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Jerome K. Vanclay
Southern Cross University

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Sustainable timber harvesting: simulation studies in the tropical rainforests of north Queensland

Jerome K. Vanclay
Department of Economics and Natural Resources, Royal Veterinary and Agricultural University,
Thorvaldsensvej 57, DK-1871 Frederiksberg C, Denmark

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Abstract

Although logging ceased in the tropical rainforests of north Queensland following their World Heritage Listing in 1988, they provide a good basis for simulation studies on sustainability of timber harvesting as reliable logging records, inventory and growth data are available. A growth model for these forests has been developed and published. The growth model is dynamic, responding to changes in stand density, composition and management history. A harvesting simulator predicts the trees removed by selection logging, and predicts changes in the residual stand. Simulation studies employ cutting cycle analysis and yield scheduling to demonstrate the sustainability of harvesting. These studies indicate that selection harvesting could sustain a viable timber harvest of about 60 000 m^3 $year^{-1}$. These results are indicative rather than definitive, as the model has not yet been formally validated with independent data.

Introduction

A century of timber production ceased in 1988 when tropical rainforests of north Queensland were included in the World Heritage List and further logging was banned. However, the availability of reliable logging records, inventory and growth data make these forests good candidates for simulation studies on sustainability of timber harvesting. These forests are located between 16 and 19° south and are confined to a narrow belt of coastal ranges receiving a relatively high rainfall (greater than 1500 mm $year^{-1}$).

One currently controversial issue is whether timber harvesting from tropical rainforests is sustainable. Certainly there are many examples where indiscriminate logging has occurred, often preceding clearing for agriculture or leading to serious land degradation. In contrast, timber harvesting operations in north Queensland have been supervised by the Forest Service and follow conservative silvicultural practices defined in tree-marking guidelines (Preston and Vanclay, 1988) and in conditions which limit road and track construction for timber harvesting and extraction (Ward and Kanowski, 1985).

Several studies have examined impacts of timber harvesting in these forests. Whilst timber harvesting causes localised destruction, its impacts may be localised and the ecological impact may be less than the visual impact. Crome et al. (1992) found that logging tracks and canopy loss were confined to 5% and 20% of the area, respectively. However, the light climate may be altered in areas with no direct canopy loss. Nicholson et al. (1988) found that logging did not lead to loss of any tree species. Stocker (1981, 1983), Unwin et al. (1988) and Webb and Tracey (1981) have investigated other aspects of the dynamics and regenerative capacity of these rainforests. Crome and Moore (1989) discussed effects of logging on some fauna. Gilmour (1971) found that effects of logging on stream flow and sedimentation were small scale and short lived. Gillman et al. (1985) examined soil chemical properties and found that most topsoil nutrients regained their initial levels within 4 years after logging. Whilst nutrient cycles were disrupted by logging, losses appeared to be small and quickly replaced by natural inputs, provided that logging was of low intensity, short duration and infrequent (Congdon and Lamb, 1990).

It has been estimated that a timber harvest of 60 000 m^3 $year^{-1}$ could be sustained from these forests (Preston and Vanclay, 1988). Vanclay and Preston (1989) examined the long-term sustainability of such a harvest, and concluded that selection logging could be sustained by the growth of residual trees and regeneration, and need not rely upon trees missed during previous harvests. Research into the relationship between diameter (breast high or above buttress, over bark) and log volume provided no evidence to suggest that there was any increase in defect or any reduction in log length in trees harvested from previously logged stands (Henry, 1989). Vanclay (1990) demonstrated that repeated selection harvesting had no measurable long-term effect on the growth rates of individual trees in these forests.

This simulation study demonstrates a practical application of a growth model and examines different methodologies which may be used to estimate long-term yields. The model is used to estimate short- and long-term timber yields, and to examine if the recent timber harvesting practices would have been sustainable in terms of timber production.

Calculation of the sustainable yield

Calculation of the sustainable yield entails several basic operations.

- The area of forest zoned for and capable of producing timber is determined. Forest subject to special management (e.g. Scientific Areas, buffer strips along creeks), and inaccessible or unproductive forest is excluded.
- A detailed description of the existing forest is prepared from inventory which entails the measurement of temporary plots and recording the species, size and merchantability of each tree within the plot.
- The future condition (number, size and merchantability of trees) of each inventory plot is predicted by simulating the growth (diameter increment, mortality and recruitment) of the residual forest over time.
- At selected intervals, a timber harvest is simulated to indicate which stems would be removed in logging, and to predict mortality to the residual stand arising from felling and snigging damage.
- The anticipated harvest volume is then calculated using volume equations.
- The growth and harvesting of each inventory plot is simulated over a long period to ensure the continuity of future timber harvests.

This procedure provides an estimate of the timber yield which can be sustained under the specified management regime and assumed economic conditions. Timber harvesting can be sustained at any level not exceeding this yield.

Area estimates

Area estimates are an essential component of the resource forecast, and due account must be taken of unproductive land such as rock outcrops, stream buffers, and other areas which cannot be logged. The present calculation employs data derived from a Geographical Information System (GIS) which was compiled to assist in planning and management of the Wet Tropics region. The GIS is a vector-based system (ESRI Arc/Info) and includes both anthropogenic and environmental information, mostly captured at 1:50 000 scale. This system was used to calculate the gross productive area utilised for timber production within the study area (Table 1) . Data were digitised primarily from timber management maps and include tenure, management intention, logging history, etc. These maps were prepared by field staff during 1978-1980 using historical timber sales records dating back to the mid-1950's, and have been regularly updated. Where no records were available, estimates of accessibility and productivity were prepared from interpretation of 1:25 000 scale aerial photographs.

The GIS was used to stratify on geology, bioclimatic zone, logging and treatment history, and subcatchment. Islands of rainforest less than 10 ha were ignored. Stratum 'slivers' smaller than 10 ha were amalgamated with adjoining strata. The GIS computed the gross productive area within each such stratum.

Table 1. Rainforest areas at cessation of logging in 1988 (Anonymous, 1989)

Category	Study area (Townsville-Cooktown) (ha)	Total north Queensland area (ha)
Nett timber production area	153100	153100
Stream buffers, inaccessible, etc.	31000	31000
Gross timber production area	184100	184100
Other land uses (catchment protection, etc.)	354500	495400
Total State forest, timber reserve and other Crown land	538600	679500
National Park	126900	200300
Other tenures (aboriginal, private)	66000	148800
Total rainforest	731500	1028600

Not all of the timber production area provides an accessible timber harvest - it may include small fragments of inaccessible or unproductive land too small to show on maps and too small to be detected with remote sensing. Accordingly, a netting factor is used to reduce the gross productive area to a net productive area for use in yield calculations.

Preston and Vanclay (1988) identified two components comprising the netting factor. One indicated the probability that any plot would be accessible to logging equipment; the other indicated the availability of trees on accessible plots. Preston and Vanclay (1988) reported that 95.6% of trees on accessible plots were available for harvesting, and this coefficient has been used to account for stream buffers, etc. In theory, this estimate could have been revised using the GIS to estimate the actual area of stream buffer within each stratum. However, at the time these data were prepared, the streams could not be characterised sufficiently within the GIS to indicate the size of buffer required, and it was felt that the existing adjustment was preferable to an estimate from the GIS.

Statistical analyses on field data indicated a strong correlation between topographic slope and plot accessibility, and the following relationship was fitted by maximum likelihood estimation:

$$P = \left(1 + e^{-(3.129 - 0.1381 \times \mathrm{SLOPE} - 0.8356 \times \mathrm{SLOPE} \times \mathrm{SOIL})}\right)^{-1} \tag{1}$$

where P is the probability that a plot will be accessible for logging, SLOPE is the topographic slope in degrees, and SOIL is a binary variable which takes the value 1 on soils derived from coarse granite parent materials, and 0 elsewhere. If SLOPE exceeded 28°, P was set to zero. Thus the netting factor (NF) for each stratum was estimated ac

$$NF = \frac{0.956}{n} \sum_{i=1}^{n} P_i$$

where n is the number of points at which the slope was estimated, and P_i was estimated from eqn (1). A digital elevation model was used to provide systematic samples of slope within each stratum.

Inventory

A total of 518 inventory plots established during the period 1981-1988 were used in the current calculation. Three different types of plots have been employed over this period.

During the period 1981-1983, inventory employed variable area plots with sampling proportional to size. Individual plots comprised clusters of ten point samples in which an optical wedge with a basal area factor (BAF) of 10 m^2 ha^{-1} was used, and all stems exceeding 3 cm diameter (at breast height or above buttress, over bark) were measured. During 1984, fixed area plots were favoured. All stems exceeding 30 cm diameter were sampled on a 0.5 ha plot, and stems exceeding 20 cm diameter were sampled on a 0.125 ha subsample. From 1985 to 1988, plots were established using a new approach. These plots sampled all stems exceeding 40 cm diameter over 1 ha, and used four point samples (BAF 2.3 m^2 ha^{-1}) to sample stems 3-40 cm diameter. These plots were preferred by field staff, who felt that they provided a better indication of the anticipated harvest.

There is no compelling statistical advantage in the use of any of these types of plot in preference to the others for description of the current stand or to provide forecasts. For quantifying the existing stand, there is some advantage in having a large heterogeneous plot to minimise between-plot variation.

Conversely, for simulation studies, a smaller homogeneous plot may be more appropriate. In practice, cost factors and the preference of field staff are of greater consequence, provided that the plot gives a reasonable representation of the forest at that point.

Table 2 indicates the average stand table for the study area. Tree sizes are reported as at the time of inventory, and no growth has been simulated. The stand table is a simple average of all plots, and has not been weighted by the stratum areas. The strong reverse-J size distribution of trees and the large number of tree species are noteworthy. This is an average stand table, and may not be representative of the forest at any particular location. Inventory plots in the study area have recorded ten to 40 tree 'species' per plot. The actual number of true species may be higher, as inventory employs the standard trade name rather than the correct taxonomy, and trade names may apply to more than one taxon. Some species have neither trade nor common names, and these are simply grouped as miscellaneous. A total of 248 species codes have been recorded on inventory plots within the study area.

The growth model simulates a notional 1-ha plot, and data from all three plot types are converted to per-hectare values to allow input to the model.

Table 2. Stand table at time of inventory (stems ha^{-1} by species and size class)

Standard trade name	Specific name	Harvest group	Size class (cm dbh ob or above buttress) 20-39	40-49	50-59	60-69	70-79	80-89	90-99	100+	Total 40+
Northern silky oak	*Cardwellia sublimis*	A-2	3.8	1.3	1.0	0.6	0.4	0.2	0.1	0.1	3.6
Silver ash	*Flindersia bourjotiana*	A-3	6.6	1.8	1.0	0.4	0.2	0.0	0.0	0.0	3.5
Rose butternut	*Blepharocarya involucrigera*	C	3.7	1.5	1.1	0.5	0.2	0.1	0.0	0.0	3.4
Maple silkwood	*Flindersia pimenteliana*	A-2	3.8	1.2	1.0	0.5	0.3	0.1	0.1	0.0	3.3
Yellow walnut	*Beilschmiedia bancroftii*	C	*1.1*	0.9	0.9	0.5	0.3	0.1	0.1	0.0	2.8
Red tulip oak	*Argyrodendron peralatum*[1]	B	3.3	0.9	0.5	0.3	0.1	0.0	0.0	0.0	1.9
Kuranda satinash	*Syzygium kuranda*	C	6.6	1.0	0.5	0.2	0.1	0.0	0.0	0.0	1.8
Tulip sterculia	*Franciscodendron laurijolium*[1]	-	8.5	1.2	0.5	0.1	0.0	0.0	0.0	0.0	1.8
Brown salwood	*Acacia aulacocarpa*[1]	D-2	2.8	0.8	0.4	0.3	0.1	0.1	0.0	0.0	1.7
Sassafras	*Doryphora aromatica*[1]	C	4.6	0.7	0.6	0.3	0.1	0.0	0.0	0.0	1.7
Macintyre's boxwood	*Xanthophyllum octandrum*	N	5.3	0.9	0.5	0.1	0.0	0.0	0.0	0.0	1.6
Blush alder	*Sloanea australis ssp. parviflora*	D-1	1.3	0.7	0.4	0.2	0.1	0.0	0.0	0.0	1.5
Queensland maple	*Flindersia brayleyana*	A-2	1.9	0.4	0.3	0.2	0.2	0.1	0.1	0.0	1.2
Rose alder	*Caldcluvia australiensis*	C	*1.1*	0.4	0.3	0.3	0.1	0.0	0.0	0.0	1.2
Caledonian oak	*Carnavonia araliifolia*	N	2.1	0.6	0.4	0.2	0.0	0.0	0.0	0.0	1.2
Rolypoly satinash	*Syzygium endophloium*[1]	-	2.4	0.4	0.2	0.1	0.1	0.1	0.0	0.0	1.0
Satin sycamore	*Ceratopetalum succirubrum*	C	*1.0*	0.4	0.3	0.2	0.1	0.0	0.0	0.0	1.0
Pink alder	*Gillbeea adenopetala*	-	2.1	0.5	0.2	0.1	0.0	0.0	0.0	0.0	0.9
Bollywood	*Litsea leefeana*[1]	D-2	3.7	0.6	0.2	0.1	0.0	0.0	0.0	0.0	0.9
Miscellaneous			64.1	4.3	1.5	0.6	0.2	0.1	0.0	0.0	6.7
Others	(228 species codes)		85.8	16.2	8.8	4.4	2.4	1.3	0.6	0.7	34.4
Total			215.7	36.9	20.7	10.2	5.0	2.3	1.1	1.0	77.2

1. As the trade name for this timber applies to more than one species, other related species may be included in this category.

Growth model

An integral part of yield forecasting is growth prediction. Growth models for plantations and for monospecific forests have become sophisticated and highly accurate. Rainforests comprise hundreds of species, posing a much more difficult challenge. Notwithstanding this, a dynamic growth model for rainforests has been developed and was used in the present study. The model is an enhanced version of one described by Vanclay (1989a) and the data upon which it is based is summarised in *Rainforest Research in North Queensland* (Queensland Department of Forestry, 1983) and by Vanclay (1990). Enhancements are described by Vanclay (1991a,b,c,d, 1992).

Site productivity

The growth model has functions for diameter increment, tree deterioration and mortality, and recruitment of new trees into the stand. These functions take into account the site quality, soil parent material, the stand composition and density, and the size of the individual trees. Site quality, expressed as a growth index in the range 0-10, can be determined two ways. The most reliable method is to use the historical growth rates observed, but this method is only available for permanent plots. For these plots, the growth index was estimated using Vanclay's (1989b) Equation 13:

$$GI=\frac{\sum_{ij}\mathrm{Log}(DI_{ij}+\alpha)-\sum_{ij}(\beta_{0i}+\beta_{1i}D_{ij}+\beta_{2i}\mathrm{Log}(D_{ij})+\beta_{3i}\mathrm{Log}(BA)+\beta_{4i}\mathrm{OBA}_{ij}}{0.08808\times\sum_{ij}\mathrm{Log}(D_{ij})}$$

where *GI* is the growth index of the plot, D_{ij} *is* the diameter (breast high or above buttress, over bark, in cm) of tree *j* of species *i,* DI_{ij} is its diameter increment (cm year^{-1}), OBA_{ij} is its ‘overtopping basal area’, the basal area of trees within the plot that are bigger than tree *ij* (m^2 ha^{-1}), *BA* is the plot basal area (m^2 ha^{-1}), and the βs are parameters estimated by linear regression. This equation estimates growth index, a measure of site productivity based on the diameter increment adjusted for tree size and competition, of all trees of 18 reference species *(Acronychia acidula, Alphitonia whitei, Argyrodendron trifoliolatum, Cardwellia sublimis, Castanospora alphandii, Cryptocarya angulata, Cryptocarya mackinnoniana, Darlingia darlingiana, Elaeocarpus largiflorens, Endiandra sp.* aff. *Endiandra hypotephra, Flindersia bourjotiana, Flindersia brayleyana, Flindersia pimenteliana, Litsea leefeana, Sterculia laurifolia, Syzygium kuranda, Toechima erythrocarpum, Xanthophyllum octandrum)* using all available re-measures for the plot (except that where plots were re-measured more frequently, re-measurements were selected to achieve approximately 5-year intervals). The βs were estimated by fitting the equation

Log *(DI+a) =Spp +D Spp* +Log *(D) Spp* +Log(*BA*) *Spp +OBA Spp* + Log (*D) Plot*

(where *Spp* and *Plot* are qualitative variables) simultaneously for all these reference species in the development data set (80 plots, a further 64 plots were used for validation studies). The parameter a was assigned the value 0.02 after inspection of residuals and examining the residual mean squares from a range of values (Vanclay, 1989b). The value 0.08808 was subjectively determined to scale the growth indices into the range 0-10.

For temporary inventory plots used in the yield simulation studies, the growth index cannot be determined from past growth, but was estimated by inference from the soil parent material and the presence or absence of several indicator species on the plot (Vanclay, 1989b eqn. (10)):

$$GI=\left[\begin{array}{l}4.528\times AL\\ 5.934\times BV\\ 5.164\times AV\\ 6.174\times CG\\ 4.980\times SM\\ 3.837\times TG\end{array}\right]\begin{array}{l}+1.144\times\mathrm{BLO}+1.286\times\mathrm{SBN}-1.020\times\mathrm{VTX}-0.673\times\mathrm{RAP}\\ +1.027\times\mathrm{BUA}+1.008\times\mathrm{RBN}-1.223\times\mathrm{CLL}+1.516\times\mathrm{BGR}\end{array}$$

where all variables are binary (0, 1) variables which take the value 1 if the geology or species is present on the plot, and 0 otherwise, and BLO is blush silky oak *(Bleasdalea bleasdalei* and *Opisthiolepis heterophylla),* SBN is salmon bean *(Archidendron vaillantii),* VTX is vitex (*Vitex acuminata), RAP* is rapanea *(Rapanea achradifolia),* BUA is buff alder *(Apodytes brachystylis),* RBN is rose butternut *(Blepharocarya involucrigera),* CLL is cinnamon laurel *(Cryptocarya cinnamonifolia* and some affiliated species), and BGR is brown gardenia *(Randia fitzalanii),* and where the geology *AL* is alluvial, *BV* is basic volcanic, *AV* is acid volcanic, *CG* is coarse granite, *SM* is sedimentary-metamorphic, and *TG* is Tully fine-grained granite. Note that whilst the various geology types are mutually exclusive, any number of species may be present and used to evaluate the growth index. None of these species are short-lived pioneer species, and the presence/absence of these species should be relatively independent of successional status and disturbance.

Diameter increment

There are four components of growth and change which must be predicted. The growth in diameter and change in merchantability of individual trees must be simulated. The deaths of trees needs to be modelled, and recruitment of new trees into the stand has to be estimated. It is impractical to develop individual functions for each of the several hundred tree species represented in north Queensland rainforests. Accordingly, species were grouped to enable more efficient estimation of prediction functions. Different groupings were used to develop each of the functions required for the model, as studies suggested that a single grouping for all functions would be suboptimal (Vanclay, 1991c). The species were grouped on the basis of pairwise tests between equations fitted to the individual species, with the more similar growth patterns being amalgamated (Vanclay, 1991a,c). A total of 41 groups were formed to fit the diameter increment functions, 11 for mortality functions, and five and nine groups, respectively, for predicting the probability and amount of recruitment.

Diameter increment can be modelled in two ways. The more obvious approach is to predict the diameter increment (cm year^{-1}) from tree and stand conditions using a model fitted by ordinary linear regression. An alternative is to fit a logistic function to predict the probability that a tree completes a specified amount of growth. Some advantages of the probabilistic approach include robust estimates despite outliers in the data, elimination of several subjective parameters in the model (e.g. cohort splitting), and ease of implementing as a compatible deterministic-stochastic model (Vanclay, 1991 b).

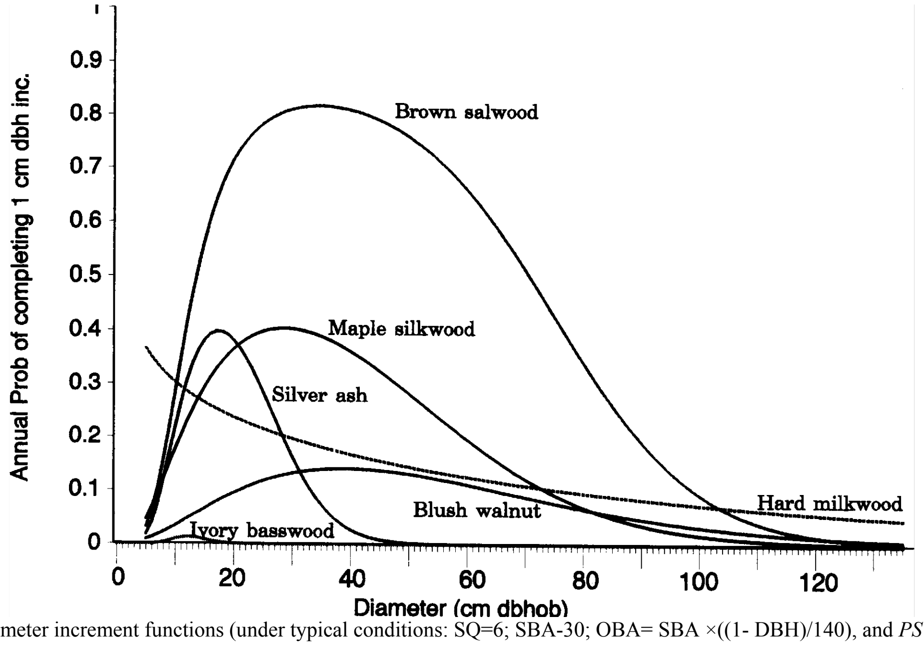

Fig. 1. Diameter increment functions (under typical conditions: SQ=6; SBA-30; OBA= SBA ×((1- DBH)/140), and *PS= 0).*

The following logistic equation (Fig. 1) was fitted using maximum likelihood estimation (e.g. for maple silkwood):

$$Z = 0.7378 - 0.1079 \times \mathrm{DBH} + 1.987 \times \mathrm{Log(DBH)} + 0.1455 \times SQ$$
$$\times Log(DBH) - 1.994 \times \mathrm{Log(SBA)} - 0.03548 \times \mathrm{OBA} + 0.4221 \times PS$$

and

$$P(\mathrm{Int}[\mathrm{DBH}_0 + (\mathrm{DBH}_n - \mathrm{DBH}_0)/n] > \mathrm{Int}[\mathrm{DBH}_0]) = (1 + e^{-Z})^{-1}$$

where P is the probability that a tree completes a centimetre of growth within that year (i.e. grows from less than *x* to greater than or equal to *x* cm diameter, where *x* is an integer number of centimetres), DBH is tree diameter (cm), *SQ* is site quality (Vanclay, 1989b), SBA is stand basal area ($m^2\ ha^{-1}$), OBA is overtopping basal topping area ($m^2\ ha^{-1}$) defined as the basal area of stems whose diameter exceeds that of the subject tree, *PS* is a binary (0, 1) variable which, for this species, takes the value 1 if the plot is located on soils derived from recent alluvial, volcanic or granitic parent materials, and 0 for soils derived from sedimentary or metamorphic parent materials, DBH_0 is the initial diameter, DBH_n is the final diameter, *n* is the number of years, and Int rounds down to an integer value.

Mortality

The groups formed for predicting diameter increment do not provide a good basis for predicting mortality, so an independent grouping was made. A similar analysis of mortality patterns led to the formation of 11 groups for the prediction of mortality (Vanclay, 1991 c). The resulting equations predict the probability of any tree dying in any year, given its species and size, and the site quality and basal area (e.g. for maple silkwood):

$$P = (1 + e^{-(11.057 - 1.6727 \times \mathrm{Log(DBH)} - 2.8801 \times \mathrm{DBH} + 0.0 \times RS^3 + 0.1043 \times SQ + 0.0 \times BA + 0.0 \times \mathrm{Log}(BA))})^{-1}$$

where P is the annual probability that any tree dies, DBH is tree diameter (cm dbhob), RS is relative size expressed as basal area of larger trees divided by total basal area (i.e. 0 is dominant, 1 is suppressed), *SQ* is site quality as measured by growth index, and *BA* is stand basal area ($m^2\ ha^{-1}$). Zero parameters indicate that the variable was not significant for this species, but is used to predict the mortality for other species.

Deterioration

Not all the trees assessed as merchantable at the time of inventory will remain merchantable until harvested; some will deteriorate and become unmerchantable. Although the annual amount of deterioration is very small, it becomes significant over a 40 year cutting cycle, and should be accounted for in the growth model and yield forecasts. An analysis of 44 000 observations on the merchantability of individual trees indicated that deterioration could be predicted from tree size, stand basal area, time since logging and soil type (Vanclay, 1991d) (e.g. maple silkwood and other durable species):

$$P = (1 + e^{-(7.450 + 0.04195 \times BA - 22.49/\mathrm{DBH} - 0.4213 \times CG)})^{-1}$$

where P is the annual probability that a merchantable tree survives as merchantable (i.e. does not become unmerchantable), *BA* is stand basal area ($m^2\ ha^{-1}$) exceeding 10 cm dbh, DBH is dbh (cm), and CG takes the value 1 for soils derived from coarse granites and 0 otherwise. The *n* year probability of remaining merchantable may be computed as P^n, and the probability of becoming unmerchantable as $1-P^n$.

Regeneration

One of the most difficult aspects of modelling forest growth and yield is the forecasting of regeneration. Because of high mortality amongst seedlings, difficulty of identification and high cost of measurement, inventory data usually only assess the larger trees (those exceeding 10 cm dbh), and the growth model simulates only the growth of this fraction. It is possible to model the growth of smaller stems, but data are scarce and this would add unnecessary complexity to the model. Thus the present model predicts the recruitment of stems at 10 cm dbh (i.e. those stems attaining 10 cm dbh or more in any year).

In contrast to the relatively steady growth of individual trees, regeneration tends to be sporadic, with little or no regeneration for several years, and often large amounts in those years in which it does occur. Such data violate assumptions inherent in regression analysis. To overcome these problems, it is expedient to adopt a two-stage approach. The first stage predicts the probability that any recruitment occurs, and the second stage predicts the amount given that some is known to occur.

These predictions are made independently for each species. The permanent sample plot database provided sufficient data to enable the analysis of recruitment of 100 species which were grouped into five groups for the prediction of probability, and nine groups for the prediction of amount of regeneration. The probability of recruitment was predicted as (e.g. for maple silkwood)

$$P = \left(1 + e^{-(-4.726 + 2.289 \times \mathrm{PRES} - 0.04703 \times BA + 0.3960 \times \mathrm{Log}(BA) + 0.2188 \times TR + 0.2073 \times \mathrm{SOIL})}\right)^{-1}$$

where *P* is the annual probability that any recruitment occurs, *BA* is the stand basal area (m^2 ha^{-1} of trees greater than 10 cm dbh). *PRES* is a binomial variable which takes the value 1 if that species (maple silkwood) is present in the existing (10+ cm dbh) stand and 0 otherwise, *TR* is the treatment response ($TR = te^{t/9}$ where *t* is years since last silvicultural treatment), and *SOIL* is a binary variable which takes the value 1 on soils derived from basic volcanic and coarse granite parent materials, and 0 otherwise. The treatment response term (*TR*) provides for a maximum response 9 years after silvicultural treatment.

The amount of recruitment, given that it was known to occur, was predicted as (e.g. for maple silkwood):

$$Log(N)=6.065-0.5803\times Log(BA)+1.845\times Log(RNO+0.2) + 0.09969\times SQ- 0.3166\times SOIL$$

where N is the expected number of recruits (stems ha^{-1} $year^{-1}$) given that recruitment of that species is known to occur, *BA* is stand basal area, *RNO* is relative number of trees (10 + cm dbh) of that species within the plot, *SQ* is site quality estimated using Vanclay's (1989b) growth index, and *SOIL* is a binary (0, 1) variable which takes the value 1 on alluvial and fine-grained (‘Tully’) granite soils and 0 elsewhere.

Harvesting model

Prior to logging, trees thought capable of producing a merchantable log are marked for removal in accordance with Forest Service guidelines (Preston and Vanclay, 1988). When felled, some stems reveal defects not evident when the tree was standing. Depending on the amount of this defect, the log may be classified as compulsory or non-compulsory. In addition, some species are non-compulsory. As only compulsory timber is debited to the sawmill allocation, the sustained yield is calculated for compulsory timber only. The harvesting model therefore comprises three essential components: the logging rule which indicates stems to be removed in logging, an allowance to predict the compulsory proportion of the logged stems, and a damage function which predicts mortality caused by felling and extraction operations.

Table 3 Harvest groups

Tree-marking class	Typical species		Cutting diameter	Retention diameter
A-1	*Endriandra palmerstonii*	Queensland walnut	100	100
A-2	*Flindersia brayleyana*	Queensland maple	80	100
A-3	*Flindersia bourjotiana*	Silver ash	70	90
B	*Argyrondendron peralatum*	Red tulip oak	70	90
C	*Beilschmiedia bancroftii*	Yellow walnut	60	80
D-1	*Sphalmium racemosum*	Buff silky oak	60	60
D-2	*Elaeocarpus sericopetalum*	Hard quandong	50	50
HWD	*Eucalyptus torrelliana*	Cadaga	70	90
Non-compulsory	*Aleurites moluccana*	Candlenut	-	-
-	Non-commercial		-	-

To simulate harvesting, species were grouped into nine harvest groups as indictated by the tree-marking guidelines (Table 3). Two diameters may influence whether a tree is selected for harvesting. Trees smaller than the cutting diameter may be removed only if they exceed 40 cm diameter and can be expected to die prior to the next logging. Stems above the cutting diameter and up to the retention diameter will generally be removed unless they have exceptional form and vigour. Stems exceeding the retention diameter are marked for logging, unless required as a seed tree.

Inventory data included an assessment of whether each tree would be logged or retained in harvesting (visual thinning), and were used to develop a prediction equation for tree marking. Logistic regression using the method of maximum likelihood was used to derive equations for each group (Vanclay, 1989c). The probability that a tree would be marked is predicted from its diameter and the time since last logging:

$$P = \left(1 + e^{-(-5.530+0.05192 \times \mathrm{DBH}-19.30/\mathrm{TSL}+6.407 \times \mathrm{RL})} \right)^{-1}$$

where P is the probability of a tree being marked for logging, DBH is tree diameter (cm dbh), 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, *RL* is a binary variable which takes the value 1 if the dbh of the tree exceeds the retention limit (Table 3) and 0 otherwise.

Prediction functions for defect and logging damage were developed from a series of logging damage studies on nine rainforest sites sampled before and after logging. The probability that a tree marked for logging will prove, after felling, to be so defective as to render it non-compulsory, can be predicted from its size. The resulting equations predict the frequency of apparently merchantable trees of compulsory species failing to yield a compulsory log:

$$P = \left(1 + e^{-(-1.565-0.0129 \times \mathrm{DBH})} \right)^{-1}$$

where P is the probability that a tree fails to yield a compulsory log, and DBH is diameter (cm dbh) .

The incidence of damage depends on the topographic slope of the site, and the proportion of the stand basal area removed in logging. Equations predict the probability that a tree will be destroyed in logging from the basal area removed, the slope, and the size of the residual trees. The resulting equation predicts the probability that a tree will be destroyed by logging:

$$P = \left(1 + e^{-(-3.990+9.689 \times \mathrm{RBA}+0.05648 \times \mathrm{SLOPE}- 0.05958 \times \mathrm{DBH})} \right)^{-1}$$

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.

Reliable rainforest volume equations are available in the form of two-way equations which predict log volume from tree diameter and log length. However, since forecasting future log lengths is unnecessarily complex and inaccurate, one-way equations predicting log volume from diameter are required. The volume predicted is gross log volume, comprising the under-bark volume of logs after defective sections have been trimmed off, but including any internal defects within the log (pipe, etc). Data were obtained from many logging operations over several years, and comprise dbh measurements for each tree and log length and centre diameters for each log in each tree. Log volumes were estimated using Huber's formula, and equations for individual species and species groups were derived using linear regression (Henry, 1989) (e.g. for maple silkwood) :

$$V = -0.66106+8.96955 \times A$$

where V is the total log volume per tree (m^3) and A is the sectional area (m^2) of the tree at breast height.

Yield forecasts

The sustained yield may be estimated using any of several approaches which vary in technical complexity and in assumptions made. Perhaps the most simplistic estimate can be derived from the yields obtained in logging, dividing this by the nominal cutting cycle (40 years) and multiplying by the nett productive area. An estimate of logging yields may be derived from the inventory data, but it is essential to select only appropriate plots. Of the 518 plots, only 89 were last logged prior to 1955 and were 'visually thinned' at time of inventory. These plots indicate that a yield of 24 m^3 ha^{-1} (sampling error (s.e.) 8%) can be expected, suggesting a sustainable yield of 92 000 m^3 $year^{-1}$. Assumptions inherent in this approach are that the 40 year cycle is valid, that there will be no decline in growing stock or logging yields, and that these inventory data provide a reasonable sample of the area proposed for logging.

An alternative simple approach, which overcomes the assumption of the 40 year logging cycle, uses the mean annual volume increment observed on permanent sample plots. Rainforest Research in North Queensland (Queensland Department of Forestry, 1983) reports that the volume increment of commercial species is 0.64 m^3 ha^{-1} $year^{-1}$ (s.e. 37%) derived from 30 plots, all previously logged and with a measurement history of 18 years. This suggests a sustained yield of 98 000 m^3 $year^{-1}$. This estimate assumes that the sample is representative and that there will be no change in the growing stock over the area proposed for logging.

However, both these approaches assume that the whole of the nett productive area will be logged in each logging cycle. Experience indicates that this need not be the case. In practice, some areas may not yield an economic yield at each cycle, and may be logged only during alternate cycles. To take account of this factor, a more sophisticated procedure for yield forecasting is required.

Cutting cycle analysis

In order to examine the stability of logging yields over time, it is necessary to use a growth model to simulate the growth of the forest and impact of harvesting over several logging cycles. One long established and widely used approach is known as cutting cycle analysis. In its most simple form, cutting cycle analysis may employ an average stand table (showing numbers of trees in broad size classes) which is updated by simple average growth rates in each class. In this form, cutting cycle analysis can be performed as a 'back of an envelope' calculation.

Computers enable many enhancements to this basic approach, but the underlying assumptions remain. It is assumed that the actual timing of logging on any part of the forest estate cannot be predicted, so the whole forest is 'grown' for half a cutting cycle before a harvest is simulated. In effect this simulates a harvest over the whole estate at the mid-point of a cycle, rather than the harvest of small areas each year. The growth of the forest is then simulated for a full cycle (40 years in the present study) and the next harvest simulated at the mid-point of the second cycle.

Thus cutting cycle analysis provides estimates of the long-term average harvest, for a given cutting cycle length and a given logging prescription. If the successive predicted yields do not decline, it may be assumed that that level of harvesting is sustainable. In the past, computational difficulties restricted such analyses to a few (often three) cutting cycles. If the successive predicted harvests were unequal, these were often averaged to estimate the sustainable yield, rather than the more desirable but more expensive solution involving iterative alterations to the cutting cycle and/or harvesting prescription.

Present computer facilities enable several enhancements. Not only can calculations be iteratively repeated until successive harvest predictions are equal, but other important enhancements can also be made. Rather than simulating the growth of the overall average stand, the growth model can simulate the growth of the individual plots, and yields can be averaged after the harvest is simulated. This both ensures more reliable predictions and enables the calculation of standard errors.

A further important enhancement is the ability to vary the area logged during each cycle according to the expected yields. Thus the present calculation omitted areas for which the estimated harvest was less than 5 m^3 ha^{-1} during any cycle. This reflects the economic operating limits prevailing prior to the recent World Heritage listing of the Wet Tropics (Preston and Vanclay, 1988). These areas were omitted for one cycle only, and were again considered for harvesting during the next cycle.

Table 4. Cutting cycle analysis results with 40 year cycle

Cycle No.	Year	Estate average		Characteristics of predicted harvest		
		Basal area 40+ cm dbh	Volume over cutting dbh	Average yield (m^3 ha^{-1})	s.e.	Annual cut (m^3 $year^{-1}$)
1	2010	36	30	19.2	3%	72558
2	2050	36	26	15.6	2%	59191
3	2090	38	28	16.4	2%	61313
4	2130	39	27	16.6	3%	62035
5	2170	40	25	16.8	2%	63217
6	2210	41	30	19.9	2%	75640
7	2250	41	35	23.4	2%	89713
8	2290	41	38	25.7	2%	95667
9	2330	41	38	25.5	2%	96937
10	2370	40	38	25.9	2%	96857

Table 4 illustrates the results of cutting cycle analysis using a 40 year cycle and a limiting yield of 5 m^3 ha^{-1}. As past logging has created a non-normal forest, it is not surprising that yields vary over time. Average annual yields remain relatively stable, and increase towards the end of the simulation. The sampling error (s.e.) reflects the error due to sampling (i.e. inventory), and takes no account of prediction errors (i.e. volume equations and growth predictions) which will initially be negligible but which increase with the duration of simulation. The sampling errors suggest that the logged forest may become more uniform. It should be noted that this reflects within-stratum uniformity with respect to loggable volume. It does not necessarily reflect species diversity or the characteristics of the unlogged fragments of forest throughout the timber production. In practice, the patchwork effect of logging would tend to maintain the overall diversity.

The cutting cycle analysis indicates that selection logging could have been sustained for an extended period. As the smallest harvest of 59 191 m^3 is predicted in cycle 2 (it appears that the allowable cut of 60 000 m^3 could have been sustained. However, this method does not provide a good basis for determining a non-declining even-flow harvest, because of several deficiencies.

The major deficiency with the cutting cycle analysis is that it examines only the long-term average growth, and not the short-term consequences. This is significant for a resource such as the rainforests of north Queensland, where until recently, harvests have been drawn primarily from previously unlogged stands with large trees and high standing volumes. In such a situation, it may well be that the short-term implications are more serious than the long-term implications of a particular harvesting plan on the resource. This weakness is exacerbated by the half cycle (i.e. 20 year) morotorium implicit in the method (i.e. first harvest simulated in the year 2010). A more sensitive approach to modelling harvesting known as yield scheduling enables the examination of this situation.

Yield scheduling

Yield scheduling attempts to simulate the growth of the forest, yields and impacts of harvesting, and the actual sequence of logging operations across the resource. Thus the resource is stratified into Management Units, reflecting the size of typical sale areas and topographic and operational considerations. Each management unit is further stratified into homogeneous subunits, each fairly uniform with respect to growing conditions and logging history. The present study employed 149 management units each of about 1000 ha (range 200-6000 ha). Each management unit was stratified into about four subunits giving a total of 568 subunits with an average area of around 270 ha.

Inventory data are obtained for each subunit. In many cases, recent inventory data were available for each subunit. However, data were unavailable for some subunits, and for these, plots were 'borrowed' from other subunits which exhibited similar soil, climate and logging history. When plots were borrowed for a subunit, one plot from each of several similar subunits was used to minimise any possible effects of selection bias. Selection was automated to eliminate subjective bias, and preference was given to plots with the closest physical proximity to the unsampled subunit. Some 518 inventory plots were available. These plots, supplemented by borrowed plots for unsampled subunits, provided 1288 samples for use in the simulation study, and ensured a minimum of two samples in each subunit.

Yield scheduling ranks management units according to pre-selected criteria, chooses the unit with the highest rank, and simulates harvesting of those subunits within this management unit which meet the specified economic criteria. The time taken to harvest this unit is determined, all management units are 'grown' accordingly, and the cycle is repeated until a sufficiently long forecast has been made. The present study ranked units according to the anticipated harvest (descending yield ha^{-1}), so that of those areas proposed for logging, the more dense stands would be selected for harvesting first. This is silviculturally desirable, and reduces within-stand competition. Other options examined included ranking by total stand basal area, and by time since last logging, and these provided similar results.

Yield scheduling enables the user to specify several economic and environmental conditions. The present simulation was restricted to ensure that at least 20 years elapsed between successive harvests on any management unit. It also ensured that the harvested yield from any subunit never fell below 5 m^3 ha^{-1}, that the average yield from any management unit always exceeded 12 m^3 ha^{-1}. These are realistic conditions to impose, assuming operational conditions prior to the recent listing of the area. Yield scheduling does not directly indicate the maximum sustainable yield, but rather indicates the outcome of harvesting some nominated amount. The maximum sustainable yield can be determined by iteratively examining several possibilities.

Prior to the cessation of logging, the allowable cut had been set at 60 000 m^3 year^{-1} (Preston and Vanclay, 1988). Table 5 examines the consequences of such a harvest simulated over a 100 year period. The average stem size (ASV) of harvested trees can be maintained, but the harvest will become more uniform in size (Table 5: dbh distribution %< 60, 60-100, 100 + cm), and species prized for fine furniture and veneers (Table 5: veneer species) will comprise an increasing proportion of the harvest. Although large trees (exceeding 100 cm dbh) of commercial species will become increasingly scarce in the logged areas of the forest, large non-commercial trees will remain. Large trees of commercial species will also remain in the buffer strips and other protected areas. The dominant species comprising the harvest do not appear to vary greatly, and differences are probably due to the geographic rather than the temporal location of the harvest.

This harvest will cause changes in the structure of the forest in those areas which are repeatedly harvested. There will be a substantial decrease in the stand basal area of trees (Table 5: estate average BA 40 + cm), and a small decrease in the total standing volume of big trees (Table 5: estate average volume over cutting limits defined in Table 3). The mean yield per harvest will decline to about 18 m^3 ha^{-1}, which may test the efficiency of some logging operations. The proportion of the nett productive area remaining loggable (i.e. satisfying the defined environmental, economic and operational constraints) at any point in time remains constant at about half the estate, and provides another indicator of sustainability.

Table 5 also indicates the sampling error associated with the predicted yield. This should not be interpreted as the error associated with the estimate, but indicates only the inventory component of that error. When a new yield estimate is required, many foresters immediately commence new inventory and devote little attention to other components of the calculation. The sampling errors displayed in Table 5 indicate that the errors attributable to inventory are relatively small, and it may be inferred that other factors will have a greater influence on the overall precision.

Table 5. Yield scheduling of 60 000 m^3 year^{-1} for 100 years

Year	Loggable area (%)	Estate average		Mean harvest characteristics from 20 successive MUs						
		BA 40+	Vol over cutting dbh	Predicted yield (m^3 ha^{-1})	s.e. (%)	ASV (m^3)	Dbh dist. -60-100-	% veneer species	Major species code[1] and %	
1998	63	36	26	34.4	10	3.48	6:72:22	11	RDT 15	WCW 14
2005	64	35	24	24.8	5	3.24	8:70:23	28	NSO 11	YWN 9
2014	59	34	23	22.2	8	2.97	9:77:14	30	NSO 12	RAL
2020	57	33	23	19.9	4	2.91	10:81:9	18	RDT 10	YWN 8
2027	53	32	22	18.8	4	2.89	12:83:6	23	YWN 9	RAL 9
2033	51	32	22	18.6	7	2.87	11:84:5	22	QSA 11	NSO 9
2040	51	31	23	18.0	5	2.94	10:82:7	19	RAL 11	RDT 9
2047	50	30	23	18.4	4	2.92	10:85:5	27	QSA 13	RDT
2054	50	30	23	17.8	4	3.04	10:84:6	21	RDT 14	RAL
2058	48	29	23	18.0	6	2.90	9:88:3	23	BSL 17	RDT
2063	50	28	23	18.0	6	2.92	9:86:5	21	QSA 11	RDT 9
2068	52	28	23	18.4	6	2.96	8:89:3	25	QSA 14	RDT
2078	52	27	23	18.3	4	3.18	8:87:5	21	QSA 17	RDT 13
2084	54	26	23	18.7	5	3.03	9:87:4	21	QSA 14	RDT
2089	54	25	22	18.9	6	3.19	7:88:5	23	RDT 15	QSA
2096	54	24	22	18.9	6	3.28	7:89:4	31	QSA 17	BSL 10
2101	53	24	21	18.8	5	3.42	8:87:6	33	RDT 15	QSA

1. BSL, brown salwood: *Acacia aulacocarpa;* NSO, northern silky oak: *Cardwellia sublimis;* QSA, silver ash: *Flindersia bourjotiana;* RAL, rose alder: *Caldcluvia australiensis;* RDT, red tulip oak: *Argyrodendron peralatum;* WCW, white cheesewood: *Alstonia scholaris;* YWN, yellow walnut: *Beilschmiedia bancroftii.*

One major advantage of yield scheduling is that it provides location-specific yield estimates and allows comparisons between predicted and realised yields. It is unlikely that estimates for any individual management unit would be exact but discrepancies should be small when averaged over several management units. Large discrepancies can be detected easily, and are indicative of bias in the forecasting system. Such errors can readily be traced to one of the components of the system: area estimates, current inventory, growth model, harvesting model, or volume equations. Such a system facilitates detection of errors and enables iterative refinement.

Sensitivity analyses indicated that yield scheduling estimates beyond 200 years are highly sensitive to small changes in the prediction of recruitment, more so than the cutting cycle analysis results. As the present growth model has not yet been formally validated with independent data, simulations are reported only for the first 100 years. Accordingly, these results should be considered indicative rather than definitive. The prediction of regeneration and recruitment remains a fertile area for further research.

The model is not intended to allow a detailed ecological forecast of species dynamics, and no predictions on non-commercial species are made. Other models have been formulated for such studies (e.g. Doyle, 1981), but are unsuited to timber yield forecasting. However, the present study does not attempt to determine the maximum yield under any regime, but examines yields derived from the application of the existing harvesting guidelines (Preston and Vanclay, 1988) which embrace sound environmental principles.

Discussion

These yield forecasts differ from previous calculations because of the additional data which have become available and because of the more sophisticated techniques employed. Specifically, the areas proposed for logging altered in response to recent land use planning studies in the region; GIS enabled better stratification and more precise area estimates; additional inventory data and a more objective method of site assessment were employed; the revised growth model retained the species identities of all trees; the deterioration of individual trees was modelled; a dynamic harvesting model enabled better predictions of removals, defect and logging damage; new species-specific volume equations were used. Thus the present yield estimates are more reliable than previous estimates.

It is not the author's intention to suggest that timber harvesting should be re-commenced within the Wet Tropics World Heritage Area in north Queensland. Rather, it is the intention of the present study, to illustrate the integration and practical application of GIS, field inventory data and a dynamic growth model to estimate short- and long-term timber yields, to indicate management alternatives and illustrate implications. There is no substitute for long computer simulations in estimating the sustainable yield. Whilst more subjective data remain an important check on simulation results, the expectation from visually thinned inventory data using an assumed logging cycle can be quite misleading (e.g. 92 000 versus 60 000 m^3 $year^{-1}$). Similarly, estimates of periodic annual volume increment from permanent sample plots can be misleading (e.g. 98 000 m^3 $year^{-1}$) unless weighted for site productivity and species composition to adequately represent the whole estate.

The popular method of cutting cycle analysis may give a reasonable indication of sustainable yields, but only if results are averaged over several cycles.

However, it too gives a biased estimate, presumably because of the 'head start' the resource gets during the first half cycle with no simulated logging. This head start consistently results in higher yields in the first cycle, which bias estimates, especially when prepared from simulations over few cycles (Vanclay and Preston, 1989). Yield scheduling is better able to indicate the shortto medium-term consequences of harvesting a given allowable cut. The longterm consequences remain dependent upon the quality of the data, and of the growth model employed.

Conclusion

The growth model employed in these studies has not been formally validated, so the results should be taken as indicative rather than definitive. Nonetheless, the model serves to illustrate discrepancies between several alternatives for estimating sustainable yields, and the deficiencies inherent in some methods have been highlighted. The approach of yield scheduling may be the best alternative, particularly as it provides location-specific yield estimates and invites comparisons between predicted and realised yields.

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