexazinone and glyphosate herbicides. For the study reported here only trees raised from seeds and the following four ground covers were used:

1. Control, no pasture understorey, i.e. bare ground.
2. Ryegrass (*Lolium perenne*)/clovers (*Trifolium ripens* and *T. pretense*) mixture.
3. Lucerne (*Medicago sativa*).
4. Ryegrass (*L. perenne*) alone.

These ground covers, which were replicated three times in a randomized complete block design, formed the main treatments. There were seven sub-treatments based on the positions in the transect, between two rows of trees, from which measurements were made:

1. 0.9 m south of trees rows (0.9 mS);
2. 1.8 m south of tree rows (1.8 mS);

3. midway (3.5 m) between the tree rows (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);
6. *in-row*, point of measurements within the rows of trees.

These positions are indicated in Fig. 1.

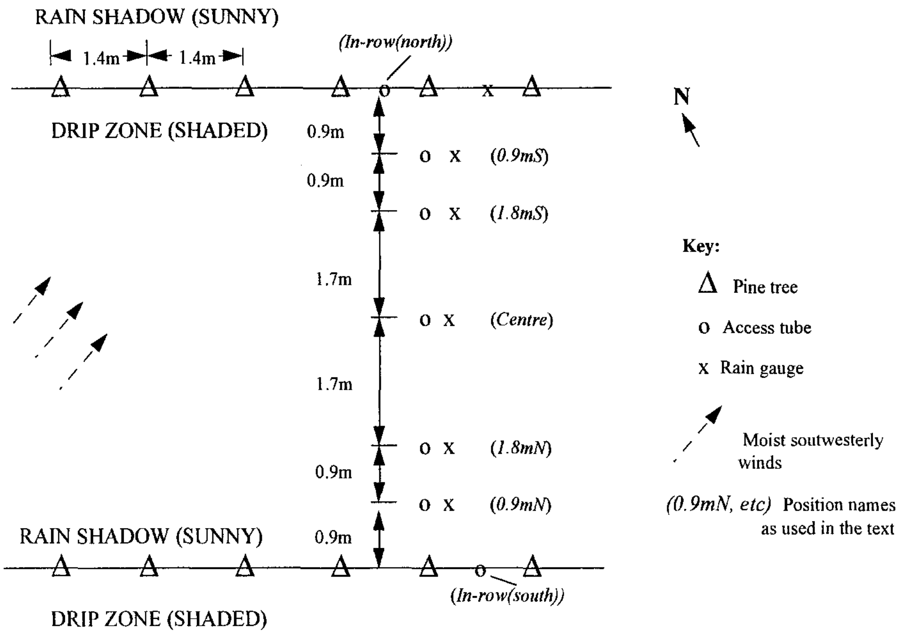


*Fig. 1.* Section of a plot showing the positions of rain gauges and neutron probe access tubes. The rainshadow zone to the north of tree rows was mostly exposed to direct solar radiation, while the wet drip zone was mostly shaded by the trees.

## 2.3. *Measurements and observations*

### 2.3.1. *Tree crown characteristics*

Diameter at breast height (DBH) and tree height were measured in July 1992, and in February and July 1993. In July 1993, the drip areas of four trees (adjacent to the access tubes for monitoring soil moisture, described below) were determined. This was achieved by measuring the maximum radii of the crown from the trunk in all the four cardinal compass directions. The mean radius was used to calculate the area. Crown volume was estimated from tree height and crown area by assuming a cone shape.

### 2.3.2. *Light interception*

The fraction of photosynthetically active radiation (PAR) transmitted through the tree crowns and reaching the surfaces of the soil or pasture canopies in the transects was measured using a combination of a 0.9 m linear (Li-COR Inc., Nebraska, USA) and a 15 mm diameter point (ES, Delta Devices, UK) quantum sensors. The measurements were made around midday at least once a month commencing from January 1993. The point sensor was used to measure the incoming radiation ($Q_0$); this sensor was placed on a 2 m pole so that it was fully exposed to direct sunlight. The linear sensor was used to measure radiation above ($Q_1$) and beneath ($Q_2$) pasture canopy at 0.9 mN, 1.8 mN, 3.5 m, 1.8 mS and 0.9 mS. In the control only $Q_0$ and $Q_2$ at the soil surface were measured. At each position the sensor was oriented parallel and longitudinally to the tree row, and four measurements were taken by shifting the sensor in an east-west direction to cover most of the length of the subplots. From June 1993 a ceptometer (Delta T Devices, UK) was used for these measurements. In this case $Q_0$ was taken in the sections of the plots that were directly exposed to full sunlight, before measurements of $Q_1$ and $Q_2$ were made. The fractions of incident PAR intercepted by the canopies were calculated as:

$$\text{pine crowns } (Q_t): \quad = \quad Q_0 - Q_1 \tag{2a}$$

$$\text{pasture canopies: } (Q_p): \quad = \quad Q_1 - Q_2 \tag{2b}$$

The $Q_t$ for the period between August and December 1992 was obtained using the following steps:

1. Mean monthly ratios of $Q_t$: tree heights were determined for each ground cover between January and June.
2. Two level polynomial regressions were fitted into the tree height data for each ground cover to predict the heights in the months of August to January; two stage regressions were used because height increments were greater between July and February than between February and July, consistent with the seasonal growth pattern of radiata pine [Whitehead et al., 1994a].
3. The ratios obtained in (1) were used to predict $Q_t$ based on the predicted tree height (2). In this case the $Q_t$ for September and October was estimated with the ratios obtained in March, and for November and December with ratios in February; this was in conformity with the month groupings given by Grace et al., 1987. Associating $Q_t$ with tree height and solar angle is commonly used in modelling light interception by rows of perrennial woody plants [Palmer and Jackson, 1977].

The $Q_t$ was used to determine the quantity of photosynthetically active radiation (PAR) intercepted by the tree crowns. PAR was taken to constitute half of the incident shortwave radiation [Monteith and Unsworth, 1990] which was measured at a nearby weather station.

2.3.3. *Precipitation and its interception*

Rain and snow falls during the study period were determined using a combination of the following:

1. Between July 1992 and February 1993 precipitation was recorded at a weather station about 1 km from the trial site.
2. Between February and October 1993 precipitation was measured with rain gauges at the six positions (see Fig. 1) in all the tree control plots. Three rain gauges were also positioned in the open to provide measurements of gross precipitation. Precipitation for each position was regressed on the gross precipitation, and the relationship was used to determine the rainfall at the various positions prior to February 1993.
3. Precipitation for the pasture ground covers was estimated assuming that, as a general rule, interception of precipitation was proportional to the size of the tree crowns [Gash, 1979]. Therefore:

$$i/tc = i'/tc' \tag{3}$$

where $i$ is the difference between the gross precipitation and that measured in the agroforestry, i.e. rainfall intercepted, and $tc$ is tree crown volume for the control treatment; these parameters are denoted by $i'$ and $tc'$ in the pasture ground cover treatments.

2.3.4. *Soil moisture*

Aluminium access tubes were installed to depths of 0.9 m in October 1991 to determine soil moisture storage ($S$) in all ground covers, except ryegrass due to limited resources. In each plot, tubes were installed at each of the seven positions (Fig. 1). All tubes were monitored with a neutron moisture meter (Troxler 4300) from 0.2 m to 0.9 m depths at increments of 0.1 m. $S$ in the top 0.2 m of the profile was measured with a Time Domain Reflectometry (TDR) for which 0.2 m rods were installed. These measurements were made at fortnightly intervals during most of the study period except during periods of low plant growth (May to September) when they were made once a month.

In February 1993, tubes at 0.9 mS, 0.9 mN and *In-row* (*south*) in the control were replaced with 2.0 m deep tubes to enable determination of $S$ at depths below 0.9 m. For the pasture ground covers, tubes at 0.9 mS, centre and 0.9 mN were similarly replaced. These deep tubes provided data which were used to correct $S$ below 0.9 m depth for the remaining shallow tubes. This approach was not expected to introduce major errors at this stage of the trial, since, in this soil, exploration by plant roots could be confined mainly to the top 1 m of the profile during growing seasons [Jamieson, 1985; Santantonio and Santantonio, 1987; Whitehead et al., 1994b].

2.3.5. *Evapotranspiration (ET)*
ET in the absence of surface run-off and through-drainage was calculated as:

$$ET = P - i - \Delta S \tag{4}$$

where P is precipitation, $i$ is rainfall intercepted (Eq. (3)) and $\Delta S$ is change in moisture storage.

Between July and September 1992 following a heavy snow fall, substantial drainage occurred below 0.9 m depth which could not be quantified with the shallow tubes available then. For this period, ET in all groundcovers was taken to equal potential evapotranspiration ($E_{pot}$) on account of frequent rainfall and low evaporative demand [Denmead and Shaw, 1962]. $E_{pot}$ was calculated using the Penman equation [Monteith and Unsworth, 1990] from the data recorded at a nearby weather station.

Transpiration by the pasture ($E_p$) was determined for short periods of contrasting evaporative demands, mainly when soil moisture was not limiting ET (when ET > 0.80 $E_{pot}$). On the basis of pasture water use being primarily dependent on radiation reaching its canopy [Black and Kelliher, 1989; Eastham and Rose, 1988; Whitehead et al., 1994b], the equation of Priestley and Taylor [1972], found to apply well to field crops in this environment [Jamieson, 1985], was used to determine the potential pasture transpiration beneath the overstorey ($E_{pp}$):

$$E_{pp} = 1.26 \frac{s}{s+g} (Rn - G)(1 - Q_t) \tag{5}$$

in which $s$ is the slope of saturation vapour pressure – temperature curve, $g$ is the psychometric constant (kPa), Rn is net radiation (W $m^{-2}$), G is soil heat flux (W $m^{-2}$), and $(1 - Q_t)$ is the fraction of radiation transmitted through the tree crowns. The use of $(1 - Q_t)$ assumes that the fraction of Rn transmitted was proportional to that for the PAR; this assumption was expected to hold under the young widely spaced tree rows in this study. Rn was obtained from the nearby weather station, while $G$ was considered negligible due to pasture cover. $E_p$ was calculated as:

$$E_p = E_{pp}(Q_p) \qquad \text{when ET} > 0.80\ E_{pot} \tag{6a}$$

$$E_p = ET(Q_p) \qquad \text{when ET} < 0.8\ E_{pot} \tag{6b}$$

An equation similar to (6a) was used previously to estimate transpiration in legumes [Singh and Sri Rama, 1989] and cereals [Yunusa et al., 1994] when soil moisture was not limiting. This equation was also used to estimate soil evaporation ($E_s$), but by scaling Rn with $Q_2$. Between late March and May, Eq. (6b) was used for both $E_p$ and $E_s$, but an upper limit of 0.1 × ET was imposed on $E_s$ during this dry period; this approach is similar to that used to estimate $E_s$ by Cooper et al. [1983].

The use of $Q_p$ in Eq. (6a) may suggest overestimation of $E_p$, since the fraction of PAR intercepted was likely to be more than the fraction of intercepted net radiation; however, this was likely to be offset by the underestimation of $E_{pp}$ because of the use of $(1 - Q_t)$, which was likely to be less than the net radiation transmitted through the tree rows, in Eq. (5).

Tree transpiration ($E_t$) was obtained as:

$$E_t = ET - E_p - E_s \tag{7}$$

2.3.6. *Statistical analysis*

Tree data were analysed according to randomized complete block design. The plot means for all the pasture and soil variables were obtained by weighting the data from each position by the fraction of the total width of the plot represented. All the data were analysed on the basis of split plot design of four (pasture data) or three (soil moisture and ET data) main treatments and five subtreatments, except for soil moisture storage with six – since both the two *In-row* positions are identical their data were pooled and averaged. No position analysis was performed for ET since there was the possibility for a lateral redistribution of soil moisture after precipitation. Analysis of variance was performed using the repeated option of GLM PC–SAS. Means were compared using the appropriate standard errors of difference (SED).

## 3. Results

### 3.1. *Tree characteristics*

Pasture ground covers significantly reduced the drip area of trees (Table 2); the drip area for the control was almost 35% greater than for ryegrass, 40% than for the ryegrass/clovers and 80% than for the lucerne. The response of crown volume (Table 2) to ground cover treatment was similar to that of the

*Table 2.* Effects of ground cover on the characteristics of pine trees adjacent to the neutron access tubes, total PAR intercepted and percentage rainfall intercepted by the trees, and evapotranspiration (ET) between July 1992 and June 1993 at Lincoln, New Zealand.

| Ground covers | Drip area ($m^2$) | Crown volume ($m^3$) | Intercepted PAR trees ($MJ\ m^{-2}$) | Rainfall intercepted (%) | ET (mm) July 1992–June 1993 |
|---|---|---|---|---|---|
| Control | 2.22 | 2.10 | 481 | 13.7 | 539 |
| Ryegrass/clovers | 1.59 | 1.53 | 326 | 10.0 | 619 |
| Ryegrass | 1.65 | 1.59 | 340 | 11.2 | na |
| Lucerne | 1.23 | 1.13 | 200 | 7.7 | 630 |
| SED | 0.07 | 0.08 | 37.2 | – | 23.1 |

na = data not available.

drip area; the volume was in the following order: control > ryegrass > ryegrass/clovers > lucerne, the differences being statistically significant, except between ryegrass and ryegrass/clovers.

3.1.1. *Light intercepted by pine trees*
The fraction of incident PAR intercepted by the tree crowns ($Q_t$) (Fig. 2) was generally around 0.15 during spring (September to November 1992) in all the ground until December when the sun zenith angle was highest; lucerne ground cover always had the lowest $Q_t$. After this period, there was a steady rise in $Q_t$ in all ground covers reaching maxima in June 1993 when the sun angle was low. The trend in $Q_t$ was always in the following order: control > ryegrass > ryegrass/clovers > lucerne, but these differences were most often not significant except that between control and lucerne. Incoming PAR totalled 1662 MJ $M^{-2}$ during the one-year period between July 1992 and June 1993; of which the trees in the control intercepted 481 MJ, which was 41 and 140% more than the trees in ryegrass and lucerne ground covers intercepted (Table 2).

3.1.2. *Effects of positions*
The pattern of PAR transmitted across the transect is presented for selected dates in Fig. 3 (i). In summer (February) differences in PAR transmitted to the pasture or soil surface were limited to the immediate south of the tree rows

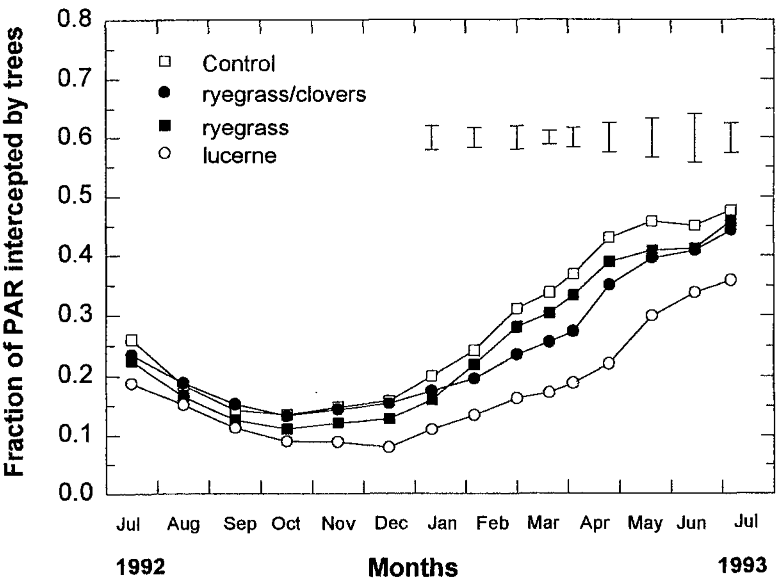


*Fig. 2.* The effects of ground covers on the fraction of photosynthetically active radiation (PAR) intercepted by the tree crowns during the 1992/93 growing season at Lincoln, New Zealand. The vertical bars are standard errors of difference (SED); the data before January were estimated (see text).

where more radiation reached 0.9 mS and 0.18 mS positions in lucerne than in the other ground covers. The centre position and those to the north received almost full incident radiation in all ground covers. In autumn (April) (Fig. 3b (i)) the PAR reaching all positions ranged between 12 and 65% in the northern half of the transect (south of the trees) while the southern half received full radiation. Transmission was always highest in the lucerne ground cover. In spring (September) full PAR was received only at 0.9 mN in lucerne ground cover; the low solar angle at this time allows more PAR to reach both 0.9 mS and 0.18 mS than during the other seasons in all ground covers (Fig. 3(c)(i)).

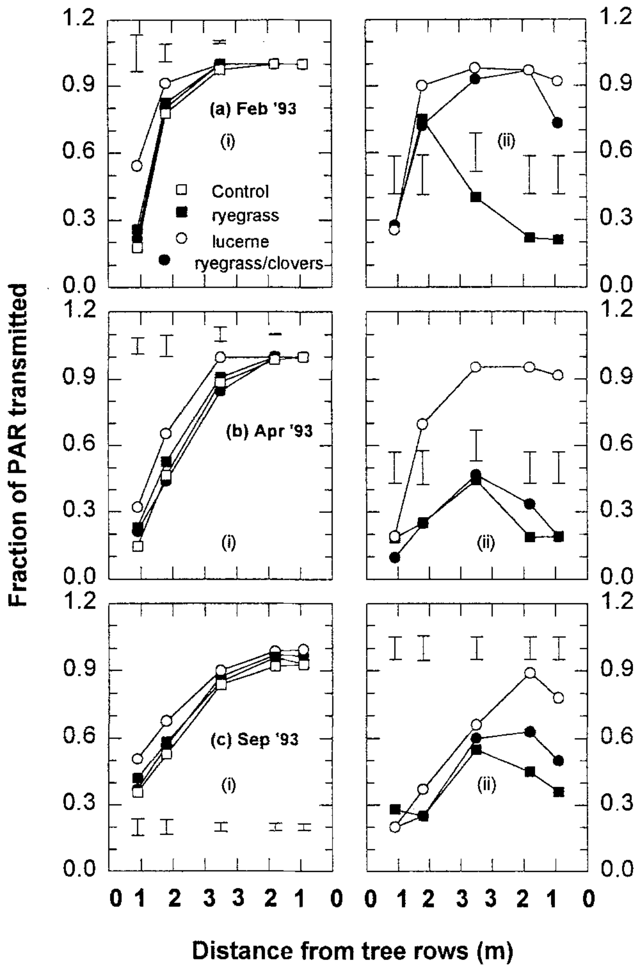


*Fig. 3.* Effects of tree rows on the fractions of photosynthetically active radiatio (PAR) (i) transmitted across the transect, and (ii) intercepted by the pasture canopies at Lincoln, New Zealand, in (a) summer (February), (b) autumn (April), and spring (September). Bars are SED; the right-hand side of the graphs correspond to the north of tree rows (i.e. south of transect), and the left-hand side south of tree rows.

3.1.3. *Fraction of light intercepted by the pasture canopies*
The pasture canopies intercepted most of the transmitted PAR in summer (February, Fig. 3(a)(ii)), although ryegrass species intercepted less than 50% of the available radiation beyond 0.18 mS, and ryegrass/clovers ony 70% at 0.9 mN. In autumn (April, Fig. 3(b)(ii)) almost all PAR transmitted through the trees was intercepted by lucerne, whereas the other two pasture species achieved complete interception only at 0.9 mS and less than half at other positions. In spring (September, Fig. 3(c)(ii)), only half of the available PAR was intercepted by the pastures at positions in the northern half of the transects (south of tree rows); however, lucerne intercepted at least 75% of available radiation in the southern half of the transect compared to a maximum of 60% by the other pasture species.

3.1.4. *Precipitation and its interception*
The validity of Eq. (3) was tested using rainfall data recorded around five selected trees of variable canopy size following a rainfall of 30 mm. The *i* was correlated with canopy volume (x):

$$i = 4.26 + 12.85x \qquad r^2 = 0.968 \tag{7}$$

Precipitation measured at the weather station during the study period (July 1992 to September 1993) totalled 915 mm of which 13.7% (125 mm) was interested by the trees in the control compared to 11% in ryegrass, 10% in the ryegrass/clovers and almost 8% in lucerne ground covers (Table 2). However, in the control plots (Fig. 4(a)), total precipitation reaching the soil surface was 1144 mm at 0.9 mS which was 48% greater than that at *In-row* (618 mm) and 75% greater than at 0.9 mN. Precipitation at other positions was largely similar to that in the open (Fig. 4(b)). The trends for other ground covers were similar to those for the control but the differences were not as large due to their smaller tree crowns.

## 3.2. *Soil moisture storage*

3.2.1. *Effects of ground covers*
In July 1992, *S* in the 0.9 m profile was significantly greater in the control than in the two pasture ground covers (Fig. 5(a)) where this variable was measured. However, *S* was similar in the tree ground covers between September 1992, when it was at maximum, and mid December. From January the *S* in the control was consistently greater than in the pasture ground covers, except in early June when both control and ryegrass/clovers had similar *S*. In the two pasture ground covers, *S* was similar until mid February (220 days), but after this period, especially following the cutting in early February and the rainfall about a week later, *S* in lucerne was consistently less than in the ryegrass/clovers ground covers.

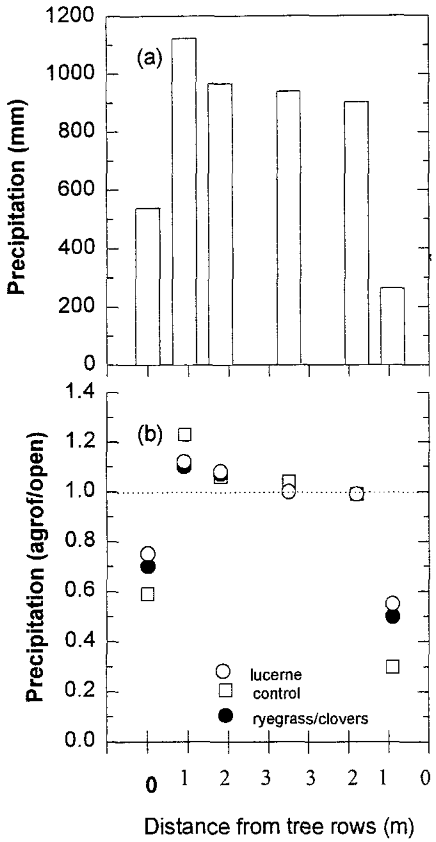


*Fig. 4.* Effects of tree rows on (a) total precipitation during the period of study for the control, and (b) ratios of precipitation in the agroforestry plots to the gross precipitation, at Lincoln, New Zealand. The dotted line in (b) is the 1:1 ratio. Graph orientation is as in Fig. 3.

### 3.2.2. *Effects of position*

Between late October and March, two groups of $S$ levels could be distinguished (Fig. 5(b)). The open positions (1.8 mS, the centre and 1.8 mN), which were well removed from the tree rows, were always wetter than the positions around the trees (0.9 mS, *In-row* and 0.9 mN), which, except for 0.9 mN, were always shaded. Recharge of the profile during winter in 1993 was variable depending on the position; the open positions were recharged above the upper levels attained in the previous winter, while both 0.9 mN and 0.9 mS between them suffered a 100 mm fall in $S$ during the one-year period.

### 3.2.3. *Distribution of moisture in the soil profile*

Moisture distribution down the profile showed how both the ground covers and trees influenced $S$ patterns. On 29 September 1992, $S$ was uniformly

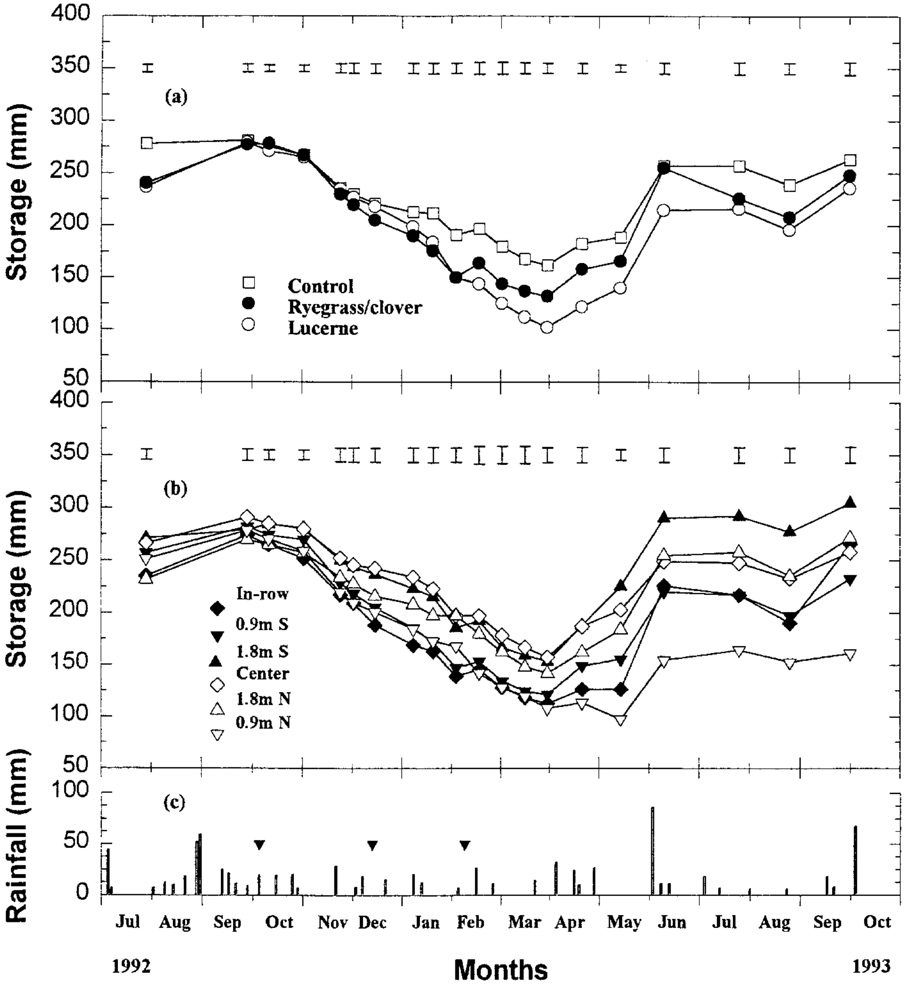


*Fig. 5.* Storage of soil moisture in the 0.9 m profile as affected by (a) ground covers and (b) positions of measurements, and (c) main rainfall events during the study period, at Lincoln, New Zealand. Bars are SED and arrows in (c) indicate when the pastures were cut.

distributed throughout the profile and across all the positions in the three ground covers (Fig. 6(a)), which illustrates the distribution pattern of soil moisture at close to field capacity. Measurement on the 30 March 1993 (Fig. 6(b)) showed how moisture had been extracted during the main growing season. *S* at all depths was higher in the control than in the pasture ground covers at all positions, especially at centre position where little extraction occurred in the control. Between the two pasture ground covers, *S* was similar in the top 0.4 m of the profile. However, at lower depths the profile was drier

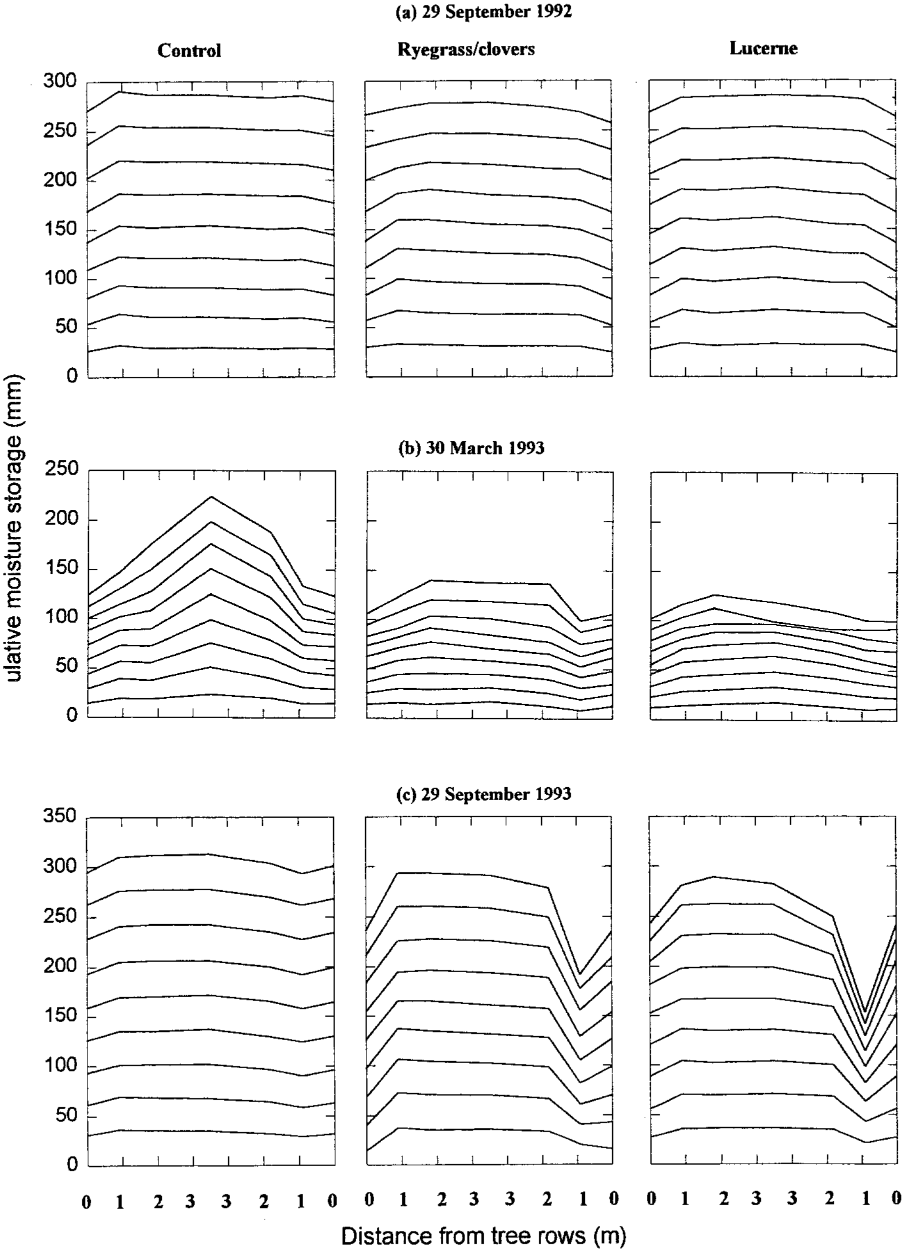


*Fig. 6.* Effects of tree rows on the distribution of soil moisture along the 0.9 m profiles under the various ground covers on three dates at Lincoln, New Zealand. In all graphs the lowest curve is the storage at 0.1 m depth and the successive curves represent cumulative storage at 0.1 m depth increments. Graph orientation is as in Fig. 3.

under lucerne than ryegrass/clovers, especially at positions away from the tree rows.

By 29 September 1993 (Fig. 6(c)), the profile for the control had been restored to maximum $S$ at all depths and positions, although the 0.9 mN and 0.9 mS were still appreciably drier below 0.3 m depth than they were in the previous September. Comparing the two pasture ground covers, the profile under lucerne was wetter at the *In-row* position, but drier at 0.9 mN and 1.8 mN than in ryegrass/clovers. At other positions moisture distribution in the profile was similar between the two pasture ground covers.

## 3.3. *Evapotranspiration (ET)*

### 3.3.1. *Effects of ground covers*

Cumulative ET (Fig. 7(a)) was similar in the three ground covers for the first five months until mid November. After this period, both pasture ground covers had similar ET rates which were greater than the rate for the control. Between February and June, when lowest $S$ was recorded, lucerne had greater cumulative ET than ryeclass/clovers. In the first six weeks following the pasture cut in February, ET rates for lucerne were almost double those for ryegrass/clovers and the control as illustrated by the ET/$E_{pot}$ data (Fig. 7(b)).

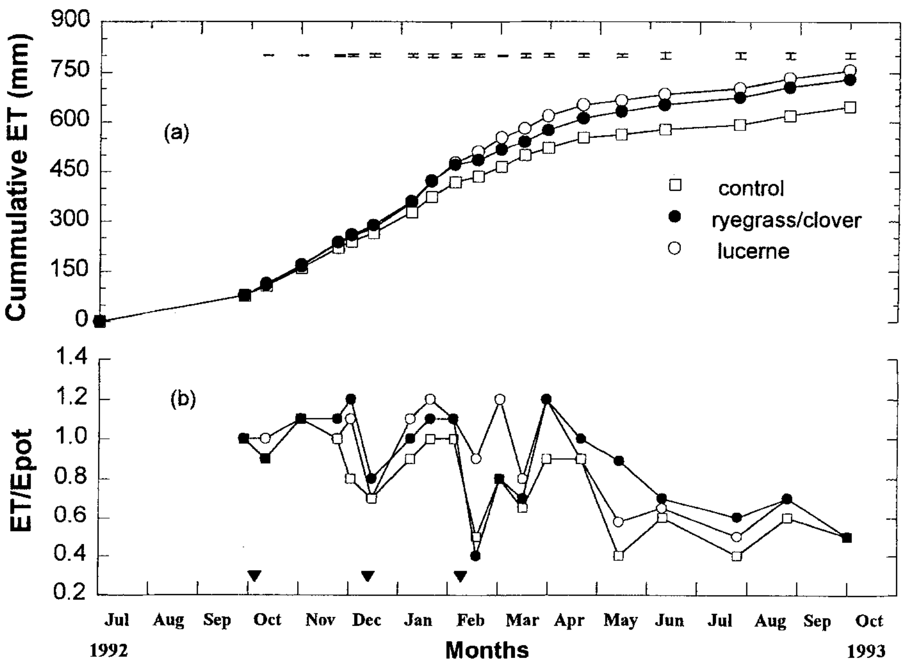


*Fig. 7.* Water use in the agroforestry plots: (a) cumulative evapotranspiration (ET) and (b) ET/$E_{pot}$, during the study period at Lincoln, New Zealand. Bars are SE and arrows in (b) indicate when the pastures were cut.

The total ET during this period was higher in lucerne (299 mm) than in ryegrass/clovers (257 mm). During periods of low soil moisture in March and early April, ET was reduced in all ground covers, but $ET/E_{pot}$ was highest for lucerne (0.82), indicating a greater water use by this ground cover than the other two which were similar (mean of 0.68). However, during the following cool season from May, ryegrass/clovers ground cover had the highest ET rates and so reduced the difference between its cummulative ET and that of lucerne ground cover by September 1993 (Fig. 7(a)). Accordingly, $ET/E_{pot}$ (Fig. 7(b)) for the ryegrass/clovers was higher than for the lucerne ground cover until August 1993 (Fig. 7(b)). Total ET during the entire study period was 757 mm for the lucerne, which was bout 3% greater than for the ryegrass/clovers and almost 17% greater than for the Control (618 mm). ET for the 1992/93 growing season (July–June) (Table 2) was highest for lucerne, which was 16% more than for the control.

### 3.3.2. *Transpiration from trees and pastures*

The ET was dominated by the pastures with $E_P$ constituting at least 50% of the total water use from both ryegrass/clovers and lucerne ground covers in summer and autumn (Table 3). Between the two ground covers, $E_P$ was always higher for lucerne than for ryegrass/clover species, except in autumn (April–May) when it was 18% higher in the latter, and in winter (July–June) when it was similar for both pasture species. The $E_t$, in contrast to the $E_P$, was always higher for ryegrass/clovers than for lucerne. In late autumn (April–May) and winter (June–July), $E_t$ dominated ET, accounting for between 40 and 53% of the water used. The trees always used more water in

*Table 3.* The partitioning of evapotranspiration (ET) between pasture transpiration ($E_p$), soil evaporation ($E_s$) and tree transpiration ($E_t$) during selected periods.

| Ground covers | ET (mm) | $E_p$ (mm) | $E_s$ (mm) | $E_t$ (mm) | $E_t$/ET |
|---|---|---|---|---|---|
| 7–19 January 1993 (Mean $E_{pot}$, 43.1 mm; $E_{PT}$, 31.6 mm; wind run, 407 km $d^{-1}$) | | | | | |
| Ryegrass/clovers | 50.2 | 25.6 | 4.8 | 19.8 | 0.39 |
| Lucerne | 46.3 | 29.5 | 1.7 | 15.1 | 0.33 |
| 2–30 March 1993 (Mean $E_{pot}$, 64.2 mm; $E_{PT}$, 54.4 mm; wind run, 164 km $d^{-1}$) | | | | | |
| Ryegrass/clovers | 58.5 | 36.5 | 1.2 | 20.7 | 0.36 |
| Lucerne | 65.5 | 41.7 | 5.2 | 18.5 | 0.28 |
| 20 April–13 May (Mean $E_{pot}$, 23.6 mm; $E_{PT}$, 23.1 mm; wind run, 255 km $d^{-1}$) | | | | | |
| Ryegrass/clovers | 21.0 | 9.1 | 2.1 | 9.8 | 0.47 |
| Lucerne | 13.6 | 7.7 | 1.4 | 6.3 | 0.47 |
| 10 June–15 July 1993 (Mean $E_{pot}$, 16.4 mm; $E_{PT}$, 16.1 mm; wind run, 234 km $d^{-1}$) | | | | | |
| Ryegrass/clovers | 21.5 | 5.6 | 4.5 | 11.4 | 0.53 |
| Lucerne | 18.4 | 5.5 | 5.5 | 7.4 | 0.40 |

ryegrass/clovers than in lucerne ground covers. In both ground covers soil evaporation ($E_s$)(Table 3) always accounted for less than 5% of ET during the active growing season in summer and autumn, but in winter it constituted up to 20% of ET in ryegrass/clovers and 30% in lucerne ground covers.

## 4. Discussion

ET was close to $E_{pot}$ for much of the study period (Fig. 7), except for a brief period between March and April when storage of soil moisture was lowest (Fig. 5), indicating that, to a large extent, ET from the combined tree and pasture canopies was not limited by soil moisture supply during most of the study period. However, this did not preclude the individual species in the mixtures from being stressed during periods of low levels of soil moisture storage [Yunusa et al., 1995]. In the period before April there was always the tendency for ET to exceed $E_{pot}$. This could be the result of $E_{pot}$ being determined from data measured over short vegetation in a standard weather station compared to the wooded trial site. Denmead [1969] found both net radiation and surface dynamics to be always greater (by up to 20%) over a pine forest than over a short wheat vegetation.

ET (Fig. 7) was primarily determined at various times by the weather and plant factors during the study period. The rates of ET, and hence depletion of soil moisture, showed strong seasonal patterns reflecting rainfall distribution and canopy transpiration. At the start of the study period in midwinter (July 1992) through spring (November), ET (Fig. 7) was associated with the evaporative demand, on account of the rainfall (2.82 mm $d^{-1}$) being in excess of the $E_{pot}$ (2.31 mm $d^{-1}$) (Table 1). The relatively small tree crowns at this time allowed transmission of most radiation to the pasture canopies and the soil (Fig. 2) to drive evaporation from these surfaces. During these wet seasons, therefore, competition for soil moisture between the trees and pastures was likely to be minimal.

The summer (December–February) season was associated with rapid decline in soil moisture storage. Rainfall during this period averaged 1.8 mm $d^{-1}$ compared to $E_{pot}$ of 4.4 mm $d^{-1}$. ET at this time was largely a result of canopy transpiration since the soil surface was mostly dry, although moisture storage in the profile was still high (Fig. 5). Taking storage at field capacity in the 0.9 m profile to be 270 mm (water-holding capacity of 30%), the soil was at least 50% of its field capacity (Fig. 5), and withdrawal of moisture by roots could be associated with the solar energy receipt at the transpiring canopy surfaces [Denmead and Shaw, 1962; Yunusa et al., 1993, 1994]. Therefore ET (Fig. 7) was least in the control, where total energy intercepted by the tree canopy alone was small compared to that intercepted by the combined canopies of both the pastures and the trees in the two pasture ground covers (Fig. 3). The low ET from the two pasture ground covers following defoliation in mid-December and early February is consistent with the reduced energy intercepted. Hence, competition for soil moisture between the tree and pasture species was likely to be intense during the summer period. Thus, canopy manipulation could be an effective tool in shifting water use between the trees and understorey species by controlling the canopy size of the appropriate component.

The dependence of ET on canopy transpiration was also evident in winter 1993, despite the restoration of soil moisture storage to the levels of the previous spring (Fig. 5). The onset of cold weather (Table 1) which killed the pasture legume species, in addition to the tree shade over much of the transect, accounted for the low water use. The persistence of ryegrass which constituted 60% of the ryegrass/clover species during this period (Irdika Mansur, unpublished) ensured a greater ET in this ground cover compared to lucerne (Table 3). Thus the incomplete recharge of soil moisture at 0.9 mN by the end of September 1993 was associated with the maintenance of limited growth during winter, and early regeneration, by the pastures at this exposed position (Fig. 3), where the soil was warmer than at the other positions (data not presented).

However, soil moisture restrained ET briefly in March when ET/$E_{pot}$ was less than unity for all ground covers, although lucerne ground cover still used the most water (Fig. 7b). Lucerne is known [Bennet and Doss, 1960] to develop extensive root systems which in the present study enabled it to exploit the soil profile at all depths almost evenly across the transect (Fig. 6(b)); the extraction of moisture went beyond the 0.9 m depth shown in Fig. 6 (data not presented). The shallow rooted ryegrass/clover species [Bennet and Doss, 1960] limited soil exploration to the near surface layers resulting in the relatively moist profile at depths (Fig. 6(b)) and produced lower ET/$E_{pot}$ compared to lucerne. The data in Fig. 6(c) also indicated a lateral redistribution of soil moisture following rainfall events, especially during periods of low plant growth in winter; thus, the small amounts of rainfall recorded at 0.9 mN (Fig. 4(a)) notwithstanding, storage at this position was only slightly reduced in the control at full recharge (Fig. 6(c)). This further supports the view that the dry profiles at 0.9 mN in the pasture ground covers could be more associated with the vigorous understorey growth [Yunusa et al., 1995] than rainfall interception at this position.

The domination of ET by $E_p$ (Table 3) is consistent with the pastures occupying most of the plot area. Although $E_p$ was determined on the basis of radiation transmitted through the trees and intercepted by the pasture canopies, it was not possible in the present study to completely discount some degree of coupling between conditions above the understorey and the bulk atmosphere, especially under the windy conditions [Black and Kelliher, 1989]. However, since wind run was found to be reduced by as much as 78% in a similar trial with 8 to 11-year-old *Pinus radiata* [Hawke and Wedderburn, 1994] the role of aerodynamics in driving $E_p$ in the transect could be limited in the present study. The $E_t$/ET data (Table 3) are similar to a range of 0.41 to 0.62 reported in a previous study [Whitehead et al., 1994b] in which the high $E_t$/ET (0.62) in winter was consistent with the large tree crowns of the seven-year-old pines used. The $E_t$/ET data also suggest that soil evaporation ($E_s$) may be significant in the control; this aspect is further explored in the following paper where $E_s$ for this treatment was determined for the whole study period.

In summary, by occupying most of the land area the pastures dominated the use of the biophysical resources – soil moisture and solar radiation – in this agroforestry system. The winter period, when the tree dominated water use, is normally associated with slow or little growth by the radiata pine [Whitehead et al., 1994a], and so the trees were not likely to gain much from the inhibited growth of pasture at this time. Increasing the partitioning of water use to the widely spaced trees could be effective during the active growing seasons and when depletion of soil moisture is chiefly determined by the level of canopy cover, especially in summer. Also, early pruning of the trees could reduce the loss of moisture due to interception of precipitation, and increase transmission of radiation to the pasture canopies. Although soil moisture data were not determined for the ryegrass ground cover, its water use was likely to be similar to that for ryegrass/clovers on account of the small differences between the two ground covers in their tree growth characteristics (Table 2 and Fig. 2) and the fraction of PAR intercepted by the pastures (Fig. 3). In the following paper [Yunusa et al., 1995], the relationships between the quantities of these biophysical resources (radiation and soil moisture) used and assimilates produced in the various ground covers are analysed.

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## Refrences

Bennet OL and Doss DB (1960). Effect of soil moisture levels on root distribution of cool-season forage species. Agron J 52: 204–207

Black TA and Kelliher FM (1989) Processes controlling understory evapotranspiration. Phil Trans R Soc London Ser B 324: 207–231

Clinton PW and Mead DJ (1990) Competition between pine and pastures: an agroforestry study. in: Proc AFDI Biennial Conference, pp 145–154. 5–8 October, Bunbury, Western Australia

Cooper PJM, Keatinge JDH and Hughes G (1983). Crop evaporation – a technique for calculation of its components by field measurements. Field Crops Res 7: 67–84

Denmead OT (1969) Comparative micrometeorology of a wheat field and a forest of *Pinus radiata*. Agr Meteorol 6: 357–371

Denmead OT and Shaw RH (1962) Availability of soil water to plants as affected by soil moisture content and meteorological conditions. Agron J 45: 385–390

Eastham J and Rose CW (1988) Pasture evapotranspiration under varying tree planting density in an agroforestry experiment. Agric Water Manage 15: 87–105

Gash JHC (1979) An analytical model of rainfall interception in forests. QJR Meteorol Soc 105: 43–55

Grace JC, Jarvis PG and Norman JM (1987). Modelling the interception of solar radiant energy in intensively managed stands. N Z J For Sci 17: 193–209

Hawke MF and Wedderburn ME (1994) Microclimate changes under *Pinus radiata* agroforestry regimes in New Zealand. Agric For Meteorol 71: 133–145

Jamieson PD (1985) Soil moisture extraction patterns from irrigated and dryland arable crops in Canterbury. Proc Agron Soc NZ 15: 1–6

Kear BS, Gibbs HS and Miller RB (compilers)(1967) Soils of the Downs and Plains of Canterbury and North Ontago, New Zealand. Soil Bureau, Wellington, New Zealand

Knowles RL, Hawke MF and Maclaren JP (1992) Agroforestry research at Tikitere. Agroforestry research collaborative Report no. 19. NZ FRI, Rotorua

Mead DJ, Lucas RJ and Mason EG (1993) Studying interactions between pastures and *Pinus radiata* in Canterbury's sub-humid temperate environment – the first two years. NZ Forestry 26–31

Monteith JL, Ong CK and Corlett JE (1991) Microclimate interactions in agroforestry systems. For Ecol Manage 45: 31–44

Monteith JL and Unsworth MH (1990) Principles of Environmental Physics. Edward Arnold, London, 241 pp

Ong CK (1990) Interaction of light, water, and nutrients in agroforestry systems. In: Avery ME, Cannell MGR and Ong CK (eds) Biophysical Research for Asian Agroforestry, pp 107–124. Winrock International, USA, and Oxford & IBH Publishing Co. PVT Ltd, New Delhi, Bombay, Calcutta.

Palmer JW and Jackson JE (1977) Seasonal light interception and canopy development in hedgerow and bed system apple orchards. J Appl Ecol 14: 539–549

Priestley CHB and Taylor RJ (1972) On the assessment of surface heat flux and evaporation using large scale parameters. Monthly Weather Rev 108: 81–92

Santantonio D and Santantonio E (1987) Effects of thinning on production and mortality of fine roots in *Pinus radiata* plantation on a fertile site in New Zealand. Can J For Res 17: 919–928

Singh P and Sri Rama YV (1989) Influence of water deficit on transpiration and radiative use efficiency of chickpea (*Cicer arietinum*). Agric For Meteorol 48: 317–330

Whitehead D, Kelliher FM, Frampton CM and Godfrey MJS (1994a). Seasonal development of leaf area in a young, widely spaced *Pinus radiata* D. Don stand. Tree Physiol 14: 1019–1038

Whitehead D, Kelliher FM, Lane PM and Pollock DS (1994b) Seasonal partitioning of evaporation between trees and understory in a widely-spaced *Pinus radiata* stand. J Appl Ecol 31: 528–542

Yunusa IAM, Mead DJ, Lucas RJ and Pollock KM (1995) Process studies in a *Pinus radiata*–pasture agroforestry system in a subhumid temperate environment. II. Analysis of dry matter yields in the third year. Agroforestry Systems 32: 185–204 (this issue)

Yunusa IAM, Sedgley RH, Belford RK and Tennant D (1993) Dynamics of water use in a dry mediterranean environment. I. Soil evaporation little affected by the presence of canopy. Agric Water Manage 24: 205–224

Yunusa IAM, Sedgley RH and Siddique KHM (1994) Influence of mulching on the pattern of growth and water use by spring wheat and soil moisture storage on a fine textured soil. Plant Soil 160: 119–130