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MODELLING SELECTION HARVESTING IN TROPICAL RAIN FORESTS

J. K. Vanclay

Department of Forestry, GPO Box 944, Brisbane 4000, Queensland, Australia.

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VANCLAY, J.K. 1989. Modelling selection harvesting in tropical rain forests. Long term yield estimates for natural forests require a harvesting model to enable future yields to be estimated reliably. The model should predict the felled stems, the proportion of these which are merchantable, and any damage to the residual stand. Regression analyses was used to develop a model of current logging practice in the rain forests of north Queensland. Logistic functions predict the probability of any tree being marked for logging, the probability of a felled tree being merchantable, and the probability of any tree in the residual stand being damaged by logging. Important predictor variables included tree species and size, merchantable basal area, basal area logged, logging history, and topography. There was no evidence to suggest that soil type or site quality influenced current treemarking practice. The approach is applicable to other mixed forest types managed for selection logging.

Key words: Yield calculation - polycyclic selection logging - moist tropical high forest - logistic regression - logging damage.

Introduction

Informed sustained yield management of natural forests requires both growth models and harvesting models to enable the reliable estimation of yields, and to enable the long term effects of repeated logging to be evaluated. Growth modelling has been the subject of considerable research and development, and published examples of successful growth models are widely available (*e.g.* Brown & Clarke 1980, Ek *et al.* 1988). Harvesting models have not received the same attention, although they are an equally important component of the yield calculation.

There are three essential components of harvesting model. It should predict which stems will be felled, the proportion of these which are merchantable, and the damage to the residual stand. Several authors (*e.g.* Fox 1968, Nicholson 1958, Wyatt-Smith & Foenander 1962) have researched logging damage, but results are rarely presented in a form suitable for inclusion in a simulation model. Preston and Vanclay (1988) presented a simplistic harvesting model for north Queensland rain forests, based on simple linear relationships fitted by eye, but the subsequent revision of the treemarking guidelines requires the revision of their model.

In Queensland, logging of publicly owned rain forests is closely supervised. Logging operations must adhere to strict environmental controls. Only trees marked by a trained treemarker, an officer of the Department of Forestry, may be felled. Marking of these trees is in accordance with published treemarking guidelines (Preston & Vanclay 1988). The objectives of these guidelines are:

- to provide available timber harvest while maintaining a vigorous residual stand capable of producing a sustainable yield;
- to ensure logging is conducted in an environmentally sensitive way;
- to encourage regeneration by retaining an adequate seed source; and
- to manage the species composition to improve the growth and wood quality of the forest.

These objectives are achieved through the use of specified diameter limits, based on the growth and durability of individual tree species, which indicate the size a tree should attain before removal (Table 1). Trees which exceed the normal cutting diameter are marked for logging unless they are required as seed trees, or are of outstanding quality as growing stock and have not attained the maximum retention diameter. In addition, defective trees may be removed down to a minimum dbh (diameter over bark at breast height [1.3 *m*] or above buttressing) of 40 *cm*.

Guidelines also require that:

- at least 50% of the canopy cover be retained;
- cutters fell trees in the direction indicated by the treemaker, to minimise damage to the residual stand, especially to retained desirable stems;
- seed trees are retained at an average spacing of 40 by 40 *m*; and
- allow additional trees with outstanding form and vigour to be retained.

Table 1. Species group recognised in treemarking guidelines

Species Group	No. in Group	Example of Species in this Group	Cutting Diameter (*cm*)	Retention Diameter (*cm*)
Protected	2	*Agathis microstachya*	Salvage only	
A-1	1	*Endiandra palmerstonii*	100	100
A-2	6	*Cardwellia sublimis*	80	100
A-3	4	*Flindersia bourjotiana*	70	90
B	9	*Backhousia bancroftii*	70	90
C	42	*Syzygium wesa*	60	80
D-1	26	*Synoum muelleri*	60	60
D-2	24	*Acacia mangium*	50	50
Hardwoods	9	*Eucalyptus torelliana*	70	90
Non-Compulsory	37	*Alphitonia whiteii*	-	-
Non-Commercial	>300	*Aleurites moluccana*	-	-

The present study develops a model to simulate the operational use of these guidelines. It makes no attempt to assess the suitability of these guidelines, or to assess whether the cutting limits are optimal. To ensure a uniformly high standard of usage, purchasers are obliged to purchase and remove all logs exceeding a specified standard. Logs containing more defect are non-compulsory; the purchaser may elect to purchase these if he wishes, but is not so obliged. Similarly, certain species are non-compulsory, and the purchaser may indicate whether he wishes to log and purchase any trees of these species. Non-compulsory logs are not debited to a purchaser's allocation, and are not included in sustained yield estimates.

Existing volume equations (Vanclay *et al.* 1987) predict the volume of compulsory logs within a tree, given its dbh and total log length. As they make no allowance for trees which fail to yield any compulsory logs, the harvesting model should adjust the predicted number of harvested stems accordingly.

Thus the present study develops equations which predict the proportion of stems marked for logging, the proportion of felled stems which fail to yield a compulsory log, and the damage to the residual stand.

Data

Data used to construct the model were derived from two different sources. The treemarking model is based on data derived from recent inventory, whereas the data relating to non-merchantable stems and to damage to the residual stand were derived from a series of logging damage studies.

The logging guidelines were revised in 1986, so only recent data were appropriate for the analysis of treemarking. The most suitable data comprised 293 inventory plots established for timber assessment purposes. These plots varied in type, with an approximately equal number of each of three different plot types enumerating a total of 182.6 *ha*:

- half hectare plots on which all stems exceeding 40 *cm* dbh were measured, with an inner plot of one eighth hectare on which all stems exceeding 20 *cm* dbh were measured;
- half hectare plots on which all stems exceeding 40 *cm* dbh were measured, and stems between 10 and 40 *cm* dbh assessed using four point samples (Beers & Miller 1964) using 2.3 $m^2\ ha^{-1}$ optical wedges; and
- one hectare plots with all stems exceeding 40 *cm* dbh measured, and stems between 10 and 40 *cm* dbh assessed using four point samples using 2.3 $m^2\ ha^{-1}$ optical wedges.

All plots recorded species, dbh, merchantability, "visual thinning" and estimated log length for all merchantable stems exceeding 40 *cm* dbh. The location of the plot and soil type were also recorded. Visual thinning indicates trees that would be marked for removal if the stand were to be logged in the near future. As each inventory team included qualified treemarkers, visual thinning is assumed to provide a reliable indication of treemarking. These plots provided 7177 individual merchantable trees (exceeding 40 *cm* dbh) for analysis. The size distribution and species composition of these data are indicated in Table 2.

Table 2. Stand derived from 293 inventory plots

	Number of Stems per *ha* by Size Class					Stems exceeding 40 *cm* dbhob		
	20-39 *cm* dbh	40-59 *cm* dbh	60-79 *cm* dbh	80-99 *cm* dbh	100+ *cm* dbh	Stocking No. ha^{-1}	Basal Area $m^2\ ha^{-1}$	Volume $m^3\ ha^{-1}$
Compulsory Species								
Total Stems/*ha*	80.2	34.8	11.4	2.9	0.9	50.0	13.4	
Merchantable Stems	63.5	29.1	9.4	2.2	0.5	41.2	10.7	63.0
Visually Thinned	0.0	1,6	3.5	1.4	0.4	6.9	2.9	17.6
Non.compulsory Species								
Total stems/*ha*	16.2	5.0	1.0	0.2	0.0	6.2	1.4	
Merchantable Stems	12.4	4.0	0.7	0.0	0.0	4.7	1.0	5.6
Visually Thinned	0.0	0.0	0.1	0.0	0.0	0.1	0.1	0.4
Non-commercial Species								
Total Stems/*ha*	106.4	16.7	3.4	0.7	0.2	21.1	5.1	
Total: All Species								
Total Stems/*ha*	202.8	56.5	15.8	3.8	1.1	77.3	19.9	

Data for assessing the incidence of non-compulsory trees (of cumpulsory species) and logging damage were derived from a series of nine logging damage studies (Experiments 567, 569, 570, 574, 576, 577, 581, 582 and 640 Atherton series) conducted during 1977 to 1980. Although these data are quite old and pre-date the current version of the treemarking guidelines, they represent the best data available. One of the major variables influencing damage is the amount (volume or basal area) of timber logged, and including this variable as a co-variate in the model enables this data to be extrapolated to current practices.

These experiments were established at a range of sites, and sampled both virgin and previously logged forest, a range of slopes and stand densities, and a variety of soil types. The stands were assessed before logging by point sampling using a 9.18 $m^2\ ha^{-1}$ optical wedge, and were re-assessed after logging to determine the fate of each tree. Five categories of fate were recorded:

- desirable tree marked for retention (115 trees);
- merchantable stem not marked for removal (2145 trees);
- unmerchantable stem (355 trees);
- stem marked for removal, felled and removed (424 trees); and
- stem marked for removal, felled and left on site as unmerchantable (36 trees).

Damage to bark, wood and crowns of remaining trees was assessed in four classes of severity. Those in the highest damage category (308 trees) were assumed to die as a direct result of logging, and are the subject of the present logging damage study. Trees in other categories (353 trees) of damage would probably recover, perhaps with some increased defect, and are not considered in the present study. Any mortality or defect developing several years after logging can be modelled using mortality and defect functions (Vanclay 1983).

These experiments provided 441 felled trees of compulsory species for an analysis of the incidence of non-compulsory stems, and 2615 individual trees in the residual stand for an analysis of logging damage.

These data were prepared for analysis by arranging a space delimited data file with one tree per line. The inventory data file contained logging history, soil type, site quality (Vanclay 1988), stand basal area (of both stems exceeding 10 *cm* dbh and stems exceeding 20 *cm* dbh), merchantable basal area (merchantable stems over 40 *cm* dbh), species, dbh and visual thinning for each tree, where visual thinning was zero if the tree would be retained, and one if it was to be removed in logging.

The non-compulsory data were arranged similarly, with soil type, logging history, species, dbh and a binary variable which was zero for compulsory stems and one for non-compulsory stems. The damage data comprised slope, relative basal area logged, soil type, logging history, species, dbh and damage which was zero if the tree survived and one if the tree was destroyed.

Method

Although the ideal formulation for a logging model is to define the desired residual stand (Vanclay 1983), this is difficult and impractical in complex mixed forests. Furthermore, the concept of a desired residual stand is not supported by the visual thinning data. Certainly, more stems are removed in dense stands, and fewer in sparse stands, but there is no evidence to suggest that the present treemarking guidelines specify a residual stocking. Preliminary analysis of the inventory data suggested that the best approach to simulate treemarking is to model the proportion of trees marked for felling.

Thus all three models are based on proportions: of the merchantable trees in the forest in any size class a proportion will be marked for removal; of those felled, a proportion will be non-compulsory; and of the trees in the residual stand, a proportion will be damaged by logging operations. Such data pose special problems in analysis. Although proportions are relevant to the population, the data concerning individual trees are dichotomous. Either a tree is felled, or it is not; it is not possible to fell part of a tree.

There are two possible ways to analyse these data. One way is to group the data into a number of classes. For the visual thinning data, the species groups defined in the treemarking guidelines suggest nine classes, and tree size could be accommodated in about 10 *cm* diameter classes. This provides 90 (10 diameter x 9 species) classes, many of which may have few or no entries. Thus it is difficult to accommodate additional co-variates in such analyses.

If the grouping is adequate, regression analysis can estimate the proportion of trees within any class marked for removal as a function of tree size. For such an analysis to provide reliable results, the regression analysis must be weighted by the number of observations within each class.

However, there are other problems. Simple linear regression of the untransformed proportions is likely to predict unrealistic estimates (exceeding one or negative). One solution is to use a logistic transformation,

$$y = Log \frac{p}{1-p}$$

and predict the transformed y instead of the raw proportions. The estimates of y can be converted back into proportions by

$$p = \frac{e^y}{1 + e^y}$$

This transformation is commonly used in modelling mortality (Monserud 1976, Hamilton 1980, Wan Razali 1988). When grouping data, the choice of origin and width of diameter classes may influence the analysis, particularly where classes contain few data, and it is essential that the actual mean dbh of each class is used, rather than the class mid-point. One advantage of grouping data in this way is that it enables the data to be plotted, and examined to see the trends in the data, and for the key variables to be detected. This solution does not work if any of the proportions are one or zero, in which case the transformed y cannot be estimated. In this case the grouping of data must be changed, or logistic regression must be used.

The best solution is to perform logistic regression on the individual tree data using the method of maximum likelihood. The approach applies the logistic transformation to the predictions, but not to the raw data, and so avoids the problems with probabilities of zero and one. It also avoids potential bias caused by grouping data, and greatly facilitates the investigation of additional co-variates such as stand basal area and logging history. The nature of such dichotomous data precludes meaningful use of r^2 as a measure of goodness-of-fit, and an analysis of deviance, similar to the familiar analysis of variance, should be performed. GLIM (Payne 1986) is one package which enables such analyses, and was used in the present study. Annotated examples of the use of GLIM for such analyses are available from the author or in Adena and Wilson (1982), while standard texts provide theoretical background (Dobson 1983, McCullagh & Nelder 1983).

Because of the disproportionate number of smaller stems in the data, and the greater influence of larger stems on volume yield and residual stand dynamics, all regressions were weighted by tree basal area. No attempt was made to analyse data by individual species, because of the large number of species which occur in these forests (160 commercial species and about 500 tree species in total), and the relatively small amount of data (131 species occur in the data). Instead, the analysis employed the species groups recognised by the treemarking guidelines. It is unlikely that this decision would significantly influence the outcome of the analysis, as these groups were prepared on the basis of growth and durability, and many of these groups did not significantly differ and were combined.

Results

Prediction functions for treemarking were fitted simulteneously to each species group, and were found to differ significantly ($p<0.01$). The most important predictor variables were tree size and the cutting limits prescribed in the treemarking guidelines. Soil type and site quality had no apparent effect on the treemarking practice. However, the stand basal area had a significant effect on the marking of non-compulsory species, with merchantable basal area (exceeding 40 *cm* dbh) being the best descriptor.

Logging history was also significant, but as the interaction of logging history and species group was not significant, it has the same coefficient for all species groups. A qualitative variable indicating whether the stand was virgin or had been logged previously, was included as well as the time since logging (years, zero for virgin stands). This indicated that 38 years after logging, treemarking in a previously logged stand reached the same selection intensity as in a virgin stand.

The following equations predict the probability of a tree being marked for felling:

$$y_1 = -5.530 + 0.05192 \times \text{DBH} - \frac{19.30}{\text{TSL}} + 6.407 \times \text{RL}$$

$$y_2 = -6.088 + 0.07411 \times \text{DBH} - \frac{19.30}{\text{TSL}} + 1.696 \times \text{RL}$$

$$y_3 = -5.238 + 0.06170 \times \text{DBH} - \frac{19.30}{\text{TSL}} + 1.422 \times \text{CL}$$

$$y_4 = -7.943 + 0.10310 \times \text{DBH} - \frac{19.30}{\text{TSL}} + 0.862 \times \text{CL}$$

$$y_5 = -5.019 + 0.05731 \times \text{DBH} - \frac{19.30}{\text{TSL}} + 2.031 \times \text{CL}$$

$$y_6 = -9.031 + 0.13640 \times \text{DBH} - \frac{19.30}{\text{TSL}} + 1.290 \times \text{CL}$$

$$y_7 = -7.688 + 0.10650 \times \text{DBH} - \frac{19.30}{\text{TSL}} + 1.778 \times \text{CL}$$

$$y_8 = -2.844 + 0.03144 \times DBH - \frac{19.30}{TSL} + 2.475 \times CL$$

$$y_9 = -6.717 + 0.10710 \times DBH - \frac{19.30}{TSL} - 0.1880 \times BA_{merch}$$

and

$$p_i = \frac{e^{y_i}}{1 + e^{y_i}}$$

where p_i is the probability of a tree in species group i (Table 3) being marked for logging, given its diameter DBH (*cm* dbh) and the basal area of merchantable stems exceeding 40 *cm* dbh BA_{merch} ($m^2\ ha^{-1}$). TSL is the time since last logging (years) for logged stands (provided it does not exceed 38), and takes the value 38 for virgin stands. The terms CL and RL are one if the dbh of the tree exceeds the cutting and retention limits (Table 3) respectively, and zero otherwise.

Table 3. Equation number for species groups

Species Group	Cutting Diameter (*cm*)	Retention Diameter (*cm*)	Tree-marking Equation	Non-compulsory Equation	Logging Damage Equation
Protected	Salvage only		-	1	1
A-1	100	100	1	1	1
A-2	80	100	2	1	1
A-3	70	90	3	1	1
B	70	90	4	2	2
C	60	80	5	2	2
D-1	60	60	6	3	2
D-2	50	50	7	3	2
Hardwoods	70	90	8	2	2
Non-Compulsory	-	-	9	-	3
Non-Commercial	-	-	-	-	3

Figures 1 and 2 illustrate these functions, and the analysis of deviance is given in Table 4. The strong inflections evident in Figure 1 are due to the terms CL and RL, which reflect the cutting and retention limits stipulated in the treemarking guidelines. Merchantable basal area was significant only for the non-compulsory group. It is logical to expect that contractors would elect to harvest more of the less desirable non-compulsory species on low yielding sites, as total yield per hectare is one of the limiting economic factors of rain forest logging in north Queensland.

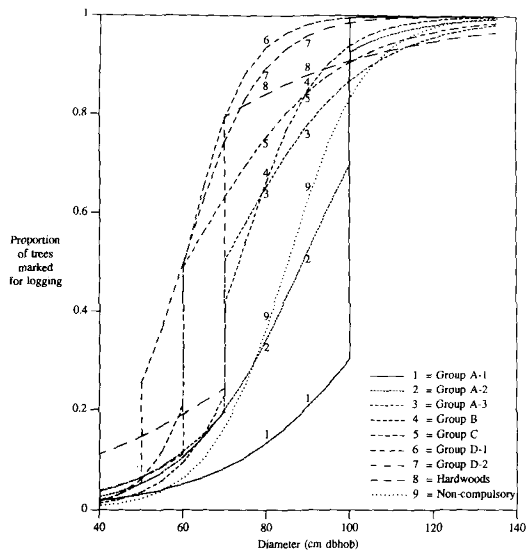

Figure 1. Treemarking for logging (40 years since last logging, Merch Basal Area 10 m^2 ha^{-1})

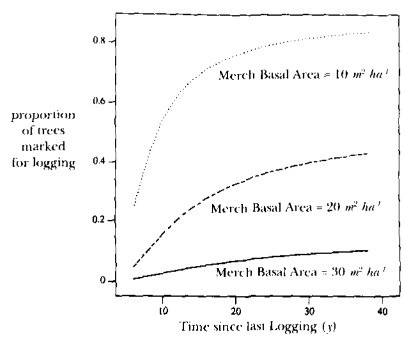

Figure 2. Treemarking for logging (Non-compulsory stems 100 *cm* dbhob)

Table 4. Analysis of deviance for treemarking

Source	D.F.	Deviance (Chi-squared)	Probability
Fitted model	27	3361.9	<0.0001
Diameter	1	2479.2	<0.0001
Cutting limits	1	693.7	<0.0001
Logging history	1	88.5	<0.0001
Spe groups	8	62.3	<0.0001
Basal area	1	10.2	0.0019
Species-dbh interaction	8	25.2	0.0019
Species-limits interaction	7	15.7	0.028
Other variables examined			
Soil type	5	7.6	0.18
Site quality	1	0.1	0.75

The treemarking guidelines obviously dictate to a large extent, the species groups for the prediction of marking for logging, but do not affect the incidence of non-compulsory trees and of logging damage to the same extent. The non-compulsory data suggested three significantly different trends: the A group species, the B and C group species and forest hardwoods, and the D group species. There was also a strong quadratic trend evident in the data. The incidence of non-compulsory stems was greatest in the smallest and largest trees, while trees near the cutting limit were more likely to be compulsory. It is stressed that this is a characteristic of the data and of the population of trees harvested under treemarking; but not of the forest as a whole. Under the treemarking guidelines, trees less than the cutting limit will only be harvested if they are defective, and of these trees, the amount of defect in a small log sufficient to render it non-compulsory, will not be sufficient to render a larger log non-compulsory. Thus the quadratic trend is logical for the population of harvested stems. For the forest as a whole, the incidence of non-compulsory stems is expected to increase progressively with tree size, as is observed in the data for trees exceeding the cutting limit.

Logging history and soil type were investigated as possible co-variates, but were found to be not significant. The resulting equations predict the frequency of apparently merchantable trees of compulsory species failing to yield a compulsory log:

$$z_1 = -1.565 - 0.0129 \times DBH$$
$$z_2 = 5.563 - 0.2027 \times DBH + 0.001111 \times DBH^2$$
$$z_3 = 12.580 - 0.4101 \times DBH + 0.002702 \times DBH^2$$

and

$$p_i = \frac{e^{z_i}}{1 + e^{z_i}}$$

where p_i is the probability that a tree in group i (Table 3) fails to yield a compulsory log, and DBH is diameter (*cm* dbh). Group 1 comprises those species identified as group A (cabinet and veneer timbers) in the treemarking guidelines, Group 2 comprises the B, C and forest hardwoods (structural) species, and Group 3 the D group (less durable) species. This function is illustrated in Figure 3 and the analysis of deviance is given in Table 5.

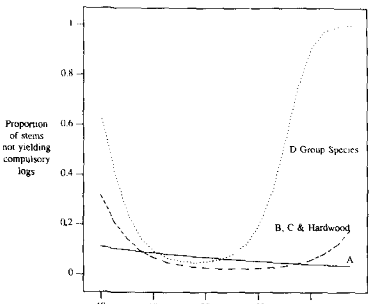

Figure 3. Frequency of non-compulsory system

Table 5. Analysis of deviance for non-compulsory stems

Source	D.F.	Deviance (Chi-squared)	Probability
Fitted model	7	111.02	<0.0001
Diameter	1	39.71	<0.0001
Diameter squared	1	40.34	<0.0001
Species groups	2	17.22	0.0004
Interaction	3	13.75	0.0038
Other variables examined			
Soil type	3	7.04	0.07
Logging history	2	3.90	0.14

The species groups defined in the treemarking guidelines may have some influence on the incidence of logging damage, as they influence the practice of marking trees for retention, and the indicated direction of felling. Thus these species groups were used, and those groups which did not significantly differ were further grouped into three significantly different groups: A group species, other compulsory species, and non-compulsory species. Soil type and logging history were found to have no significant effect on the incidence of logging damage, but the basal area felled in logging (expressed as a proportion of the initial stand basal area) and slope were found to be significantly correlated with logging damage.

The resulting equation predicts the probability that a tree will be destroyed by logging:

$$v = -3.990 + 9.689\text{xRBA} + 0.05648\text{xSLOPE} - \begin{array}{l} 0.05958\text{xDBH, Group 1} \\ 0.03611\text{xDBH, Group 2} \\ 0.01570\text{xDBH, Group 3} \end{array}$$

and

$$p = \frac{e^v}{1 + e^v}$$

where p is the probability that a tree will be destroyed, DBH is diameter (*cm* dbh), SLOPE is topographic slope (degrees) and RBA is the ratio of basal area logged to the initial stand basal area. Trigonometrical transformations of slope were also examined, but did not perform as well as the untransformed variable. These equations are illustrated in Figures 4 and 5 and the analysis of deviance is given in Table 6. The markedly lower damage experienced by A group species may be largely attributed to the practice of clearly marking for retention any desirable trees, and the directional felling of trees.

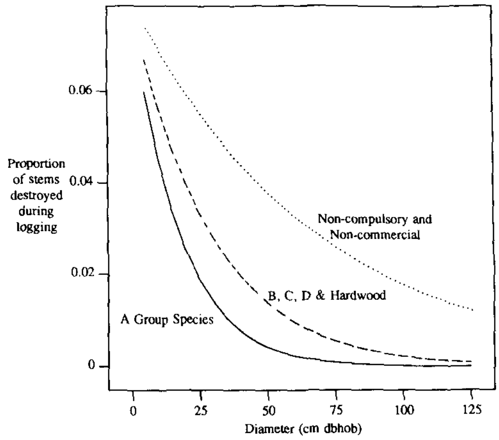

Figure 4. Logging damage (10 degree slope and 10% basal area removed)

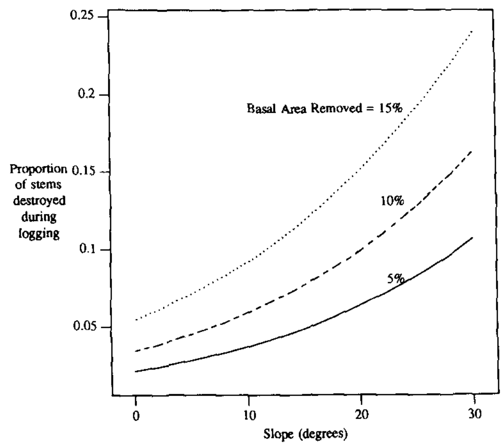

Figure 5. Logging damage (Non-commercial stems 20 *cm* dbhob)

Table 6. Analysis of deviance for logging damage

Source	D.F.	Deviance (Chi-squared)	Probability
Fitted model	5	143.9	<0.0001
Diameter	1	75.0	<0.0001
Species groups	2	53.8	<0.0001
BA logged	1	8.9	0.0033
Slope	1	6.2	0.012
Other variables examined			
Soil type	3	2.7	0.56
Logging history	2	3.9	0.14

The performance of the treemarking equation was tested on 1988 inventory data (27 plots), and is indicated in Table 7. The paired t-tests using the visually thinned volume per plot indicated that the Preston and Vanclay (1988) model differed significantly (p = 0.046) from current practice, whereas the current model gave a satisfactory approximation (p = 0.18).

Table 7. Testing the treemarking equation

Source	Predicted Removals (stems/*ha*)	Bias (stems/*ha*)	Test statistic (Student's t)	Probability
Visual thinning data	8.7	-		
Preston and Vanclay (1988)	15.0	6.3	2.07	0.046
Current Model	10.9	2.2	1.37	0.18

Discussion

All equations presented in this paper express the probability of occurrence of some event. These can be readily incorporated in simulation models using stand class based models such as stand table projection (*e.g.* Korsgaard 1988), transition matric (*e.g.* Harrison & Michie 1985) or cohort models (*e.g.* Vanclay 1987). These models group idividual trees into classes with similar attributes, and express the number of stems in each class as a number of stems per hectare (fractions are permissible). Thus it is easy to accommodate a probability, which relates to a proportion of the stocking in any class.

They can also be incorporated in stochastic individual tree simulation models. In this case, a random number is generated for each tree, for each event. If the computed probability exceeds the random number, then that tree is logged, non-compulsory or damaged.

The equations presented can be readily incorporated into simulation models such as that employed in yield calculations for the north Queensland rain forests (Preston & Vanclay 1988). They can be used in conjunction with such models, to determine not only short term yields, but also long term yields obtained under polycyclic selection logging.

The present study has developed a model which simulates the existing tree-marking practice, but makes no attempt to assess its suitability. This is an important preliminary step in such an assessment. The long term impact of any silvicultural practice, and the comparison of such practices with the theoretical ideal, can only be assessed if that practice can be quantified in a mathematically rigorous way. This study has provided such a rigorous description of the current harvesting practice. Future studies will assess the long term impact and develop an optimal treemarking strategy.

Conclusion

This study has demonstrated a technique which enables selection logging yields to be estimated, and the impact on the residual stand to be quantified.

Logistic regression enabled the development objective models for the selection of trees for harvesting, the incidence of defect in the selected trees, and for damage to the residual stand. Important predictors included tree species and size, stand basal area, basal area logged, logging history and topography. Soil type and site quality do not appear to influence harvesting.

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