DECAY DISTRIBUTION IN RELATION TO PRUNING AND GROWTH STRESS IN PLANTATION-GROWN *EUCALYPTUS REGNANS* IN NEW ZEALAND

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ABSTRACT

Pruning has been adopted in managing eucalypt plantations for sawlog and veneer log production in New Zealand; however, internal decay can gain entry through pruned branch stubs. Longitudinal movement of decay along the pith was observed in 15 destructively sampled *Eucalyptus regnans* F. Mueller, as was radial movement towards the pith, but no decay was detected outwards into wood laid down after pruning. Eucalypt pruning guidelines with respect to branch diameter at time of pruning were supported.

Three core zones are distinguishable in eucalypts — the decay core, the defect core, and the brittle heart core. In *E. regnans,* brittle heart rather than internal decay or pruned branch stubs will probably determine the ultimate diameter of the central core.

The silvicultural trade-offs involved in the timing and frequency of pruning mean that future research will need to focus on occlusion of pruned branch stubs, patterns of spread of internal decay, and a quick and simple means of detecting brittle heart in standing trees.

Keywords: decay; pruning; growth stress; brittle heart; *Eucalyptus regnans.*

INTRODUCTION

Eucalypts have been planted in New Zealand for many years, but it is only recently that efforts have been made to establish a plantation resource of sufficient size for sustained wood production. Emphasis has been on growing eucalypts with known utilisation characteristics either for biomass (e.g., for pulp and fuel) or for sawlog and veneer log production. This paper concentrates on production of sawlogs and veneer logs containing a high proportion of knot-free clearwood.

Management of eucalypts for sawlog and veneer log production initially relied on choice of silvicultural growing system (e.g., interplanting, row-by-row mixtures with other species) and manipulation of stocking (in single species plantations) to achieve branch control (Revell 1981). The stubborn persistence of branches made natural branch shed unreliable as a means of branch control, even in species renowned for effective natural branch shed. Pruning appeared to be the most effective method of branch control.

Decay was observed as early as 1976 to have gained entry through pruned branch stubs (Gadgil & Bawden 1981). Gadgil & Bawden also reported the presence of internal decay in both unpruned and pruned eucalypts in New Zealand. For successful eucalypt management there is a need to understand how decay develops and its significance compared to other wood characteristics.

The objectives of this paper are to:

(1) Report on the distribution of internal decay in a study of *Eucalyptus regnans* trees 3 years after a second pruning lift and relate findings to Australian studies;

(2) Examine the distribution of decay in relation to other characteristics within the stem, namely branch stubs and brittle heart;

(3) Derive implications for silvicultural practices (pruning, in particular) and further research.

INTERNAL DECAY PATTERNS IN 8-YEAR-OLD *E. REGNANS*

Method

Fifteen cull trees from two similar treatments in an *E. regnans* regime trial (Table 1) were selected for cross-sectional examination. The trees had been pruned in winter to 2.5 and 4.0 m at ages 4 and 5 years respectively and the pruned branch stubs sprayed with a 2% aqueous captafol solution.

TABLE 1–History of two treatments from which thinned trees were cross-sectionally examined for signs of internal decay, *E. regnans* regimes trial, Kaingaroa Forest

Year	Operation	Dbhob*† (cm)	Height* (m)
1978	Planted, 1100 stems/ha		
1982	First pruning, 2.5 m	9.7	8.1
1983	Second pruning, 4.2 m	11.8	9.9
	Waste thinning (to 500 or 650 stems/ha)		
1986	Waste thinning (concurrent with sampling)	16.0	14.1

* Dbh and height measurements are for sample trees only, not treatments
† Dbhob = over-bark diameter at breast height

Stump height, pruned height, and total tree height were measured after felling. From a position equivalent to 12.5 cm above ground and then at approximately 12.5-cm intervals, discs were cut from the pruned length of the stem. Actual cuts were made where possible through any visible occlusion scars in the immediate vicinity of each 12.5-cm step so that any internal decay pockets present could be examined in relation to pruned branch stubs. If decay was present, then appropriate extra cuts were made to determine, if possible, the entry point of the decay.

The tree number and disc height were recorded. All discs were gathered for subsequent photocopying on the same day as being cut. Generally the uppermost disc surface was copied, except when the decay entry point or longitudinal limit was visible on the lower surface. On each copy the boundaries of any decay present were outlined. This procedure provided a permanent record of the sampled stems and thus allowed later measurement of disc features from the disc copy with little loss of accuracy.

The decay status of individual branch stubs was classified as undecayed, decay confined to the stub (including the stub trace), or decay spread beyond the stub (and stub trace) (*see* Fig. 1). The "diameter" of any infected branch stub was measured if the disc was judged to have been cut close enough to expose the maximum diameter of that stub (**wy** in Fig. 1). The greatest radial distance of decay from the pith was measured also (**vx** in Fig. 1). The longitudinal extent of decay was found by observing contiguous decay in each disc copy and noting the discs in which the upper and lower limits of decay occurred.

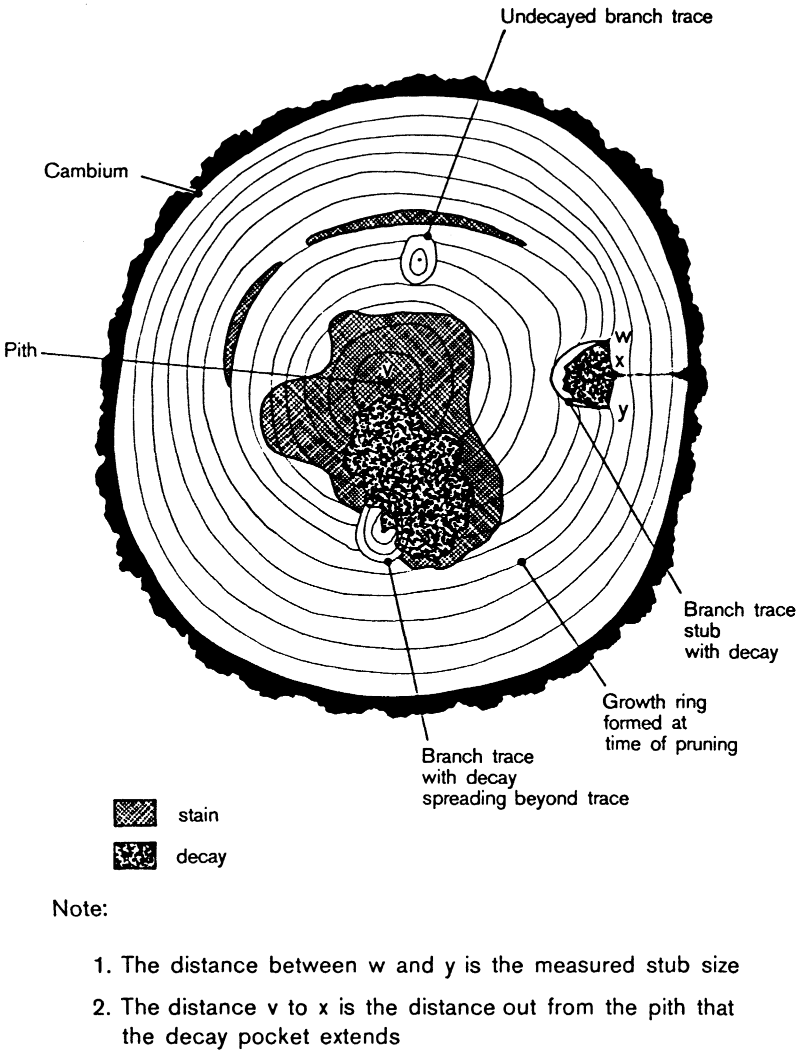

FIG. 1 — Representation of a disc copy for *E. regnans* illustrating decay and other disc features, along with measurement of radial decay and branch stub diameter.

Results

Twelve of 15 trees had decay which had spread beyond branch stubs and traces in the pruned portion of the stem and only two instances of decay were associated with the second pruning lift (in Trees 5 and 7, *see* Table 2). Decay was not always confined to isolated pockets. In Trees 5 and 7 linked pockets of decay (termed a "decay system") were detected and decay entry could not be ascribed to an individual branch stub. In both trees two branches could have been entry points for development of a decay system starting as separate decay pockets. Nine trees contained only a single decay pocket, two trees (Trees 2 and 7) contained one decay pocket and one decay system, and a single tree (Tree 5) contained two decay pockets and one decay system.

TABLE 2–Summary of decay dimensions and height and stub diameter of probable decay entry point for 12 of 15 *E. regnans* trees 3 years after pruning in a regimes trial, Kaingaroa Forest

Tree (No.)	Decay distance from pith* (cm)	Vertical length of decay† (cm)	Stub diameter‡ (cm)	Stub disc height§ (m)
First pruning lift				
(a) Decay pockets				
12	1.0	120	n.l.	2.0
10	1.8	10	n.l.	0.4
4	2.8	10	1.8	2.2
6	4.0	40	2.4	1.5
1	5.5	10	1.0	0.5
11	5.5	90	n.l.	0.3
9	6.0	30	7.0	0.5
2	6.5	40	1.5	1.5
8	7.0	70	3.3	1.5
2	7.5	40	1.0	0.5
3	8.0	50	1.2	0.6
5	9.0	100	1.8	0.5
(b) Decay systems				
5	3.4	30	2.0	1.9
5	n.a.	n.a.	2.2	2.0
7	8.5	50	3.6	1.9
7	n.a.	n.a.	1.9	1.9
Second pruning lift (decay pockets detected only)				
5	5.5	20	3.6	2.7
7	8.0	50	4.2	3.3

n.a. = Measurement not applicable (for decay systems only)
n.l. = Probable decay entry point was not located
* The greatest radial distance decay extended from the pith, i.e., vx in Fig. 1
† The height difference between discs at longitudinal extremes of a decay pocket or system
‡ The diameter of the branch stub through which decay entered the stem, i.e., wy in Fig. 1
§ The height of the disc containing the infected branch stub

In Trees 10, 11, and 12 decay pockets were detected, but it was not possible to determine an entry point (branch stub or otherwise). A single branch was identified as the probable decay entry point for the other trees.

Most of the pruned branch stubs examined did not contain decay (189 stubs or 63%). The estimated diameter of these uninfected stubs averaged 1.4 cm. Ninety-five stubs had decay confined to the stub (32%); stub diameter averaged 1.8 cm. Only 15 stubs (5%) had decay spreading beyond the branch stub; average stub diameter was 2.6 cm. The average stub diameter for all infected branch stubs was 1.9 cm.

The longest radial distance decay extended from the pith was always less than the radial distance to the pruned branch stub entry point (5.6 cm over both pruning lifts). Where decay had no identifiable source, the decay was confined within the growth ring present at the time of pruning. Decay extended above and below the branch identified as the entry point, with the average longitudinal spread of decay for both pruning lifts being about 0.5 m. Longitudinal decay movement tended to follow the pith.

Observed stain was confined within the growth ring formed at the time of pruning. Staining was both contiguous with decay and also in patches apparently unconnected to decay. Whereas decay did not spread extensively tangentially around the growth rings, stain did, creating arcs and rings, and sometimes filling in the central portion of the sector or wedge.

Discussion

This study confirmed that decay can be associated with pruning wounds in plantation-grown *E. regnans*. The results obtained are similar to those in Australian reports, except that unpruned branches exclusively were the decay entry points in the Australian studies (e.g., Wilkes 1985; Marks *et al.* 1986 — *E. obliqua* (L'Herit.), *E. regnans, E. globulus* (Labill.), and *E. delegatensis* (R.T. Bak.) in plantation and regrowth stands between 24 and 73 years of age, T. Wardlaw pers. comm.).

In this study decay entry appeared to be related to the diameter of the pruned branch stub. For decay which could be traced to a probable entry point, median stub diameter was 2.0 cm. Average stub diameter increased with a change in branch stub status from "undecayed" to "decay spreading beyond the stub". A similar trend has been observed in independent trials in New Zealand with eucalypt species other than *E. regnans* (P.D. Gadgil pers. comm.). The trend is also consistent with recent Australian findings that large-diameter branches are the most likely decay entry points owing to a higher probability of unsuccessful occlusion compared to small diameter branches (Marks *et al.* 1986).

INTERNAL DECAY AND OTHER WOOD CHARACTERISTICS

Types of Central Core Zones

The central core in the tree stem is particularly important in eucalypts since sawing relies on being able to isolate this core from the surrounding outerwood sheath. Three core zones may be defined in eucalypts. Each includes widening effects due to stem sinuosity. The "decay" core contains decay and associated wood discoloration and staining. The "defect" core has been defined by Park (1980 p. 425) as:

> ". . . the 'cylinder' containing pith, branch stubs and occlusion scars . . . The size of this core [is] expressed as its diameter (in mm)".

The third core zone is the brittle heart core, which contains wood characterised by fractures across the grain (brash fractures) resulting from longitudinal compressive stress failure. These brash fractures are difficult to detect visually, often requiring microscopic examination (Marsh & Burgers 1967).

Extent and Shape of Core Zones

Decay core

Over time, patterns of decay along with associated discoloration and staining within the stem change. Decay has been observed above and below the apparent initial entry point both in this study and elsewhere (Gadgil & Bawden 1981; Marks *et al.* 1986; Wilkes 1985), indicating that the fungal organisms causing internal decay can move longitudinally within the stem. In moving upwards decay conceivably can enter wood younger than the wood in which infection initially occurred, particularly if longitudinal decay movement tends to follow the pith as observed above. However, neither the maximum longitudinal distance over which decay can travel is known (1.2 m in this study; see Table 2), nor has the rate of longitudinal movement been quantified (cf. Marks *et al.* 1986).

At a given height, radial movement of decay towards the centre of the stem has been reported (Marks *et al.* 1986). Radial movement outward into growth rings beyond the ring in which initial infection occurred apparently is not common; a frequency of only 4% was recorded in one study (P.D. Gadgil pers. comm.) and for the study reported here no such movement was detected. To the extent that internal decay remains within the shape defined by the external stem taper at the time of the last pruning lift, the decay core shape will be roughly conical.

Defect core

The portion of the tree containing the pruned branch stubs is the main component of the defect core (Knowles *et al.* 1987). Tree diameter at the time of pruning delimits the radial extent of the "diameter-over-pruned-branch-stubs" (DOS). For plantation-grown *E. regnans* in New Zealand, DOS can be predicted from over-bark diameter at breast height (dbhob), the diameter of the pruned stub of the largest branch, and DOS height above ground (Deadman & Calderon 1988).

After pruning, the pruned branch stub soon becomes occluded forming scar tissue before healing is completed. The radial extent of individual occlusion scars in eucalypts has not been measured yet.

The shape of the defect core depends on the height of the largest DOS for each pruning lift. The shape of the defect core in eucalypts managed for pruned log production is unknown, but *E. regnans* DOS measurements indicate a shape similar to that commonly obtained for *Pinus radiata* D. Don (and consistent with that noted by Jacobs 1955), i.e., an inverted truncated cone (unpubl. data) possibly bulging outwards if a pruning lift is delayed.

Brittle heart core

Growth stresses are common in eucalypts. When relieved, growth stress is manifest in the form of strain, i.e., physical distortion of the wood taking forms such as end-splitting, bow, and crook. Different types of growth stress are distinguished by the direction in which they act. The growth stress contributing to the development of brittle heart acts longitudinally (Jacobs 1945).

Longitudinal growth stress is tensile near the external surface of the tree stem (the periphery), but becomes compressive towards the stem pith. The compressive forces can exceed the green crushing strength of the wood parallel to the grain. The wood then fractures, giving rise to brittle heart (Boyd 1950).

Wood density plays a role in brittle heart formation since the longitudinal crushing strength of the wood is directly proportional to wood basic density, at least up to the proportional limit (Bier 1984). Radial and vertical density gradients exist within the tree; in New Zealand-grown ash and eastern blue gum eucalypts, wood density generally increases with increasing distance from the centre of the tree and with height up the tree stem (Harrris & Young 1988; Haslett 1988). These density gradients then must be coupled with a vertical growth stress gradient (cf. Chafé 1981) before the radial extent of the brittle heart core at various heights within the tree stem can be determined.

An illustrative analysis

An individual tree approach has been adopted here based on a hypothetical *E. regnans* tree which has grown straight and vertical for its entire life. This assumption removes complications associated with abnormal wood and other features which give rise to asymmetric distributions of growth stress within the stem. The tree is assumed to have grown under the following regime: three pruning lifts to 6 m at mean top heights and ages of 5, 9, and 13 m at 3, 6, and 8 years respectively, and contemporaneous waste thinnings from an initial stocking of 1250 stems/ha to residual stockings of 600, 300, and 100 stems/ha (Cavana & Glass 1985). The tree is assumed to have dbhob at each pruning lift of 5, 10, and 15 cm, consistent with mean dbhob measurements obtained in similar silvicultural treatments in a comprehensive *E. regnans* regimes trial (unpubl. data). Under-bark taper profiles at the time of each pruning lift, derived using Hayward's (1987) taper function, are given in Fig. 2.

Decay core: Estimates of the maximum decay core diameter can be obtained from Fig. 2 also. If decay enters through a pruned branch stub after high pruning, then the maximum decay core diameter will be about 15 cm, assuming the decay travels 4–6 m to ground level and stays within the growth ring sheath present at the time of pruning. The shape of the decay core in the bottom 6 m of the tree stem will be a truncated cone.

Decay entering the stem above 13 m after the third pruning lift, upon travelling 13 m or more to ground level may increase the radial dimensions of the decay core lower in the stem. The likelihood of this happening is unknown, but our observations suggest longitudinal decay movement tends to follow the pith rather than a growth ring sheath.

Defect core: The maximum DOS for each pruning lift tends to occur at the base of the lift. In conjunction with a (large) 75-mm-diameter branch, the profile described by DOS estimates obtained using Deadman & Calderon's (1988) relationship approximates an inverted truncated cone in shape, with diameter dimensions of about 12, 11, and 14 cm at 0, 2, and 4 m height, respectively. Further refinement of these estimates to derive an

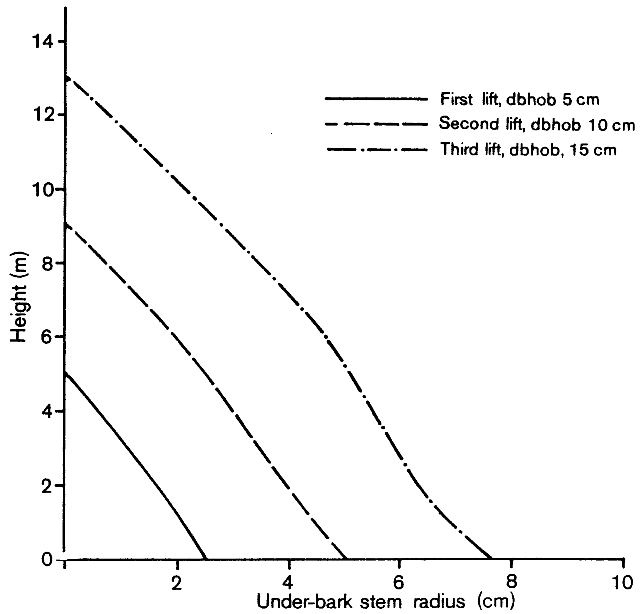

FIG. 2 — Under-bark taper of *E. regnans* by pruning lift (after Hayward 1987).

estimate of defect core diameter is not possible until the occlusion process in *E. regnans* is modelled satisfactorily.

Brittle heart core: Basic density estimates of 410, 428, 452, 488, 520 and 550 kg/m^3 at 0, 6, 12, 18, 24, and 30 m heights, respectively, were derived for New Zealand-grown *E. regnans* from data reported by Harris & Young (1988) and Haslett (1988). The corresponding maximum green crushing strengths parallel to the grain were estimated to be 21, 22, 23, 24, 27, and 29 MPa for 0, 6, 12, 18, 24, and 30 m heights, respectively (Bier 1984).

For a target tree 35 m tall and 75 cm dbhob at felling (cf. Cavana & Glass 1985 p. 183), using Kubler's (1959) empirical stress relationship and under-bark diameter estimates derived from Hayward's (1987) taper function*, along with a vertical peripheral stress gradient based on a ground-level peripheral stress of 9 MPa (Nicholson 1973; Nicholson *et al.* 1975; Chafé 1979), the stress gradients presented in Fig. 3 were derived. Superimposing the estimates of maximum green crushing strength parallel to the grain provided brittle heart core diameter estimates of about 14, 16, 16, 14, 10, and 5 cm for heights of 0, 6, 12, 18, 24, and 30 m respectively (Table 3). Thus the brittle heart core bulged radially outwards in the lower third of the stem but was otherwise roughly conical in shape.

*These dimensions exceed the data upon which Hayward's (1987) taper function is based. The sensitivity of results to this extrapolation is covered in the next section.

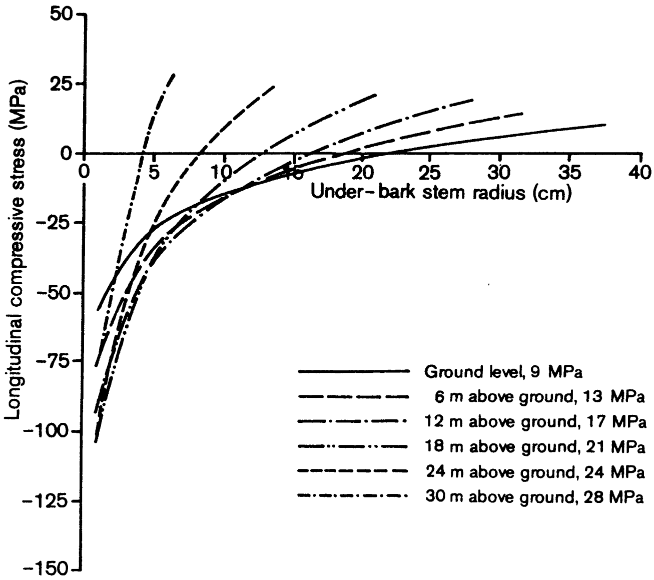

FIG. 3 — Longitudinal growth stress gradients at 6-m height intervals in 75-cm dbhob *E. regnans* by height, based on 9 MPa peripheral stress at ground level (after Kubler 1959).

TABLE 3–Radii of brittle heart cores in a straight, vertical, *E. regnans* tree for three peripheral growth stress gradients

Height (m)	External radius under-bark (cm)	Maximum green crushing strength (MPa)	Brittle heart core radius by peripheral stress gradients					
			Stress (MPa)	Radius (cm)	Stress (MPa)	Radius (cm)	Stress (MPa)	Radius (cm)
0	37.9	-21.1	4.0	1.6	9.0	7.1	17.0	12.4
6	31.1	-22.1	7.8	4.6	12.8	8.0	20.8	11.1
12	26.9	-23.2	11.7	6.1	16.7	8.1	24.7	10.2
18	20.9	-24.4	15.5	5.8	20.5	7.0	28.5	8.3
24	13.7	-26.5	19.4	4.2	24.4	4.8	32.4	5.5
30	6.5	-29.1	23.2	2.1	28.2	2.4	36.2	2.6

Sensitivity analysis

Increasing or decreasing the maximum branch diameter had a negligible effect on DOS. Assuming a uniform stem taper independent of height generally decreased both decay and brittle heart core diameters. Decreasing (increasing) green crushing strength parallel to the grain by 10% increased (decreased) brittle heart core diameter by a maximum of about 2 cm (1.6 cm) at ground level — this effect is equivalent to decreasing (increasing) basic density by 10%. A 5-cm dbhob increase (decrease) at felling increased (decreased) the brittle heart core diameter by 1.6 cm or less.

By contrast, a change in the ground-level peripheral growth stress had a dramatic impact upon brittle heart core diameter (Fig. 4). For the lower and upper stress values reported in the literature from Australia (i.e., 4 and 17 MPa respectively—Nicholson 1973; Nicholson *et al.* 1975) the maximum brittle heart core diameter was reduced and increased respectively to about 12 cm and 25 cm. The shape of the brittle heart core changed also, with the bulge being further exaggerated at about 12–18 m height on the one hand (4 MPa), and changing to a steep-sided cone on the other hand (17 MPa) (Table 3).

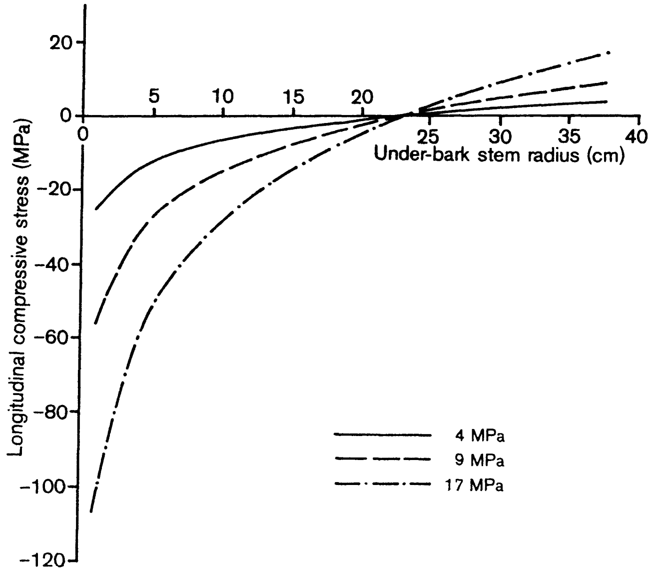

FIG. 4 — Longitudinal growth stress gradients at ground level in 75-cm dbhob *E. regnans* for 4-, 9-, and 17-MPa peripheral stress values (after Kubler 1959).

SILVICULTURE AND RESEARCH IMPLICATIONS

Silviculture

The trend detected in this study towards increased infection incidence with increasing branch diameter provides support for the branch diameter guideline for eucalypt pruning (Forest Research Institute 1982 pp. 46–7). The pruning recommendations are as follows:

> "... prune branches which are less than one inch [2.5 cm] in diameter, during the winter months. Pruned stocks [sic, stubs] should be sprayed with a 2% aqueous solution of captafol immediately after pruning."

Captafol is no longer readily available in New Zealand. Its use has been banned in some countries and will probably be banned in New Zealand also (M. Hedley, pers. comm.).

Once infection has occurred, extent of decay appears to be independent of stub diameter (Table 2).

The average pith-decay distance derived by cross-sectional analysis implies a decay core diameter of about 11 cm could be anticipated, which is well below the 15-cm estimate based on tree taper. Futhermore, comparison of Fig. 2 and 3 indicates that if all pruning were delayed until the tree was about 13 m tall, then a single-or two-lift pruning schedule would confine both the defect and the decay cores to within the brittle heart core, provided the peripheral growth stress was about 9 MPa.

Research

The number of pruning lifts determines the frequency of exposure to infection. Frequent pruning lifts (i.e., exposures) imply small-diameter branches are pruned so the total pruned branch stub (cross-sectional) area exposed to infection diminishes for an individual pruning lift. When the number of pruning lifts is reduced then pruning, in effect, is delayed, and the pruned branch stub area exposed to infection increases for that pruning lift.

The number of pruning lifts also influences the duration for which branch stubs are exposed to conditions favouring infection after pruning but before occlusion is completed. Large-diameter stubs will be exposed to infection for longer than small-diameter stubs because occlusion slows as branch diameter increases, so infrequent rather than frequent pruning lifts imply the likelihood of infection increases. The net effect of these trade-offs on infection occurrence is not known.

Another trade-off may exist with respect to tree growth, particularly if pruning, timed to remove branches before the 2.5-cm branch diameter limit is reached, results in removal of an excessive proportion of green crown. From this perspective, the effects of single- or two-lift pruning schedules on tree growth also remain unknown as yet.

DOS was used above as a proxy for defect core diameter though, other things being equal, it will consistently understate defect core diameter. The principal limitation in estimating defect core diameter concerns the occlusion process in pruned eucalypts. Deriving a relationship between DOS and the defect core would remedy this deficiency.

Development of decay within the stem, particularly in the longitudinal and outward radial directions, is of acute relevance to eucalypt silviculture. In Australia radial outward movement of internal decay associated with thinning damage, rather than pruning, has been reported as occurring in *E. regnans* 15 years after wounding (G. Kile pers. comm.). The frequency and possible extent of radial decay movement outward into wood laid down after infection needs further study.

Results of investigations into growth stress have been reported in two forms—growth stress and growth strain. Results reported solely in either form are of extremely limited use for examining stress-related phenomena such as brittle heart, unless associated crushing strengths or basic densities are measured also.

A more convenient means than microscopic examination for identifying the presence of brittle heart is required before the propositions derived here can be tested. Basic density measurement will be fundamental in detecting brittle heart in stem sections using any methods based on strength testing.

The most detailed eucalypt growth stress and strain measurements reported are for the ash group, particularly *E. regnans, E. obliqua,* and *E. delegatensis.* Other species have received considerably less study, although in New Zealand experience the consequences of growth stress may be more prominent than for the ash eucalypts (e.g., end-splitting in *E. saligna*—Kininmonth *et al.* 1974).

There are at least two other aspects requiring further investigation. The first covers between-tree growth stress variation and related factors, including both genetic and silvicultural effects on growth stresses. The second involves mapping within-tree growth stress variation, including longitudinal growth stress variation with height.

CONCLUSIONS

Internal decay in pruned *E. regnans* trees travelled upwards and downwards from the initial entry point, tending to follow the pith. Continuous decay systems formed when the decay pockets resulting from initial infection entry sometimes linked up. Decay was not detected in wood laid down after infection occurred. Eucalypt pruning guidelines with respect to branch diameter were supported by infection incidence in relation to pruned branch stub diameter.

It is inappropriate to view the effect of decay on eucalypts grown in New Zealand in isolation from the effects of either tending operations (and especially pruning) or longitudinal growth stress. Brittle heart, in particular, is likely to have a greater impact on the delimitation of the central core zone than decay alone, especially if outward radial movement of decay occurs infrequently.

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