EXOTIC TREES IN THE CANTERBURY HIGH COUNTRY

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ABSTRACT

A survey of exotic trees in the Canterbury high country showed that less than 0.1% of the 1.8 million ha region is occupied by exotic trees. The major species present were Corsican pine (**Pinus nigra** subsp. **laricio** (Poir.) Maire) > ponderosa pine (**P. ponderosa** C. Lawson > radiata pine (**P. radiata** D. Don) > European larch (**Larix decidua** Mill.) > Douglas fir (**Pseudotsuga menziesii** (Mirb.) Franco). A strong rainfall gradient was the major determinant of growth and, on average, could account for over 75% of the variability in wood production. In the moist zone growth rates were good, with basal areas and volumes of over 130 m^2/ha and 1500 m^3/ha respectively being attained by 40–50 years. Maximum net annual increment ranged from <10 m^3/ha to >30 m^3/ha, depending on moisture availability. Other site factors such as slope, aspect, and exposure appeared to influence growth but made minor contributions to the statistical analysis. Malformation (excluding butt sweep in larch) was worst in radiata pine (43% of all stems measured) > larch (32%) > Douglas fir (21%) > Corsican pine (18%) > ponderosa pine (10%). Wood densities tended to be low, in line with the national trend of decreasing density with increasing latitude and altitude. European larch showed the greatest incidence of spread of self-sown seedlings (62% of all stands), followed by Corsican pine (42%), ponderosa pine (37%), Douglas fir (36%), and radiata pine (25%). The incidence of forest pathogens was low. Forestry is an efficient form of land use in parts of the Canterbury high country, and has a definite role in any diversification away from traditional pastoral land use.

Keywords: forest inventories; Canterbury; high country; **Pinus nigra** subsp. **laricio**; **Pinus ponderosa**; **Pinus radiata**; **Pseudotsuga menziesii**; **Larix decidua**; site factors; productivity.

INTRODUCTION

Trees have been planted in the high country since the early days of pastoralism, but forestry has not been practised extensively. Early runholders in the Canterbury high country planted trees for local shelter, timber and firewood supplies, and occasionally as a requirement of land tenure. The larger areas of mature plantations originate from these tenure plantings and from the enthusiasm of individuals such

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as T. D. Burnett of Mt Cook Station and H. E. M. Hart of Lake Coleridge Power Station. The major species planted were radiata pine, Corsican pine, ponderosa pine, Douglas fir, and European larch.

The high country has been used mainly for extensive pastoral farming of fine-woolled sheep. In the Canterbury region, a little over 100 runholders manage approximately 1 million ha with an over-all stocking rate of approximately 1 stock unit/ha (Kerr *et al.* 1979). In recent years, the future of extensive pastoralism has been questioned, and forestry has been suggested as a possible form of diversification. Past observations (Morrison 1919) and more recent research by the Forest Research Institute at altitudes above 900 m have shown that the high country climate is suitable for tree growth (Benecke *et al.* 1975; McCracken 1980; Ledgard & Baker 1982). However, information on tree growth in the high country has been inadequate for proper evaluation of land use options. This survey investigates the performance of existing Canterbury high country stands as part of an assessment of the growth and potential of exotic trees in the South Island high country.

SURVEY AREA

The eastern South Island high country covers approximately 3.5 million ha, of which the Canterbury region occupies about 1.8 million ha (Fig. 1). For our survey the Canterbury region was defined as the area bounded to the west by the Southern Alps and to the east by the frontal ranges, and includes the basins and valleys of the upper catchments of the Waiau, Hurunui, Waimakariri, Rakaia, Ashburton, Rangitata, and Waitaki Rivers. The survey was restricted to areas below 900 m (approximately 500 000 ha) and did not include the remote and physically rugged, western montane valley systems. Lower altitudinal limits in the region are approximately 450 m.

The climate is characterised by an even seasonal distribution of rainfall and high levels of solar radiation. However, strong winds, unseasonal frosts, occasional heavy wet snows, and in some locations drought, may adversely affect tree growth. Rainfall increases in the survey area from 500 mm/year in the east to 2000 mm/year in the west.

Landforms are generally gently sloping outwash fans and extensive flat river terraces. Soils developed on these surfaces are mostly yellow-grey and yellow-brown earths derived from greywacke parent materials.

The original extensive cover of woody vegetation (trees and shrubs) has largely disappeared as a result of repeated fires and overgrazing. Present day high country vegetation is dominated by modified short tussock grasslands composed principally of hard tussock (*Festuca novae-zelandiae* (Hack.) Ckn.) and introduced grasses (mainly *Agrostis tenuis* Sibth. and *Anthoxanthum odoratum* L.) with an increasing herbal component, notably of hawkweeds (*Hieracium* spp.). Less intensively grazed areas contain scrub associations dominated by matagouri (*Discaria toumatou* Raoul), *Dracophyllum* spp., *Cassinia* spp., and manuka (*Leptospermum scoparium* Forst.).

METHODS

The objective of the survey was to characterise the potential for tree growth. Sampling was therefore restricted to the fully stocked portions of plantations. Most stands also contained some incompletely stocked areas resulting from poor establishment

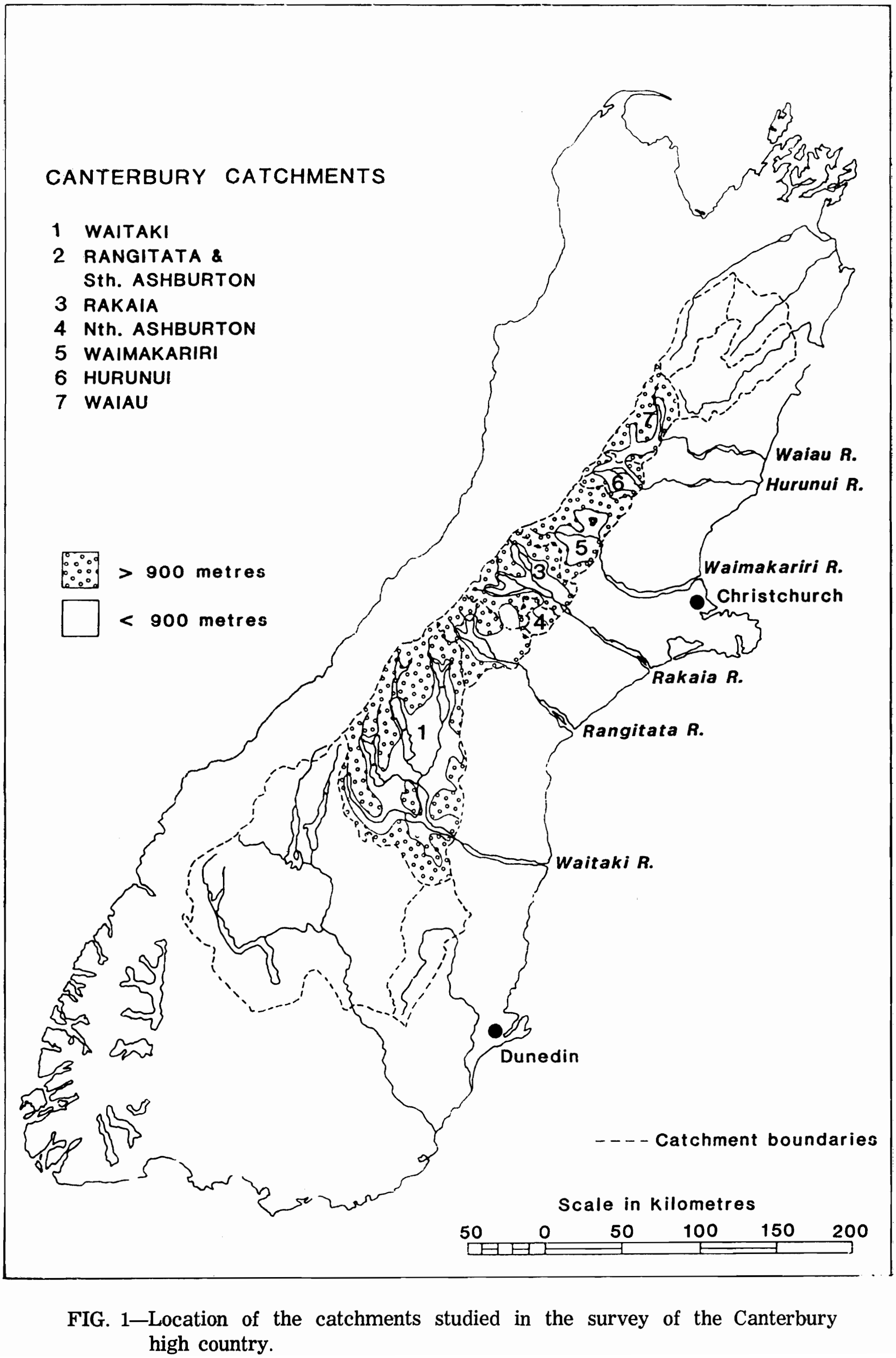

FIG. 1—Location of the catchments studied in the survey of the Canterbury high country.

or damage from severe climatic events, but these areas were not sampled. Therefore the results do not express the average growth of each plantation visited, but the potential growth which should be achieved with good establishment and average climatic conditions.

Plots were established in 281 stands. Wherever possible, plots were located on topographically uniform sites. Areas of trees showing edge effects were excluded.

Sampling Technique

Three plot types were used:

(a) Hexagonal 500-m^2 plots, slope-corrected on six axes, were used wherever possible. Of the 169 plots eventually used in the analysis, 93 (55%) were of this type.

(b) Rectangular plots (400–500 m^2) were used mainly on flatter sites where no slope compensation was required and in woodlots or wide shelterbelts too small to accommodate the 500-m^2 plots. Thirty-seven (22%) of the plots analysed were rectangular.

(c) Where stands were too small or irregular in shape for the use of bounded plots, 25 adjoining trees were sampled by the following modification of a point-centred quarter method (Mueller-Dombois & Ellenberg 1974). The horizontal distance from the centre of each sample tree to the nearest tree in each 90° sector (0–89°, 90–179°, 180–269°, and 270–359°) was measured and mean distances (100 in all) were squared to obtain the area occupied by each tree and hence the stocking. The method was adopted after comparisons with conventional bounded plot techniques showed it to be accurate and easy to implement. Thirty-nine (23%) of the plots analysed were of this type.

Stand Information

The species, its origin or provenance (if ascertainable), the area covered, original spacing, and silviculture were recorded for each stand. Stand age was determined by ring counts on recently cut stumps, by increment cores, or by counting branch whorls.

The following variables were measured in each plot:

- Diameter of each stem at breast height (1.4 m above ground level, on the uphill side on sloping ground);
- Heights of 10 trees selected from three diameter classes (excluding suppressed trees); large (four trees, including the largest), medium (two trees), and small (four trees);
- Numbers of malformed trees (those with multiple leaders, or any stem defect such as twist, bend, or sweep, which would adversely affect recoverable volume);
- Distance of spread of self-sown seedlings (0–20 m, 21–100 m, and >100 m).

Average stand height, mean top height (average height of tallest 100 trees/ha), basal area (over bark), and total stem volume (under bark) were calculated from these measurements and relevant volume tables (N.Z. Forest Service unpubl. data).

Severe malformation (no stemwood considered recoverable), butt sweep in larch, the presence/absence of cones, and any evidence of insect attack and fungal disease were also noted.

Core samples (5 mm in diameter) were taken for wood density measurements from between nine and 20 plots in each of the five major species. The sites sampled covered the whole range of precipitation. Basic densities were determined after drying and the extraction of resins. Weighted densities were determined by adjusting the density of consecutive five-ring sections from pith or bark according to their relative basal area.

Tree Growth Rate

Three indices of growth rate were calculated: mean annual volume increment (MAIV), mean annual basal area increment (MAIB), and mean annual top height increment (MAIH). Each index is a net stand value and excludes any losses from mortality.

Preliminary analysis indicated that rainfall was the major site variable influencing tree growth and that the best relationships between growth rate and average annual rainfall were obtained using MAIV. The survey results showed that high country stands have higher basal areas than normal for a given stand height and age in relation to general yield table values. Therefore height indices (such as MAIH and site index) are less reliable indicators of volume yield and reliability declines further when making comparisons between species as height/volume relationships vary with species.

The age of sample stands varied from 25 to 75 years with a mean age of 44 years. To provide a basis for comparison of data of different ages, and to fulfil the objective of characterising the potential productivity of high country stands, net plot volume increment (MAIV) was adjusted to give an estimate of maximum net volume increment per hectare prior to age 50 (MAIV max.). Maximum volume increment was selected because it is the only variable that can provide an unbiased and concise productivity comparison. A benchmark of 50 years was selected because most stands had achieved their maximum MAIV before this age, or were close to their maximum at age 50 so that any further increases were small and of no practical significance.

Age correction was made from MAIV/age models of the form $\mathrm{MAIV} = \mathrm{EXP}\,(B_0 + B_1 \times (\frac{1}{T}) + B_2 \times (\frac{1}{T})^2)$ (Appendix 1) which were developed for each species (and for moist and dry areas where necessary) using data from the present survey and from higher altitude, unthinned, N.Z. Forest Service permanent sample plots (N.Z. Forest Service unpubl. data). MAIV max. was then calculated by multiplying the actual plot MAIV by the ratio: model estimate of maximum MAIV/model estimate of MAIV at the given plot age.

No age adjustment was applied to stands older than the peak MAIV age in the relevant model, or to stands aged 50 years or over. In practice only 32% of all stands were age adjusted, and within these stands the mean increase in MAIV due to adjustment was 22%. The average MAIV max. for each species differed from the average MAIV by 5% (radiata pine), 10% (Corsican pine), 4% (ponderosa pine), 8% (Douglas fir), and 3% (European larch).

Age-adjusted mean volume increment (MAIV max.) had a better relationship with rainfall than MAIV, and was used to relate tree growth to site variables, and for comparison of species' growth rates.

Climate

A revised isohyetal map (Belton & Ledgard 1984) was used for all rainfall records. Local farmers were consulted on the frequency and severity of strong winds, droughts, heavy or unseasonal frosts, floods, or heavy snowfalls. Climatic events of historical importance (e.g., the hard winter of 1968, the heavy snows of August 1973) and their effects on tree growth were recorded.

Physiography

Plot altitude was obtained from NZMS 1 topography maps. Five topographic categories (A – flat slopes <5°; B – lower gentle slopes 5–16°; C – mid/upper steeper slopes >16°; D – gullies; and E – ridges), and three drainage categories (good, moderate, impeded) were used to describe sites. Aspect and slope were measured and exposure estimated by topex ratings (Pyatt *et al.* 1969). Macrotopex (Mactpx) was determined by summing the angles from the plot centre to the horizon, measured along the eight principal compass points. Microtopex (Mictpx) was determined by reading angles from the plot centre to a point 50 m distant, again along the eight principal compass points. Weighted microtopex (WMictpx) was calculated by adjusting microtopex readings to emphasise the influence of the prevailing north-west wind. Weightings were: NW × 3; N and W × 2; E, NE, S, SE, and SW × 1.

Soils

A profile was exposed at each site and described in terms of horizon depth, structure, organic content, colour, and biological activity. Soils were then grouped into one of three categories to give an index of soil quality.

Poor soils – eroded soils; podzolised soils in higher rainfall zones, or recent alluvial soils with a high proportion of stones or gravel and few fines.

Medium soils – well-developed soils of limited depth, with shallow A horizons and relatively compact B horizons.

Good soils – younger soils with continuing inputs of loess, and soils with deep A horizons of good structure and no obvious restriction to rooting depth.

The basement material at each site was noted and the effective rooting depth was estimated, either from soil pits, from road cuts, or from pits exposed by windthrown trees. Soil sets were identified from the N.Z. Land Resource Inventory Worksheets (National Water and Soil Conservation Organisation 1975). Because sample size for some sets was small, soils were classed into five generic groups representing different moisture regimes and soil development processes:

Brown-grey earths and yellow-grey earths (Grampians, Meyer Hill, Otematata Hill sets);

Dry hygrous yellow-brown earths (Pukaki, Dalgety, Mackenzie, Tekapo, Tekapo Hill sets);

Hygrous yellow-brown earths (Craigieburn, Cass, Cass Hill, Tekoa Hill sets);

Recent hygrous yellow-brown earths (Mesopotamia set);

Recent alluvial soils (Tasman, Dobson sets).

Soil samples from the top 0–15 cm of mineral soil were collected from 130 representative sites where nutrient enrichment from animals or fertiliser topdressing of adjacent areas were judged negligible. Samples were analysed for pH (H_2O); total nitrogen, determined calorimetrically with an automated Pye Unicam modification of the indolphenyl blue method; and inorganic (0.5 m H_2SO_4) phosphorus, using the method of Blakemore *et al.* (1972).

Land Use Capability

Each site was ascribed to a Land Use Capability Class (LUC) (National Water and Soil Conservation Organisation 1975).

Statistical Analysis

Of the 281 plots established, 27 were located in stands of minor species too poorly represented numerically for inclusion in the analysis. A further 85 plots located within stands of the five major species were rejected because the trees were immature (<20 years old), or because of inferior provenance (e.g., *P. ponderosa* var. *scopulorum*), access to ground water, unknown or significant thinning histories, major storm damage, or variable stocking or age. The remaining 169 plots used in the analysis were distributed as follows: radiata pine 34, Corsican pine 42, ponderosa pine 41, Douglas fir 24, and European larch 28.

The GENSTAT (Lawes Agricultural Trust 1984) regression analysis package was used for examining relationships between growth indices and site factors. Initially, correlation matrices were generated for each species as an aid to selection and ordering of site variables for development of multiple regressions. Further sorting was achieved by stepwise testing of multiple regressions, with the final criterion for inclusion or exclusion of variables in the optimal multiple regression being sufficient reduction of the residual variance (residual standard deviation). Multiple regressions relating MAIV max. to site factors were developed for each species.

Classificatory variables, which could not be ascribed values, were analysed by the contrasts between a selected "average" class and the other (n-1) classes. For soils, topography, and land use capability classes, the "average" classes selected were soil group C, topographic group A, and LUC Class IV.

RESULTS

Area and Location of Exotic Trees

The area of exotic trees over 5 years of age in the Canterbury high country was estimated to be 1250 ha (about 0.2% of the approximately 500 000 ha surveyed, or less than 0.1% of the total area of the Canterbury high country – 1.8 million ha). Most stands were less than 2 ha in size, and approximately 10% were shelterbelts. Nearly 70% of all plantings were located in the southern (Waitaki) part of the region.

Apart from comparatively recently, little planting has been done over the last 25 years. Consequently, two-thirds of all exotic stands were aged over 20 years. The average age of sample stands was 44 years (radiata pine 43, Corsican pine 42, ponderosa pine 45, Douglas fir 41, and European larch 46). The largest areas of young trees have grown from self-sown seedlings.

Corsican pine and ponderosa pine were the most common species encountered, together comprising more than 50% of all plantings (Table 1). However, the distribution of coniferous species was uneven between catchments, and stands of these two pines and of European larch were most common in the Waitaki catchment. Radiata pine was the most common species in the central and northern areas of the survey region, but was scarce in the Waitaki catchment. Douglas fir stands were thinly but evenly distributed throughout the survey area. Other conifers were encountered less frequently, the most common being *Pinus contorta* Loud. > *P. muricata* D. Don > *P. pinaster* Ait. > *P. sylvestris* L., and occurred mostly in small groups or as isolated trees.

Most plantations occurred on LUC Class VI land (61% of the plots), with Class IV 27%, Class III 8%, and Class VII 4%.

TABLE 1—Area of the major exotic tree species found in the Canterbury high country

Species	Area (ha)	(%)
Corsican pine	438	35
Ponderosa pine	248	20
Radiata pine	161	13
European larch	149	12
Douglas fir	112	9
Other conifers (**P. contorta** > **P. muricata** > **P. pinaster**)	120	10
Broadleaved species	12	1
TOTAL	1240	100

Exotic broadleaved species were found mainly in sheltered moist sites. Their absence from exposed sites and their low total area may have reflected their unsuitability for much of the high country environment rather than limited plantings in the past. Sycamore (*Acer pseudoplatanus* L.) was the most common broadleaved species. Others occurred in small groups or as isolated specimens, mostly in the better sites adjacent to homesteads. Of these, the silver birch (*Betula pendula* Roth.) and the English rowan (*Sorbus aucuparia* L.) were the most frequent. Other broadleaved trees often encountered were the oaks (mainly *Quercus robur* L. and *Q. palustris* Muenchh.), English elm (*Ulmus procera* Salisb.), common ash (*Fraxinus excelsior* L.), claret ash (*F. excelsior* 'raywoodii'), common lime (*Tilia europaea* L.), copper beech (*Fagus sylvatica* L.

'purpurea'), *Laburnum anagyroides* Med., common walnut (*Juglans regia* L.), hazel (*Corylus avellana* L.), black alder (*Alnus glutinosa* (L.) Gaertn.), Gean cherry (*Prunus avium* L.), false acacia (*Robinia pseudoacacia* L.), poplars (lombardy – *Populus nigra* 'Italica', silver – *P. alba* L., black – *P. deltoides* Marsh.), willows (crack – *Salix fragilis* L., golden weeping – *S. babylonica* L. var. *vitellina*), eucalypts (mainly *Eucalyptus gunnii* Hook. f.), and fruit trees (mostly pip fruits).

Growth Rates of the Five Major Exotic Tree Species

The net basal areas and volumes of older plots in the moist zone were very high. More than one-third of all Douglas fir and ponderosa pine plots of 40 years or older had total basal areas of over 130 m^2/ha and contained standing volumes of over 1300 m^3/ha. The highest ponderosa pine basal area and volume measurements recorded were 175 m^2/ha and 1728 m^3/ha. The best stands of radiata pine and Corsican pine had basal areas of about 120 m^2/ha and contained over 1300 m^3/ha in standing volume. Only two European larch stands had basal areas of over 100 m^2/ha, but five stands contained over 1000 m^3/ha in total volume. One exceptional 60-year-old larch stand had a basal area of 120 m^2/ha and a standing volume of 1550 m^3/ha.

Projections of growth rates from regressions on rainfall for each of the five major species are given in Table 2. Generally volume growth rates were in the order radiata

TABLE 2—Mean annual increments of top height (MAIH), stand basal area (MAIB), and stand volume increment (MAIV max.) in four rainfall zones* in the Canterbury high country

	Rainfall (mm)			
	600–800	800–1000	1000–1200	1200–1400
Radiata pine				
MAIH (m/yr)	0.66	0.73	0.78	0.84
MAIB (m^2/ha/yr)	2.02	2.41	2.67	2.81
MAIV max. (m^3/ha/yr)	18.7	24.0	27.7	29.6
Corsican pine				
MAIH (m/yr)	0.45	0.49	0.53	0.57
MAIB (m^2/ha/yr)	1.78	2.10	2.38	2.61
MAIV max. (m^3/ha/yr)	13.1	17.6	21.3	24.0
Ponderosa pine				
MAIH (m/yr)	0.46	0.51	0.56	0.62
MAIB (m^2/ha/yr)	2.08	2.51	2.78	2.91
MAIV max. (m^3/ha/yr)	14.5	19.6	23.5	26.2
Douglas fir				
MAIH (m/yr)	0.57	0.58	0.63	0.70
MAIB (m^2/ha/yr)	1.70	2.27	2.69	2.95
MAIV max. (m^3/ha/yr)	14.4	20.5	26.1	31.2
European larch				
MAIH (m/yr)	0.46	0.50	0.56	0.64
MAIB (m^2/ha/yr)	1.32	1.56	1.72	1.82
MAIV max. (m^3/ha/yr)	11.9	14.6	17.4	20.4

* Values calculated from regressions on rainfall

pine > Douglas fir > ponderosa pine > Corsican pine > European larch, the main exception being Douglas fir, which had the highest growth rate in the moist (>1200 mm) zone, and lower growth than ponderosa pine below 800 mm rainfall. Annual basal area increments were higher for ponderosa pine than radiata pine but Douglas fir was again ahead in the moist zone. European larch had the lowest rate of basal area growth in all rainfall zones. Mean top height increments were on average 18% better for radiata pine than for Douglas fir. Larch and ponderosa pine had similar height increments and Corsican pine had marginally the slowest.

Mean annual volume increments of mature stands of all species in the higher rainfall high country zones compared well with stands in other regions, both in New Zealand and overseas (Table 3). Mean annual basal area increments were consistently higher than those from other regions, but mean annual height increments were mostly lower. Because stand stockings were similar in wet and dry regions, the MAIB/MAIH ratios (Table 3) indicate that trees from the wetter zones were stouter than trees of the same species grown in drier parts of the high country. Similarly, the ratios indicated that high country trees generally were shorter but broader than their counterparts elsewhere.

Stocking rates in unmanaged stands were high. Mean stockings for the five major species were radiata pine – 685 stems/ha, Corsican pine – 1360 stems/ha, ponderosa pine – 1400 stems/ha, Douglas fir – 1085 stems/ha, and larch – 1175 stems/ha. Similar stocking rates have been found in mature, unthinned stands of the same species in other parts of New Zealand (N.Z. Forest Service permanent sample plots, unpubl. data). High stocking rates do not explain the good productivity of the stands in wetter areas.

Growth and Site Factor Relationships

Of the site variables tested, rainfall consistently had the strongest influence on growth. Mean volume increment was most strongly related to average annual rainfall, followed by basal area increment, while mean top height increment correlations were the weakest (Table 4). Correction of age bias in volume increment data (MAIV→MAIV max.) improved the correlations for all species except European larch.

The importance of rainfall in plot productivity is immediately apparent from Fig. 2. For European larch and Douglas fir, the influence of rainfall is represented by a simple (linear) function which expresses a consistent limiting effect of moisture on growth over the whole range of sites sampled. For the three pines, quadratic (curvilinear) functions more accurately characterised growth. The ranges of productivity values for Corsican pine and ponderosa pine at any point along the rainfall gradient were comparatively restricted. Over 85% of the stands were within 3.0 m^3/ha/yr of the rainfall-based regression line, and the narrow range of values was maintained even in the higher rainfall zone where increase in productivity was levelling off. This pattern, together with the observation that the growth rates of the best stands on moist sites in these favourable conditions were amongst the highest recorded for these species, suggests that the physiological limits to growth were being approached. The dispersion of plots for radiata pine increased as productivity levelled off and rainfall became less limiting to growth. Radiata pine is capable of much higher rates of growth than we

TABLE 3—Growth rates of five coniferous species in the Canterbury high country and other forest growing regions

Species	Location	Age (yr)	MAIH (m/yr)	MAIB (m^2/ha/yr)	MAIB/MAIH ratio	MAIV (m^3/ha/yr)	Source
Radiata pine	Canterbury high country (dry <800 mm)	c.45	0.66	2.02	3.1	18.7	1
	Canterbury high country (wet >1000 mm)	c.45	0.81	2.74	3.4	28.6	1
	Kaingaroa	40	1.16	1.90	1.6	28.0	2
	Chile (average)	27	—	—	—	24.0	3
Corsican pine	Canterbury high country (dry)	c.45	0.45	1.80	3.9	13.1	1
	Canterbury high country (wet)	c.45	0.55	2.50	4.6	22.9	1
	N.Z. Site Quality 1	50	0.56	1.84	3.3	17.3	4
	United Kingdom (best)*	50	0.53	1.90	3.5	20.0	5
Ponderosa pine	Canterbury high country (dry)	c.45	0.46	2.08	4.5	14.5	1
	Canterbury high country (wet)	c.45	0.59	2.84	4.8	24.8	1
	N.Z. Site Quality 1	50	0.65	1.91	2.9	19.1	4
	U.S.A. (N. California)	50	0.61	1.38	2.3	15.0	6
Douglas fir	Canterbury high country (dry)	c.45	0.57	1.70	3.0	14.4	1
	Canterbury high country (wet)	c.45	0.67	2.82	4.2	28.6	1
	N.Z. Site Quality 1	50	0.78	1.68	2.2	23.1	4
	United Kingdom (best)*	50	0.69	2.27	3.3	24.0	5
	Canada (best)	70	0.74	1.09	1.5	18.5	7
European larch	Canterbury high country (dry)	c.45	0.46	1.32	2.9	11.9	1
	Canterbury high country (wet)	c.45	0.60	1.77	3.0	18.9	1
	North Island pumice land	65	0.52	0.85	1.6	9.8	2
	United Kingdom (best)*	50	0.51	1.36	2.7	12.0	5

* United Kingdom volumes and basal areas are cumulative (i.e., include thinnings).

Sources:

1. High country survey.
2. Unpublished N.Z. Forest Service permanent sample plot data.
3. Matte 1971.
4. Duff 1956.
5. Hamilton & Christie 1971.
6. Oliver & Powers 1978.
7. Klinka et al. 1981.

TABLE 4—Comparison of r^2 values between four growth indices and rainfall for the five major conifers in the Canterbury high country

	MAIV max.	MAIV	MAIB	MAIH
Radiata pine	0.56	0.43	0.38	0.31
Corsican pine	0.76	0.72	0.42	0.27
Ponderosa pine	0.85	0.76	0.57	0.53
Douglas fir	0.77	0.70	0.56	0.21
European larch	0.52	0.56	0.37	0.20

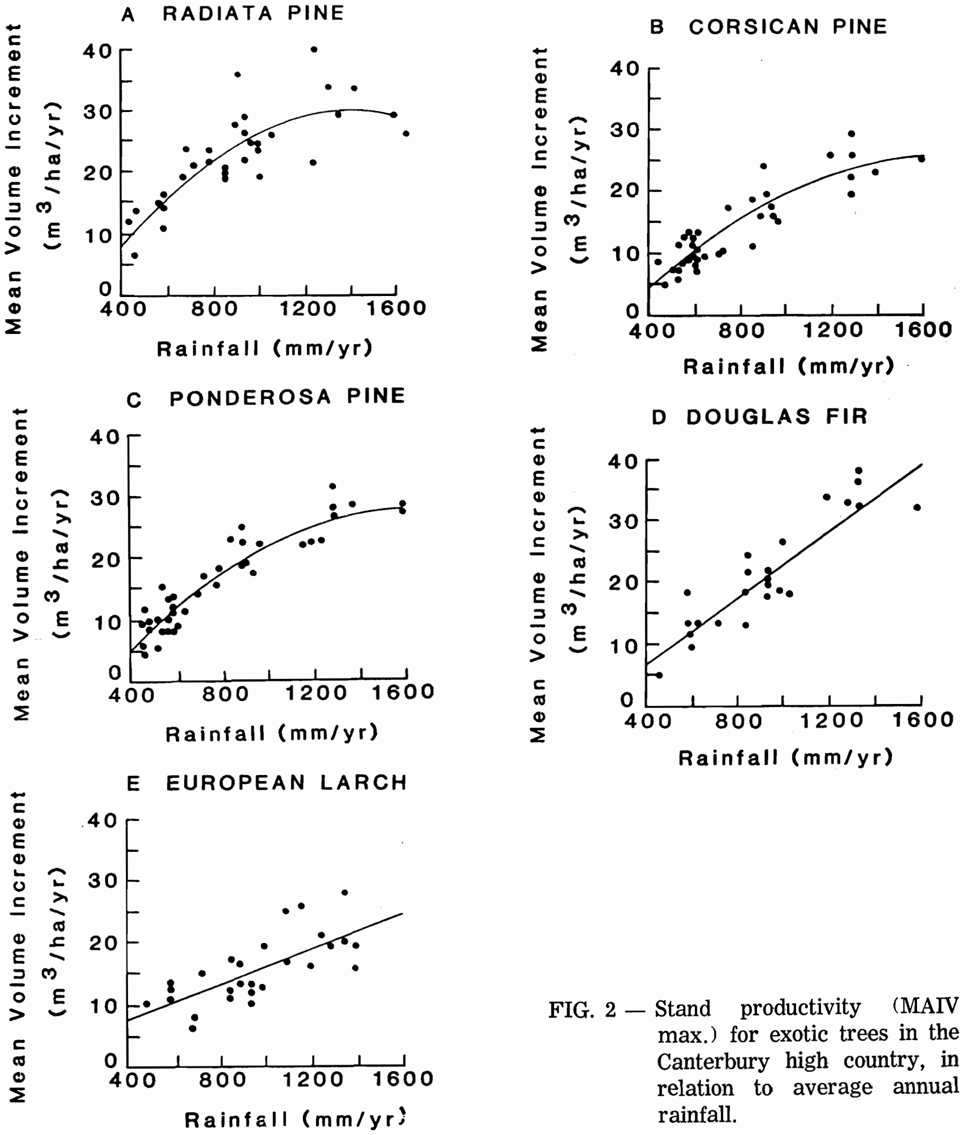

FIG. 2 — Stand productivity (MAIV max.) for exotic trees in the Canterbury high country, in relation to average annual rainfall.

recorded, and it would appear that growth rates in the moist zone were particularly sensitive to the influence of other site factors.

The dominant influence of rainfall and the linkage between rainfall and many other site factors limited the usefulness of simple correlations between growth and individual site factors. For example, a strong relationship was indicated for each species between growth and macrotopex, but similar levels of relationship were also found between macrotopex and rainfall. This can be explained by the coincidence of higher macrotopex readings westward amidst the more mountainous terrain with the zone of higher rainfall. Many of the other relationships between growth and site variables indicated in the correlation matrices could also be explained by linkage with rainfall.

The uneven and often poor representation of plots amongst the major groups of soil sets limited the usefulness of comparisons of mean growth rates with soil groups (Table 5). Comparisons of growth based on soil groups were further compromised by the wide variation in rainfall within the groups and by the bias within the dry hygrous yellow-brown earth group of Douglas fir and European larch plots towards moister sites and ponderosa pine and Corsican pine plots towards the drier sites. Nevertheless, a trend of faster growth with increasing soil moisture was evident. Only the poorest soils markedly retarded growth, but too few plots were affected for reliable characterisation by regression analysis. It may be surmised that, for the sites sampled, soil type had little or no bearing on growth independent of moisture factors.

In relation to N.Z. Soil Bureau ratings (Miller 1968), soils beneath stands contained medium nitrogen and high inorganic phosphorus levels (Table 6). Both elements were generally in sufficient quantities for good tree growth except for some recent gravelly alluvial soils and strongly leached and erosion-degraded steepland soils. The average level of inorganic phosphorus for each soil group fell into the "Very High" category, whereas generally these soils possess medium to high inorganic phosphorus levels (Miller 1968). Other investigations of more readily exchangeable inorganic phosphorus levels for the conifers in comparison to data for grassland topsoils indicated probable phosphate enrichment (Belton pers. comm.), which may have considerable implications for the management of combined forestry/pastoral systems.

All soil types were moderately to strongly acid (Table 6) with pH values consistent over a wide range of soil moisture regimes despite the expectation that soil pH would decline with increasing rainfall (Walker & Adams 1959). In the moist zone the range of pH values corresponded with those expected (Miller 1968); however, in soils of the drier regions, particularly the brown-grey earths and recent soils, topsoil acidity had increased by up to 1 pH unit.

The best multiple regressions found, representing the more influential site factors in terms of reduction of residual variance, are given for each species in Table 7. In the same table r^2 values for regressions on rainfall alone are shown to illustrate the improvements in accountability achieved by the multiple regressions. The largest improvements were 34% for European larch and 15% for radiata pine. For both species, the r^2 values for MAIV max. on rainfall alone were comparatively low, which suggests that their growth rates were more sensitive to other site factor influences than the growth rates of Corsican pine (10% improvement) and ponderosa pine and Douglas fir (<3% improvement). Over-all, however, the relationships between productivity and site

TABLE 5—Productivity of conifers and the frequency of their occurrence within five soil groups in the Canterbury high country

	Brown-grey and yellow-brown earths	Dry hygrous yellow-brown earths	Hygrous yellow-brown earths	Recent hygrous yellow-brown earths	Recent alluvial soils
Corsican pine					
(n = 42) Freq. (%)	11.9	47.6	14.0	9.5	17.0
MAIV max. ± s.d. (m³/ha/yr)	9.5 ± 2.3	13.8 ± 5.9	20.0 ± 5.3	22.5 ± 3.6	9.3 ± 2.3
Douglas fir					
(n = 24) Freq. (%)	4.1	42.4	8.0	33.4	12.1
MAIV max. ± s.d. (m³/ha/yr)	5.5 ± 0.8	16.8 ± 5.0	26.0 ± 10.3	24.7 ± 9.1	19.7 ± 11.4
Ponderosa pine					
(n = 41) Freq. (%)	12.2	46.4	12.2	14.6	14.6
MAIV max. ± s.d. (m³/ha/yr)	7.7 ± 2.3	13.2 ± 4.7	22.3 ± 8.0	24.5 ± 4.1	15.6 ± 8.2
Radiata pine					
(n = 34) Freq. (%)	11.8	38.2	20.6	20.6	8.8
MAIV max. ± s.d. (m³/ha/yr)	14.0 ± 2.3	18.3 ± 5.9	19.5 ± 9.5	30.0 ± 3.3	28.4 ± 9.2
European larch					
(n = 28) Freq. (%)	3.6	39.3	35.7	21.4	—
MAIV max. ± s.d. (m³/ha/yr)	10.8 —	12.1 ± 3.1	19.0 ± 4.3	17.7 ± 6.5	—

TABLE 6—Mean soil (0-15 cm) pH, total nitrogen, and inorganic phosphorus (0.5 m H_2SO_4 - mg %) for soils under exotic forest in the survey area (standard deviations are shown in parentheses)

Soil	pH (H_2O)	Nitrogen (%)	Phosphorus (mg %)
Brown-grey and yellow-grey earths n = 12	5.2 (0.2)	0.32 (0.15)	47.7 (11.3)
Dry hygrous yellow-brown earths n = 40	5.3 (0.3)	0.32 (0.07)	47.2 (14.2)
Hygrous yellow-brown earths n = 28	5.2 (0.3)	0.40 (0.12)	34.8 (15.6)
Recent hygrous yellow-brown earths n = 22	5.2 (0.4)	0.38 (0.11)	52.1 (19.1)
Recent alluvial soils n = 19	5.6 (0.3)	0.32 (0.11)	44.9 (16.0)

variables were similar in each multiple regression, being characterised by strong rainfall coefficients and by relatively insubstantial coefficients representing (almost exclusively) physiographic site factors.

The multiple regressions (Table 7) indicated a positive relationship between slope and productivity for the three pine species, particularly Corsican pine. However, for Corsican pine, and to a lesser degree ponderosa pine, the hill terrain topography classes were generally associated with poorer growth. The apparent contradiction may be partly explained by positive effects of slope within individual topography classes.

Positive effects of general local shelter (microtopex) were also indicated for radiata pine and Corsican pine stands. For radiata pine, indications of better growth on sites with north-west aspects could reflect a response to higher temperatures. Higher skylines (higher macrotopex values) were positively related to European larch and Douglas fir growth. This effect may be related to better conditions for moisture conservation in the more mountainous areas. Field observations on species other than radiata pine indicated some benefit from sloping southerly aspects in dry areas where protection from desiccating northerly winds and direct sunlight may have lessened moisture stress.

An improved relationship from inclusion of soil quality index was achieved only for Corsican pine. Although small positive effects were obtained for most species by addition of soil classes to the optimal regressions, only one soil group coefficient (for Douglas fir – indicating reduced growth on dry hygrous yellow-brown earths) was significant ($p = 0.05$). Lower growth rates on alluvial soils were also indicated for three species, but because sample sizes were small the individual soil group coefficients were not significant. Consequently, it was decided to omit soil groups from the multiple regressions.

TABLE 7—Best multiple regressions found for the relationship between MAIV max. (m^3/ha/yr) and environmental variables

Environmental variables*	Corsican pine	Douglas fir	Ponderosa pine	Radiata pine	European larch
Constant term	0.64	-5.09	-0.81	-14.32	-11.10
Rain	10.70	23.24	48.98	66.20	13.81
Rain^2	4.28		-14.31	-24.96	
Topo B v. A	-1.78n		-1.69n		4.77
Topo C v. A	-5.51		-7.58		-1.31n
Topo D v. A	-9.17				-2.11n
Topo E v. A	-8.19		-3.19n		1.71n
Slope	0.375		0.193	0.119	
Mictpx	6.0 E^{-2}			0.115	
WMictpx				-6.6 E^{-2}	
Mactpx		7.38 E^{-2}			4.9 E^{-2}
Alt					1.3 E^{-2}
Soil quality index	1.36				
r^2	0.88	0.82	0.90	0.82	0.84
residual s.d.	2.51	3.79	2.57	3.40	2.48
On rainfall alone					
r^2	0.78	0.79	0.88	0.67	0.52
residual s.d.	3.08	4.03	2.63	4.32	3.77

Coefficients are not significantly different from zero ($p < 0.05$) if denoted by "n"

* For explanation of variables, see METHODS Physiography

A series of multiple regressions were run on the smaller number of plots from which topsoils were sampled to examine any effect of total nitrogen and inorganic phosphorus on productivity. No improvement to the relationship between MAIV max. and rainfall was achieved.

The categorical variables representing drainage, basement material, and land use capability were all eliminated at early stages of the analysis, as they were ineffective in explaining variation in productivity.

The range of altitudes sampled (450–750 m) on this survey did not have any significant bearing on growth, except for larch for which altitude was positively related to growth. Field observations also indicated that, up to approximately 900 m, moisture and exposure had a greater effect on growth than altitude *per se.*

Wood Density

Weighted cross-sectional basic wood densities for the five major species were between 3% and 5% lower than the unweighted densities (Table 8). The high stocking and advanced age of the stands resulted in marked compression of rings in the middle and outer sections of the stem, and hence a lower outerwood influence compared to the less dense but wider rings closer to the pith. Unweighted and weighted average cross-sectional densities fell in the order European larch > radiata pine > Corsican pine >

TABLE 8—Average basic wood densities of the five major exotic tree species in the Canterbury high country (standard deviations are shown in parentheses)

Species	No. of sites sampled	Average age (yr)	Mean cross-sectional density (kg/m³)		Outerwood density, rings 31–35 incl. (kg/m³)
			Unweighted	Weighted	
Radiata pine	17	39	395 (23)	378 (18)	423 (20)
Corsican pine	20	50	390 (32)	374 (22)	425 (30)
Ponderosa pine	19	46	361 (25)	347 (19)	392 (29)
Douglas fir	9	42	380 (20)	367 (10)	400 (44)
European larch	10	55	427 (33)	409 (32)	457 (27)

Douglas fir > ponderosa pine. However, timber strength properties do not necessarily follow the same order, as other wood characteristics such as knot distribution and grain deviation also influence wood strength.

The sites sampled for wood density were in rainfall zones varying from 500 mm to 1600 mm, but no relationship was found between rainfall and density, nor between growth rate and density. The total sample was too small to test other site variables.

The radiata pine stands conformed to the normal pattern of density increase from the pith outwards, with values ranging from 350 kg/m^3 at the pith to a maximum of 445 kg/m^3 in the outerwood. Weighted cross-sectional densities varied from 342 to 406 kg/m^3. By New Zealand standards the timber was generally of low density, similar to other Canterbury/Southland material (Cown & McConchie 1984).

Corsican pine density levels ranged from 350 kg/m^3 at the pith to 400–450 kg/m^3 in the outerwood. These values represent the low end of the range in New Zealand (Cown 1974). Weighted cross-sectional densities varied from 344 to 421 kg/m^3. They were highest (395–409 kg/m^3) in the Mt Cook region and near Lake Coleridge (421 kg/m^3), but 90% of the samples had mean densities of under 400 kg/m^3.

Ponderosa pine density increased from around 320 kg/m^3 at the pith to a maximum of 470 kg/m^3 (near Mt Cook) in the outerwood, but over 60% of the samples had weighted cross-sectional densities of less than 350 kg/m^3. Differences in provenances may contribute to some of the variation found in ponderosa pine, as it has been found that a New Zealand provenance (originating from the Mackenzie Basin) growing in Craigieburn Forest Park, is significantly denser than two imported provenances of similar age.

Douglas fir density increased from 350 kg/m^3 at the pith to around 430 kg/m^3 in the outerwood. Cross-sectional densities were low by New Zealand standards, with the weighted average density of 368 kg/m^3 being substantially lower than the 400 kg/m^3 given by Harris & Orman (1958) for 35-year-old stands sampled from 11 New Zealand sites.

The density of European larch timber increased from about 350 kg/m^3 at the pith up to 500 kg/m^3 in the outerwood, with an average outerwood value of 457 kg/m^3.

This is considerably lower than overseas outerwood values and also lower than the mean density of 512 kg/m^3 for four North Island and three South Island clearwood samples given by Bier (1983).

These results conform with the trend established by other surveys (Harris 1973; Cown 1974; Cown & McConchie 1984) of a decrease in basic wood density with increasing latitude and altitude. The sites included in our survey were mostly beyond the altitudinal range of material examined in these surveys and showed correspondingly lower density levels.

Malformation

Malformation was most severe in the species with fast initial height growth. The percentage of malformed stems (including multiple leaders, stem twist, bend, or sweep, but excluding butt sweep in larch) fell in the order radiata pine (43%) > European larch (32%) > Douglas fir (21%) > Corsican pine (18%) > ponderosa pine (10%). Observations during the survey and those of farmers suggested that strong winds were the most frequent cause of damage. Heavy wet snows may also cause extensive damage (Hughes 1969, 1974), but no relationship was found between malformation and rainfall, despite the likely increase in frequency of falls of heavy wet snow with increasing rainfall. However, younger stands, which are more prone than older stands to damage from climatic events, were not frequently encountered on the survey, and light damage in the early phases of stand development may have been difficult to detect in the more mature stands, especially in the higher rainfall zones where recovery would have been more rapid.

Severe malformation where no stem wood, including roundwood, is recoverable, was noted most often in European larch and radiata pine. European larch was more susceptible than the other species to wind damage, mostly in the form of butt sweep, and radiata pine was most prone to snow damage. The incidence of severe malformation within the other three species was low (<2%).

Over 60% of all European larch stands contained a high proportion (>60%) of stems severely affected by butt sweep over the first 1–2 m of the stem. The few stands where the incidence of butt sweep was minor were on steep (>20°) slopes with south to south-east aspects and were well sheltered from the prevailing westerly winds.

Insect Pests and Diseases

Symptoms of insect pests and fungal diseases were usually observed in combination with stress caused by factors such as low rainfall or infertile soils. For example, radiata pine was largely free of disease in the high rainfall areas north of the Mackenzie Basin but within the Mackenzie, where radiata pine is of minor occurrence, *Diplodea pinea* (Desm.) Kickx and *Sclerophoma* sp. were identified and were probably a major cause of the few cases of terminal dieback observed. Similarly, in ponderosa pine terminal dieback caused by *D. pinea* was observed most frequently in the drier regions, as were holes of *Sirex noctilio* Fabricius in suppressed trees. Premature needle cast, probably caused by *Cyclaneusma* sp., was occasionally noted on ponderosa pine throughout the high country. The pests and diseases found in ponderosa pine were also present in Corsican pine, but this species seemed less affected.

Douglas fir and European larch were largely free of pests and diseases. Chlorotic foliage and premature needle cast were observed on some Douglas fir stands on poor soils, but these symptoms were attributed primarily to nutrient deficiencies.

Insect infestations were common amongst some of the minor species. The pine woolly aphid, *Pineus laevis* (Maskell), was observed in the few *P. sylvestris* stands visited, and in one, defoliation was severe. Minor infestations were also noted on *P. mugo* Turra, mainly in the wetter regions. The spruce aphids (*Elatobium* sp. and *Adelges* sp.) were present throughout the high country, and severe defoliation of spruces was common. The common eucalypt insect pests, *Paropsis charybdis* Stål and *Gonipterus scutellatus* Gyllenhal, were occasionally observed throughout the region, but infestation levels high enough to retard tree growth were rare.

Although a variety of symptoms, insects, and diseases have been mentioned, the incidence of forest pathogens was generally low, with a few exceptions for minor species (e.g., the spruces). The absence or very low incidence of important pathogens, such as *Dothistroma pini* Hulbary amongst the pines and *Phaeocryptopus gaeumannii* (Rohde) Petrak on Douglas fir, indicates an unfavourable environment for these fungal diseases.

Self-sown Seedlings

Self-sown seedlings were present outside 39% of all stands of the five major species (Table 9). The most vigorous self-seeding species was European larch (62% of all larch stands) and radiata pine was the least vigorous (25% of all radiata pine stands).

Seedling spread could not be significantly related to any of the major site factors even though field observations suggested that European larch spread more rapidly in the higher rainfall zones.

The ranking of species for distance of spread from the parent trees was similar, with European larch showing most spread further than 100 m (47% of all stands) and radiata pine the least (8%). With one exception, distance of spread was inversely related to seed weight, the anomaly being Douglas fir, the seed of which is lighter than that of Corsican pine and ponderosa pine.

TABLE 9—Frequency of occurrence of self-sown seedlings and distance of spread from parent trees in the Canterbury high country

Species	n	Number of sites with spread	Distance of spread		
			<20 m	20–100 m	>100 m
European larch	32	20 (62%)	2 (6%)	3 (9%)	15 (47%)
Corsican pine	57	24 (42%)	2 (3%)	9 (16%)	13 (23%)
Ponderosa pine	59	22 (37%)	1 (2%)	10 (16%)	11 (19%)
Douglas fir	42	15 (36%)	1 (2%)	6 (15%)	8 (19%)
Radiata pine	53	13 (25%)	1 (2%)	8 (15%)	4 (8%)
TOTAL	243	94 (39%)	7 (3%)	36 (15%)	51 (21%)

Self-sown seedlings were present adjacent to five of the seven *P. contorta* stands sampled. The seed of this species is lighter than that of European larch, and seedlings had established more than 100 m from the parent trees. Many of the earlier plantings of *P. contorta* were of the variety 'murrayana', which appears a less vigorous self-seeder than the variety 'contorta', which has been planted more in recent years.

Of the remaining pine species, 15% of the *P. muricata,* 50% of the *P. pinaster,* and both of the two *P. sylvestris* stands sampled had parented self-sown seedlings, but no seedlings were present under or adjacent to stands of *P. uncinata* Mirb., *P. mugo,* or *P. strobus* L.

Amongst other conifers significant spread (>20 m) of seedlings was recorded only from one group of *Chamaecyparis lawsoniana* (A. Murr.) Parl.

Of broadleaved species, sycamore, rowan, and wild or Gean cherry were most frequently accompanied by self-sown seedlings. Seedlings or root suckers were occasionally observed adjacent to stands of oaks, elms, false acacia, and some poplars and willows.

DISCUSSION

Growth Rates and Patterns

The growth potential for exotic trees in the Canterbury high country was better than expected. Growth rates for Douglas fir, European larch, Corsican pine, and ponderosa pine in the moist western zone were amongst the highest recorded for these species. Most notable were high standing volumes and basal areas relative to age. For example, the mean basal area of 41-year-old Douglas fir stands was 87 m^2/ha, with a maximum of 143 m^2/ha. In comparison, mean and maximum basal areas of 89 m^2/ha and 127 m^2/ha were measured for 250- to 1000-year-old Douglas fir/Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) forests in the Pacific north-west of the United States (Franklin & Waring 1980). Basal areas of 71 m^2/ha and standing volumes of about 1300 m^3/ha were measured in 70-year-old Douglas fir on the best sites in southern British Columbia (Klinka *et al.* 1981). One-third of the Douglas fir plots measured in the Canterbury high country exceeded 1300 m^3/ha in standing volume, with the best plot measured at 1568 m^3/ha. Stands of 49-year-old ponderosa pine near Flagstaff in Arizona (570 mm rainfall) had accumulated 59 tonnes dry matter/ha in bole material (approximately 150 m^3/ha) (Klemmedson 1975). Similar-aged stands growing under the same rainfall in our study averaged around 500 m^3/ha.

Only Karioi State Forest in the central North Island has basal areas and standing volumes as high as those recorded in the South Island high country. A mean basal area of 135 m^2/ha (best plot 158 m^2/ha) and a mean standing volume of 1573 m^3/ha (best plot 1949 m^3/ha) were recorded on 14 unthinned Douglas fir plots (average age 50 years) in this forest (N.Z. Forest Service permanent sample plots, unpubl. data). The average altitude of the Douglas fir stands at Karioi was 901 m, considerably higher than the altitudes usually encountered in exotic forests but similar, when corrected for latitude, to plots in the South Island high country.

The reason for such good productivity in the high country is not well understood, but is likely to involve the combined effects of an even seasonal distribution of rainfall, low incidence of pathogens, long needle retention and hence high leaf surface areas (A. H. Nordmeyer, pers. comm.), high levels of radiation, and marked diurnal temperature fluctuations, which are conducive to more-efficient carbon fixation.

In contrast to the high level of volume growth, height growth in the high country was generally slow, with mean top height increments rarely exceeding those recorded on better sites elsewhere. Use of site index for assessment of productivity in high country stands would have given a misleading impression of poorer growth.

Although the conditions for tree growth in the high country are different from those in most other New Zealand forestry regions, the patterns of growth of the five major exotic conifers surveyed were broadly similar to those found in other studies. New Zealand-grown, well-sited, unthinned Douglas fir has better height and volume growth than Corsican and ponderosa pine, but is superseded by ponderosa pine in basal area growth (Duff 1956). Our study established the same rankings, other than in the wettest rainfall zone (>1200 mm) where ponderosa pine was marginally inferior to Douglas fir in basal area increment. Duff noted that Douglas fir basal areas were always greater than radiata pine's and that, although the pine volume growth was initially faster, Douglas fir increased at a faster rate after about year 30. High country and other high altitude data (N.Z. Forest Service permanent sample plots, unpubl. data) indicated similar trends. Duff also showed ponderosa pine at age 50 to be approximately 15% faster than Corsican pine (12% at age 70), whereas high country figures indicated a difference of nearer 10% at age 40–50.

Growth patterns of high country radiata pine and Douglas fir stands could follow a similar trend to that found at Karioi. At age 50 in Karioi, both species have similar MAIVs, but a comparison of annual volume increments over recent years showed that growth of radiata pine was levelling off while growth of Douglas fir was still climbing. Radiata pine and Douglas fir stands at Karioi did not achieve maximum MAIV before ages 40 and 50 respectively, whereas at lower altitudes, peaks are reached at least 10 years earlier (Beekhuis 1978). Spurr (1963) found also that growth patterns for Douglas fir from Karioi were similar to those from the Canterbury high country. MAIV had not peaked before age 50 and high basal area increments were encountered at Karioi, although basal areas were generally higher in the South Island, with North Island trees being taller. At higher altitudes, therefore, peak volumes are reached later but often at higher levels than those of stands in lower lying regions.

Wood Density

Although growth rates in moister parts of the high country compared favourably with other New Zealand regions, wood density did not. In line with a trend of decreasing wood density with increasing latitude and altitude, Cown & McConchie (1984) found mean annual temperature gave the best correlations with density. They concluded that regional differences in wood densities will affect future end-use patterns. For example, for roundwood production the wood strength properties of load-bearing piles and poles are critical, and if radiata pine is to be managed for such produce, the areas growing higher density wood must be favoured (Cown & Hutchison 1983).

Corsican pine is generally acknowledged to be a similar timber to radiata pine (Weston 1957), and high-country-grown timber of this species is well received on the local sawlog market. Cosican pine is also regarded as an ideal species for roundwood (posts and poles) where strength, particularly in structural poles, is paramount. The density of the outer 20% of a pole is closely related to its strength (Cown & Hutchison 1983) and an outerwood density of around 450 kg/m^3 (D. J. Cown pers. comm.) is considered necessary for non-load-sharing poles (e.g., transmission lines, orchard windbreaks). Only four of the 20 Corsican pine samples in our survey had outerwood values of 440 kg/m^3 or more, but it is unclear why these samples were superior or why densities varied so widely, especially as Cown (1974) found genotypic variation in Corsican pine wood density to be minimal amongst the 41 sites he sampled. Before plantings of Corsican pine for roundwood in the high country are undertaken on a larger scale, further work is needed on this aspect.

Ponderosa pine is used mainly for non-structural purposes (e.g., pallet manufacture) and low-density timber from the high country should find a place in this market.

Douglas fir and European larch are two of the stronger softwoods and to date there has been no indication that their normal structural end-uses are likely to be jeopardised by their lower than normal density.

Site Factors Influencing Growth

The search for relationships between growth rate and site factors was handicapped by the inadequate representation of many site types in stands of exotic trees in the high country. In particular, hilly terrain, where the effect of factors such as slope, aspect, and shelter could be examined, was not well represented. In addition, the limited range of soil types and values recorded for soil quality index, total nitrogen, and inorganic phosphorus meant that no significant contribution to stand growth (in addition to rainfall) could be identified from these variables.

The results show that average annual rainfall is the primary influence on forest productivity in the Canterbury high country. On average 75% of the variability in volume growth could be attributed to rainfall.

Forest Productivity

Forestry potential within the Canterbury high country can be broadly defined by referring to rainfall isohyets (Belton & Ledgard 1984). The rainfall zone where good growth can be achieved lies between 800 and 1200 mm, with best growth rates being attained in the 1200- to 1600-mm zone. These two zones contain 200 000 ha of land which is physically suited to forestry (Table 10). The bulk of the remaining land below 800 mm (which possesses no physical limitation to forestry) lies within the Waitaki Basin.

The average potential growth rates determined from this survey can be exceeded where ground conditions are wetter than normal, and where the best management practices are employed. However, there are also areas of poor soils, notably recent stony alluvials and degraded hygrous yellow-brown earths (Belton & Davis in prep.), where growth could be severely limited.

TABLE 10—Land suited to forestry (by rainfall zones) within Land Use Capability Classes VI and VII in the Canterbury high country

Rainfall zones (mm)	Catchment areas (ha)					Total (ha)
	Waitaki	Rangitata	Rakaia	Waimakariri	Hope	
1200-1600	22 225	3 898	14 578	15 356	7 291	63 348
1000-1200	20 830	8 100	9 250	13 300	3 095	54 575
800-1000	26 899	21 600	16 451	12 548	—	77 498
500- 800	213 665	3 158	1 003	—	—	217 826
TOTAL	283 619	36 756	41 282	41 204	10 386	413 247

Note: All LUC Class III, IV, and V lands were excluded on the basis that they were suited for development for intensive farming. Also excluded, for reasons of climatic, soil, and topographic limitation, were all Class VIII lands, 80% of Class VII lands, and 5% of Class VI lands.

Forestry Potential

Traditionally, trees in the high country have been grown for non-commercial reasons such as erosion control, shelter, fuelwood production, and landscaping. This survey has identified commercial forestry as a potential land-use option. While the rather limited pool of data makes it unwise to draw firm conclusions as to how this forestry potential could be realised, the indications are that trees do grow well over a range of high country sites, particularly in the moist zone, and that certain species are more successful than others in adapting to high country conditions. Reasons for and against commercial forestry in the region have been discussed by Ledgard & Belton (1985) who pointed out that farm forestry would probably be the most compatible form of forestry under the existing forms of land tenure and management. There is no shortage of land suitable for such purposes. Within the Canterbury survey region alone, approximately 400 000 ha could be described as suitable for forestry.

Self-sown seedlings have sometimes been considered a problem in the context of forestry in the high country. However, most of the stands sampled were not spreading which implies that management options are available for controlling spread. For example, Benecke (1967) showed that seed spread could be checked by occasional heavy grazing. The location of plantations and the management of surrounding land are the keys to control of tree spread.

Forestry development in the high country has been restricted in the past by lack of information about tree growth in the region, by traditions of pastoralism, and by institutional restrictions linked with land tenure. Knowledge about growing trees in the high country has improved considerably over the last two decades, and has helped promote more confidence in trees amongst farmers. Progress in removing the institutional restrictions has been less rapid. Recognition of the potential of forestry as a land-use option in the high country is now justified, but must be considered in the context of other important high country uses such as pastoralism, tourism, and conservation.

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APPENDIX 1

AGE/MAIV MODELS (AVERAGE ANNUAL RAINFALL LIMITS IN PARENTHESES)

Radiata pine	(>1000 mm)	$\text{MAIV} = \text{EXP}\ (3.68 - 9.18 \times \left[\frac{1}{T}\right] - 37.3 \times \left[\frac{1}{T}\right]^2)$
	(700–1000 mm)	$\text{MAIV} = \text{EXP}\ (3.29 - 4.70 \times \left[\frac{1}{T}\right] - 50.7 \times \left[\frac{1}{T}\right]^2)$
	(<700 mm)	$\text{MAIV} = \text{EXP}\ (1.25 + 58.10 \times \left[\frac{1}{T}\right] - 672.7 \times \left[\frac{1}{T}\right]^2) + 1807.9 \times \left[\frac{1}{A}\right]^3)$
Corsican pine	(all sites)	$\text{MAIV} = \text{EXP}\ (3.22 + 6.93 \times \left[\frac{1}{T}\right] - 372.2 \times \left[\frac{1}{T}\right]^2)$
Ponderosa pine	(>650 mm)	$\text{MAIV} = \text{EXP}\ (3.22 + 0.20 \times \left[\frac{1}{T}\right] - 275.4 \times \left[\frac{1}{T}\right]^2)$
	(<650 mm)	$\text{MAIV} = \text{EXP}\ (2.34 + 9.06 \times \left[\frac{1}{T}\right] - 284.6 \times \left[\frac{1}{T}\right]^2)$
Douglas fir	(>850 mm)	$\text{MAIV} = \text{EXP}\ (3.23 + 13.35 \times \left[\frac{1}{T}\right] - 512.2 \times \left[\frac{1}{T}\right]^2)$
	(<850 mm)	$\text{MAIV} = \text{EXP}\ (3.24 - 9.62 \times \left[\frac{1}{T}\right] - 238.1 \times \left[\frac{1}{T}\right]^2)$
European larch	(all sites)	$\text{MAIV} = \text{EXP}\ (3.02 + 0.13 \times \left[\frac{1}{T}\right] - 145.1 \times \left[\frac{1}{T}\right]^2)$

T = age