Stem decay in final-crop eucalypts from regrowth forests identified for intensive management

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Abstract

Four hundred and thirty-six young, final-crop eucalypts from 20 coupes identified for intensive management were felled, dissected and assessed for stem decay. Coupes dominated by Eucalyptus obliqua *had higher levels of stem decay than those dominated by* E. regnans *and* E. delegatensis. *Overall, 15.2% and 29.3% of the potentially merchantable sawlog volume at rotation was downgraded because of excessive decay in the butt (0–6 m) and head (6–12 m) log sections respectively. This level of downgrading represents an annual loss in royalties of $6.80/ha and $12.70/ha for the butt and head logs respectively, with the annual value-adding loss to the Tasmanian economy being estimated as $107.10/ha and $154.30/ha.*

The abundance of dead branches (12–28 mm diameter), live branches in the 0–12 m stem section and surface area decayed at 2.5 m have been used to model decay states of individual trees. The incorporation into the current selection criteria for cull trees of external stem features, with or without a measure of sectional area decayed in the lower stem, could reduce by 20–30% the losses due to downgrading sawlogs because of stem decay in the final crop. However, operational trials are needed to evaluate whether these alternative selection criteria can be applied in a cost-effective manner.

Introduction

The Forests and Forest Industry Strategy for Tasmania recommended the need to implement, at the maximum feasible level, intensified management by thinning regrowth eucalypt forests to enhance future hardwood sawlog supply (FFIC 1990). For this strategy of intensive management to succeed, it is imperative that the maximum volume contained in trees retained following thinning is suitable for sawn timber production. While it has been demonstrated that damage inflicted on retained eucalypts during thinning operations will reduce sawlog yield (White and Kile 1991), current cable-thinning operations are consistently achieving very low damage levels (Cunningham 1997). However, Wardlaw (1996) has shown that the background levels of stem decay in these regrowth forests selected for intensive management can be locally high. The impact of such levels of background decay on sawlog yield has not been established, nor is it known how extensive the level of decay is in regrowth forests suitable for intensive management in other regions of Tasmania.

In 1992, the Forestry Commission, Tasmania, (now Forestry Tasmania) initiated a pilot study in young eucalypt regrowth forests in the Florentine and Styx Valleys to develop a methodology to sample, measure and identify the causes of stem decay in final-crop trees (Wardlaw 1996). Knowledge gained from the pilot study has been applied to a more extensive, Tasmania-wide survey of stem-decay levels in regrowth forests identified for thinning. The objectives of this survey were to:

1. Measure the incidence and extent of decay in potential final-crop trees;

Table 1. Site and stand characteristics, and decay summaries of coupes sampled for the decay survey. (DBH = diameter at breast height, MDH = mean dominant height.)

									Number of trees in decay class				
Coupe	District	Dominant eucalypt	Altitude (m)	Area (ha)	Age (years)	Sample size	DBH (cm)	MDH (m)	No Decay	Low (< 2%)	Moderate (2 to < 5%)	Severe (≥ 5%)	Decay (% total vol.)
AR12	Huon	*E. regnans – E. obliqua*	252	41	28	36	37.2	30.3	3	19	8	6	2.3
AR60	Huon	*E. obliqua – E. regnans*	200	125	29	42	30.5	31.8	7	26	7	4	1.7
CL314t	Mersey	*E. delegatensis*	835	34.4	54	21	43.6	31.4	0	11	5	5	3
EP1	Huon	*E. obliqua – E. regnans*	90	62	28	30	32.6	30.8	6	18	3	3	1.5
EV28	Eastern Tiers	*E. regnans – E. delegatensis*	600	7.5	30	7	32.2	27.4	0	5	0	2	3.4
F01	Derwent	*E. regnans*	623	29	25	24	29.4	29.0	7	13	3	1	0.9
F02a	Derwent	*E. regnans*	535	26	29	20	32.5	28.9	2	10	4	4	2.7
HA24	Huon	*E. obliqua*	140	11.6	26	11	33.4	31.2	0	6	2	3	5.3
HA29	Huon	*E. obliqua*	30	12.6	33	8	31.8	30.6	1	2	2	3	4
HA30	Huon	*E. obliqua*	35	7	28	6	30.9	28.4	0	0	0	6	16.9
KY7z	Derwent	*E. obliqua*	287	13	52	9	39.1	36.1	1	2	1	5	16.4
PC4	Huon	*E. obliqua*	130	46.4	26	30	28.2	29.8	5	7	7	11	3.8
RP03	Derwent	*E. regnans*	491	18.2	29	17	28.9	30.9	2	9	4	2	1.7
RP123	Derwent	*E. delegatensis – E. regnans*	595	58	26	40	29.5	26.6	2	30	4	4	2
SM108b	Mersey	*E. delegatensis*	630	9.9	51	8	43.6	30.5	0	2	4	2	4.6
SO23	Huon	*E. obliqua – E. globulus*	260	35.6	31	27	29.6	29.7	2	14	5	6	3.3
TA18	Derwent	*E. obliqua*	95	59.9	22	48	31.3	27.5	3	13	12	20	6
TN52	Derwent	*E. delegatensis – E. regnans*	621	39	34	33	31.3	30.3	7	17	5	4	2.1
TO53	Eastern Tiers	*E. delegatensis*	665	14	50	11	46	30.3	0	10	1	0	0.8
WE9	Derwent	*E. regnans*	340	7	23	8	33.2	29.9	2	5	0	1	1

2. Predict the impact of stem decay on sawlog yields;
3. Better identify trees likely to contain high levels of stem decay; and
4. Identify site factors associated with high levels of stem decay.

Methods

1. Incidence and severity of stem decay

Twenty coupes from among those considered suitable for intensive management were selected for assessment. Details of the coupes sampled are presented in Table 1. Within the selected coupes, trees chosen for decay assessment were those closest to the intercepts of a two-dimensional grid (100 m x 100 m) surveyed through the coupe, and which met the criteria for retention during thinning (defined in Wardlaw 1996).

Prior to felling, the selected trees were painted with a band at breast height (1.3 m) and a line to mark the north side of the stem. After felling, and with reference to the band, marks for cross-cutting were painted along the stem at heights of 0.5, 2.5, 4.5, 6, 9, 10.5 and 12 m. A longitudinal strip was painted along the top side of the stem and its bearing in relation to the north mark was measured. After cross-cutting, the end of each billet was inspected for discoloration and decay and, if these were present on the end of any billet, further cross-cuts were made at 50 cm intervals above and below that point until the ends of the columns of discoloration and decay were reached.

Diameter-under-bark measurements (taken at the widest point and the axis perpendicular to the widest point) were taken at the distal end of each billet. The surface area of any discoloration and decay on the distal end of each billet was measured with a transparent grid according to the method outlined in Wardlaw (1996). The location of each patch of discoloration and decay was measured as the radial distance from the centre of the patch to the pith and the bearing of that radius (with reference to the longitudinal line painted on the stem). External features such as bumps, live and dead branches (or branch stubs) and wounds were noted for each billet and their location measured (height and bearing).

The volume of discoloration and decay and total stem volume for each tree were calculated using Smalian's Formula as described in Wardlaw (1996). Each tree was then assigned one of four decay-severity classes: no decay; low (< 2% of total volume decayed); moderate (2 to < 5% of total volume decayed); and severe (≥ 5% of total volume decayed). For each coupe sampled, the incidence and severity of decay was expressed as the proportion of trees in each of the four decay classes.

2. Economic impact of stem decay on sawlog yields

The impact of decay on merchantable sawlog recovery depends on the width of decay-free wood remaining outside the decay columns. Sawlog merchantabilty standards used in Tasmania specify a maximum allowable log-end defect which increases with increasing log diameter (Forestry Tasmania 1994). To apply these standards, trees sampled for decay were 'grown-on' to rotation age using Forestry Tasmania's native forest eucalypt growth model. Tree and stand inputs used in this model were:

- Diameter at breast height over bark (DBHOB) of the sample trees;
- Plot size (no. trees sampled/post-thinning stocking);
- Site index (calculated using Forestry Tasmania's site index model for native forest eucalypts, with inputs of stand mean dominant height [MDH] and corresponding stand age);
- Post-thinning stocking;
- Stand age at assessment; and
- Stand age at rotation.

The growth model predicts stand basal-area increment at rotation age which was assigned back to individual sample trees in proportion to their contribution to the total basal area of sample trees in each coupe at the time of assessment. Rotation age for each coupe was determined after 'growing-on' that coupe to a variety of ages and selecting that age which predicted a stand basal area of 60 m^2/ha and an average DBHOB of the sample trees of at least 50 cm.

Diameter-under-bark measurements (DUB) of 'grown-on' sample trees, corresponding to heights at which decay measurements were made, were predicted using Forestry Tasmania's taper model for native forest eucalypts (Goodwin 1992). Variables entered into the taper model for individual sample trees were:

- Predicted DBHOB at rotation;
- Species (to allow bark thickness to be estimated);
- MDH (predicted using the site index model, with inputs of age at rotation and site index calculated previously for the coupe) which was assigned to that tree with a height closest to the stand MDH at the time of assessment; and
- Heights corresponding to points at which decay assessments were made.

The merchantabilty as category 3 sawlogs (Forestry Tasmania 1994) of billets in each 'grown-on' tree was determined using predicted DUB measurements and assessed diameter of decay columns corresponding to each DUB height. A billet was classed as merchantable if the DUB at both ends was at least 30 cm and the assessed diameter of decay of either end was below the maximum allowable (as specified in the merchantability standards). The cumulative length of adjacent billets within each tree which met merchantability standards was calculated and, if that length was at least 2.4 m, a merchantable category 3 sawlog was determined present. The volume of merchantable category 3 sawlogs in the butt and head log section of each 'grown-on' tree, together with total log volume, was calculated using Smalian's Formula.

Table 2. Financial parameters used for calculating the economic impact of decay.

Attribute	Value
Royalty – Category 1	\$27.92/m^3
Royalty – Category 2	\$17.87/m^3
Royalty – Pulpwood	\$14.67/m^3
Export value – Woodchips	\$71.30/m^3
Average price sawn timber	\$750/m^3
Average sawn timber recovery	33%
Chip recovery (sawlog residue)	45%

The value of individual 'grown-on' trees was calculated both in terms of royalty to the grower and total value to the Tasmanian economy. Financial inputs are shown in Table 2. Average stumpage rates for category 3 sawlogs and pulpwood were obtained from Forestry Tasmania's 1996–97 *Annual Report* (Forestry Tasmania 1997). Export value of pulpwood was obtained from current sale contracts (R. Rich, pers. comm.) and estimated value of sawn timber, average sawn timber recovered and pulpwood recovery of sawlog waste were based on informed estimates (R. Rich, pers. comm.). Maximum potential values were calculated on the basis that all of the 'grown-on' volume was merchantable as category 3 sawlogs. Actual values were calculated on predicted volumes of merchantable category 3 sawlogs, with the remaining volume (unmerchantable as sawlogs) assumed to be merchantable as pulpwood. Equations used to calculate financial values are given by Formulae 1 and 2.

Values calculated for the assessed trees using these formulae were converted to per-hectare-per-annum values by dividing calculated results by the predicted rotation age and the ratio of number of trees assessed to the post-thinning stocking (stems/ha).

Because the above economic impact analysis is based on the assumption that the size of the decay columns at rotation is the same as that measured at the time of assessment (some 30–40 years prior to rotation age), the calculated impacts are likely to be conservative, particularly in those trees with severe decay

Formulae for calculating financial values

Formula 1—for royalties

$$\text{Value} = (\text{Volume}_{cat3} \times \text{Stumpage}_{cat3}) + (\text{Volume}_{pulp} \times \text{Stumpage}_{pulp})$$

Formula 2—for value to State economy

$$\text{Value} = (\text{Volume}_{cat3} \times \text{Recovery}_{sawn} \times \text{Value}_{sawn}) + (\text{Volume}_{cat3} \times \text{Recovery}_{pulp} \times \text{Value}_{pulp}) + (\text{Volume}_{pulp} \times \text{Value}_{pulp})$$

at assessment but predicted to contain merchantable sawlog at rotation. To provide a potentially more realistic estimate of economic impact to account for the expected more rapid development of decay in those trees assessed to have severe decay, a second analysis was done. This analysis assumed that the entire volume contained in butt or head log sections assessed to have severe decay was downgraded to pulpwood.

3. *Prediction of stem decay in individual trees*

At the time of decay assessment, tree and local site attributes of each sample tree were also scored. Tree attributes scored were:

- Size (DBH, total height, and height to the base of the live crown [bole height]);
- Species; and
- Stem features:
  - bumps (small, medium, large),
  - dead branches and branch stubs (and their diameter),
  - holes (unoccluded shed branches),
  - live branches (and their diameter),
  - epicormic branches,
  - stem-boring insect damage and
  - open and closed wounds (and their size).

Local site attributes scored were:

- Slope;
- Aspect;
- Drainage (impeded, free, excessively free);
- Basal area of surrounding eucalypts; and
- Vegetation (species composition).

The relationship between these tree and site attributes and the level of stem decay in individual trees was explored by linear least squares regression, analysis of variance and logistic regression using the statistical program STATGRAPHICS (Statistical Graphics Corporation 1995).

LeMay (1993) demonstrated the usefulness of the percentage cross-sectional area decayed at stump height in improving the reliability of predicting the total stem decay volume. This relationship was explored with the eucalypts assessed in the current study using cross tabulation of the number of trees in each of the four severity classes of stem decay (0, < 2%, 2 to < 5% and 5%) by the number of trees in each of four classes of sectional area decayed (0, < 2%, 2 to < 5% and 5%), measured at 2.5 m. Logistic regression was used to test the usefulness of a measure of sectional area decayed at 2.5 m in improving the predicted stem-decay classification of trees based on external stem features.

4. *Factors influencing the level of stem decay at the stand level*

Data used to examine the influence of stand attributes were obtained from surveys conducted during the Florentine Valley decay survey (see Wardlaw 1996). During that survey, the level of stem decay was measured at four sites, each with two or three plots. For the current analysis, each plot/site combination was considered to be a separate stand.

Independent variables examined were:

- Stocking of all eucalypts counted in each 0.2 ha plot;
- Basal area of all eucalypts greater than 10 cm diameter in each 0.2 ha plot;
- Stand age;
- Average number of dead and live branches per tree (standardised to number per metre of stem); and
- Average diameter of dead and live branches.

Three measures of decay at the stand level were calculated:

- Stand average decay volume (per cent of total merchantable volume decayed);
- Stand average of the number of decay columns per tree; and
- The proportion of trees in each stand with moderate to severe decay (≥ 2% stem volume decayed).

Least squares regression was used to test the significance of the relationship of the independent variables with each of the three measures of decay.

Results

1. Incidence and severity of stem decay

Average decay levels measured in the 438 trees sampled were 2.7% (± 0.273), 3.8% (± 0.333) and 3.2% (± 0.259) for the butt (0.5–6 m), head (6–12 m) and total (0.5–12 m) log sections respectively (see Table 3). Only 26%, 24% and 13% of the trees had no decay within the butt, head and total log lengths respectively. Fifteen percent, 24% and 11% of the trees had severe decay (> 5% of volume) within the butt, head and total log lengths respectively. There were, however, substantial differences between coupes in both the incidence of trees with severe decay and the average amount of decay (Table 1, Figure 1).

Those coupes dominated by *E. obliqua* had particularly high levels of decay (Table 1). This species had more than double the proportion of trees with severe decay than the other two ash species, *E. regnans* and *E. delegatensis* (Figure 2). The high incidence of severe decay in *E. obliqua* was due mainly to more severe decay in the head log (6–12 m) of that species compared with *E. regnans* and *E. delegatensis*.

2. Economic impact of stem decay

The total volume at rotation was predicted to be 230 m^3/ha and 175 m^3/ha (averaged across all coupes) for the butt and head logs respectively. Of this volume, 94% and 83% of the butt and head logs respectively were predicted to meet minimum end-diameter specifications for category 3 sawlogs. In the butt log, 15.2% (range 3.4–37.6%) of the potentially merchantable category 3 sawlog volume failed to meet specifications because of excessive log-end defect. When the volume contained in butt logs assessed as having severe decay but meeting merchantability standards at rotation was also discounted, the percentage of potential category 3 sawlogs downgraded to pulpwood increased to 21.3% (range 8.2–49.1%). In the head log, average loss of potentially merchantable category 3 sawlogs because of excessive log-end defect was 29.3% (range 0–85.6%), increasing to 38.2% (range 0–85.6%) if head logs assessed as having severe decay but

Table 3. Percentage of final-crop eucalypts in each of four decay-severity classes, with the logs partitioned into butt section, head section and the total log.

Decay class	Butt log (0.5–6 m)	Head log (6–12 m)	Total log (0.5–12 m)
No decay	25.6	24.4	13
Low (< 2%)	41.8	37.8	50.7
Moderate (2 to < 5%)	17.8	13.7	16.4
Severe (≥ 5%)	14.8	22.6	19.9

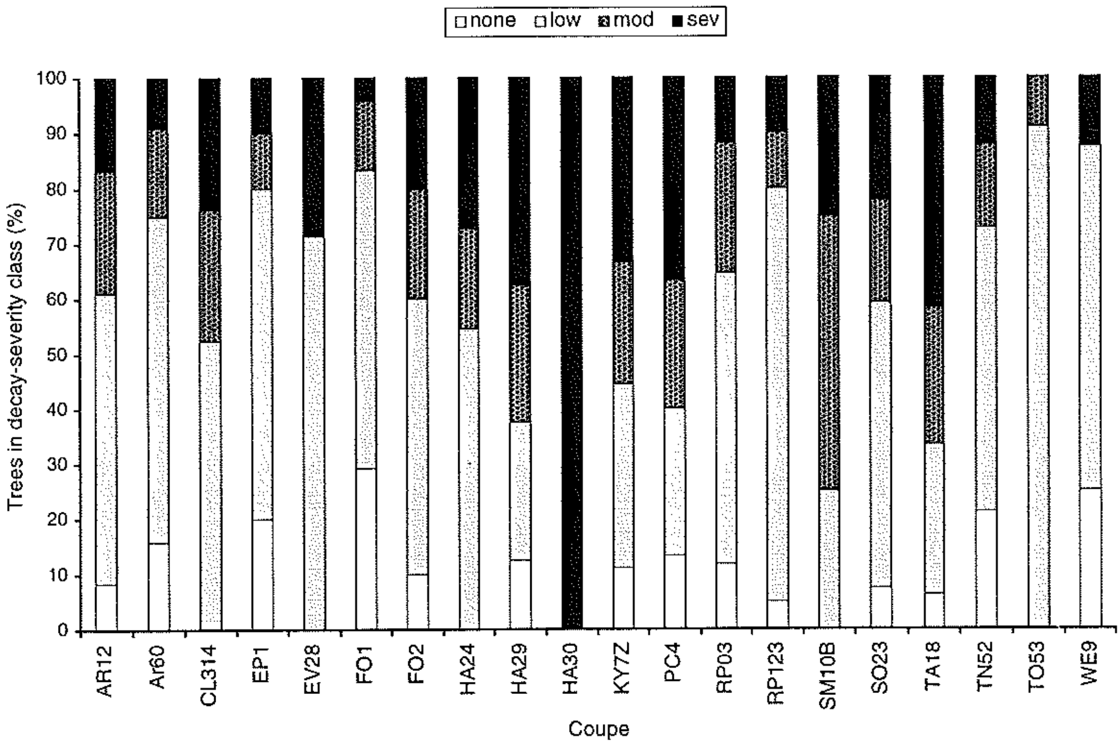

Figure 1. Per cent of final-crop eucalypts in each of four decay-severity classes, based on surveys in 20 coupes.

meeting merchantability standards at rotation were also discounted.

The calculated potentially merchantable category 3 sawlog volume downgraded to pulpwood because of excessive log-end defect represented an average loss in royalties of 7.4% (range 1.7–18.6%) and 15.1% (range 0–41.5%) for the butt and head logs respectively. These equate to average annual royalty losses of $6.80/ha (range $1.70–$15.80) and $9.80/ha (range $0.00–$31.50) for the butt and head logs respectively (Figure 3). These annual royalty losses inflate to $9.70/ha (range $3.20–$26.10) and $12.70/ha (range $0.00–$31.50) for the butt and head logs respectively if logs assessed as having severe decay but meeting merchantability standards at rotation are also discounted.

The average annual loss in value-adding to the Tasmanian economy from the downgrading of potential category 3 sawlog volume to pulpwood because of excessive log-end defect was calculated to be $107.10/ha (range $26.40–$247.90) and $154.30/ha (range 0–$494.40) for the butt and head log respectively. If logs assessed as having severe decay but meeting merchantability standards at rotation are also discounted, the average annual value-adding loss increases to $151.90/ha (range $50.40–$409.70) and $200.40/ha (range 0–$494.40) for the butt and head logs respectively.

3. Prediction of stem decay in individual trees

Tree size.—Trees with no decay were significantly smaller in diameter (measured at breast height) than trees with decay ($P < 0.05$). However, neither diameter nor total height could discriminate trees with severe decay in either the butt or head log from trees with lesser amounts of decay.

Local site factors.—None of the site factors examined show promise of being able to

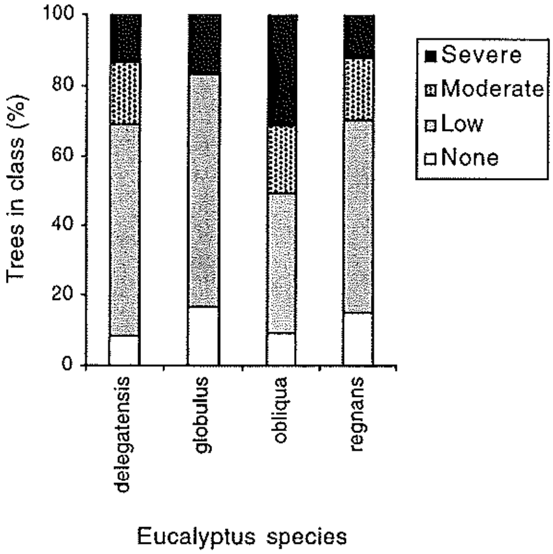

Figure 2. Proportion of trees in each of four decay-severity classes for each of four eucalypt species. Data are based on decay in the total log (0.5–12 m).

predict the level of stem decay in individual trees with any reliability.

External stem features.—The abundance of all of the external stem features except epicormic branches (E), closed wounds (V), large bumps (B2) and large dead branches (D4) were significantly correlated with the amount of stem decay in the butt, head and total log sections (Table 4). Despite this, the correlations were quite weak (Figure 4), with the strongest (D2) only accounting for 13.7% of the variation in the dependent variable (% decay in the butt log). Similar results were obtained when the individual external stem features were used as independent variables in logistic regressions, with the dependent variables being decay state (severe or not severe decay) in the butt, head and total log sections.

The combination of the abundance of several external stem features substantially improved

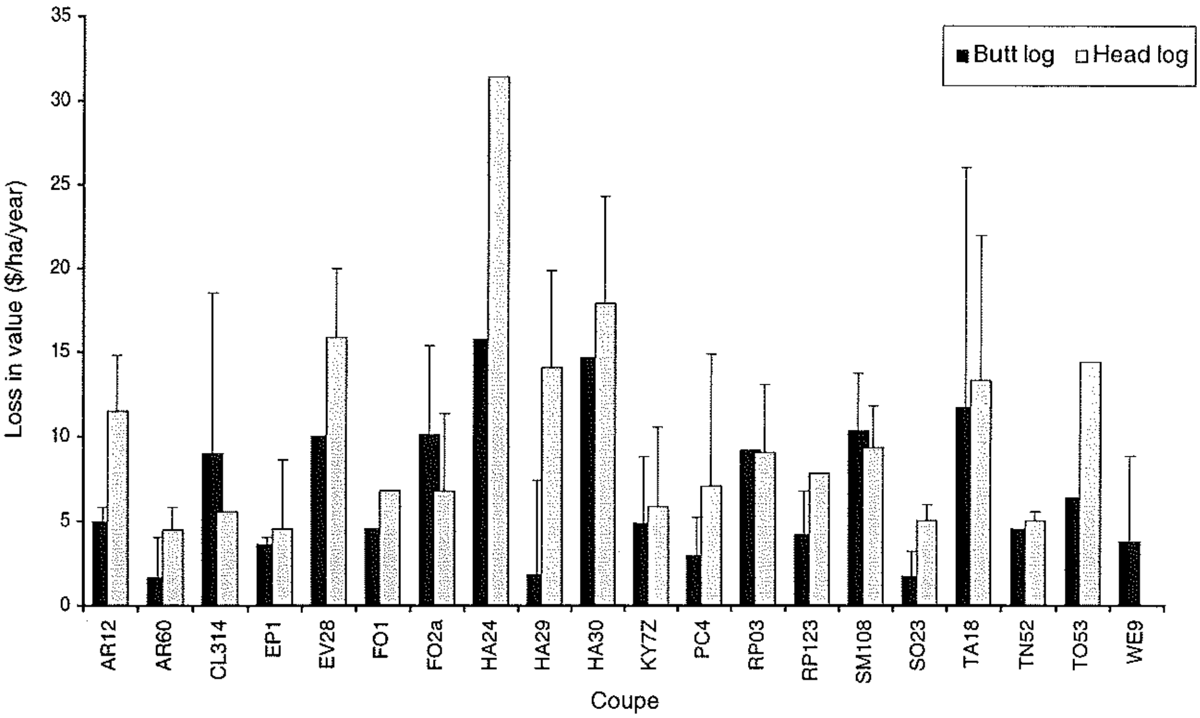

Figure 3. Annual loss in royalties due to downgrading of potential sawlogs to pulpwood because of excessive decay in the head and butt log sections. Solid bars are based on discounts calculated using merchantability standards for allowable end defect, and the lines show the additional loss when trees assessed with severe decay but meeting merchantability standards at rotation are also discounted.

Table 4. Least squares regression models, Pearson's correlation coefficients and significance level for the abundance of individual external features versus per cent volume decayed in the butt, head and total log sections.

	Model coefficents (Pearson's correlation/significance)		
External Feature	Butt log (% decay)	Head log (% decay)	Total log (% decay)
Bump small (B0)	$(0.77 + 0.047B0)^2$ (0.26, $P < 0.001$)	$(1.11 + 0.056B0)^2$ (0.25, $P < 0.001$)	$(1.7 + 0.051B0)^2$ (0.28, $P < 0.001$)
Bump med (B1)	$(0.79 + 0.069B1)^2$ (0.23, $P < 0.001$)	$(1.03 + 0.101B1)^2$ (0.28, $P < 0.001$)	$(1.03 + 0.085B1)^2$ (0.24, $P < 0.001$)
Bump large (B2)	- (-0.04, n.s.)	- (-0.02, n.s.)	- (-0.03, n.s.)
Dead branch < 12mm (D1)	$(0.95 + 0.095D1)^2$ (0.30, $P < 0.001$)	$(1.43 + 0.073D1)^2$ (0.19, $P < 0.01$)	$(1.33 + 0.08D1)^2$ (0.25, $P < 0.001$)
Dead branch 12–18mm (D2)	$(0.81 + 0.142D2)^2$ (0.37, $P < 0.001$)	$(1.27 + 0.127D2)^2$ (0.28, $P < 0.001$)	$(1.17 + 0.131D2)^2$ (0.35, $P < 0.001$)
Dead branch 18–28 mm (D3)	$(0.77 + 0.158D3)^2$ (0.31, $P < 0.001$)	$(1.21 + 0.152D3)^2$ (0.25, $P < 0.001$)	$(1.10 + 0.159D3)^2$ (0.31, $P < 0.001$)
Dead branch > 28mm (D4)	$(1.2 + 0.077D4)^2$ (0.14, $P < 0.05$)	- (-0.08, n.s.)	- (0.06, n.s.)
Epicormic (E)	- (-0.01, n.s.)	- (-0.02, n.s.)	- (-0.02, n.s.)
Hole (H)	$(1.4 + 0.164H)^2$ (0.17, $P < 0.01$)	$(1.38 + 0.263H)^2$ (0.23, $P < 0.001$)	$(1.35 + 0.192H)^2$ (0.20, $P < 0.01$)
Stem boring insect (I)	- (0.11, n.s.)	$(4.87 + 5.094I)^{0.5}$ (0.15, $P < 0.05$)	$(3.83 + 3.843I)^{0.5}$ (0.15, $P < 0.05$)
Live branch (L)	$(1.26 - 0.08L)^2$ (-0.13, $P < 0.05$)	$(5.88 - 1.758L)^{0.5}$ (-0.17, $P < 0.01$)	$(4.51 - 1.151L)^{0.5}$ (-0.15, $P < 0.05$)
Closed wound (V)	- (0.013, n.s.)	- (0.04, n.s.)	- (0.02, n.s.)
Open wound (W)	2.97 + 13.769W (0.25, $P < 0.001$)	- 0.075, n.s.)	3.88 + 9.844W (0.18, $P < 0.01$)

the fit of logistic regressions models of decay state in the butt, head and total log sections. Coefficients of the final models for each of the three log sections are presented in Table 5.

Decayed surface area measurement.—Figure 5 shows that there is a strong association between the severity of stem decay and the surface area decayed at a point in the lower stem. This diagram shows that a high proportion of the trees with severe decay (≥ 5% of volume decayed) also have a high percentage (> 5%) of the surface area decayed at 2.5 m. Similarly, a relatively low proportion of trees from the lower decay-severity classes have a high percentage of the surface area decayed at 2.5 m.

The addition of the percentage of surface area decayed at 2.5 m into the logistic regression models to predict decay state (severe or not severe) in individual trees produced significant improvements in fit (Table 6) compared with models containing just external stem features. Table 7 summarises the changes in merchantable sawlog volumes downgraded because of excessive decay and associated loss in royalties due to the removal of trees predicted to contain severe decay using the logistic regression

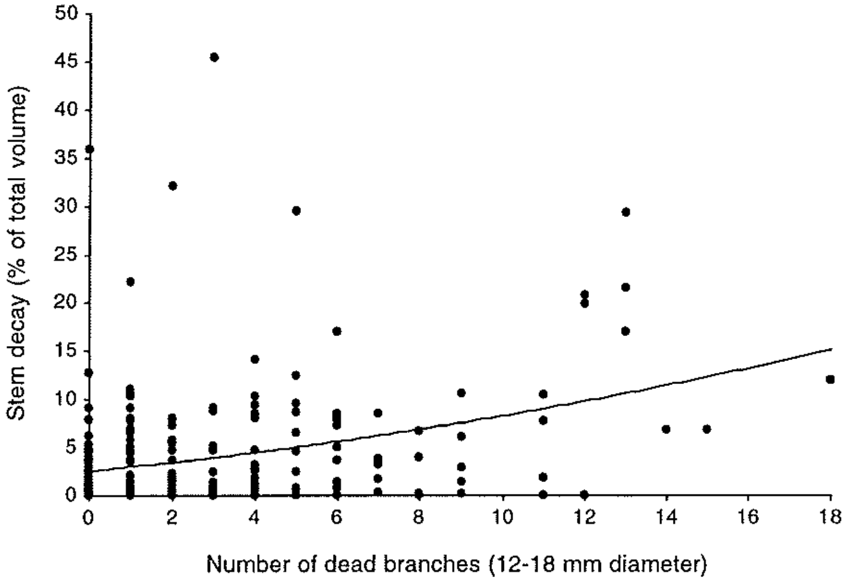

Figure 4. Plot of the number of dead branches (12–18 mm diameter) versus stem decay (as per cent of total volume) for the total log section (0–12 m) with fitted least squares regression model of the form $(a + bx)^2$.

Table 5. Coefficients (and their standard errors) of logistic regressions models of decay state (severe or not severe decay) in each of the butt, head and total log sections versus external stem features. Independent variables (codes as defined in Table 4) are listed in order of the significance of their contribution to the final model.

	Butt log	Head log	Total log
Constant	-3.318 (0.5008)	-1.637 (0.3742)	-1.982 (0.3546)
Independent variable 1	0.325xD3 (0.1087)	0.253xD2 (0.0687)	0.217xD2 (0.0720)
Independent variable 2	0.168xD2 (0.0691)	-0.637xL (0.2449)	-0.504xL (0.2015)
Independent variable 3	1.344xI (0.7510)	0.103xB1 (0.0461)	0.298xD3 (0.9952)
% deviance explained	29.5 (24.0 adjusted)	21.6 (17.5 adjusted)	24.0 (19.7 adjusted)

Table 6. Coefficients (and their standard errors) of logistic regressions models of decay state (severe or not severe decay) in each of the butt, head and total log sections versus external stem features and per cent surface area decayed at 2.5m. Independent variables (codes given in Table 4) are listed in order of the significance of their contribution to the final model.

	Butt log	Head log	Total log
Constant	-4.4693 (0.7811)	-1.869 (0.3996)	-2.297 (0.3919)
Independent variable 1	0.341xSA (0.0939)	0.222xD2 (0.0708)	0.168xSA (0.0534)
Independent variable 2	0.444xD3 (0.144)	-0.628xL (0.2332)	-0.642xL (0.2489)
Independent variable 3	0.176xD2 (0.0943)	0.119xB1 (0.0479)	0.308xD3 (0.1053)
Independent variable 4	-0.656xL (0.0.4918)	0.087xSA (0.0366)	0.195xD2 (0.0830)
% deviance explained	58.6 (51.7 adjusted)	25.0 (19.8 adjusted)	34.2 (28.9 adjusted)

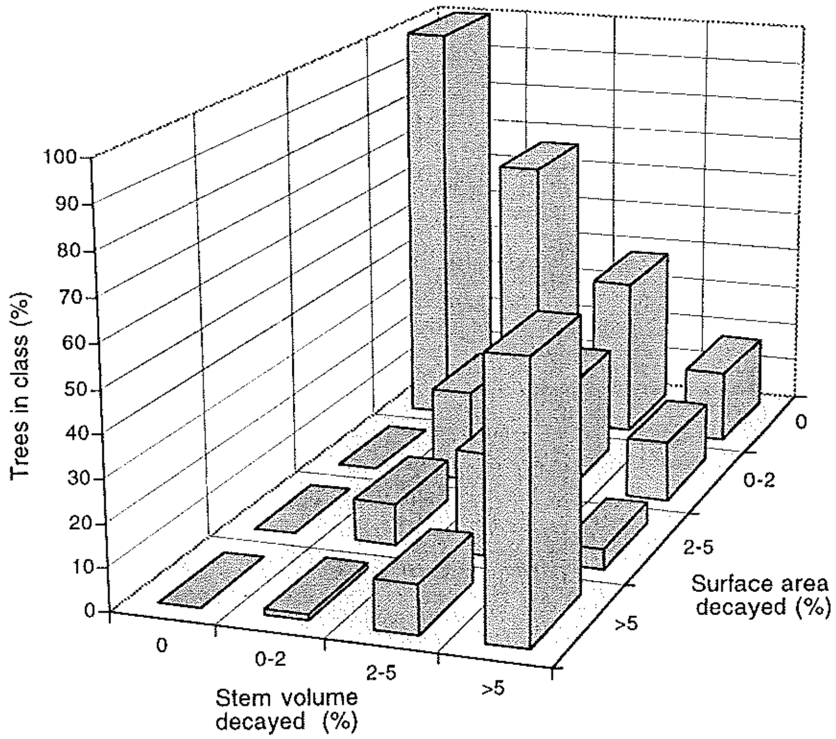

Figure 5. Percentage of final-crop eucalypts in each of four stem decay classes, each partitioned into four classes of surface area decayed as measured 2.5 m up the stem.

models (one model using external features only and the other using both external features and surface area decayed). The incorporation of a measure of surface area decayed to predict trees with severe decay reduced losses in merchantable sawlog volumes and associated royalties by 20–50% above that achieved when only external features are used for predictions.

4. *Factors influencing the level of stem decay at the stand level*

Trends between stand factors and the three measures of decay were more obvious at the stand level than at the individual tree level. Table 8 summarises the results of the linear regressions of the stand and tree factors with the three measures of decay. Stand age was positively correlated with each of the three measures of decay (Figures 6a–c) but was only significant for the number of decay columns and proportion of trees with moderate or severe decay. Stocking had significant negative correlation with each of the three measures of decay (Figures 7a–c). The number and diameter of live branches (Figures 8a–c, 9a–c), and the diameter of dead branches, were positively correlated with the measures of decay, but the relationships reached statistical significance only in three of the nine regressions. Each of these three branch characteristics had strong negative correlations with stocking so that the relationships between stocking and the measures of decay were largely due to the effect of stocking on branch attributes. Neither basal area nor the number of dead branches showed any consistent trends in their relationship with the three measures of decay.

Table 7. Summary of losses, expressed as percentage of sawlog volume downgraded to pulpwood and resultant percentage loss in royalties, for three methods of selecting final-crop trees in intensively managed regrowth eucalypt forests. Losses are calculated for two methods of determining merchantability: (i) maximum allowable end defect; (ii) maximum allowable end defect plus complete discounting of volume in butt or head logs with severe decay at time of assessment. Figures in brackets indicate percentage reduction in losses compared with current selection criteria.

	% loss of potential merchantable sawlog volume		% loss in royalties due to sawlog volume downgrade to pulpwood	
Final-crop selection	End defect	End defect + severe	End defect	End defect + severe
Current criteria	19.8	31.4	11.1	17.5
External features only	15.9 (19.8)	21.6 (31.3)	7.1 (20.5)	9.7 (31.9)
External features plus surface area decay	14.0 (29.4)	19.5 (38)	7.8 (29.8)	10.8 (38.3)

Table 8. Pearson correlation coefficients and significance level (in brackets) for linear least squares regressions of three measures of stem decay (site averages) versus seven site and tree factors (stand averages).

	Measure of stem decay		
Independent variables	No. of decay columns	Average decay (% of total volume)	Proportion moderate or severe decay
Stand age (years)	0.73 ($P < 0.05$)	0.46 (n.s.)	0.81 ($P < 0.01$)
Stocking (stems/ha)	-0.64 ($P < 0.05$)	-0.70 ($P < 0.05$)	-0.79 ($P < 0.01$)
Basal area (m^2/ha)	0.28 (n.s.)	-0.25 (n.s.)	-0.18 (n.s.)
No. of dead branches	0.22 (n.s.)	-0.13 (n.s.)	-0.23 (n.s.)
Diameter dead branches (mm)	0.48 (n.s.)	0.53 (n.s.)	0.66 ($P < 0.05$)
No. live branches	0.38 (n.s.)	0.66 ($P < 0.05$)	0.57 (n.s.)
Diameter live branches (mm)	0.65 ($P < 0.05$)	0.55 (n.s.)	0.46 (n.s.)

Discussion

The levels of decay measured during this survey were higher than those found in the earlier survey confined to regrowth forests in the Florentine Valley area (Wardlaw 1996). However, coupes from the Florentine area sampled during this survey had comparable decay levels to those in the earlier survey. The higher decay levels in the current survey were due mainly to the high levels of decay in regrowth forests dominated by *E. obliqua*.

The economic impact of the levels of decay measured in these regrowth forests, while substantial, must be considered only as an preliminary prediction. The application of merchantability standards to log-end defect measurements which pre-date log dimensions of trees 'grown-on' to harvest age by some 30–40 years would almost certainly underestimate the volume of sawlogs that are downgraded because of excessive decay. In particular, the more rapid spread of decay in trees with severe decay at the time of assessment would almost certainly be underestimated using the above method and the complete discounting of merchantable sawlogs at harvest in such trees might provide a more reasonable estimate of impact. Another factor complicating the estimation of economic impacts is the differentiation, in the merchantability standards, of incipient decay (discoloration) from true rot, whereby only

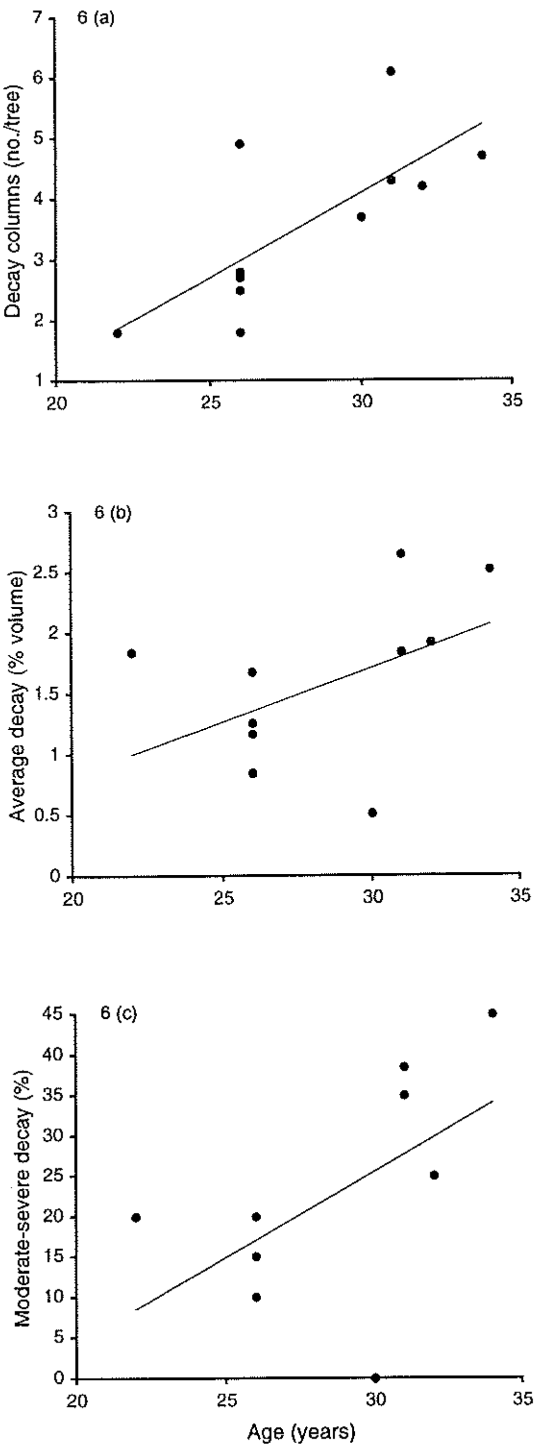

Figure 6. Scatter plot and linear regression trend-line of stand age versus: (a) average number of decay columns/tree; (b) average decay column; and (c) proportion of trees in the stand with moderate or severe decay.

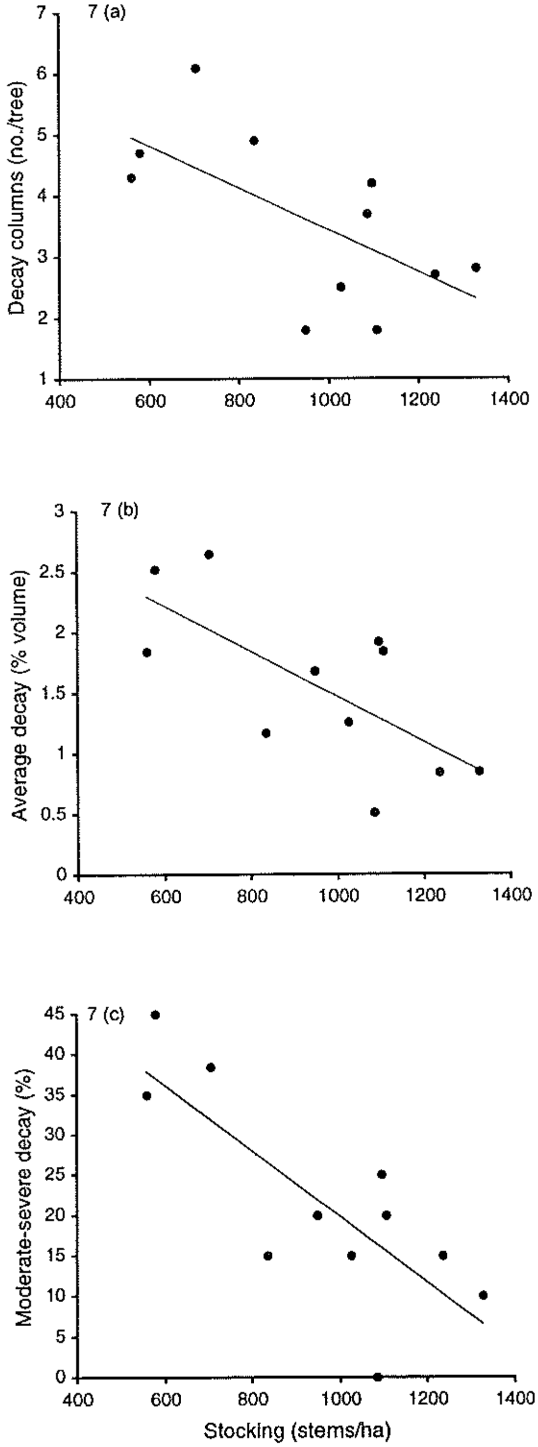

Figure 7. Scatter plot and linear regression trend-line of stocking (of eucalypts) versus: (a) average number of decay columns/tree; (b) average decay column; and (c) proportion of trees in the stand with moderate or severe decay.

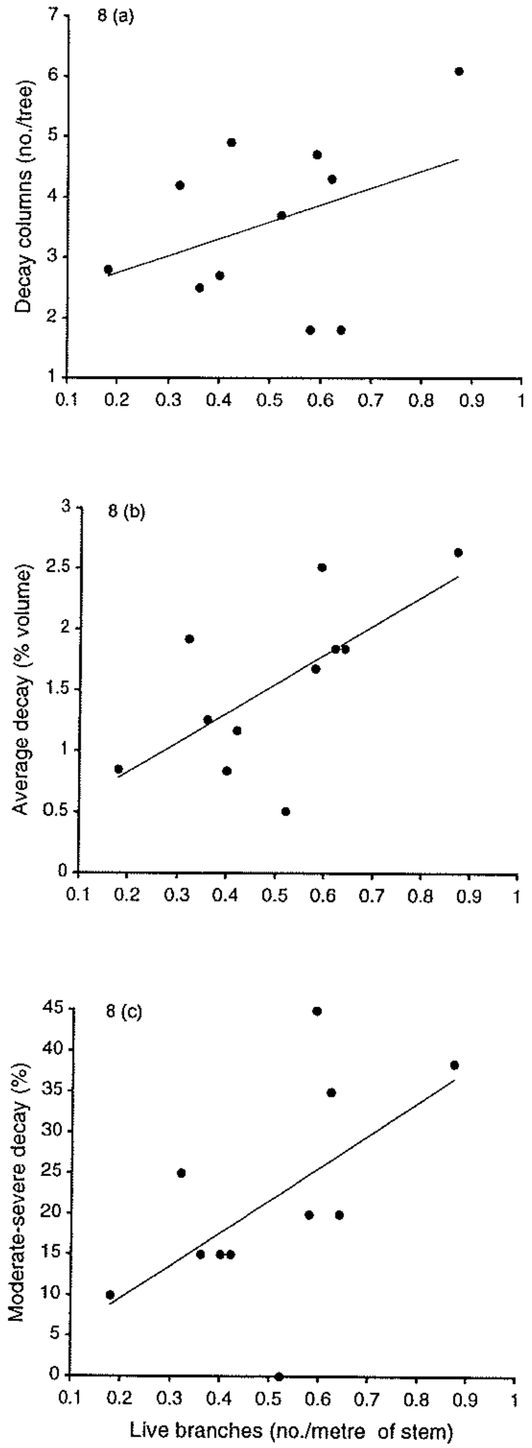

Figure 8. Scatter plot and linear regression trend-line of number of live branches versus: (a) average number of decay columns/tree; (b) average decay column; and (c) proportion of trees in the stand with moderate or severe decay.

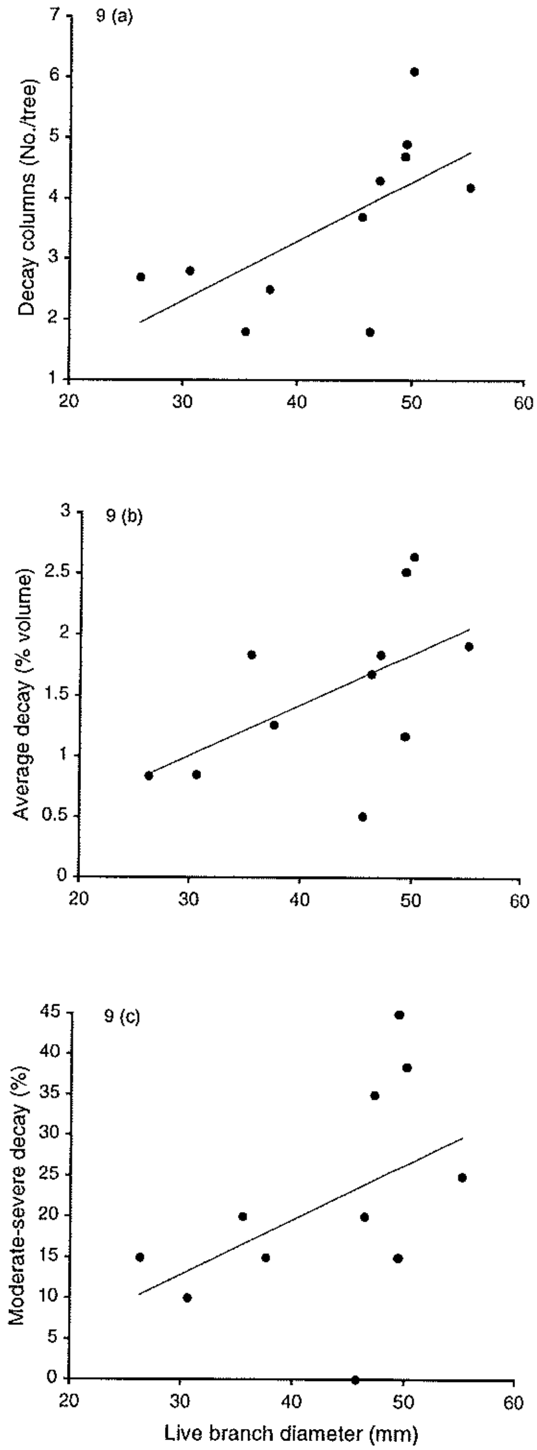

Figure 9. Scatter plot and linear regression trend-line of average diameter of live branches versus: (a) average number of decay columns/tree; (b) average decay column; and (c) proportion of trees in the stand with moderate or severe decay.

the amount of rot is considered in the application of the standards. The application of merchantability standards to combined measurements of incipient decay and rot in our study could lead to an overestimation of impacts but this would be counteracted, at least partially, by not having 'grown-on' the decay columns in tandem with tree growth. Despite the limitations of these predictions, it is clear that the economic viability of intensive management of regrowth eucalypt forests to accelerate sawlog production would be improved if the proportion of severely decayed trees in the final crop were reduced from that achieved using the current selection criteria for final-crop trees.

Clearly, the best way of reducing the incidence of trees with severe decay in the final crop after thinning is to identify those trees at the time of thinning, and cull them. The use of the abundance of particular external stem features to allow calculation of the predicted decay state was shown to reduce losses from downgrading sawlogs by between 20.5–31.9%. The operational feasibility of assessing the relevant external stem features on individual trees, particularly their upper bole (below approximately 12 m in forests to be thinned) and where understorey is dense, remains to be determined. The addition of the abundance of particular external stem features in selection criteria to identify trees with severe decay for culling may be impractical in stands where the stocking of potential final-crop trees, based on existing selection criteria, is near the desired post-thinning stocking. This is because a proportion of trees not containing severe decay are incorrectly predicted as having severe decay and hence culled.

The inclusion of a measure of surface area decayed at a point in the lower stem further improves the correct identification of severely decayed trees for culling such that the predicted losses due to excessive decay in the final-crop are between 29.8–38.3% less than selection using existing selection criteria. LeMay *et al.* (1994) also found that the inclusion of a measure of surface area decayed improved the reliability in classifying sound and decayed trees above that achieved using only easily measured external tree characteristics.

While the use of a measure of surface area decay at a point in the lower stem offers gains in our ability to correctly identify severely decayed trees, a methodology needs to be developed to obtain this measure in standing trees. LeMay *et al.* (1994) suggested the use of increment cores or a wood density measuring device such as the RESISTOGRAPH® (W. Kamm and F. Rinn, Heidelberg, Germany) to obtain a measure of the amount of decay in a cross-section at some point in the lower stem. The latter method has been chosen for evaluation on regrowth eucalypts in Tasmania, and preliminary trials indicate that the RESISTOGRAPH® is able to differentiate decayed from sound wood in eucalypts (T. Wardlaw and A. Walsh, unpublished data).

The adoption of more complex selection criteria to identify and cull severely decayed trees at the time of thinning is required only in stands likely to have high levels of stem decay. The criteria by which such stands may be identified have not been explored in great depth to date. However, based on analyses using data from a small number of stands, some tree and stand characteristics have emerged as potentially useful predictors of decay levels. In particular, low stocking, and the corresponding increase in average abundance and size of branches, appears to be associated with an increased level of decay. This association, if it is strengthened by analysis of data from a larger number of sites, becomes significant if more poorly stocked stands need to be considered for thinning to achieve desired targets for the area thinned.

Many of the results contained in this report are the subject of more detailed studies currently in progress or planned for the near future. When the results of those studies become available, we will be in a better position to identify alternative management prescriptions to minimise the levels of decay in intensively managed eucalypt forests in Tasmania.

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