ESTABLISHMENT PRACTICE ON FROST-PRONE SITES AT KAINGAROA FOREST

R. W. Washbourn

Abstract

Kaingaroa Forest is located on an elevated inland plateau at altitudes in excess of 500 m. It experiences a cold winter climate, and frosts (which occur throughout the year) have a major influence on forest establishment practices. Most of the first-rotation crop at Kaingaroa was established in less than a decade from 1924 and, despite the use of frost-hardy species, 5% of the area remained unstocked owing to frost problems. Establishment of the second-rotation forest commenced in 1946 on easy country, and it was not until 1964 that any serious attempts were made to establish or re-establish the higher frost flats and terraces above 610 m in southern Kaingaroa Forest. Radiata pine has now been successfully established on cold sites up to 885 m and under extreme summer/winter frost levels of $-4.5^\circ$C to $-14.0^\circ$C. The species had not previously been established on such sites. Trials showed that successful establishment requires: (1) Cultivation of the site prior to planting; (2) the use of well-conditioned planting stock; (3) planting no earlier in the winter than July; (4) the positioning of seedlings on mounds or ridges wherever possible; and (5) maintenance of a weed-free site for two years following establishment.

INTRODUCTION

Most of the 130 275 ha Kaingaroa State Forest lies on the central North Island's Kaingaroa Plateau, an elevated plain ranging in altitude from 490 m in the north to nearly 900 m in the south. About 60% of the forest (77 865 ha) has an average slope of less than $3^\circ$, a value too low to allow natural air drainage. It is thus prone to the formation of frost lakes or pockets (Page, 1971).

Restricted air drainage, particularly at altitudes of 540 m and above, gives rise to sites on which frosts can occur during any month of the year. In winter these can reach $-14^\circ$C. The Wairapukao† Forest meteorological station at 437 m re-

*N.Z. Forest Service, Kaingaroa Forest, via Rotorua.
†Place names mentioned in the text are shown on the map in Fig. 2.
cords an annual average of 124 days with a ground frost, and further south at Iwitahi up to 230 days per annum, with ground frosts have been registered. The climate of these high, flat parts of the forest is severe in comparison with most other areas being established in exotic production forests in New Zealand. In contrast, however, rolling and steep country bordering the plains generally has good air drainage and the microclimate is not severe.

**ESTABLISHMENT OF THE FIRST ROTATION CROP**

Establishment of the first-rotation crop at Kaingaroa Forest commenced in 1901 at Waioitapu. During the first 20 years, species were sited with some care, and planting and seedling quality were of a high standard (Kirkland, 1969). Nearly 14,500 ha of forest was planted during this period, but the area did not then include many of the hard sites on the Waioitapu/Waireka flats.

In the six years from 1924 (the plantation boom period), there was an enormous expansion of the establishment programme, and some 65,680 ha — or nearly one half of the total area of the forest — were planted. As the area established each year increased progressively, it was not possible to continue thorough preparation techniques, and every attempt was made to reduce costs. The standard planting espacement (initially 2 x 2 m) was increased to 2.4 x 2.4 m. Direct establishment was tried with line drilling, spot sowing, and broadcast sowing, though without great success. In the areas covered with silver tussock (*Poa caespitosa*) and monoao (*Dracophyllum subulatum*), tree seedlings were planted directly into the unprepared site. The hardest frost flats were either bypassed or established with species which subsequently failed. Little blanking or releasing was practised, and this general lack of attention, together with the depredations of rabbits, contributed to many poorly stocked stands.

By the time major planting ceased in 1936, Kaingaroa Forest consisted of nearly 107,000 ha of “stocked” forest, made up of radiata pine 45% by area, ponderosa pine 21%, Douglas fir 15%, Corsican pine 12%, lodgepole pine (*P. contorta*) 5%, and other species (*Larix decidua*, *Pinus muricata*, *P. strobus*, and *P. patula*) 2%.

Failures due to frost in Corsican and lodgepole pine stands are almost unknown, although these species were not planted on some of the hardest sites. Frost mortality did occur, however, in small areas of ponderosa pine, particularly along the lower-lying drainage channels. In Douglas fir stands, Kirkland (1969) estimated that frost accounted for the total failure of
approximately 2,440 ha of young established plantings in southern Kaingaroa, and was also implicated in the damage or partial failure of several hundreds of hectares in other areas.

For radiata pine a very different picture is evident. Frost was directly responsible for both partial stand failure and post-establishment damage. On uniformly flat country (e.g., the Waireka flats and western Matea), establishment was largely successful, with the exception of narrow stream channels where artificial frost pockets became concentrated as developing stands enclosed stream courses. In the rolling country of eastern Matea, the survival of radiata pine was clearly dependent on slope. The flat portions of many compartments failed completely, while even slight slopes allowed survival. Slopes of 3° carry a reasonable stocking, while slopes of 4° or more support nearly complete stockings.

There are many areas within the forest which have never carried a timber crop, either because they were unplanted in the first rotation or because original species failed. These sites, which may have scattered trees from an original planting, are characterised by the presence of monoao up to 1 m tall, with large sponge-like masses (8 cm to 20 cm thick) underfoot of the lichens Cladonia retepora and C. pycnoclada. One recent survey assessed these totally unstocked areas at 5,340 ha, or 5% of the total area of forest established as a first-rotation crop.

ESTABLISHMENT OF THE SECOND-ROTATION CROP

Clearfelling of the first-rotation radiata pine stands commenced in 1946 near the western escarpment of the Kaingaroa Plains at an altitude of 548 m. Natural regeneration was relied upon for the restocking of cutovers. The sites were gently undulating, and while there were numerous small hollows where damaging frosts occurred throughout the growing season, these were regarded as being of very local significance only.

The presence of frost-prone areas in the forest was recognised at an early stage by Ure (1950) who used the natural vegetation of the Kaingaroa Plains as an ecological indicator of site quality for exotic afforestation. He delineated the frost flats which had resulted in the unstocked components of the first-rotation forest, and doubted the wisdom of planting such sites.

Soil cultivation on frost flats was first tried in 1960, when a small area of previously unstocked forest land was double-disced and established with 2/0 radiata pine. Survivals were 82%, comparing favourably with the range of 77 to 95%
normally obtained on unprepared better site quality cutovers. The result was repeated in 1961 and complete site cultivation then became accepted as an economic silvicultural tool for new establishment on hard sites.

Aerial application of seed to supplement natural regeneration was initiated in the mid-1960s after winter-logged cutovers failed to regenerate adequately. The method was replaced by hand-planting, however, when seed losses from birds and rodents reached an unacceptable level.

During the first 20 years of second-rotation establishment only the relatively milder lowland sites were restocked, but after 1966 clearfelling moved towards the south of the forest, and cutovers were left for re-establishment on the flat country in Matea above 610 m. Initially the plantings were of lodgepole and Corsican pines, but in 1967 it was decided to cease further use of Corsican pine because of the impact of *Dothistroma pini* needle blight. Radiata pine was planted exclusively from then on.

Those hard site cutovers above 610 m which were re-established in 1966 and 1967 without any site preparation were largely unsuccessful. Examination of 588 ha of these cutovers planted in the three years 1966 to 1968 showed less than 15% of them to be adequately restocked.

**HARD SITE ESTABLISHMENT STUDIES**

Consequent on the re-establishment problem occurring on hard sites, a period of intensive establishment studies was started in 1967. Carried out both by forest staff and staff from the Forest Research Institute, these were designed to measure environmental factors and to formulate techniques for better hard site establishment.

(a) **Climate Studies**

Kaingaroa Forest is served by three synoptic weather stations, at Kaingaroa H.Q. (544 m) and Wairapukao Forest (437 m) in the north, and Waimihia Forest (743 m) to the south. Additionally, from about 1960 a number of temporary climate study stations (measuring rainfall, screen and ground minimum temperatures) have been maintained periodically within a number of different compartments on hard sites. Since 1967 these have been concentrated in southern Kaingaroa Forest. They have been located and serviced as part of a continuous climate study to define the limits of commercial establishment of radiata pine, Douglas fir, and other species, and to correlate their performance with prevailing conditions.
Fig. 1: Cold air temperature inversion over cultivated soil, compared with the growth of 2/0 radiata pine in the first 3 years following planting on a hard site at 580 m.

One of the most detailed temperature studies made was over a period of 14 months by Stolwyk (1970) in compartments 841 and 890. His important findings were:

(1) There was a clear association between silver tussock ground vegetation and severity of frost. The combination of lichens, mosses, monoao, and tussock acted as an insulator, thereby retarding heat flow to and from the soil; thus frosts were more severe over a vegetative cover than over cultivated or bared soil.

(2) Removal of all ground vegetation decreased frost levels at the soil surface by 2.2°C to 3.4°C. The colder the site, the more were temperatures ameliorated by vegetation removal.

(3) During frosts, a temperature inversion occurs between 3 cm and 18 cm above a cultivated soil surface (see Fig. 1).

An indication of the cold temperature regimes currently experienced on hard sites is given in Table 1, based on a compartment established with radiata pine in July 1975.

It is not the effect of winter frosts which damages young stands of radiata pine so much as unseasonal spring and autumn frosts. The frequency of unseasonal frosts at Kai-
TABLE 1: MONTHLY TEMPERATURE DATA FROM COMPARTMENT 1400 (885 m), KAINGAROA FOREST 1974-1977

Soils were free of vegetation. Lowest ground minimum temperatures (LGMT) and numbers of ground frost days (available from March 1976 only).

<table>
<thead>
<tr>
<th>Month</th>
<th>1974 LGMT (°C)</th>
<th>1975 LGMT (°C)</th>
<th>1976 LGMT (°C)</th>
<th>No. of Frost Days</th>
<th>1977 LGMT (°C)</th>
<th>No. of Frost Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan.</td>
<td>1.9</td>
<td>1.7</td>
<td>0.9</td>
<td>n.a.</td>
<td>5.3</td>
<td>1</td>
</tr>
<tr>
<td>Feb.</td>
<td>1.6</td>
<td>3.5</td>
<td>5.2</td>
<td>n.a.</td>
<td>1.8</td>
<td>0</td>
</tr>
<tr>
<td>Mar.</td>
<td>7.9</td>
<td>4.4</td>
<td>4.4</td>
<td>6</td>
<td>3.0</td>
<td>6</td>
</tr>
<tr>
<td>Apr.</td>
<td>5.3</td>
<td>5.5</td>
<td>6.9</td>
<td>8</td>
<td>6.1</td>
<td>13</td>
</tr>
<tr>
<td>May</td>
<td>9.5</td>
<td>8.7</td>
<td>10.6</td>
<td>24</td>
<td>7.5</td>
<td>20</td>
</tr>
<tr>
<td>Jun.</td>
<td>12.9</td>
<td>10.3</td>
<td>13.3</td>
<td>25</td>
<td>8.3</td>
<td>18</td>
</tr>
<tr>
<td>Jul.</td>
<td>8.6</td>
<td>13.7</td>
<td>12.5</td>
<td>22</td>
<td>4.6</td>
<td>18</td>
</tr>
<tr>
<td>Aug.</td>
<td>9.4</td>
<td>11.3</td>
<td>7.5</td>
<td>15</td>
<td>6.8</td>
<td>15</td>
</tr>
<tr>
<td>Sep.</td>
<td>10.6</td>
<td>9.9</td>
<td>7.8</td>
<td>11</td>
<td>6.7</td>
<td>20</td>
</tr>
<tr>
<td>Oct.</td>
<td>7.7</td>
<td>7.3</td>
<td>5.5</td>
<td>15</td>
<td>5.4</td>
<td>15</td>
</tr>
<tr>
<td>Nov.</td>
<td>6.8</td>
<td>7.8</td>
<td>8.1</td>
<td>8</td>
<td>4.0</td>
<td>14</td>
</tr>
<tr>
<td>Dec.</td>
<td>1.1</td>
<td>6.7</td>
<td>0.3</td>
<td>3</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>133</td>
<td></td>
<td>142</td>
</tr>
</tbody>
</table>

Ground minimum temperatures are from installations conforming to N.Z. Meteorological Service standards — i.e., from thermometers exposed horizontally with the bulb 2.5 cm above a level surface.

Kaingaroa Forest is such that minimum ground temperatures of $-5^\circ C$ and lower are recorded at least once between November and April in 3 years out of 5 (P. C. Brown, 1974, unpubl. rep.). Severely damaging frosts of $-10^\circ C$ and below in the spring and autumn months occur approximately every 5 years. In the last 20 years they have been recorded at Kaingaroa in 1958, 1963, 1969, and 1974.

The frost of 3 March 1974, for example ($-11^\circ C$ ground temperature), caught young stands in the autumn growth flush, and the damage was such that 550 ha of 1- and 2-year-old stands required replanting later that year.

(b) Species Selection

Radiata pine proved to be the most suitable species of several tried. Although lodgepole pine was easily established on hard sites, neither lodgepole nor muricata pines could match the growth of radiata pine in hard site establishment trials reported by Chavasse and Kearns (1973) and Menzies (1976c) at Kaingaroa Forest, and Menzies (1976a) at Karioi Forest.
(c) **Planting Stock**

Seedling quality is a critical factor in successful hard site establishment. Clear trends in both survival and growth were shown by Chavasse (1973), who demonstrated that larger trees grown at wider spacings in the nursery performed better than smaller trees or those grown at closer nursery spacings. The ability to put on rapid early growth immediately after planting was of paramount importance.

About 75% of Kaingaroa Forest's radiata pine seedling requirements for the annual planting programmes are currently drawn from Kaingaroa Nursery. This nursery, at an altitude of 544 m, concentrates its production of 2/0 stock for outplanting on the hard sites of the Kaingaroa Plateau. The specification calls for seedlings of not less than 30 cm in height, with a sturdy stem, a height to root collar diameter ratio of 60:1 or less, a well-developed fibrous root system, and a well-formed terminal bud. Using the DSIR's Climate Laboratory, Rook *et al.* (1974) showed that Kaingaroa stock was more resistant to frost than that of a number of other lower altitude nurseries.

(d) **Frost Hardiness**

On hard sites frost hardiness starts developing in March, increasing sharply in May (G. J. Brunsden, unpubl. FRI rep. 1975). A peak is reached in late August, and hardness is rapidly lost during September and October.

From measurements recorded at climate stations in Kaingaroa Forest, it appears that radiata pine seedlings can easily tolerate ground minimum temperatures of \(-4^\circ C\) or \(-5^\circ C\) in the summer and up to \(-12^\circ C\) in the winter of the first few years following planting. Critical frost levels for the autumn and winter months appear to be \(-7^\circ C\) for March and April, \(-8\) to \(-9^\circ C\) for May, building up to \(-14^\circ C\) for August (the winter peak), then dropping to \(-9\) to \(-11^\circ C\) for September and \(-8^\circ C\) for October. Menzies (1976b) suggests that, depending on the nursery of origin, \(-13^\circ C\) in the winter can be too severe for radiata pine, but this extreme has been exceeded on at least two occasions involving Kaingaroa stock without damage to young stands.

Investigations of natural frost tolerance of individual trees have been made only in recent years. First, seed collections have been made from isolated radiata pine trees of good form from the generally frost-damaged first-rotation crops on the Matea flats; stock raised from this seed has been outplanted since 1975 on several known frost flats. Secondly, the Forest Research Institute has selected surviving healthy seedlings
from frost-failed plantings. These have been propagated vegetatively and are under test for frost resistance.

Menzies (1976e) demonstrated significant differences in tolerance to spring frosts between families of radiata pine already in the Forest Research Institute breeding programme. It thus appears probable that, in the future, genotypes with increased frost resistance may become available for planting.

(e) Time of Planting

The best time to plant hard sites is after mid-winter, when trees are naturally hardened and the possibility of a prolonged period of hard frosts less likely (Chavasse and Kearns, 1973; Menzies, 1976d). Hardened and well-conditioned seedlings planted from July onwards are relatively unaffected by severe frosts in the first season, and put on rapid growth in the second season which helps lift them above damaging frost levels.

(f) Growth Studies

Most of the mortality in several Kaingaroa hard site trials was found to be due to unseasonal frosts in the second or third growing season after planting. Experience with radiata pine over the past 5 years suggests that mortality as a result of secondary infections by pathogenic fungi, as reported by Gilmour (1960), is very much less than death due to frost effects alone. Chavasse (1973) concluded significantly that frost damage appeared to be cumulative — i.e., once a young tree suffered serious physiological frost damage, it became more susceptible to later frosts. It was also demonstrated that almost all trees less than 25 cm in height were either killed or suffered severe frost damage at the time, whilst virtually all trees which had reached 75 cm height were unaffected. The reasons for this pattern are explained by Stolwyk’s (1970) data (Fig. 1), which showed that the coldest temperatures above bare earth lay from 18 cm to 48 cm above the surface. Once seedlings grow above 50 cm in height, their leading shoots become steadily less liable to frost injury, and may be out of the main frost damage zone by the time they attain a height of 100 cm. Measurements made in a conservancy growth trial have shown that radiata pine in southern Kaingaroa surpasses this 100 cm datum in the third growing season following planting (Table 2).

Experiments to determine whether fertilisers could increase height growth of newly planted stock, and thus carry seedlings above frost levels more rapidly, were carried out by Brunsden (1976). He concluded that, whilst a significant growth response was achieved, fertiliser application could not
TABLE 2: HEIGHT GROWTH OF THREE RADIATA PINE TREE STOCK TYPES ON A HARD SITE: TRIAL R.1655, COMPT. 566 (683 m).

<table>
<thead>
<tr>
<th>Nursery and Seedling</th>
<th>Year of Planting</th>
<th>Height (cm) in September</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nursery Age at Planting</td>
<td>1 yr after Planting</td>
</tr>
<tr>
<td>Owhata 1/0</td>
<td>38.1</td>
<td>51.5</td>
</tr>
<tr>
<td>Kaingaroa 1/0</td>
<td>28.3*</td>
<td>36.4</td>
</tr>
<tr>
<td>Kaingaroa 2/0</td>
<td>34.5</td>
<td>44.2</td>
</tr>
</tbody>
</table>

*Assessed 5 months later than the other seedlings.

be recommended for establishment on frosty sites; the frost tolerance of radiata pine was in fact lowered by fertiliser application. Other trials have not confirmed this result, and further research on this topic is currently being carried out in the DSIR's growth room (D. A. Rook, pers. comm.).

(g) Site Preparation

Two land preparation techniques were developed in the late 1960s after the recognition that natural regeneration would not adequately restock second-rotation stands on hard sites above 610 m. Windrowing with heavy machinery was introduced in Matea in 1968, and fire was used for land clearing prior to planting. Windrowing was preferred to burning, but the size of the potential programme prohibited all suitable country from being thus treated. The exposure of the mineral soil and the cultivation resulting from the windrowing operation had the effect of lifting frost levels, and allowed easier planting. Care had to be taken, however, not to impede downslope air drainage by aligning windrows across the slopes.

Cultivation of previously unstocked flat planting sites was practised on a large scale from 1972. Unstocked frost flats of 352 ha were intensively prepared by burning, discing and heavy chain harrowing, prior to machine-planting with 2/0 radiata pine. Ripping to 60 cm was necessary when subsurface pumice compaction was encountered. In 1973, rotary hoeing was shown to be significantly cheaper than discing and harrowing, and was used in the preparation of a large continuous block of 1 410 ha in southern Kaingaroa. Besides being cheaper, it produced a finer tilth to a greater depth, and thus became the preferred method on unstocked sites.

The invasion of Kaingaroa cutovers by weeds and grasses had been a gradual one since the mid-1950s, and by 1974 grasses were widespread even in southern regions of the forest. In that year, the significance of the relationship be-
tween grassy ground covers and severe frost damage to trees was finally recognised. Extensive use is now made of modified logging skidder spraying units for current weed control programmes of 3 500 ha per year on Kaingaroa Forest frost flats (Washbourn, 1977), with the aim of maintaining a vegetation-free ground surface for up to three years following planting. Rotary hoeing between the tree rows in cultivated stands (as a cheaper alternative to chemical weed control) has been found impracticable in northern Kaingaroa where there is a prolific and vigorous weed regrowth situation. It

Fig. 2: Kaingaroa State Forest showing the extent of frost-prone country with slopes of less than 3° according to Page’s (1971) classification, and place-names mentioned in the text.
appears, however, to have some potential on hard cultivated sites above 610 m.

Bedding harrows were tested at Kaingaroa in 1975, and have since been used in the preparation of about 350 ha per year. They can be used for the preparation of cutovers as well as previously unstocked sites, and the cultivated and compacted beds provide ideal soil conditions for seedling growth. Most importantly of all, tree seedlings planted along the crest of the bed are raised by up to 30 cm above the surrounding ground level — a clear benefit on frost-prone sites.

CURRENT ESTABLISHMENT PRACTICES ON HARD SITES

All of the frost-prone land with slopes of less than 3° in Kaingaroa Forest is included in two re-establishment classes (Page, 1971) which together amount to 77 860 ha, or 59% of the total area of the forest (see Fig. 2).

Over the last 5 years, annual restocking of areas on hard sites has averaged 62% of the total establishment programme. This proportion is likely to be maintained over the next 3 to 4 years with some 3 700 ha of frost flats being re-established each year. Radiata pine constitutes about 92% by area of today's establishment programmes, and is currently used on all hard sites in the forest.

The treatments used in hard site preparation over the last 4 years are detailed in Table 3.* Standard site preparation on formerly unstocked frost flats now involves up to three treatments — crushing and burning, occasionally some discing, ripping, and bedding. The resultant clean site, with varying degrees of bared and cultivated soil, is subsequently kept weed-free by spraying. Burning, windrowing, or bedding remain the preferred methods on cutovers. The use of bedding harrows will have increased significance as conversion of an extra 1 000 ha of flat cutovers in southern Kaingaroa, at altitudes of more than 610 m, becomes due for treatment each year. Climate studies have shown these sites to be among the hardest frost flats on which second-rotation establishment has been attempted in the last decade.

While mean top heights (at age 20 years) of first-rotation radiata pine were some 3 m lower on extensive frost flats than on hill country forest at the same latitude and altitude, improvements in establishment techniques of the second rotation are increasing site indexes by up to 5 m compared with the first-rotation forest (C. J. Mountfort, pers. comm.).

*With the exception of some of the windrowing and ripping, these operations are not carried out on parts of Kaingaroa Forest without a frost problem.
Radiata pine is growing satisfactorily as a 2-year-old crop on a hard frost flat at an altitude of 884 m in the Matea Extension. Further plantings of this species will extend to just over 900 m on rolling hill country in the same block, but on sites where there is very little frost risk. These altitudinal limits for Kaingaroa Forest correspond well with that of Menzies (1976a), who suggested that 880 m is nearing the ceiling for commercial stands of radiata pine.

CONCLUSIONS

From the results of studies commenced in the 1960s, general guides can be derived for ensuring a high degree of success in the establishment of radiata pine on hard sites of the central North Island. These include:

(1) The removal of all grass and weed vegetation from the planting site.

(2) Tree stocks should be obtained from an inland high-altitude nursery.

(3) Because seedling quality, size, and the ability to make rapid height growth after planting are of paramount importance, only balanced and well-conditioned tree seedlings, some 30 cm in height, should be planted on frost-prone sites.
(4) Planting should not be carried out earlier than July, when trees are naturally hardened and the possibility of prolonged frosty periods is less likely.

(5) Long-term survival and height growth are markedly superior when the trees can be planted on ridges or mounds where there has been some degree of soil cultivation.

(6) There is a need to control re-invasion of grasses and weeds for two to three seasons after planting.

If these provisions are followed, it should be possible to successfully establish radiata pine on hard sites up to about 900 m in altitude, having a minimum temperature frost regime of \(-4^\circ\text{C}\) in the summer and up to \(-14^\circ\text{C}\) in the winter.

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