# EFFECTS OF HEDGING RADIATA PINE ON PRODUCTION, ROOTING, AND EARLY GROWTH OF CUTTINGS

W. J. LIBBY
School of Forestry and Conservation,
University of California, Berkeley, California
and
A. G. BROWN and J. M. FIELDING*
Forestry and Timber Bureau, Canberra, Australian Capital Territory

(Received for publication 29 September 1971)

ABSTRACT

Genetic, physiological and morphological aspects of using rooted cuttings of radiata pine (**Pinus radiata** D. Don) for plantation forestry are reviewed. Techniques for providing low-cost cuttings which root and grow well have been investigated both at Berkeley, USA, and at Canberra, Australia. Over the 7-8 yr of the studies, the training of trees as hedges arrested the normal decline in rooting percentage quality of roots, and growth potential of cuttings taken from ageing tree-form plants. The hedges soon yielded over 100 straight cuttings per square metre of hedge top per year. The method could be a practical means of providing cuttings for raising large numbers of select stock for plantation establishment.

## INTRODUCTION

The case for using rooted cuttings of radiata pine (*Pinus radiata* D. Don) in production plantations has been presented (Fielding, 1964, 1970; Thulin and Faulds, 1968). This paper describes work conducted in the Australian Capital Territory and in California† during the past decade. The results suggest that the technique of hedging young radiata pine (*see* Figs. 1, 2 and 4) will provide an efficient method of mass-producing cuttings of desirable clones, maintaining a physiological condition which allows both continued high rooting success and subsequent growth vigour, while capturing some of the favourable developmental characteristics of radiata pine associated with maturation beyond its adolescent stages.

## BACKGROUND

The improvement of radiata pine via selection and sexual reproduction of the selected trees is well started in several centres, and offers great promise. At least four

* Present address: Forest Research Institute, Kepong, Selangor, Malaysia.

† The California experiments were supported in part by NSFGB 2550 and 5053. A comparison of the Australia and California experiments was made possible by travel grants to W.J.L. by the New Zealand-United States, and Australian-American Educational Foundations.

additional advantages can be gained by coupling vegetative propagation with a genetic selection programme: (1) Sexual reproduction captures only the additive genetic component of superiority among selected trees, while vegetative propagation *captures both the additive and non-additive genetic components of outstanding clones.* (2) Sexual reproduction results in genetic recombination, and thus a high degree of variability even within single families. Vegetative reproduction results in both *greater uniformity and predictability of many important characteristics* (selected and unselected) within each clone, and perhaps even within trees because of a reduction of the juvenile-to-mature transition as the tree grows. (3) Radiata pine, while a precocious seed producer, is frequently not a copious seed producer. The collection of sufficiently large quantities of seed to meet planting demands is proving to be both difficult and costly in many radiata seed orchards. The goal of planting genetically-improved trees in most or all radiata plantations can be quickly achieved by *expanding a limited number of genetically-improved seedlings via vegetative propagation.* (4) The *defects associated with radiata's adolescence can be partly or wholly avoided* by using rooted cuttings of a developmental stage beyond adolescence.

Several serious defects associated with radiata's early and later adolescent stages, such as retarded leader, crooked internodes, and excessive branching (Jacobs, 1937), can be reduced in frequency or degree by using physiologically more mature planting stock. Needle-blight susceptibility (Barnes, 1970; Garcia and Kummerow, 1970) and frost susceptibility (unpublished data from Dr G. B. Sweet to W.J.L.) may similarly be reduced. Many characteristics of the upper stem, such as straighter bole, lighter and more horizontal branching, and less forking, are maintained via vegetative propagules (Thulin and Faulds, 1968; Fielding, 1970). The valuable lower logs have less taper (about 70% of the taper of trees planted as seedlings), smoother and thinner bark, smaller and fewer branches (thus producing only 55%-75% of the knot area per unit surface compared to trees planted as seedlings), and less lean (50%-70% of trees planted as seedlings). Furthermore the growth in height of seedlings and rooted cuttings (from young ortets*) growing in adjacent plantations is similar. For instance, 28-yr-old rooted cuttings have attained heights of 36 m, and are similar to those of neighbouring trees planted as seedlings (Fielding, 1970).

On the negative side, stem cones are produced lower and more frequently on the valuable lower logs (Thulin and Faulds, 1968; Fielding, 1970). This is less serious if they are knocked off during early pruning, an operation made less costly with rooted cuttings by their fewer and smaller low branches. Browsing by various animals has been more severe on rooted cuttings than seedlings in Australia (Pawsey, 1950; Fielding, 1970) and New Zealand (Beveridge and Knowles, 1971), but the reverse has been true in California (W.J.L., unpublished data). As browsing animals react to the nutritional as well as morphological status of shoots, these differences may be a reflection of the different nursery environments of cuttings and seedlings, as well as different species of animals inflicting the damage. In addition, vegetative propagules from trees 20-30 yr-old may produce wood that is less dense and which has more spiral grain than that produced by seedlings of the same genotype (Nicholls and Brown, 1971).

* Ortet: original plant from which the vegetative propagules, called ramets, are taken.

The high cost of grafting, plus the probable loss of an unacceptable proportion of established plants because of graft incompatability at present makes it appear unlikely that grafting will be a practical technique for attaining the advantages of vegetative propagation on a large scale.

If rooted cuttings are used, a direct conflict with advantage (1) above develops. Genetically very good clones will not be identified until a large number of their cuttings have been grown for some time under a variety of conditions. Additionally, the clone's value further increases as management gains experience with it under a variety of conditions. However, rooting percentage and quality of the rooted cuttings both decline as the age of a clone increases (Libby and Conkle, 1966; Thulin and Faulds, 1968). Thus, as a clone becomes better identified genetically, and better known as a management entity, it also becomes more difficult to reproduce via rooted cuttings.

Moreover, whether rooted cuttings or grafts, at least the early growth rate of vegetative propagules from older trees is significantly less than that of propagules from younger trees or seedlings (Sweet, 1964; Fielding, 1969; Pawsey, 1971).

Thus there are serious adverse effects of increasing clone age on growth rate, rooting of cuttings, and some important aspects of wood quality. Re-propagation from the younger propagules, instead of from the original ortet, reduces these effects on at least rooting and growth rate (Fielding, 1969; Pawsey, 1971), but does not completely halt this process of maturation, given that the propagules are repeatedly allowed to develop a tree form. But Fielding (1954, 1969) and Matthews (1952, and pers. comm.) independently noticed* that cuttings from radiata pines which had been hedged (and their height growth repeatedly restricted) rooted more like young tree-form plants of about the same height, than like large tree-form plants of the same chronological age as the hedged plants. This observation on the apparent arresting of the changes in rooting normally associated with ageing of ortets led to the experiments reported below.

## CALIFORNIA EXPERIMENTS

### *Features*

(1) Ramets of a large number of clones, from the native populations, were hedged.
(2) The sample of clones included several ortet ages.
(3) Hedged and tree-form control plants were identical in genotype.
(4) Hedged and tree-form plants were grown in alternate planting spots on the site.
(5) Environmental conditions and rooting success varied from year to year.
(6) Rooting and root system form were evaluated.

### *Materials and Methods*

In 1962, cuttings were collected from 540 randomly selected trees: 15 trees from each of 12 stands in each of the three mainland populations of radiata (details of sampling and rooting given in Libby, 1964, 1969; Libby and Conkle, 1966). The rooting of these primary ramets was shown to be closely related to the age of the ortet (Libby and Conkle, 1966).

Two cuttings from each of 270 clones (nine randomly-selected clones from each

* Matthews based his work on investigations with hedged apple trees at the East Malling Research Station (Hatton and Rogers, 1942; Vyvyan, 1942; Garner **et al.,** 1955; Garner and Hatcher, 1955, 1957).

of 10 stands from each mainland population) were planted at Gill Tract near Berkeley, one in each of two adjacent blocks. Most were planted during spring 1963. Most of the remainder from slow-rooting clones or replacements for mortality, were planted in winter 1963-64. Most clones rooted, and thus there is little bias for better rooting ability within this 270-clone sample.

Starting in 1965, alternate plants were hedged or pruned into modified tree form in each block. The treatments were applied reciprocally so that for example clones 1, 3, and 5 were hedged in Block 1 and pruned as trees in Block 2, while the alternate trees of clones 2, 4, and 6 were pruned as trees in Block 1 and hedged in Block 2 (Figs. 1 and 2). The hedged plants were clipped annually to waist height (approx. 1 m) and the sides trimmed to form a dense rectangular box-shaped plant (Fig. 2). Most shoots of hedged plants originated from fascicle meristems.

Starting in 1967, all branches below 2-m height were pruned from the tree-form plants. Additionally, to prevent crown closure and facilitate climbing the trees for cutting-collection and later pollination work, all branches except those with approximate north-south orientation were pruned from the tree-form plants. Although the hedged plants were increasingly shaded when the sun was in the east or west, they were in

FIG. 1—Gill Tract Clone Bank, 1971. Plants are at 1.52 m centres. The alternate hedge-tree-hedge-tree arrangement is visible in the left half of the picture, and a hedged border row of ramets (not used in these experiments) is in the centre of the picture. The degree of shading is typical of late-afternoon sun.

FIG. 2—Russell Reservation Clone Bank, 1971. These ramets of the population sample were planted one or more years later than the Gill Tract ramets, and are at 1.83 m centres. Hedging began in 1966 and continued later. These trees were not used as cutting donors in the experiments described in this paper. The hedge-tree arrangement is shown as it existed at Gill Tract shortly after the time significant differences in rooting of cuttings from the two types of plant first occurred, and better illustrates the form of a single hedged plant.

nearly full sunlight at midday (Fig. 1). All cuttings from tree-form plants were first-order shoots of winter-bud origin.

In autumn or early winter 1966 and each subsequent year, cuttings were taken from the upper surface of most of the hedged ramets. In some years, a few clones were omitted in error, because of the death of the hedged plant, or through other causes. Following a generally short period of cold storage, the freshly-cut ends of the cuttings were treated with 4,000 ppm indole-butyric acid (IBA) as a quick dip. Cuttings taken in 1966, 1967, and 1968 were placed in a perlite rooting medium at approximately 23°C, water was sprayed over the cuttings at frequent (2-10 min.) intervals during the daylight hours, and daylength was artificially extended to 16 hr with incandescent lamps. In order to combat *Rhizoctonia* infection, which increased each year and accounted for most of the mortality among the cuttings, the frequency of watering was reduced in 1969, and the greenhouse ventilation sharply increased. *Rhizoctonia* nevertheless persisted as the major cause of mortality in 1969. In 1970 and 1971, just prior to the 5-sec IBA treatment, a 30-min. soak of the entire cutting in Dupont's

1991 (subsequently marketed as Benlate) eliminated *Rhizoctonia* as a serious pathogen in the greenhouse. Additionally, the cuttings were placed in tubes containing a complex rooting medium of peat moss, sawdust, and oak mould (Hill and Libby, 1969-70), and watering was further reduced to five 1-min. sprays per day. The bottom heat was maintained, but necessarily at a greater distance from the cuttings in the tubes. Those cuttings rooted outdoors in 1970 were given no bottom heat nor supplemental light, both day and night ambient temperatures were cooler, and humidity was generally lower than in the greenhouse.

Within the 270-clone sample, 68 clones (25 from Ano Nuevo, 23 from Cambria, 20 from Monterey) were available in which both ramets were of similar size in 1965 and both had been planted within 2 days of each other in 1963. By 1971, this subsample was reduced to 65 clones (24 from Ano Nuevo, 23 from Cambria and 18 from Monterey) because of the death of a ramet in each of three clones. In 1971, rooting of cuttings from hedged plants in this 65-clone subsample was 33.8%, while rooting of hedged cuttings from 148 of the residual clones in the 270-clone sample was 29.7%. Similarly, rooting of cuttings from tree-form plants in this subsample was 14.5% and only 12.5% from the residual clones. Neither difference was statistically significant. Thus this subsample is not greatly different from the 270-clone sample, even though all must have rooted quickly enough and well enough to establish two comparable plants in 1963. Starting in late 1966, cuttings were collected from the upper surface of the hedged ramet and from the upper part of the crown of the tree-form ramet of each of these 68 clones. They were treated similarly to the cuttings of the 270-clone sample each year.

In late winter 1970, cuttings were taken from the tree-form ramets of the full 270-clone sample at Gill Tract. If the tree-form ramet was planted after May 1964 (that is, more than a year after the first ramets were planted), the data for cuttings from both the hedged and tree-form plants of that clone were excluded from the 1971 analyses, as the effects of the repropagation necessary to re-establish ramets which had failed are uncertain. Hedged plants repropagated at any time after May 1963 were accepted in the 1971 analyses, if not disqualified by the planting history of the tree-form ramet.

## *Results*

The clones were grouped into four age-classes based on 1962 ortet age, and rooting was analysed (Table 1). The highly significant relationship of rooting percentage to ortet age in 1963 largely disappeared in 1967. A highly significant relationship occurred again in 1968, with cuttings from younger clones rooting better than cuttings from older clones. In 1969, no consistent pattern of rooting by clone age developed, and the differences observed were not statistically significant. In 1970, there appears to be a relationship of rooting to clone age, although the differences are not statistically significant and span a range of only 7%, compared to 19% in 1963. Further analysis of the 1970 data by population (Table 2) shows that the effect of clone age on rooting is not consistent between populations. (The difference between populations, however, is statistically significant. It is expected that this aspect of rooting, of less immediate practical importance, will be discussed in a later paper.)

In 1971, the relationship between clone age and rooting is without pattern and

TABLE 1—Rooting percentages of California cuttings by age of ortet, together with some details of individual experiments

| Ortet Age in 1962 years | Form of Donor Plant and Rooting Year (Cuttings Taken Previous Year) Tree-form 1963* % | Hedged 1967 % | Hedged 1968 % | Hedged 1969 % | Hedged 1970†‡ % | Hedged 1971‡ % | Tree-form 1971‡ % |
|---|---|---|---|---|---|---|---|
| 2- 4 | 59 | 16 | 13 | 26 | 60 | 30 | 15 |
| 5- 7 | 52 | 14 | 15 | 27 | 56 | 31 | 12 |
| 8-10 | 45 | 14 | 8 | 23 | 54 | 36 | 17 |
| 11-17 | 40 | 22 | 2 | 32 | 53 | 20 | 0 |
| $X^2$ test of differences§ | ** | N.S | ** | N.S. | N.S. | N.S. | N.S. |
| Chronological age of clones (yr) | Or¶ | Or +(4) | Or +(5) | Or +(6) | Or +(7) | OR +(8) | Or +(8) |
| Years since hedging began | — | 1 | 2 | 3 | 4 | 5 | — |
| Numbers‖ of cuttings | 3421 | 2549 | 4148 | 3518 | 646 | 1065 | 1065 |

* In 1962, the chronological age of the tree-form donor plants was generally related to the maturation of the plant, although the older trees (> 9 yr) were suppressed and thus may not have been of the same state of maturation as open-grown trees of the same chronological age.

† The 1970 cuttings were mostly rooted outdoors. The 144 cuttings set indoors in 1970 rooted 83%.

‡ The 1963-69 data are based on rooting for a full year. The 1970 data are for only 11 months' rooting and the 1971 data for only 3 months' rooting.

§ Statistical significance of rooting differences between age classes or original ortets: N.S. = not significant; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$.

‖ Departures from multiples of 270 are due to cuttings accidentally killed or otherwise invalidated, or entire clones dropped from the experiment for one or more years.

¶ Or = age of ortet in 1962.

TABLE 2—Rooting percentage in 1970 of California cuttings by population and ortet age, together with some experimental details

| Ortet Age in 1962 years | Rooting Percentage by Populations from: Ano Nuevo % | Cambria % | Monterey % |
|---|---|---|---|
| 2- 4 | 51 | 57 | 70 |
| 5- 7 | 42 | 63 | 55 |
| 8-10 | 45 | 61 | 56 |
| 11-17 | 53 | — | — |
| $X^2$ test of differences by ortet age | N.S. | N.S. | N.S. |
| Numbers of cuttings | 225 | 216 | 205 |

N.S. = not significant

statistically non-significant among cuttings from both hedged and tree-form plants (Table 1). The data on the 8-10 and 11-17 age classes, however, are based on only 110 and 10 cuttings from 22 and 2 clones respectively, as many of the older clones were disqualified from the analysis because of late establishment. Table 3 presents the data for age classes 2-7 in more detail for both the 65-clone subsample and the 213-clone sample. While none of these comparisons is statistically significant, there

TABLE 3—Rooting percentages in 1971 of California cuttings by age of ortet

| Ortet Age in 1962 years | 65-Clone Subsample Hedged % | 65-Clone Subsample Tree-form % | 213-Clone Sample* Hedged % | 213-Clone Sample* Tree-form % | Clone Chronological Age in 1971 years |
|---|---|---|---|---|---|
| 2-3 | 31 | 22 | 29 | 17 | 10-11 |
| 4-5 | 33 | 15 | 31 | 13 | 12-13 |
| 6-7 | 33 | 12 | 31 | 12 | 14-15 |
| 8+ | 48 | 8 | 35 | 16 | 16-17 |
| $X^2$ test by ortet ages | N.S. | N.S. | N.S. | N.S. | |
| Number of cuttings | 325 | 325 | 1065 | 1065 | |

* Fifty-seven clones were eliminated from the analysis because of late repropagation of the tree-form ramets. Many of the "older" clones ($>$ 8 yr old in 1962) either rooted late or required repropagation, and are thus not included in this 1971 analysis.

N.S. = not significant.

is some evidence for a continuing age-rooting relationship among cuttings from tree-form plants, while no such relationship is evident among cuttings from hedged plants.

In 1965, at the time of first hedging, there should have been no consistent differences between cuttings from plants which were hedged and from plants allowed to continue growth in tree form. Cuttings taken in late 1966 and late 1967 (rooting years 1967 and 1968) in fact show no significant differences in rooting (Table 4). In each of the

TABLE 4—Rooting percentage of cuttings from California hedged and tree-form ramets of 68 clones, together with some details of the individual experiments

| | Rooting Year (Cuttings Taken Previous Year)* | | | | | |
|---|---|---|---|---|---|---|
| | 1967 | 1968 | 1969 | 1970† | | 1971 |
| | | | | Tubes | Soil | |
| Cutting Origin | % | % | % | % | % | % |
| Hedged ramets | 13 | 23 | 31 | 65 | 32 | 34 |
| Tree-form ramets | 8 | 25 | 8 | 33 | 10 | 14 |
| $X^2$ test of differences‡ | N.S. | N.S. | *** | *** | *** | *** |
| Chronological age of clones (yr) | Or§ +(4) | Or +(5) | Or +(6) | Or +(7) | Or +(7) | Or +(8) |
| Years since hedging began | 1 | 2 | 3 | 4 | 4 | 5 |
| Numbers of cuttings | 493 | 143 | 425 | 220 | 296 | 650 |

* The 1967-69 data are based on rooting for a full year. The 1970 data are for only 11 months' rooting and the 1971 for only 3 months' rooting.

† All the 1970 cuttings of this 59-clone subsample were set outdoors. The experiment was split, with 2/5 of the cuttings in tubes containing peat, sawdust, and oak mould, and 3/5 in an adjacent bed of sandy soil.

‡ See footnote (§) to Table 1.

§ Or = age of ortet in 1962.

subsequent 3 yr, however, the differences in rooting between hedged cuttings and tree cuttings of the same clones are highly significant, statistically, biologically, and practically.

Quality of a rooted cutting has many components, among them fibrousness, symmetry (Fig. 3), and number of roots initiated from the cutting base. The cuttings from

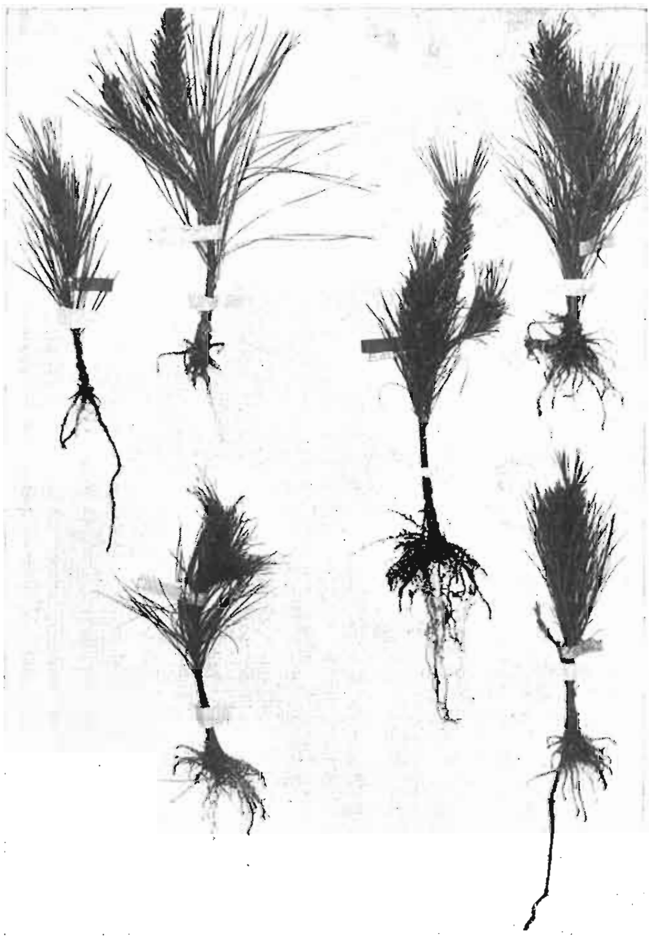

FIG. 3—Typical California rooted cuttings, 1971. The three cuttings on the left are from tree-form ramets, and the three on the right are from hedged ramets. Note the straighter stems (of the original cuttings, below the new growth) and more symmetrical and fibrous root systems of the cuttings from hedged plants. Elongation of existing buds before rooting typically produces the short-needled "rat tails" visible in three of the four upper cuttings. Growth of the needle meristems and the beginning of further growth and elongation of the stems is particularly visible on the three cuttings on the right.

hedged plants produced significantly more roots per rooted cutting than did cuttings from tree-form plants, and this relationship was consistent within each age class (Table 5). The differences between age classes, however, form no consistent pattern nor are they statistically significant for either hedged or tree-form plants.

TABLE 5—Number of 1971 roots per rooted cutting of California cuttings by age of ortet

| Ortet Age in 1962 years | 65-Clone Subsample Hedged | 65-Clone Subsample Tree-form | 213-Clone Sample Hedged | 213-Clone Sample Tree-form | Clone Chronological Age in 1971 years |
|---|---|---|---|---|---|
| | (Average number of roots per rooted cutting) | | | | |
| 2-3 | 6.8 | 4.9 | 7.2 | 5.8 | 10-11 |
| 4-5 | 7.7 | 6.8 | 7.7 | 6.6 | 12-13 |
| 6-7 | 6.8 | 5.4 | 7.3 | 6.4 | 14-15 |
| 8+ | 9.0 | 6.5 | 8.7 | 6.5 | 16-17 |
| $X^2$ test by ortet ages | N.S. | N.S. | N.S. | N.S. | |
| Number of rooted cuttings | 110 | 47 | 330 | 142 | |
| Unweighted mean | 7.44 | 5.94 | 7.61 | 6.40 | |
| $X^2$ test by hedged and tree-form | *** | | *** | | |

N.S. = not significant.

*** = p <0.001.

## AUSTRALIAN CAPITAL TERRITORY EXPERIMENTS

### *Features*

(1) Twelve ortets, of uncertain provenance, were hedged.
(2) The hedged ortets sampled a single ortet age class.
(3) The main controls were a series of 4-yr-old tree-form plants.
(4) Hedged and tree-form plants were usually from different sites.
(5) Environmental conditions and rooting success varied from year to year.
(6) Rooting and subsequent shoot growth were evaluated.

### *Materials and Methods*

In 1964, 12 widely-spaced naturally-regenerated radiata seedlings in Hall's Block of Uriarra Plantation were measured (mean height 2.2 m) and their ages were estimated (4-6 yr-old). In the autumn of 1964 and of each subsequent year, cuttings were taken from each of the 12 trees, and they were then completely disbudded by cutting off all remaining long-shoot buds. The leading shoots were sheared annually as required to keep the plant at a height of approximately 2 m. Thus, these plants (Fig. 4) were double the height and of greater overall size than the hedged California plants. After 1964, all shoots originated from fascicle meristems.

Each year, 10 or more 4-yr-old seedlings were located a few kilometres away (in Blue Range or Gibraltar Creek plantations) or on a drier site about 40 km distant (in Kowen plantations). Additionally, in 1967 and 1970, adjacent 7-to-9-yr-old and 10-to-12-yr-old non-disbudded trees served as cutting donors (Fig. 4). All cuttings from these tree-form seedlings were first-order shoots, mostly of winter-bud origin.

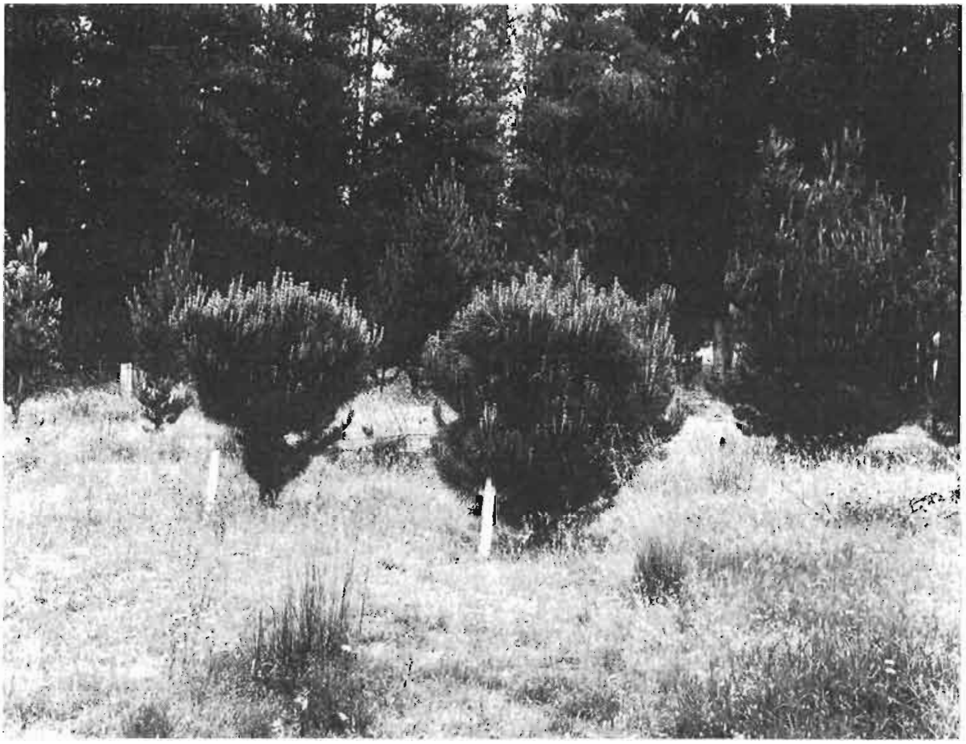

FIG. 4—Hall's Block, Uriarra Plantation, 1966. Annual disbudding of the two foreground trees began in 1964, and further increases in height were prevented by annual shearing of leading shoots. Control tree-form seedlings which donated cuttings in 1967 and 1970 are in the near background. The picture was taken in December when the new crop of cuttings was partly grown.

The cuttings were trimmed to uniform length and set to uniform depth in a light soil medium contained in tubes placed in the open nursery at Canberra (Fielding, 1969). Environmental conditions, particularly moisture supply, varied from year to year both in the plantations and in the nursery. This affected both rooting capacity of the cuttings and their subsequent rooting and growth performance. The A.C.T. rooting percentages were transformed to arcsin for statistical analysis, and then retransformed to percentages for presentation here.

Heights of rooted cuttings with live tops were measured at the end of the rooting season. Rooted cuttings from the 1966 collection were planted in 1967 (on a cold dry site), and their heights were measured in 1971 following four growing seasons.

### *Results*

Statistically highly significant differences in rooting were observed in three of the seven test years (Table 6). However, the direction of the differences is not consistent, nor do the differences between cuttings from 4-yr-old tree-form seedlings and cuttings from hedged plants increase as the chronological age of the hedged plants increases from 4-6 yr to 10-12 yr. Analysis of variance of transformed rooting percentages for the entire experiment indicates high significance ($p < 0.001$) for differences among years, among the 12 hedged plants, and for the interaction between donor plants and years. The overall difference between hedged plants and 4-yr-old tree-form seedlings, however, is not significant.

In both cases where the performance of cuttings from hedged plants was compared to cuttings from adjacent tree-form seedlings, the rooting percentage and the subsequent growth of the rooted cuttings during the rooting year were greater for cuttings from hedged plants (Table 7). Column 2 of Table 7 is most comparable to column 3 of Table 4, as the donor plants in each experiment differ by 3 yr of hedged or normal growth.

As with the rooting data, statistically significant differences in subsequent growth were observed in three of the seven test years, but the direction of the difference was not consistent, nor did its magnitude increase with chronological age of the hedged plants (Table 8). Analysis of variance of growth indicates highly significant differences ($p < 0.001$) among years, and among the 12 hedged plants, and ($p < 0.01$) an interaction between hedged plants and years, but the overall difference in growth of rooted cuttings from hedged plants and from 4-yr-old tree-form seedlings is not significant.

The differences between cuttings from hedged plants and from tree-form seedlings following four growing seasons on a cold, infertile site are not statistically significant (Table 9).

Regression analyses of the yearly performance of cuttings from each hedged plant and from the different 4-yr-old seedlings yield four interesting results: (1) There are significant differences between the performances of different clones in both rooting percentage and subsequent growth of the rooted cuttings, thus supporting the among-plant differences found significant in the analyses of variance. (It is hoped to discuss these differences among clones in greater detail in a later paper.) (2) There was a significant decline in rooting percentage from 1964 to 1968, and then a partial recovery during 1968-71. This trend is exhibited by cuttings from 11 of the 12 clones, and from the 4-yr-old tree-form seedlings as a group. (3) The rooting trends of cuttings from eight of the hedged plants and from the 4-yr-old tree-form seedlings are similar to each other over the 7-yr period of the experiments. Rooting of cuttings from two of the hedged plants (trees 8 and 9) are better both absolutely and relatively near the end of the experiment than at the beginning, and cuttings from two others (trees 3 and

TABLE 6—Rooting percentage of cuttings from A.C.T. hedged and 4-yr-old tree-form seedlings, together with some details of individual experiments

| | Rooting Percentage in the Years: | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1964-65 % | 1965-66 % | 1966-67 % | 1967-68 % | 1968-69 % | 1969-70 % | 1970-71 % |
| Cutting origin | | | | | | | |
| Hedged seedlings | 97 | 82 | 66 | 20 | 41 | 59 | 41 |
| 4-yr-old tree-form seedlings | 89 | 35 | 75 | 36 | 19 | 54 | 45 |
| ANOVA test of difference | N.S. | ** | N.S. | ** | *** | N.S. | N.S. |
| Chronological age of hedged seedlings | 4-6 | 4-6+(1) | 4-6+(2) | 4-6+(3) | 4-6+(4) | 4-6+(5) | 4-6+(6) |
| Number of cuttings | 240 | 260 | 390 | 980 | 1470 | 1470 | 1875 |

N.S. = not significant; ** = $p < 0.01$; *** = $p < 0.001$.

TABLE 7—Rooting percentage and subsequent growth of cuttings from adjacent A.C.T. hedged and tree-form seedlings. and tree-form seedlings

| Rooting Year | 1967-68 | | | 1970-71 | | |
|---|---|---|---|---|---|---|
| Cutting Origin | Chronological Age years | Rooting % | Subsequent Growth* cm | Chronological Age years | Rooting % | Subsequent Growth* cm |
| Hedged seedlings | 4-6+(3) | 20 | 24 | 4-6+(6) | 41 | 23 |
| Adjacent tree-form seedlings | 7-9 | 11 | 11 | 10-12 | 33 | 8 |
| ANOVA test of difference | | N.S. | *** | | *** | *** |
| Number of cuttings | | 910 | 175 | | 1665 | 527 |

* Growth during rooting year

N.S. = not significant

*** = $p < 0.001$

TABLE 8—Mean heights of A.C.T. live-top rooted cuttings at end of rooting year

| Cutting Origin | Rooting Year<br>1964-65<br>cm | <br>1965-66<br>cm | <br>1966-67<br>cm | <br>1967-68<br>cm | <br>1968-69<br>cm | <br>1969-70<br>cm | <br>1970-71<br>cm |
|---|---|---|---|---|---|---|---|
| Hedged seedlings | 24 | 15 | 20 | 24 | 19 | 25 | 23 |
| Four-yr-old tree-form seedlings | 21 | 12 | 23 | 25 | 17 | 26 | 24 |
| ANOVA test of difference | N.S. | * | N.S. | N.S. | * | N.S. | ** |
| Chronological age of hedged seedlings (yr) | 4-6 | 4-6+(1) | 4-6+(2) | 4-6+(3) | 4-6+(4) | 4-6+(5) | 4-6+(6) |
| Number of cuttings | 177 | 184 | 184 | 236 | 475 | 842 | 721 |

N.S. = not significant

* = $p < 0.05$

** = $p < 0.01$

TABLE 9—Mean heights of A.C.T. rooted cuttings following four growing seasons

| | Cutting Origin | | |
|---|---|---|---|
| | Hedged | Tree-form seedlings* | |
| | | Randomised | Adjacent |
| Ortet age in 1966 (yr) | 4-6+(2) | 4 | 4 |
| Cutting height in 1971 (cm) | 101 | 107 | 85 |
| Number of trees | 32† | 3 | 7 |

* Only three of the 10 cuttings from 4-yr-old tree-form seedlings were growing among the cuttings from hedged plants. The remaining seven were immediately adjacent.

† From six of the 12 hedged plants.

11) show a considerable drop in absolute (from 57% and 71% to 8% and 22% respectively) and relative rooting. These differences in trends, however, are not statistically significant. (4) While there was no significant difference in regression slopes between the 13 regressions (one for each of the 12 hedged clones and one for the 4-yr-old tree-form seedlings) of height growth in the rooting bed one year, rooted cuttings of the 4-yr-old tree-form seedlings were ranked 10th of 13 in 1964-66, 8th in 1967-68, and tied for 4th and 5th in 1969-71.

## DISCUSSION

The relationship of ortet age to rooting percentage of cuttings was strongly expressed within the California population sample at the beginning of the experiment. Cuttings from younger ortets rooted at approximately 150% of the rate of those from older ortets in 1963. Following repropagation in 1963, and hedging commencing in 1965, differences associated with original ortet age became non-significant statistically, and were not consistent from year to year, or among subsamples of the main sample (Tables 1 and 2). The relationship of clone age to rooting among tree-form ramets is equivocal. The data on roots per rooted cuttings (Table 5), and on rooting percentage (1967 hedged and 1971 tree-form data, Table 1) all indicate that the age-rooting relationship may become much weaker or disappear following a single vegetative propagation. Yet the recast 1971 data (Table 3) suggest that an effect of ortet age on rooting percentage may still exist 8 yr after these tree-form cutting donors were propagated as rooted cuttings. It is clear that the age-rooting relationship does lessen or disappear among hedged plants.

If maturation of a hedged plant is continuing, one aspect of such maturation would be reduced rooting capacity. This was difficult to judge directly in both the California and A.C.T. experiments because of the fluctuations in the environments of the hedged plants and of the cuttings while rooting. However, cuttings from maturing hedged plants should root relatively less well in each subsequent year when compared to cuttings from a series of plants attaining a given level of maturity. This did not occur when cuttings from the hedged A.C.T. plants were rooted with cuttings from a series of 4-yr-old tree-form seedlings over a period of 7 yr (Table 6). It appears, on the basis of this evidence, that hedged plants continue to root relatively the same for at least 6 yr following hedging, and in the case of the A.C.T. hedged plants, they root rather like 4-yr-old seedlings. There is some evidence that both rooting and subsequent growth of rooted cuttings can be manipulated by altering the height of the hedge (Garner and Hatcher, 1962).

It has been shown that repropagation of radiata pine either temporarily halts or reduces the rate of maturation (Fielding, 1969; Pawsey, 1971). However, the A.C.T. trees were not repropagated, but were merely hedged seedlings. In addition, the California experiment used hedged and tree-form ramets of the same clones, each of which was repropagated only once and at the same time. Significant differences in rooting between hedged and tree-form ramets of the 68-clone California subsample did not occur during the first 2 yr following the initiation of annual hedging, supporting the assumption that these plants were at the same stage of maturation when hedging was begun. By the third year of annual hedging, the hedged and non-hedged ramets of each clone were distinctly different in height and form (Figs. 2 and 4), and cuttings from the hedged ramets rooted significantly better than cuttings from the tree-form ramets in this and each subsequent year (Tables 4 and 7), and in 1971 produced more roots per rooted cutting (Table 5). Thus, the effect of hedging on arresting the decline in rooting normally associated with clone age is real, and the observations by Fielding and Matthews on the different rooting performance of cuttings from hedged and tree-form radiata pine of the same age are supported by these experiments. It appears that the association of maturation with chronological age of a clone is not a direct cause-and-effect association, but that both are normally associated with some third variable such as growth in height. These hedging experiments appear to have broken that mutual association with the third and causative variable(s).

The growth of a rooted cutting during the rooting year depends on at least three factors: (1) when it roots; (2) the size and nutrient status of the cutting; and (3) the form of the root system and physiological condition of both roots and shoots.

There is some evidence that cuttings from younger ortets root more quickly than cuttings from older ortets (Libby and Conkle, 1966). Since there is little or no growth of new shoots before rooting in radiata pine (existing buds may elongate, with partial extension of the needles—*see* Fig. 3), cuttings which root earlier will have a longer period in which to grow during that first season in the rooting bed. Actual time of rooting was not recorded in the A.C.T. experiments, but data are available from the California experiments. In general, most rooting occurred earlier among cuttings from hedged ramets than among cuttings from tree-form ramets.

Among cuttings of the same plant, or from similar ortets of the same age, early growth is strongly related to size and nutrient status of the propagule (Fielding, 1954, 1969; Garner and Hatcher, 1957; Cameron, 1968), particularly if that growth is largely the elongation of an existing bud (Sweet, 1964). In both the California and A.C.T. experiments, the cuttings from hedged plants were generally much thinner than the cuttings from tree-form plants. In particular, winter buds were generally smaller and sometimes absent on cuttings from hedged plants, compared to the large and invariably present winter buds on cuttings from tree-form plants. (In both classes of cuttings some tops died, necessitating growth initiation from fascicle meristems. Nutrient status of the two cutting types was not determined.)

Numbers of roots initiated from the stems of cuttings were similar in the 1971 California experiment (Table 5), but it was apparent that cuttings from hedged plants produced many more secondary roots, and thus a more fibrous root system (Fig. 3). Many factors are lumped in the term "physiological condition", but such factors, albeit poorly defined, must be invoked to explain the continuing differences in growth observed by Pawsey (1971) and Sweet (data subsequent to 1964).

The rooting-year growth of the rooted cuttings from hedged plants, which increased their chronological age from 4-6 yr to 10-12 yr during the experiments, remained comparable to that of cuttings from 4-yr-old tree-form plants (Table 8). In the two comparisons with adjacent tree-form plants, cuttings from hedged plants grew significantly better than cuttings from 7-9-yr-old and 10-12-yr-old tree-form plants (Table 7). The one experiment where the rooted cuttings grew for longer periods indicates that the cuttings of hedged plants 6-8-yr-old continued to grow at a rate comparable to that of cuttings of 4-yr-old tree-form plants (Table 9). This latter experiment can be more meaningfully repeated now that the chronological ages of the available hedged plants are considerably greater than ages of young tree-form seedlings.

The greater chronological age and smaller size of the cuttings from the hedged A.C.T. plants would both predict greater growth by the larger cuttings from the younger tree-form plants. The fact this did not occur indicates that the hedged-plant cuttings must have some advantage in either speed of rooting, or physiological condition of the rooted cutting, to offset at least the effect of greater size of the tree-form cuttings.

The phenomenon of "rejuvenation" is briefly reviewed and discussed by Cameron (1968). This phenomenon, as poorly understood as "maturation" and/or "ageing" (reviewed by Sweet, 1964), was not specifically investigated in these studies (*see* Fielding, 1964). However, if rejuvenation does occur via hedging (*see* Garner and Hatcher, 1955, 1957), this could help explain the early growth rate of the smaller cuttings from hedged plants, and perhaps also the increasing similarity in rooting of cuttings from hedged ramets of different-aged ortets (Table 1). It remains to be seen what influence hedging will have on the morphological features which distinguish seedling plants from plants propagated vegetatively from maturing ortets.

The statistically significant differences between cuttings from the 12 hedged A.C.T. trees in both rooting and subsequent growth cannot be clearly assigned to genetic differences, as microsite differences or other environmental factors could also cause such consistent differences. These differences, plus statistically significant clone-by-year interactions in both rooting and subsequent growth, do emphasise the operational advantages of knowing the particular performance and requirements of different selected clones, whatever the underlying causes of the differences. The rooting trends of cuttings from plants 8 and 9, compared to plants 3 and 11, suggest that the rooting response to hedging may not be uniform for all plants, but may vary because of differences in genotype, plant environment, or both (*see* Garner and Hatcher, 1955, 1962).

Finally, a comment on the efficiencies of cutting production and collection by hedging: At the beginning of the A.C.T. hedging experiments in 1964, the average number of cuttings available per plant was 45. The number of cuttings available per hedged plant increased sharply during the next 3 yr, and subsequently varied between 250 and 500 per year during 1967-71. This, however, includes cuttings from the sides as well as tops of the plants. Cuttings from the sides of hedged plants have, in common with branch cuttings from tree-form plants, a "banana" shape. This makes insertion in the rooting medium, particularly by automated mechanical means, more difficult. Furthermore, the symmetry of the root system may be affected, thus adversely affecting the quality of the rooted cutting. Cuttings which develop from the flat top of a hedged plant, on the other hand, tend to be straight and to develop more symmetrical root systems (Fig. 3). A long flat hedge also lends itself to mass collection of cuttings by means of a motorised hedge pruner. Hundreds of cuttings can be severed per minute, and with skill, all will lie on top of the hedge facing the same direction, facilitating mechanised processing and setting in rooting beds. Counts on the upper surfaces of 10 of the hedged plants at Russell Reservation (an experimental site 15 km from Gill Tract) (Fig. 2), show that these plants produced 1974 acceptable cuttings from an area of 15.35 $m^2$, or 129 (92 to 157) acceptable cuttings per square metre of hedge top during the 1971 growing season. Costs of harvesting from such hedges must compare very favourably with the costs of individually clipping branches from tree-form plants Watering and other cultural treatments, to offset the reductions in rooting success noted during the hot dry periods in A.C.T., are much more feasible with small hedged plants than with large trees.

## CONCLUSIONS

1. Hedging effectively arrests the decline in rooting percentage normally associated with ageing of a clone.
2. Hedging appears to arrest the decline in quality of rooted cuttings normally associated with ageing of a clone.
3. Hedging appears to arrest the decline in growth rate of rooted cuttings normally associated with ageing of a clone.
4. Hedging provides a method of mass-producing large numbers of symmetrical and straight cuttings, which can be efficiently collected by mechanised techniques.
5. It remains to be seen how the hedging technique will influence the typical differences between trees grown from seed and trees grown from cuttings which were collected from maturing tree-form plants. It further remains to be seen how long the hedging technique can arrest the maturation of radiata pine clones.

## ACKNOWLEDGMENTS

For the California experiments, the valuable and dedicated help of T. Conkle, Y. Linhart, W. Sager, S. Hill, C. Lewis, A. Tufuor, A. Bianchi, and T. Vold, and of the many students who lent a hand in the collection of cuttings and data, is gratefully acknowledged. At Canberra, the interest and assistance of K. Willcocks throughout the study is gratefully acknowledged. The photograph for Fig. 4 was taken by A. Edward.

## REFERENCES

BARNES, R. D. 1970: The prospects for re-establishing **Pinus radiata** as a commercially important species in Rhodesia. **South African Forestry Journal 72:** 17-9.

BEVERIDGE, A. E. and KNOWLES, R. L. 1971: Grazing in forests. **New Zealand Forest**

**Service, Forest Research Institute, Economics of Silviculture Branch Report 40** (unpublished).

CAMERON, R. J. 1968: The propagation of **Pinus radiata** by cuttings. Influences affecting the rooting of cuttings. **New Zealand Journal of Forestry 13:** 78-89.

FIELDING, J. M. 1954: Methods of raising Monterey pine from cuttings in the open nursery. **Australia Forestry and Timber Bureau Bulletin 32.** 29pp.

——— 1964: The possibility of using cuttings for the establishment of commercial plantations of Monterey pine. **FAO World Consultation Forest Genetics and Tree Improvement. Proceedings. Stockholm Vol. II 5/10.** 8pp.

——— 1969: Factors affecting the rooting and growth of **Pinus radiata** cuttings in the open nursery. **Australia Forestry and Timber Bureau Bulletin 45.** 38pp.

——— 1970: Trees grown from cuttings compared with trees grown from seed (**Pinus radiata**). **Silvae Genetica 19:** 54-63.

GARCIA, J. and KUMMEROW, J. 1970: Infection of Monterey pine graftings with **Dothistroma pini. Plant Disease Reporter 54:** 51-2.

GARNER, R. J. and HATCHER, E. S. J. 1955: The interplay of factors influencing rooting behaviour of shoot cuttings. **Proceedings XIV International Horticultural Congress, Netherlands, 1955.** Pp. 204-14.

——— 1957: Aspects of root propagation V. The behaviour of root cuttings from plants of different age of establishment. Pp. 57-61 in **Annual Report (45th Year) East Malling Research Station.**

——— 1962: Regeneration in relation to vegetative vigour and flowering. **Proceedings XVI International Horticultural Congress, Brussels, 1962. Vol. 3:** 105-11.

GARNER, R. J.; HATCHER, E. S. and KEMP, R. W. 1955: A comparison of blackcurrant cuttings from stooled plants and fruiting bushes. Pp. 61-3 in **Annual Report (43rd Year) East Malling Research Station.**

HATTON, R. G. and ROGERS, W. S. 1942: Pomology. Tree fruits—propagation. P. 14 **in Annual Report (30th Year) East Malling Research Station.**

HILL, S. R. and LIBBY, W. J. 1969-70: Outdoor rooting of **Pinus radiata. The Plant Propagator 15(4):** 13-6.

JACOBS, M. R. 1937: The detection of annual stages of growth in the crown of **Pinus radiata. Australia Commonwealth Forestry Bureau Bulletin 19.** 16pp.

LIBBY, W. J. 1964: The rooting of Monterey pine. **Combined Proceedings, International Plant Propagator's Society 14:** 280-8.

——— 1969: Some possibilities of the clone in forest genetics research. Pp. 121-36 **in** Bogart, R. (Ed.) "Genetics Lectures". Oregon State University Press, Corvallis.

LIBBY, W. J. and CONKLE, M. T. 1966: Effects of auxin treatment, tree age, tree vigor, and cold storage on rooting young Monterey pine. **Forest Science 12:** 484-502.

MATTHEWS, J. D. 1952: Forest genetics (Propagation). Pp. 76-7 **in Report on Forest Research for the Year Ending March 1951:** Great Britain Forestry Commission.

NICHOLLS, J. W. P. and BROWN, A. G. 1971: The ortet-ramet relationship in wood characteristics of **Pinus radiata. Appita** 25 (3): 200-9.

PAWSEY, C. K. 1950: Some observations upon the vegetative reproduction of Monterey pine. **Australian Forestry 14:** 99-4.

——— 1971: Development of grafts of **Pinus radiata** in relation to age of scion source. **Australian Forest Research 5 (1):** 15-8.

SWEET, G. B. 1964: The effect of physiological age of scion on growth of grafts in **Pinus radiata. New Zealand Forest Service, Forest Research Institute, Forest Research Note 37.** 8pp.

THULIN, I. J. and FAULDS, T. 1968: The use of cuttings in the breeding and afforestation of **Pinus radiata. New Zealand Journal of Forestry 13:** 66-77.

VYVYAN, M. C. 1942: The propagation of fruit tree stocks by stem cuttings. III. Further observations on hardwood cuttings. Pp. 40-7 **in Annual Report (30th Year) East Malling Research Station.**