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Water loss from plantations of Douglas-fir and radiata pine on the Canterbury Plains, South Island, New Zealand

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Abstract

There are about 1.4 million ha of exotic forests in New Zealand, much of which is planted in radiata pine (*Pinus radiata).* In recent years, Douglas-fir (*Pseudotsuga menziesii*) has become a popular alternative species, especially in drier and colder areas. To assess the impact of planting Douglas-fir on water yield, it is crucial to examine the expected transpiration and interception losses likely to be associated with this species under the currently practised silvicultural regime. However, little information is available on interception loss and transpiration from Douglas-fir as a plantation species in New Zealand.

Estimations of throughfall and stemflow were made at three sites on the Canterbury Plains, 60 km west of Christchurch, from November 1998 to June 2000, and of transpiration (using sapflow meters) from October 1999 to May 2000. Measurements were carried out in 18-year-old (1360 stems/ha) and 54-year-old (570 stems/ha) stands of Douglas-fir and for comparision, in an 18-year-old (650 stems/ha) radiata pine stand. Average annual rainfall for the area is about 900 mm. Estimated interception loss was 29% of gross rainfall for young Douglas-fir, 28% for old Douglas-fir, and 20% for radiata pine. These percentages are comparable to those measured elsewhere for these two species. Transpiration losses were 47%, 58%, and 42% of gross rainfall for the young Douglas-fir, old Douglas-fir, and radiata stands, respectively. When compared over the same intervals, total water loss during the warmer months (October 1998 to May 2000) from interception and transpiration was greatest in the old Douglas-fir (87%), followed by young Douglas-fir (74%), and lowest in the radiata pine stand (66%). Thus in the low-to-moderate rainfall regime of inland mid-Canterbury, less water is likely to drain to the soil and groundwater store from spring to late autumn under Douglas-fir plantations than under radiata pine. In cooler, wetter climates where transpiration rates are lower, and interception dominates, total water losses from the two species may be similar.

Introduction

There are about 1.4 m ha of exotic forests in New Zealand, and current afforestation is increasing by 50 000 ha per year, mostly on land originally in pasture. The bulk of the plantation estate is in radiata pine *(Pinus radiata)*. In recent years, Douglas-fir (*Pseudotsuga menziesii*) has become a popular alternative species, especially in the drier and colder areas of Canterbury and Otago (Belton and Law, 1996). In the Canterbury region, this species now makes up 8% of the planted forest resource (Law, 1997).

When pasture is converted to plantation forest, changes in surface water yield and ground water recharge are largely controlled by changes in wet canopy evaporation (interception) and dry canopy evaporation (transpiration). To properly assess the impact of Douglas-fir plantings, an understanding is required of the expected losses from interception and transpiration in relation to the silvicultural regime as currently practised in New Zealand. Rainfall interception by radiata pine has been widely investigated throughout Australasia (e.g., Blake, 1975; Feller, 1981; Crockford and Richardson, 1990; Myers and Talsma, 1992). However, little information is available on interception and transpiration losses from Douglas-fir. This study presents results that compare water losses from wet and dry canopy evaporation from two stands of different-aged Douglas-fir with those from a stand of mature radiata pine.

Study area

The study was conducted just east of the foothills on the Canterbury Plains near Hororata, 60 km west of Christchurch (Fig. 1). The Canterbury Plains comprise a series of large coalescing alluvial gravel fans and glacial outwash formed over the last 2 million years. Orthic Brown soils (Hewitt, 1998) characterise the study area (Webb, pers. comm.). Kear *et al.* (1967) described the soils in the western part of the study area as Lismore stony silt loams, and those in the east as Ruapuna very stony silt loams. Both soils are shallow and free draining, and are subject to seasonal drought. The weather is dominated by sequences of anticyclones and frontal systems in a prevailing westerly flow. Cold fronts are often preceded by strong drying winds from the north-west, typically in spring and autumn. Winters are cool with frequent frosts. The mean annual temperature (1961–1999) at Hororata is 11°C (January 16.7°C and July 5.1°C), and the mean annual rainfall (1961–1999) is 852 mm (Tomlinson and Sansom, 1994a; 1994b).

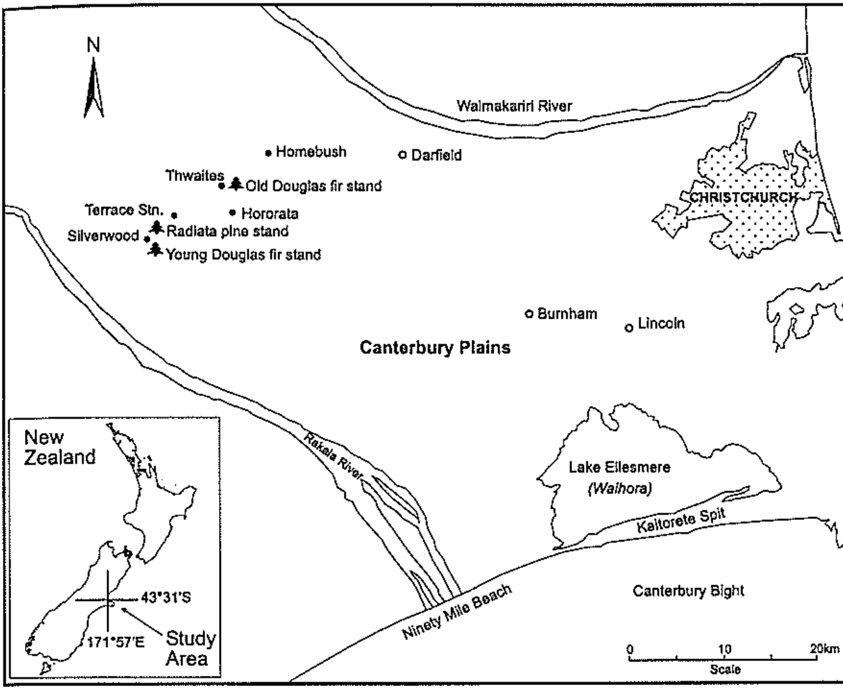

Figure 1 – Map showing location of forest stands (tree symbols) and rainfall stations (black dots).

Site selection and description

Traditionally, Douglas-fir is grown on a rotation of 50–70 years. It is normally planted at 1370 stems/ha, then thinned at about age 15 to 500–600 stems/ha (Ministry of Forestry, 1995). Based on the foregoing, two representative stands of Douglas-fir were chosen for this study (Fig. 1). The younger stand (32.4 ha), which is located beside Steeles Road (elevation 250 m), 8 km west of Hororata, was planted in 1982 at a stand density of 1348 stems/ ha. The older stand was established in 1943, 3.5 km north of Hororata beside Plantation Road (elevation 230 m). It covers 13.4 ha and has a current stand density of 550 stems/ ha. A mature stand of radiata pine was chosen for comparison (Fig. 1). Located 1 km north of the young Douglas-fir stand, it was planted in 1982, has an area of 37.5 ha and a current stand density of 654 stems/ha. Additional information on stand parameters is given in Table 1. All three stands are part of the Selwyn Plantation Board estate.

They have closed canopies, and while ground cover is absent in the young Douglas-fir stand, the old Douglas-fir and mature radiata stands have a scattered covering (<15%) of blackberry and gorse. All sites are effectively flat, with no surface runoff

Table 1 – Forest stand parameters

	Young Douglas-fir (Steeles Rd)	Old Douglas-fir (PlantationRd)	Radiata pine (Steeles Rd)
Age (years)	18	54	18
Height (m)[†]	11	28	20
Stocking (stems/ha)[†]	1350	550	650
Avg. DBH (cm)[†]	19	38	30
Avg. stand BA (m^2/ha)	38	67	46
Sapwood area (m^2/ha)	14	9	27

[†] Based on measurements made in five 12 m-radius plots in the young Douglas-fir stand (total area = 0.23 ha), three 20 m-radius plots in the old Douglas-fir stand (total area = 0.38 ha), and one plot in the radiata stand (radius 20 m; area 0.13 ha).
DBH = diameter at breast height (1.4 m); BA = basal area

Instrumentation and methods

Rainfall

A Belfort weighing-bucket recording gauge and a 127-mm manual gauge were installed at Silverwood farm (500 m west of Steeles Road). The manual gauge was used to check the accuracy of the recording gauge between visits. There is also a manual gauge at the site with a daily record extending back to 1969. These gauges were used to estimate gross rainfall at the young Douglas-fir and radiata pine stands. A Unidata tipping-bucket automatic recording gauge and a 127-mm manual gauge were installed about 150 m to the west of Plantation Road on Thwaites' farm, and were used to estimate gross rainfall at the old Douglas-fir stand. Both sets of rain gauges were located in flat, open, and unobstructed farmland.

Throughfall

In each stand we used three sample plots, each with three collecting troughs, to obtain a good estimate of mean stand throughfall (i.e., with 95% confidence that the population mean was within 10% of the actual stand mean). Each of the three 314-m^2 plots was randomly located within a stand, at least 50 m from the nearest forest boundary.

The three plastic troughs in each plot were 500 × 10 cm in size, giving a total collecting area of 1.5 m^2 per plot. Allowances were made for any minor distortions in trough width after installation. The troughs were randomly located with respect to both direction and position, and raised about 1 m above the ground. Water was collected in 30 L containers and throughfall estimated by weighing each container. A one-way analysis of variance was used to compare mean throughfall and interception among the three stands. Where there were significant differences, pair-wise comparisons of stands were made using the Bonferroni method (Hsu, 1996).

Stemflow

Stemflow was collected using u-shaped lead collars spirally wrapped around the stem of each tree. Subplots of nine trees were sampled in the two Douglas-fir stands, and five in the radiata pine stand. Individual stemflow volumes were summed and then converted to millimetre depths on the basis of the subplot areas.

Transpiration

Within each stand sapflow meters were used to estimate the transpiration of selected trees growing in the vicinity of one of the randomly chosen throughfall plots. Sapflow velocities were measured using the compensation heat-pulse technique described by Swanson and Whitfield (1981). Sapflow sensors, (model SF300, Greenspan Technology, Warwick, Australia) were inserted to mid-sapwood width at a height of about 1.4 m on the north- and south-facing sides of each tree. Width of bark, sapwood (conducting tissue), heartwood (non-conducting tissue), and wood and water volume fractions associated with each sensor were obtained from 5-mm-diameter increment-cores taken prior to installation. Sapflow velocity measurements were recorded at 20-min intervals and subsequently corrected for the effects of wounding, based on the numerical analysis of Swanson and Whitfield (1981), using a mean wound width of 2.3 mm.

The threshold sapflow velocity (mm/h) is the value below which low flow cannot be distinguished from no flow. Consequently, it can be assumed that values numerically less than the threshold value represented zero flow, i.e. sapflow velocity = 0 (Benyon, 1999). This value was determined for each sensor by selecting, from the graphs of raw sapflow velocities, several nights when the apparent flows were at a minimum. The mean and standard deviation of the 0000 to 0500 hours data for such nights were computed for each sensor and the upper 1% confidence limit taken as the threshold or zero value.

Using the increment-core information, the sapwood area associated with each sensor was calculated and then multiplied by the sensor sapflow velocity to give sap flux (L/h). The mean of the sap flux from each north and south sensor pair was used as the value of sap flux for the tree. These values were then averaged over each 24-h period to give mean daily tree water-use (L/day).

Before installation of the sensors, tree size distribution within stands (based on diameter at breast height, or DBH), was estimated using the methods described by Goulding and Lawrence (1992). A fixed/roaming technique for sensor monitoring (Vertessy *et al.*, 1994) was employed to cover the range of tree size classes within each stand. For each stand four trees representative of the dominant size classes were selected and continuously monitored for the duration of the study. These were supplemented with roaming 3–4 week monitoring of additional trees selected to represent the subdominant size classes.

For each stand, a non-linear relationship was established, using the curve-fitting package "Table curve 2D v4", between tree size class and tree daily water-use. Knowing the number of trees per hectare within each size class, the size class contribution as a percentage of total daily water-use per hectare was calculated. The four long-term monitored trees in each stand were allotted to their appropriate size class and their mean daily individual water-use multiplied by the size class contribution, then averaged, to give a value of mean daily water-use (mm) per stand.

We recorded throughfall and stemflow in the three stands from 26 November 1998 to 6 June 2000, i.e., approximately 18 months, with a full calendar year of data for 1999. The transpiration record began in late September 1999 and ceased at all sites in mid-June 2000.

Results

Gross rainfall

Rainfall data are listed in Table 2. Mean annual totals increased from Silverwood Farm in the west (832 mm) to Homebush 15 km to the north-east (913 mm). However, the same pattern is not apparent in the rainfall totals through the period of record for throughfall. For example, Silverwood Farm (Fig. 1) recorded more rainfall than any other station (1586 mm), whereas Homebush recorded only 1323 mm. A similar reversal of trend is seen in the annual totals for 1999. However, Table 2 also shows that rainfall in 1999 was close to or slightly below average across the study area.

A double-mass curve comparing daily rainfall for the period August 1998 to June 2000 at Silverwood with that at Thwaites showed no deviations from a straight line. In addition, the regression of the daily record at Silverwood against that at Thwaites revealed an r^2 of 0.938. This strong and consistent relationship between the daily totals showed that measurement conditions at the two stations were stable over the period of record.

Table 2 – Rainfall totals (mm) for the study area

Station	Mean annual	1999	Period of record for throughfall (mm)
Silverwood (Steeles Road)	832†	923	1586
Terrace	813†	900†	1238
Hororata	852*	899†	1368 †
Thwaites (Plantation Rd)	–	858	1397
Homebush	913†	886†	1323 †

† Data source, Selwyn Plantation Board.

*Data source, Tomlinson and Sansom (1994a).

As the sites were not visited after every rain event, it was not possible to associate throughfall with discrete storms. Thus in many instances more than one storm had to be included in the throughfall event. Between 26 November 1998 and 6 June 2000, 38 such events were recorded. The gross precipitation per throughfall event ranged from 10.3 to 87.0 mm at Silverwood (Steeles Road) and 6.7 to 90.0 mm at Thwaites' (Plantation Road).

Throughfall

There was a strong positive relationship between event size and throughfall for all three stands (r^2 = 0.96, 0.93, and 0.92 for the young Douglas-fir, the old Douglas-fir, and the radiata stand, respectively). Details of the relationship for the old Douglas-fir stand are shown in Figure 2.

Table 3 shows that the mean throughfall between 26 November 1998 and 6 June 2000, expressed as a percentage of the gross rainfall, was virtually the same for the two Douglas-fir stands (~67%), whereas that recorded at the radiata pine site was 75% of the gross rainfall. Despite the 8% difference in the throughfall record between the radiata stand and the Douglas-fir stands, a one-way analysis of variance showed that the percentage throughfall is not statistically different among the three stands ($F_{2,6} = 2.26$, $P = 0.185$). If, however, it is assumed that all nine troughs were randomly located throughout each stand, and therefore are independent, a one-way analysis of variance suggests that the mean throughfall of the radiata stand is different from the mean throughfall of the two Douglas-fir stands ($F_{2,24} = 3.70$, $P = 0.039$).

Stemflow

Stemflow during events was often highly variable among individual trees, due in part to variations in tree diameter and in part to storm characteristics,

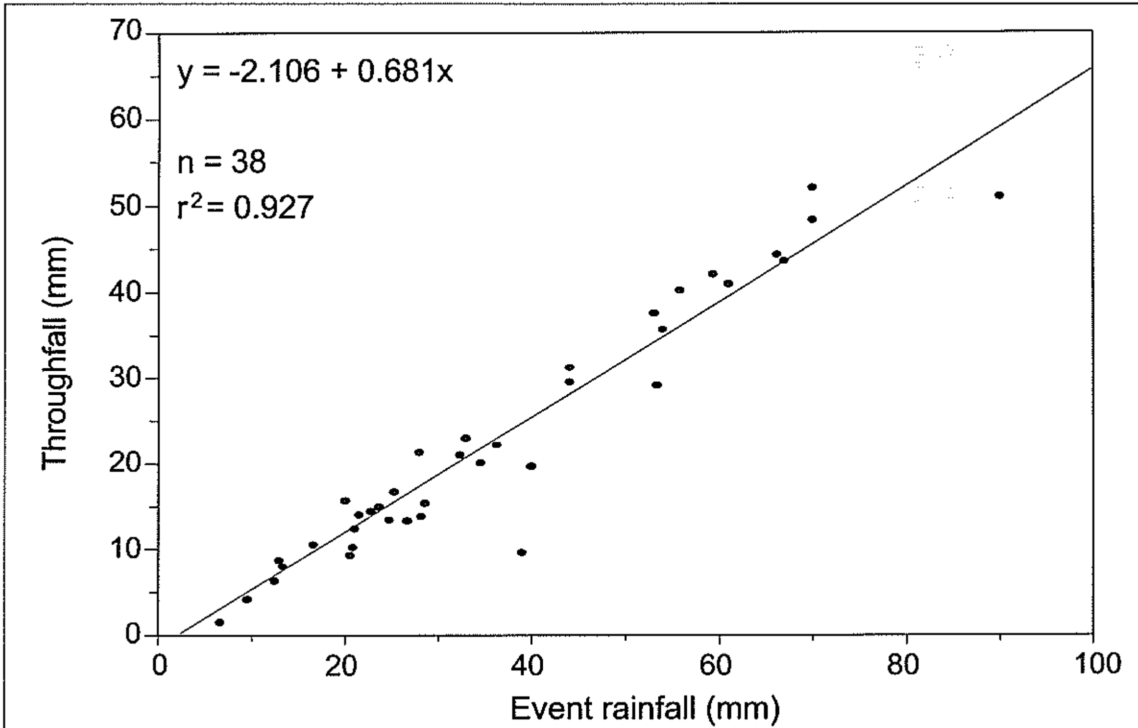

Figure 2 – Relationship between event rainfall and throughfall for the old Douglas-fir stand (26 November 1998 to 6 June 2000).

particularly rainfall intensity and prevailing wind direction. There was a modest relationship between event size and stemflow contribution (r^2 = 0.67, 0.64, and 0.55 for the young Douglas-fir, old Douglas-fir, and radiata pine plots respectively).

Table 3 – Throughfall data (mm) and accompanying descriptive statistics for the three forest stands (26 November 1998 to 6 June 2000)

	Young Douglas-fir			Old Douglas-fir			Radiata pine		
	Plot 1	Plot 2	Plot 3	Plot 1	Plot 2	Plot 3	Plot 1	Plot 2	Plot 3
Throughfall total (mean of 3 troughs)	1083	1115	995	994	906	860	1323	1128	1133
SD[†]	104	60	54	47	109	75	127	24	24
Confidence Limits (95%)	301	175	153	136	338	206	385	74	73
Throughfall total (mean of 3 plots)	-	1064 (±62)[†]	–	–	920 (±68)[†]	–	–	1195 (±111)[†]	–
Gross rainfall (mm)	-	1586	-	-	1397	-	-	1586	-
Mean throughfall (%)	-	67	-	-	66	-	-	75	-

[†] Standard deviation

The minimum event recorded at Silverwood near Steeles Road was 10 mm, but stemflow in the young Douglas-fir and radiata stands was still sufficient to be measured (0.1 to 0.6 mm, respectively). However, in the old Douglas-fir stand at Plantation Road, the event size required to trigger measurable stemflow was 19 mm. At the other end of the scale, the largest events (-90 mm) produced stemflows ranging from 3 to 7 mm for the three stands, or 3–8% of gross rainfall. Over the period of record the totals attributed to stemflow were 61, 70, and 90 mm, which converted to 3.9%, 5.0%, and 5.7% of rainfall for the young Douglas-fir, the radiata pine, and old Douglas-fir stands respectively.

Interception loss

Interception loss for the period 26 November 1998 to 6 June 2000 was calculated by subtracting the sum of total throughfall and stemflow from gross precipitation. Totals for the young Douglas-fir, old Douglas-fir, and radiata pine stands were estimated at 29%, 28%, and 20% respectively. A one-way analysis of variance comparing the interception means, based on the three plots in the two Douglas-fir stands and the radiata stand, showed no significant difference ($F_{2,6}$ = 2.69; P = 0.146), whereas that comparing the interception means, assuming the independence of the nine troughs in each of the three stands, showed evidence for a difference ($F_{2,24}$ = 4.74; P = 0.018). The pairwise comparisons showed there was evidence that both Douglas-fir stands differed from the radiata stand ($0.01 < P < 0.05$), but no evidence that they differed from each other ($P > 0.05$).

Transpiration

The extrapolation of measurements of water use by individual trees to that of a stand of trees is a critical step in linking plant physiology and hydrology (Hatton and Wu, 1995). Limitations in sampling resources and variation in tree size within a stand necessitate the use of some scalar relationship. In this study good relationships of the form $y = ax^b$ were found between mean daily water-use (y) and sapwood area (x) for individual trees in both the young and old Douglas-fir stands, and the radiata pine stand, with r^2 values of 0.84, 0.80, 0.79 respectively (Table 4). When similarly treated, a comparison between mean daily water-use (y) and tree diameter at breast height (x) of the three stands yielded r^2 values of 0.84, 0.82, and 0.85 (Table 4). A strong power relationship was also found between sapwood area (y) and tree diameter at breast height (x) for both tree species (r^2 = 0.93, 0.97). Thus, in this study, given that the relationships between tree diameter and tree water-use appear to be a little more robust than that between sapwood area and tree water-use, the strong correlation between diameter

Table 4 – Relationships of the form $y = ax^b$ between mean daily water-use (L/day) and size parameters of monitored trees

Stand	y	x	n	a	b	±95% CI	r^2
Young Douglas-fir	water-use	sapwood area (m^2)	10	100	0.97	±0.46	0.84
Old Douglas-fir	,,	,,	9	88	1.04	±0.60	0.80
Radiata pine,,	,,	,,	9	57	1.05	±0.67	0.79
Young Douglas-fir	water-use	DBH (m)	10	655	2.32	±1.09	0.84
Old Douglas-fir	,,	,,	9	284	2.52	±1.11	0.82
Radiata pine,,	,,	,,	9	355	2.23	±1.06	0.85

DBH – tree diameter at breast height

at breast height and sapwood area, and the accessibility of diameter as a measure of tree size, tree diameter at breast height was used as the scalar parameter (Fig. 3). The use of tree diameter as a scaling parameter between individual tree water-use and stand water-use has previously been proposed by Thorburn *et al.* (1993), Hatton *et al.* (1995), and Turner *et al.*(2000). For the three stands, the exponents (b) describing the relationships between mean daily water-use (y) and sapwood area (x) are not significantly different from 1 at the 95% confidence level (Table 4), hence the relationships can be considered linear. Therefore an estimation of stand transpiration could be reduced to that of estimating the total sapwood area of the stand.

Transpiration measurements are only available for the 8-month period October 1999 to May 2000. They are derived as estimates of the stand transpiration based on the average of the measurements of water-use (L/day) by the four trees representative of the dominant size classes in each stand. During this period water loss through transpiration was greatest in the old Douglas-fir stand (426 mm ±86), followed by the young Douglas-fir stand (397 mm ±119), and was lowest in the radiata pine stand (348 mm ±86).

Total water losses

Total water losses from wet and dry canopy evaporation were calculated for the period 8 October 1999 to 26 May 2000 (Table 5). Losses from transpiration at all three sites were substantially higher than those attributed to interception. The old Douglas-fir stand, for example, lost more than twice as much water from transpiration as it did from interception during this period. The combined losses from interception and transpiration were greatest for the young Douglas-fir stand (601 mm, or 82% of gross rainfall), followed by the old Douglas-fir stand (576 mm, or 74% of gross rainfall) and the stand of radiata (495 mm, or 61% of gross rainfall).

Table 5 – Water loss (mm) from interception and transpiration for the three stands (8 October 1999 to 26 May 2000)

	Young Douglas-fir	Old Douglas-fir	Radiata pine
Interception	219(±21)[†]	170(±23)	155(±31)
Transpiration	382(±118)	406(±106)	341(±88)
Total	601(±139)	576(±129)	495(±119)

[†] Standard deviation

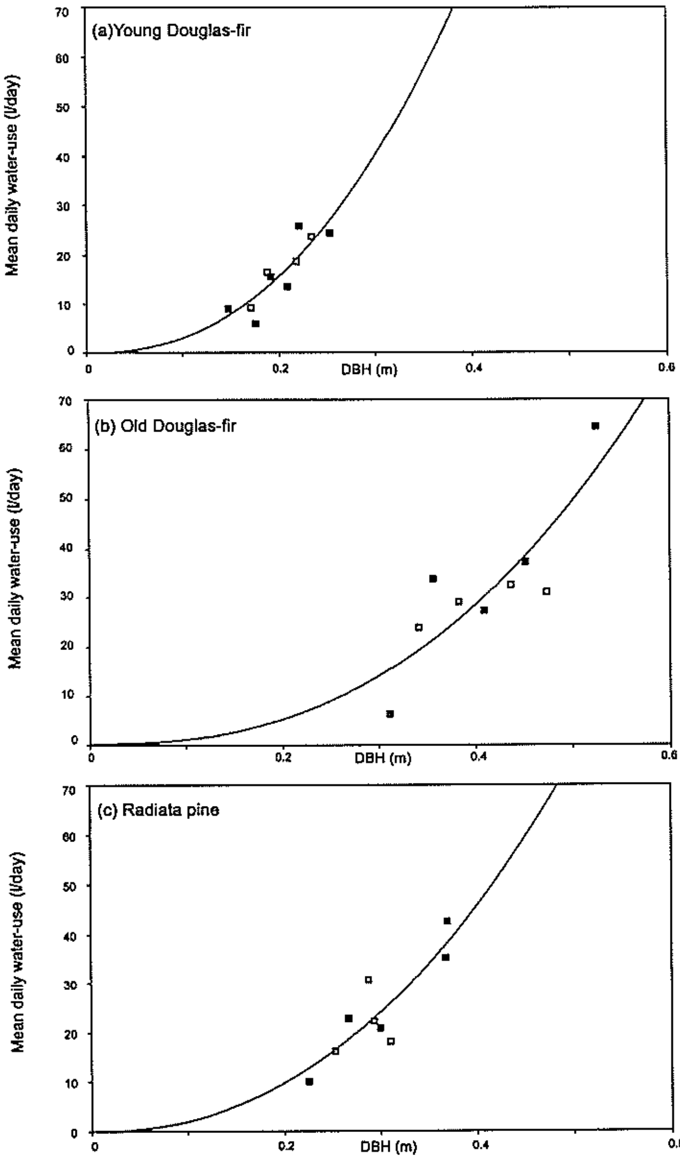

Figure 3 – Relationship between tree diameter at breast height DBH (m) and mean daily water loss (L/day), from which estimates of mean daily water use for each stand were derived. Open squares indicate the results for the four representative trees at each stand.

Discussion

Review of previous work on interception and transpiration

Douglas-fir interception

The only previously published report on interception by Douglas-fir in New Zealand is by Hogg *et al.* (1977). They compared throughfall totals beneath a 6-ha stand of 50-year-old Douglas-fir in Flagstaff Forest 11 km west of Dunedin (elev. 400 m). Measurements were taken for 6 months between December 1974 and May 1975. Mean throughfall in this period was 40.5% but varied from 11% to 76%. Thus, mean interception loss is about 60%, but with no allowance for stemflow.

Rothacher (1963) collected throughfall data from six plots in old-growth Douglas-fir in the H.J. Andrews Forest, Oregon. Stand density ranged from 417 to 1200 stems/ha. Interception loss averaged 24%. Zinke (1967) reported on interception measurements made by McMinn (1960) beneath stands on Vancouver Island. Averaged over 5 years, and ignoring stemflow, interception loss varied between 28% and 44% depending on stand height.

Rutter *et al.* (1975) compared monthly interception loss with model predictions for a 45-year-old Douglas-fir stand (stocking density, 660 stems/ha and a basal area of 14.3 m²/ha) in Hampshire in the United Kingdom. Interception loss averaged 25.5 mm/month or 39% of gross rainfall. Aussenac and Granier (1988) measured interception by a 19-year-old stand near Nancy in north-eastern France (rainfall 700 mm) to gauge the effects of thinning on water use and growth. Averaged over 3 years, the control stand at 2930 stems/ha and a basal area of 30 m²/ha intercepted 45% of gross rainfall, whereas the thinned stand (1500 stems/ha and a basal area of 20 m²/ha) intercepted 35%. Finally, Tiktak and Bouten (1994) calculated interception loss beneath a 29-year-old stand (stocking density, 992 stems/ha, and basal area 33.4 m²/ha) in the central Netherlands (mean annual precipitation at 830 mm) at 38%.

Radiata pine interception.

Studies of interception by radiata pine in New Zealand show losses ranging between 20% and 30% (Blake, 1975). More recently, Duncan (1995) measured throughfall and stemflow near Moutere in the Nelson area for 6 years under young radiata pine with a stocking density of 500 stems/ha. Interception averaged 23% over the period.

A number of studies on interception by radiata pine have been conducted in Australia over the last 25 years. Smith (1974), for example, estimated interception by a 34-year-old stand in Lidsdale State Forest, New South Wales, Australia at 18.7%. Feller (1981) monitored interception by a 35-year-old plantation in the Maroondah catchment north-east of Melbourne over a 24-month period. In the first 12 months, interception was 30%, and in the second 21% of total rainfall. In the same general area, Langford and O'Shaughnessy (1978) compared interception by five native communities and three conifer plantations, including a 17-year-old radiata pine stand (stocking density, 1745 stems/ha) and a 47-year-old Douglas-fir stand (stocking density, 668 stems/ha). The interception losses quoted were 21.4% for radiata pine, and 27.9% for Douglas-fir. Crockford and Richardson (1990) conducted a detailed investigation into interception by eucalypt forests and radiata pine stands in the Upper Yass Representative Basin north-east of Canberra, Australia. The radiata pine was planted at 1700 stems/ha in 1962, and thinned to 700 stems/ha in 1982. Before thinning, annual interception was 22%. Finally, Myers and Talsma (1992) measured interception in three stands of a 10-year-old radiata pine plantation (700 stems/ha) in ACT, Australia, over 2½ years and found the annual rate to be 20.4%.

The above review suggests that interception by Douglas-fir ranges from 24% to 60% of gross rainfall, whereas interception for radiata pine plantations in New Zealand and Australia ranges from 19% to 30%. The reason for the wider range in interception loss for Douglas-fir is unclear, but, unlike the radiata figures, the data include results from natural as well as plantation forests. However, they support the main findings of the present study, that plantations of Douglas-fir are likely to intercept more water than their radiata counterparts.

Douglas-fir transpiration.

Few studies have sought to estimate long-term water loss by transpiration from either species. At a site near Nancy in north-eastern France, Granier (1987), using heat-pulse techniques, measured the total transpiration in an unthinned (2545 stems/ha) 24-year-old Douglas-fir stand over a 2-month summer period at 74 mm. During the equivalent southern hemisphere months (January and February) transpiration by the young and old Douglas-fir stands in this study was 100 and 138 mm respectively. The lower transpiration from the French investigation can be partially explained by a decrease in available water within the rooting zone during the latter part of the study period.

Radiata pine transpiration.

Whitehead and Kelliher (1991a) used the Penman–Monteith equation to estimate transpiration by a 13-year-old radiata pine stand in the Purukohukohu experimental catchments, near Rotorua, New Zealand, from November 1986 to February 1987 at 370 mm. Teskey and Sheriff (1996) used Greenspan heat-pulse velocity probes to estimate transpiration by a 16-year-old radiata pine plantation in South Australia over a 5-month period from November 1993 to March 1994. Transpiration rates ranged from 6.8

to 1.4 mm/day, and total water loss for the study was 346 mm. Both these amounts are higher than that recorded during equivalent times at the Hororata pine stand (234 mm over 5 months, and 192 mm over 3 months). The higher totals in the Rotorua study may be attributable to non-limiting soil water conditions during the study period.

Water balance

The amount of water available for soil-water and groundwater recharge in a given period is calculated from the water balance equation, which apportions rainfall into interception loss, transpiration from the canopy, understorey evaporation, the change in soil-water storage, and drainage through the soil.

In this study, no measurements were made of evaporation from the understorey and forest floor. A number of New Zealand studies have sought to estimate components of the forest water balance for radiata pine, including understorey evaporation. For example, Whitehead and Kelliher (1991b) used a biophysical model to establish the water balance for an 11-year-old radiata pine stand at Longmile, near Rotorua, before and after thinning. Before thinning (stand density 754 stems/ha), and with an annual rainfall of 1623 mm, dry canopy evaporation was calculated at 639 mm (39%), wet canopy evaporation at 267 mm (17%), and understorey evaporation at 93 mm (6%), leaving 624 mm (38%) for the net addition to soil storage. The use of the same model by Whitehead and Kelliher (1991a) to calculate the annual water balance of a small catchment with a 13-year-old radiata pine cover (stand density, 575 stems/ha) at Puruki showed evaporation from the understorey and the forest floor to be 7% of rainfall (1403 mm). Dry canopy evaporation was estimated at 704 mm (50%), and wet canopy evaporation at 203 mm (15%). These data suggest that midway through the rotation for radiata pine, understorey evaporation may be 6–7% of gross rainfall. Given the maturity of the radiata stand at Steeles Road, understorey evaporation is estimated at 5%. Although there are no comparable data for Douglas-fir, we have assumed the same percentage loss from understorey evaporation for the old Douglas-fir stand at Plantation Road. The lack of an understorey at the young Douglas-fir stand, plus the high stand density (1360 stems/ha) suggest that little or no evaporation from the forest floor is likely at this site.

The total water storage capacity available for transpiration and recharge by excess rainfall in winter in mid-Canterbury is thought to be about 200 mm in 2.5 m of soil (Jackson *et al.*, 1993). Data for a Lismore soil near Burnham, 30 km east of Hororata, show readily available water in the upper metre at 38 mm, and total available water at 81 mm (Watt and Burgham, 1992).

Monthly rainfall totals for the period October 1999 to May 2000 at Hororata, midway between Steeles Road and Plantation Road, were compared with those for the long-term mean (Tomlinson and Sansom, 1994b). They show that rainfall for December, February, and May was less than normal, with February experiencing the greatest deviation (-22.7%). In November and January rainfall was well above average. Thus, the rainfall climate for the period during which transpiration measurements were available does not show any major departures from normal.

An approximation of the water balance for the three stands is presented in Table 6. Estimates of total evaporative water losses from the three stands were similar in magnitude, but differed in percentage terms. They suggest that, during the warmer months, losses from wet and dry canopy evaporation are likely to be greater for Douglas-fir throughout the rotation than for radiata. This pattern is also reflected in the estimates of water surpluses available for soil-water and groundwater recharge. About 34% of the rainfall was potentially available for recharge at the radiata stand, and 26% at the young Douglas-fir stand. The low figure of 13% listed for the old Douglas-fir stand is partly explained by the lower rainfall at this site.

Table 6 – Water balance estimates (mm) for the three stands for the period 8 October 1999 to 26 May 2000. Figure in brackets is percent of gross rainfall

	Young Douglas-fir	**Old Douglas-fir**	**Radiata pine**
Gross rainfall	816	700	816
Interception	219 (27)	170 (24)	155 (19)
Transpiration	382 (47)	406 (58)	341 (42)
Understorey evap.	0	35 (5)	41 (5)
Total losses	601 (74)	611 (87)	536 (66)
Avail. for recharge	215 (26)	89 (13)	280 (34)

Conclusions

This study shows that in the low-to-moderate rainfall regimes of mid-Canterbury, Douglas-fir plantations through much of the rotation are likely to lose more water through interception and transpiration than those in radiata pine. In terms of gross rainfall, Douglas-fir may intercept 5–10% more water than radiata pine, especially early in the rotation. When the two plantation species are compared, interception loss from Douglas fir may be 40% higher than that from radiata pine. Whereas the statistical level of significance identifying the difference in interception is only marginal, the observed difference between the two species under plantation conditions is similar to that recorded in the literature. When related to gross rainfall, transpiration by mature stands of Douglas-fir may be 10–20% higher than by equivalent stands of radiata pine.

The reduction in water available for soil-water and groundwater recharge quoted above for the two species will only be applicable in areas of low-to-moderate rainfall. When Douglas-fir is grown in cooler, high-rainfall areas, the annual interception loss in percentage terms may not be much different from that recorded in this study. However, it is likely that transpiration losses, both in absolute and in percentage terms, will be lower. For example, Pearce and Rowe (1979) concluded from a review of the New Zealand literature that, in areas where annual rainfall exceeds 1500 mm, losses through evaporation of intercepted water may be as much as 70% of the total losses. This of course would be true for both Douglas-fir and radiata pine planted in the cooler, wetter climates of New Zealand. Therefore the total water loss from both species in these climates may lead to similar reductions in runoff through the course of a planting rotation. The only difference would be in the rate of change, with the faster-growing radiata pine causing the more rapid reduction.

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