A Growth Model for North Queensland Rainforests

J.K. VANCLAY

Department of Forestry, G.P.O. Box 944, Brisbane, Qld. 4001 (Australia)

ABSTRACT

Vanclay, J.K., *1989.* A growth model for north Queensland rainforests. *For. Ecol. Manage.,* *27: 245-271.*

A model to predict the growth of commercial timber in north Queensland's rainforests is described. More than 100 commercial species and several hundred other tree species are aggregated into about 20 species groups based on growth habit, volume relationships and commercial criteria. Trees are grouped according to species group and tree size into cohorts, which form the basis for simulation. Equations for predicting increment, mortality and recruitment are presented. The implications of the model on rainforest management for timber production are examined. The model has been used in setting the timber harvest from these rainforests, and should provide an objective basis for investigating the impact of rainforest management strategies. The approach should be applicable to other indigenous forests.

INTRODUCTION

Efficient yield regulation in indigenous forests requires a reliable growth model to facilitate the determination of the sustainable yield. This paper describes a growth model used for yield prediction (Preston and Vanclay, 1988) in the rainforests of north Queensland. These are tall closed forests (Fig. 1) comprising over 900 tree species, including about 150 of commercial interest.

Although numerous sophisticated models exist for plantation yield regulation (e.g. Clutter et al., 1983, pp. 88 ff), relatively few models have been produced for indigenous forests. The majority of indigenous forest models address monospecific stands, and very few attempt to model mixed species unevenaged stands. Several models have been constructed to examine ecological succession in various forest types (e.g. Shugart, 1984), but these are generally unsuited to yield regulation applications.

Higgins (1977) developed a transition matrix model for yield prediction in Queensland rainforests, based on the work of Usher (1966). This is an efficient and effective method of summarizing data, but contributes little towards an understanding of the process of growth within the forest. It may give reliable yield estimates provided the stands do not depart greatly from the average stand condition represented in the data (Vanclay, 1983, pp. 65 ff).

The U.S. Forest Service (Anonymous, 1979) developed a more flexible approach for temperate mixed-species forests in the Great Lakes region. This approach employed regression equations for increment and mortality, but took no account of regeneration and recruitment.

Vanclay (1988) presented a model for monospecific stands of cypress pine which can readily be modified to suit the demands of mixed-species stands. The key feature of this approach is to identify 'cohorts' (Reed, 1980), groups of individual trees which may be assumed to exhibit similar growth and which may be treated as single entities within the model. Cohorts are formed by grouping trees according to species affiliation and stem size.
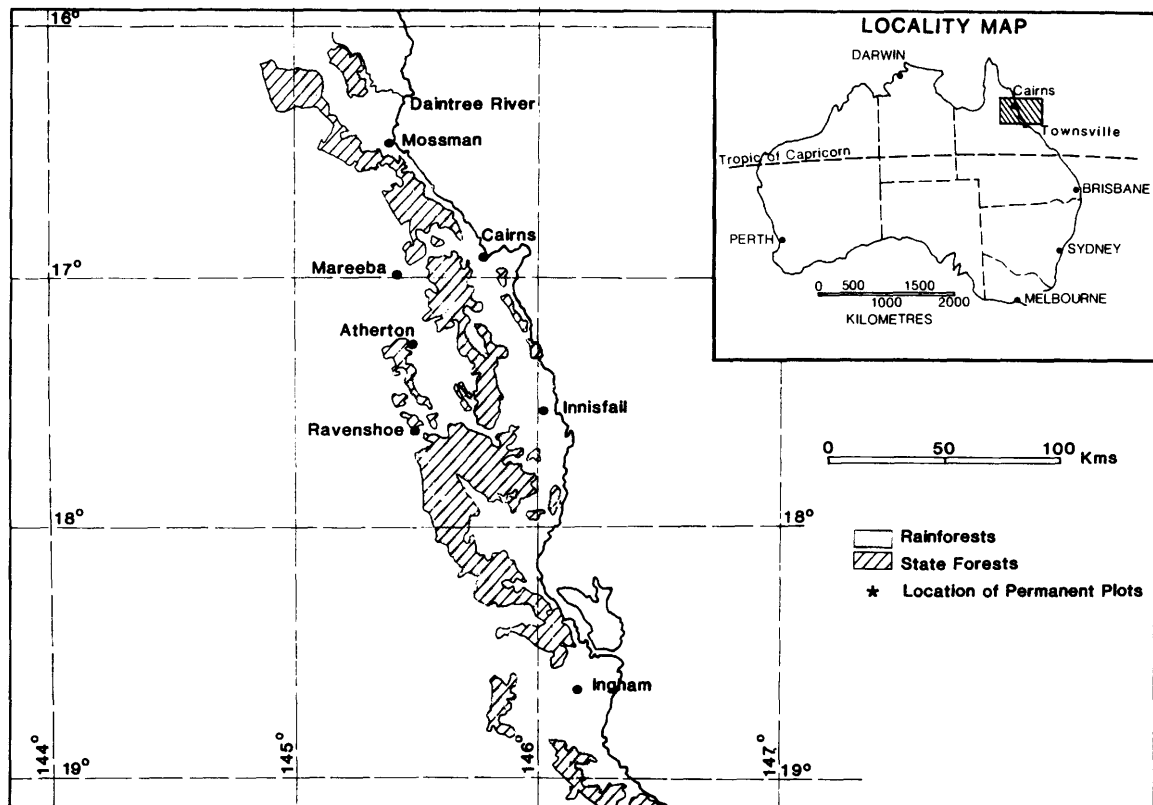

Fig. 2. Location of study area.

DATA SOURCES

Thirty-seven permanent plots, varying in size from 0.1 to 0.4 ha and representing over 200 000 tree-years (i.e. 37 plots × ca. 30 years × ca. 200 trees per plot) of measurement, were used in developing the model. These plots sample both virgin and logged rainforest on a variety of forest and soil types. Figure 2 illustrates the geographic distribution of the plots, and of rainforests in north Queensland.

A further 23 permanent plots were available, but were omitted from the analysis, as they had been subjected to silvicultural treatment. This entails the poisoning of selected non-commercial stems in the stand to favour the growth of commercial trees. This practice significantly increases the production of merchantable volume (Nicholson et al.,1983), but is used only experimentally and there is no intention to 'treat' commercial stands.

TABLE 1. Example of the cohort approach

Specific name	Trade name	Inventory data	Cohort list group SVLG	Cohort											
				Year 0		Year 1		Year 2		Year 3		Year 10		Year 25	
				DBH	N/ha	DBH	N/ha	DBH	N/ha	DBH	N/ha	DBH	N/ha	DBH	N/ha
						41.97	1.85	42.30	1.85	42.64	1.84	44.99	1.83	49.96	1.81
Cardwellia sublimis	Northern silky oak	NSO 41 L	322	41.50	7.39	41.83	5.54	42.26	1.38	42.59	1.38	44.94	1.38	49.92	1.36
								42.13	4.15	42.46	4.15	44.81	4.13	49.78	4.08
Sloanea australis	Blush alder	BLA 49 L	374	49.50	5.20	49.92	1.29	50.22	1.29	50.51	1.28	52.57	1.23	56.81	1.14
						49.79	3.88	50.09	3.86	50.38	3.84	52.44	3.70	56.68	3.41
Cardwellia sublimis	Northern silky oak	NSO 26	492	26.50	18.13	26.80	18.10	27.08	18.07	27.36	18.05	29.35	17.86	33.67	17.51
Canarium baileyanum	Brown cudgerie	BRC 68	495	68.50	2.71	68.85	2.69	69.18	2.67	69.51	2.65	71.82	2.51	76.60	2.24
Xanthophyllum octandrum	Macintyre's boxwood	MCB 42	495	42.50	7.05	42.82	6.99	43.13	6.94	43.43	6.89	45.56	6.52	50.11	5.81
		MCB 36	495	36.50	9.56	36.81	9.48	37.09	9.41	37.38	9.34	39.41	8.84	43.76	7.86
	Miscellaneous	MIS 24	495	24.50	21.21	24.76	21.04	24.99	20.87	25.24	20.71	26.95	19.58	30.69	17.39
	Miscellaneous	MIS 16 MIS 16 MIS 16	495	16.50	140.30	16.71	139.14	16.90	138.00	17.10	136.86	18.50	129.19	21.62	114.34
	Flag 1		2491	15.00	1.00	15.20	1.00	15.39	0.99	15.57	0.99	16.91	0.96	19.88	0.90
	Flag 2		2492	15.00	1.00	15.22	1.00	15.43	0.99	15.64	0.99	17.15	0.97		
	Flag 3		2493	15.00	1.00	15.29	0.99	15.57	0.99	15.85	0.98	17.90	0.93		
	Flag 4		2494	15.00	1.00	15.19	0.99	15.36	0.99	15.54	0.98	16.79	0.94	19.59	0.86
	Flag 5		2495	15.00	1.00	15.20	0.99	15.38	0.98	15.57	0.98	16.90	0.92	19.87	0.81
	Recruits group 2		1322											20.11	0.66
			1492											20.39	0.38
	Recruits group 3		1493											22.21	2.29
			1493											21.24	3.42
			1493											20.31	3.56

MODEL STRUCTURE

To satisfy the requirements of yield regulation, a model's characteristics must be as follows:
- stand-growth model, which predicts annual growth;
- deterministic, to enable efficient yield forecasting;
- modular, to facilitate substitution of components;
- sufficiently flexible to utilize data derived from a variety of inventory procedures; and
- facilitate investigation of a wide range of logging strategies.

Three modelling approaches (stand-table projection, cohorts, and distance-independent individual tree models) may be considered for this application. Stand-table projection and transition matrices have been popular for such applications in the past, but have several disadvantages limiting the precision of forecasts (Vanclay, 1983, pp. 64 ff). Individual tree models pose difficulties in accurately and deterministically forecasting mortality. Stand-based approaches are more flexible. The cohort approach (Reed, 1980) is particularly versatile, and was used for the rainforest growth model.

The rainforest growth model admits a maximum of 200 cohorts for each stand. Stems from the same species group and whose diameters, over bark at breast height (DBHOB) or above buttressing, differ by less than 5 mm, are grouped into a single cohort. If necessary, size differences greater than 5 mm are accommodated by forming groups of stems most similar in size.

During simulation, cohorts comprising more than a critical number of stems or exhibiting diameter increments exceeding 5 mm per year may split into two new cohorts, one with 25% of the stems and 1.3 × the predicted current annual increment, and one with 75% of the stems and 0.9 × the predicted current annual increment

(Table 1). This reflects the skewed nature of increment commonly observed in rainforest stands (Bragg and Henry, 1985). The critical number of stems varies with stem size, being 20 stems per ha for stems below 40-cm diameter, five stems per ha for stems exceeding 40-cm diameter, and two stems per ha for stems exceeding the normal merchantable size (50-100 cm diameter, depending upon species). During the simulation, the total number of cohorts is maintained below 200 by merging cohorts with similar diameters and identical species groups.

SPECIES GROUPS

Several hundred tree species are represented in Queensland rainforests (Hyland, 1982), of which more than 100 are of commercial importance. As it is clearly impractical to develop separate functional relationships for each tree species, some aggregation is essential. It is expedient to employ three criteria, namely the volume/size relationship, logging practice, and growth patterns. In the model, species groups are identified by a four-digit code, SVLG, where S represents the datum source (0 = inventory, 1 = predicted ingrowth), V indicates the volume relationship to be used (1 to 4), L indicates the logging rule applicable (1 to 9 inclusive), and G indicates the growth group. Five growth groups are identified:
> (1) commercial species which grow rapidly to a large size;
> (2) commercial species which grow slowly to a large size;
> (3) commercial species which grow rapidly to a small size;
> (4) commercial species which grow slowly to a small size; and
> (5) non-commercial species.

TABLE 2. Large. fast-growing species

Botanical nomenclature	Standard trade name	QFD species code	D_{max} (cm)	Source[a]
			Literature	
Acmenosperma claviflorum	Grey Satinash	GRS	270	Boland
Agathis atropurpurea	Northern Kauri Pine	NKP		
Agathis microstachya	Northern Kauri Pine	NKP		
Agathis robusta	Northern Kauri Pine	NKP	180	Boland
Albizia toona	Red Siris	RSR	60	Francis
Alstonia actinophylla	White Cheesewood	WCW	100	Boland
Alstonia scholaris	White Cheesewood	WCW		
Argyrodendron peralatum	Red Tulip Oak	RDT	150	Boland
Elaeocarpus grandis	Silver Quandong	SLQ	200	Boland
Endiandra palmerstonii	Queensland Walnut	QWN	220	Boland
Eucalyptus grandis	Rose Gum	RSG	200	Boland
Flindersia brayleyana	Queensland Maple	QMP	250	Boland
Flindersia ifflaiana	Hickory Ash	HKA	120	Francis
Flindersia pimenteliana	Maple Silkwood	MSW	220	Boland
Palaquium galactoxylum	Red Silkwood	RSW	70	Francis
Prumnopitys amara	Black Pine	BKP		
Syzygium claviflorum	Grey Satinash	GRS	180	Boland
Syzygium gustavioides	Grey Satinash	GRS		
Toona australis	Red Cedar	RCD	300	Boland
Wrightia laevis	White Cheesewood	WCW		

[a]Boland = Boland et al. (1984); Francis = Francis and Chippendale (1981).

The actual composition of these groups is indicated in Tables 2 to 5. These Tables also indicate maximum size quoted elsewhere (Shugart et al., 1980; Francis and Chippendale, 1981; Boland et al., 1984). The species code employed during inventory, marketing and in the model, is based on the standard trade name (Anonymous, 1983a), and may in a few instances refer to more than one taxon.

Practical necessity required the use of a single group for all non-commercial species. Resource inventory identified only commercial and potentially commercial species, and most non-commercial species were simply recorded as miscellaneous (MIS).

TABLE 3. Large, slow-growing species

Botanical nomenclature	Standard trade name	QFD species code	D_{max} (cm)	Source[a]
Acmena resa	Rose Alder	RAL		
Backhousia bancroftii	Red Eungella Satinash	RES		
Backhousia hughesii	Johnstone River Hardwood	JHR		
Beilschmiedia bancroftii	Stony Backhousia	SBH	60	Francis
Beilschmiedia sp.	Yellow Walnut	YWN	90	Francis
Beilschmiedia sp.	Boonjie Blush Walnut	BOW		
Blepharocarya involucrigera	Brown Walnut	BRW		
Caldcluvia australensis	Rose Butternut	RBN	75	Francis
Cardwellia sublimis	Northern Silky Oak	NSO	200	Boland
Castanospermum australe	Black Bean	BBN	120	Boland
Ceratopetalum succirubrum	Satin Sycamore	STS	50	Francis
Cinnamomum oliveri	Camphorwood	CMY	90	Francis
Dysoxylum cerebriforme	Miva Mahogany	MMH		
Dysoxylum fraseranum	Rose Mahogany	RMH	150	Boland
Dysoxylum micranthum	Spicy Mahogany	SPM		
Dysoxylum muelleri	Miva Mahogany	MMH	152	Shugart
Dysoxylum pettigrewianum	Spur Mahogany	SMH	60	Francis
Elaeocarpus coorangooloo	Brown Quandong	BRQ		
Elaeocarpus ruminatus	Brown Quandong	BRQ	60	Francis
Endiandra acuminata	Brown Walnut	BRW		
Endiandra dichrophylla	Brown Walnut	BRW	50	Francis
Endiandra glauca	Brown Walnut	NRW		
Endiandra montana	Brown Walnut	BRW		
Endiandra tooram	Brown Walnut	BRW		
Flindersia laevicarpa	Scented Maple	SMP	75	Francis
Galbulimima belgraveana	Magnolia	MGN	90	Francis
Geissois biagiana	Northern Brush Mahogany	NBM		
Gmelina dalrympleana	White Beech	WBH	122	Shugart
Gmelina fasciculiflora	White Beech	WBH		
Gmelina leichardtii	White Beech	WBH	200	Boland
Metrosideros queenslandica	Pink Myrtle	PMR		
Musgravea heterophylla	Briar Silky Oak	BSO		
Musgravea stenostachya	Crater Silky Oak	CSO		
Neorites kevediana	Fishtail Silky Oak	FSO		
Ormosia ormondii	Yellow Bean	YBN		
Syncarpia glomulifera	Turpentine	TRP	130	Boland
Syzygium canicortex	Yellow Satinash	YLS	90	Francis
Syzygium wesa	White Eungella Satinash	WES		
Xanthostemon whitei	Red Penda	RPN	140	Francis

[a]As Table 2; Shugart - Shugart et al. (1980).

TABLE 4. Small, fast-growing species

Botanical nomenclature	Standard trade name	QFD species code	Dmax (cm)	Source
Acacia aulacocarpa	Brown Salwood	BSL	100	Boland
Acacia crassicarpa	Brown Salwood	BSL		
Acacia implexa	Lightwood	LTW		
Acacia mangium	Brown Salwood	BSL		
Acacia melanoxylon	Blackwood	BKD	90	Francis
Albizia xanthoxylon	Yellow Siris	YSR	50	Francis
Alpitonia petriei	Pink Ash	PKA	60	Francis
Barringtonia asiatica	Barringtonia	BGT		
Barringtonia calyptrata	Barringtonia	BGT		
Barringtonia racemosa	Barringtonia	BGT		
Bleasdalei bleasdalei	Blush Silky Oak	BLO	20	Francis
Callitris macleayana	Cypress Brush Pine	BCP	80	Boland
Cinnamomum laubatii	Pepperwood	PPW	60	Francis
Cryptocarya oblata	Bolly Silkwood	BSW		
Daphnandra repandula	Northern Sassafras	NSS	25	Francis
Darlingia ferruginea	Rose Silky Oak	ROO		
Doryphora aromatica	Northern Sassafras	NSS	60	Francis
Elaeocarpus largiflorens	Tropical Quandong	TRQ	40	Francis
Elaeocarpus sericopetalus	Northern Hard Quandong	NHQ	50	Francis
Eucalyptus tereticornis	Forest Red Gum	FRG	200	Boland
Eucalyptus torelliana	Cadaga	CDG	100	Boland
Eucalyptus resinifera	Red Mahogany	RMY	150	Boland
Eucalyptus pellita	Red Mahogany	RMY	100	Boland
Euodia bonwickii	Yellow Evodia	YEV	60	Francis
Euodia elleryana	Evodia	EVD		
Euodia vitiflora	Northern Evodia	NEV	50	Francis
Euodia xanthoxyloides	Yellow Evodia	YEV		
Flindersia acuminata	Silver Silkwood	SSW	50	Francis
Flindersia bourjotiana	Queensland Silver Ash	QSA	100	Boland
Litsea bindoniana	Bollywood	BWD		
Litsea glutinosa	Bollywood	BWD		
Litsea leefeana	Bollywood	BWD	30	Francis
Litsea reticulata	Bollywood	BWD	150	Francis
Melaleuca argentea	Broad-leaved Tea-tree	BTT		
Melaleuca leucadendra	Broad-leaved Tea-tree	BTT	150	Boland
Melaleuca quinquenervia	Broad-leaved Tea-tree	BTT		
Melaleuca viridiflora	Broad-leaved Tea-tree	BTT	30	Boland
Melia azedarach	White Cedar	WCD	120	Francis
Myristica insipida	Nutmeg	NTG	60	Francis
Opistheolepis heterophylla	Blush Silky Oak	BLO		
Placospermum coriaceum	Rose Silky Oak	ROO		
Podocarpus elatus	Brown Pine	BRP	90	Boland
Prumnopitys ladei	Brown Pine	BRP		
Prunus turnerana	Almondbark	ALB		
Sloanea langii	White Carabeen	WCB	50	Francis
Sloanea macbrydei	Grey Carabeen	GCB	60	Francis
Terminalia sericocarpa	Damson	DMN	100	Boland

TABLE 5. Small, slow-growing species

Botanical nomenclature	Standard trade name	QFD species code	Dmax (cm)	Source
Acmena divaricata	Cassowary Satinash	CSS		
Acmena graveolens	Cassowary Satinash	CSS		
Acmena smithii	Lillipilly Satinash		60	Boland
Ailanthus triphysa	White Siris	WSR	60	Francis
Alstonia muellerana	Hard Milkwood	HMW		
Alstonia spectabilis	Hard Milkwood	HMW		
Archidendron vaillantii	Salmon Bean	SBN		
Argyrodendron polyandrum	Brown Tulip Oak	BRT		
Argyrodendron trifoliolatum	Brown Tulip Oak	BRT	120	Francis
Cryptocarya erythroxylon	Rose Maple	RMP	125	Boland
Cryptocarya ridiga	Rose Maple	RMP	60	Francis
Darlingia darlingiana	Brown Silky Oak	BRO	50	Francis
Dysaxylum oppositifolium	Pink Mahogany	PMH	40	Francis
Elaeocarpus foveolatus	Northern Quandong	NTQ	75	Francis
Endiandra cowleyana	Northern Rose Walnut	NRW		
Endiandra hypotephra	Northern Rose Walnut	NRW		
Endospermum myrmecophilum	Endospermum	ESP		
Endospermum peltatum	Endospermum	ESP		
Eucalyptus drepanophylla	Grey Ironbark	GRI		
Eucalyptus siderophloia	Grey Ironbark	GRI		
Intsia bijuga	Kwila	KWL		
Neuclea orientalis	Cheesewood	CWD	100	Boland
Neonauclea gordoniana	Hard Lichhardt	HLH		
Oreocallis wickhamii	Satin Oak	STO	60	Francis
Orites racemosa	Buff Silky Oak	BFO		
Planchonella arnhemica •	Northern Yellow Boxwood	NYB		
Planchonella obovata	Northern Yellow Boxwood	NYB		
Planchonella obouoidea	Northern Yellow Boxwood	NYB		
Planchonella pohlmaniana	Yellow Boxwood	YBW	50	Francis
Pleiogynium timorense	Tulip Plum	TPL	50	Francis
Polyalthia michaelii	Canary Beech	CBH		
Pseudoweinmannia lachnocarpa	Mararie	MRR	110	Francis
Ristantia pachysperma	Yellow Penda	YPN		
Schizomeria ovata	White Birch	WBR	150	Francis
Schizomeria whitei	White Birch	WBR		
Sloanea australia	Blush Alder	BLA	60	Francis
Symplocos cochinchinensis	White Hazelwood	WHZ	75	Francis
Synoum muelleri	Northern Scentless Rosewood	NSR	50	Francis
Syzygium kuranda	Kuranda Satinash	KRS		
Syzygium luehmannii	Ch$_v$rry Satinash	CHS	90	Francis
Syzygium paniculatum	Creek Satinash	CKS	30	Francis
Syzygium papyraceum	Paperbark Satinash	PBS		
Syzygium sayeri	Pink Satinash	PKS		
Syzygium trachyphloia	Rough-barked Satinash	RBS		
Syzygium wilsonii	Plum Satinash	PLS		

SITE CLASSIFICATION

As rainforests in north Queensland exhibit a considerable variation in growth rate and timber production, it is necessary to assess site productivity. To facilitate efficient site assessment during routine inventory, it is desirable to identify quality classes, and an objective means of appraisal.

The 37 permanent plots were ranked according to their past basal area and volume increments, and local field-staff attempted to identify meaningful plot attributes correlated with rank. They identified four factors which may influence and indicate volume increment: soil parent material; species composition; standing volume; and log length. The appraisal scheme assigned points to each attribute, producing a total score ranging from 1 to 30. The point scores for each attribute were initially subjectively assigned, and were iteratively refined until the total scores allocated to each of the permanent plots reflected their ranking.

Webb and Tracey (1967) reported that the productivity of hoop-pine plantations could be predicted from surface geology. In particular, they found that acid rock produced soils of low fertility, while more basic parent material produced soils of higher nutrient status. Nicholson et al. (1983) reported a strong correlation between soil parent material and tree diameter increment. Six soil parent materials commonly occur within the study area (Anonymous, 1972); the scores allocated to each of these are indicated in Table 6.

Webb et al. (1971) reported that productivity of rainforest sites in north Queensland could be determined from indicator plants even after clearing. Thus the use of indicator plants offers some potential for site-productivity assessment. Floristic records for each permanent plot were examined, and 16 tree species selected as potential site-productivity indicators. Strong interaction between soil parent material and the occurrence of these indicators was evident. Table 7 indicates the scores allocated to these indicator species on each soil parent material. If more than one of these species was present on any plot, the highest score tabulated for the 'preferred species' was used. If no preferred species were present, the highest tabulated score for 'alternative species' was used. Blank entries imply a zero score. Where none of the tabulated species were present in the vicinity, a zero score was assumed.

Havel (1980) reported the use of natural basal area as an indicator of site productivity in Western Australia. However, this is sensitive to logging, and the residual volume after 'visual thinning' according to the Queensland Department of Forestry tree-marking guidelines may be more robust. The score allocated to this volume was calculated as the volume (m') per ha divided by 10, and rounded down to a whole number. If the score exceeded 10, the value 10 was used.

TABLE 6. Site assessment scores for soils

Soil parent material	Abbreviation	Score
Alluvial and Colluvial	AC	10
Coarse Grained Granite	CG	10
Basic Volcanic (e.g. Basalt)	BV	10
Tully (fine grained) Granite	TG	7
Sedimentary and Metamorphic	SM	3
Acid Volcanic (e.g. Rhyolite)	AV	2

TABLE 7. Site assessment scores for species

Species name.	Species code	Soil parent material					
Preferred species	NKP	CG	BV	TG	SM	AV	AC
Agathis spp		-1					
Alstonia spp.	HMW			-1	-1		
Argyrodendron spp.	BRT		+ 1		+ 2		
Backhousia bancroftii	JHR		+1				
Blepharocarya involucrigera	RBN	+ 2	+ 2		- 2		
Caldcluvia australiensis	RAL			+ 1			
Flindersia brayleyana	QMP	- 2					
Flindersia laevicarpa	SMP	- 3			- 2		
Planchonella euphlebia	HKB					+ 1	
Syzygium kuranda	KRS	+ 1			+ 2		
Syzygium spp. and *Acmenosperma claviflorum*	GRS		+ 1				
Alternative species *Argyrodendron spp.*	RDT		+ 1		+ 2		
Beilschmiedia brancroftii	YWN	*-1*	*-1*			+ *1*	
Casuarina torulosa	ROS			+ 1	+ 2	+ *3*	
Flindersia pimenteliana	MSW				+ 1		
Xanthophyllum octandrum	MSB			-1			+ *3*

Canonizado (1978) reported that the average total height of dominant trees remaining after logging was useful as an indicator of site productivity in the Philippines. In this study, average log length was used for ease of measurement, and was based on the assessed log length of commercial stems 40-60-cm diameter to minimize the impact of logging. The score was calculated as the average log length (m) minus 4, rounded down to a whole number, subject to a maximum of 7 and a minimum of 0.

These four scores were summed to yield a score in the range 1-30. Initially, three site-quality classes were envisaged (1-10, 11-20, 21-30). However, statistical analyses revealed a significant ($P < 0.05$) difference in the gross basal area increments of the poor (1-10) and other classes, but no significant difference between the better two classes. Thus the final scheme was a simple good/poor classification, which inventory officers were able to allocate confidently without explicitly calculating the scores.

This assessment served primarily to classify acid volcanic and sedimentary-metamorphic soils, as other parent materials, with few exceptions, gave rise to 'good' site classifications.

DIAMETER INCREMENT

In order to simulate the growth of the forest, the growth model requires functions to predict increment, mortality and recruitment within each of the five growth groups identified above. Vanclay *(1983, pp. 90* ff.) reviewed published diameter-increment functions and concluded that few were suitable for modelling increment of stems in indigenous stands, especially where data are limited or variable. To ensure reliable estimates, an increment function was devised which:
  - resulted in a growth pattern similar to that observed, and to that employed in other growth models (e.g. Botkin et al., 1972; Leary, 1980; Reed, 1980; Shugart et al., 1980);
  - would be sensitive to site and stand conditions; and
  - could be readily established using linear regression.
This function has the form:

$$DI = f(SBA, SQ, PM) (Dmax - D) D^k \tag{1}$$

where DI is the diameter increment (cm year^{-1}), D is the diameter (cm) at breast height (or above buttressing), D_{max} is the maximum attainable diameter, k is a parameter to be estimated, and $f(SBA, SQ, PM)$ is a linear expression in stand basal area, site quality, and soil parent material. Despite its strong contribution to the site-quality classification, soil parent material was significant in its own right.

Attainable diameter

As trees become very large, irrespective of their general health and vigour, their diameter increment declines as a consequence of increasing respiratory demands relative to the effective photosynthetic area. Thus, for most tree species it is appropriate to identify a maximum attainable diameter (D_{max}), the size which a given species on a nominated site can barely attain.

The D_{max} can be estimated using statistical analyses where sufficient data are available. However, in rainforests (even virgin stands), very large stems occur infrequently, and few data exist for these stems. Thus it is expedient to subjectively determine the D_{max} for each growth group, based on inspection of available data, relevant literature (Shugart et al., *1980;* Francis and Chippendale, 1981; Boland et al., *1984)* and local knowledge. The variation in D_{max} on the different soil parent materials is due both to different growth habits of individual species, and to the different species composition of growth groups.

Growth pattern

The predicted growth pattern is determined largely by the parameter *k* in Equation (1). This parameter may be expected to take a value between 0 and 1, depending upon the growth habits of the species comprising the group. Graphical analysis revealed that for most groups a value of 0.667 appeared to be appropriate. Statistical analysis revealed that, for groups 1, 2 and 5 on all sites, the estimated values were very close to and not significantly (P < 0.05) different from 0.667, which was consequently adopted. Slightly different values were obtained for growth groups 3 and 4.

Growth rates

In Equation (1), the predicted rate of growth is determined by the expression *f(SBA, SQ, PM)* which was determined by ordinary least-squares linear regression. Because of the vast amount of data, and the disproportionate representation of smaller size classes, and to facilitate graphical analyses of the residuals, the data were grouped into site quality, soil parent material and 5 cm-diameter cells. Some cells were further grouped to enable the estimation of the variance within each cell. The mean diameter of each cell was used in the analysis, and site quality and soil parent material were included as dummy (0, 1) variables. Linear regression, weighted by the inverse of the variance, produced the following results (all parameters significant at P< 0.05 or better throughout the paper):

$$DI_1 = (140 - 20\,TD - D)\,D^{0.667}\,(2.497 + 1.196\,SQ - 1.061\,BV - 0.02859\,SBA) \times 10^{-4}$$

$$DI_2 = (160\,TG - D)\,D^{0.667}\,(2.543 + 0.2737\,CG - 0.02902\,SBA) \times 10^{-4}$$

$$DI_3 = (120 - D)\,D^{0.765-0.051\,TG}\,(2.478 + 1.055\,SQ - 0.8328\,CG - 0.03364\,SBA) \times 10^{-4}$$

$$DI_4 = (110 - D)\,D^{0.83+0.013\,TG}\,(1.542 + 0.3924\,CG - 0.01741\,SBA) \times 10^{-4}$$

$$DI_5 = (170 - 40\,SA - 60\,TG - D)\,D^{0.667}\,(2.076 - 0.3831\,CG - 0.01894\,SBA) \times 10^{-4}$$

where DI_j is the diameter increment (cm year^{-1}) of growth group *i, D* is diameter (cm), SBA is stand basal area (m^2 ha^{-1} of stems exceeding 20 cm diameter), *SQ* is 1 for good sites and 0 for poor sites, *BV* is 1 on Basic Volcanic parent material, *CG* is 1 on Coarse Granite parent material, *SA* is 1 on Sedimentary, Metamorphic and Acid Volcanic parent material, and *TG* is 1 on Tully Granite parent material.

These functions are illustrated in Figs. 3 to 7. It is noteworthy that site quality and stand basal area affect only the rate of increment, and not the growth pattern. The growth pattern for any growth group is determined solely by the soil parent material. This strong interaction of soil parent material on the growth pattern of species groups is consistent with earlier observations (Nicholson et al., 1983).
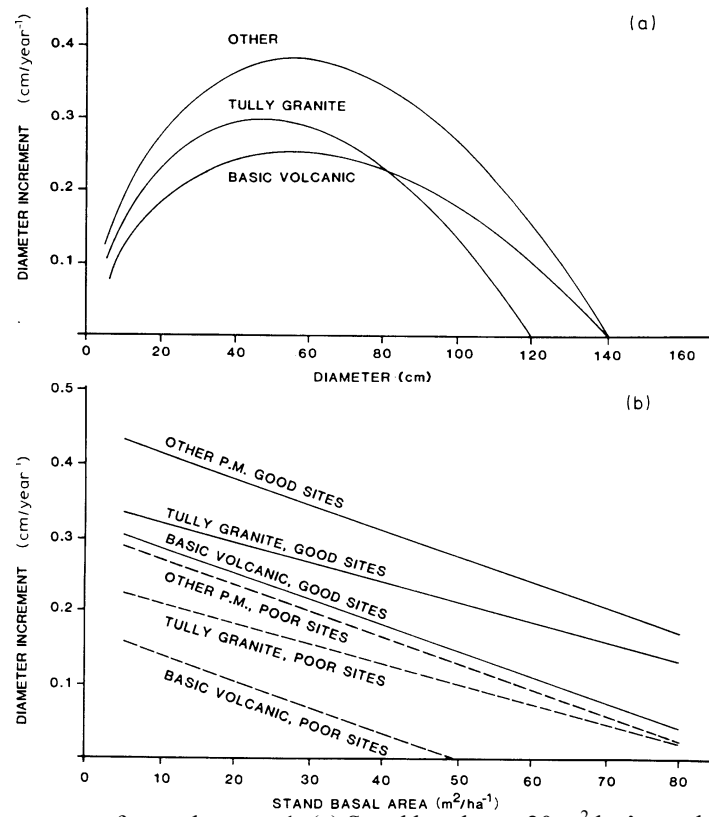
Fig. 3. Diameter increment of growth-group 1. (a) Stand basal area 20 m² ha⁻¹, good sites. (b) Diameter= 50 cm DBHOB.

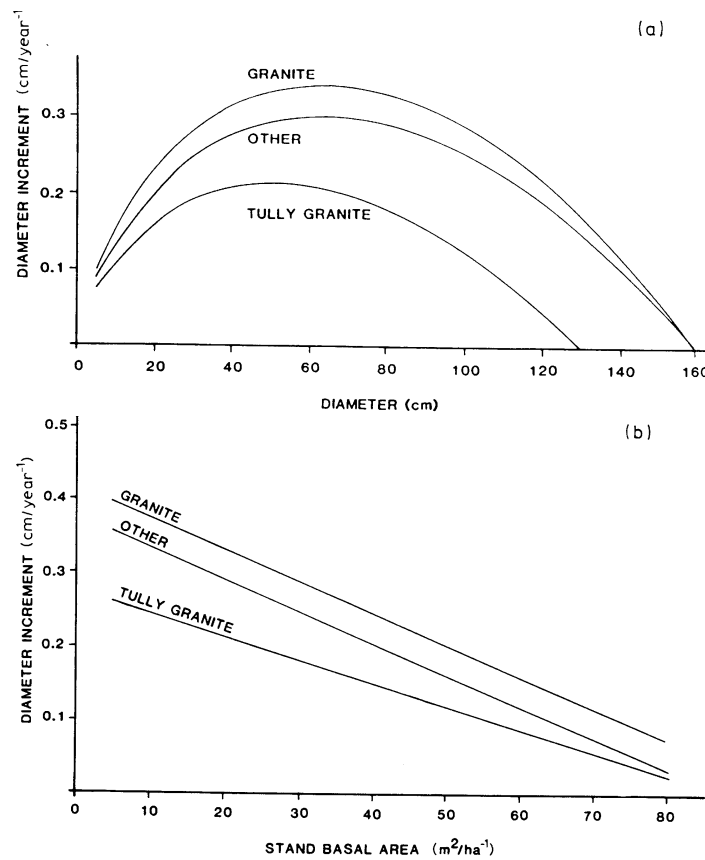**Fig. 4**. Diameter increment of growth-group 2. (a) Stand basal area 20 m² ha⁻¹, all sites. (b) Diameter= 50 cm DBHOB.

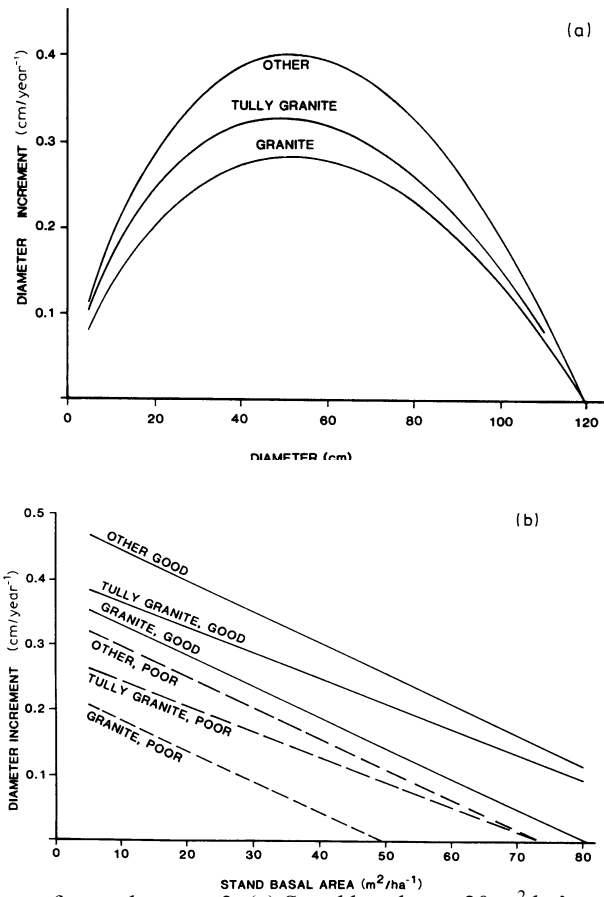**Fig. 5**. Diameter increment of growth-group 3. (a) Stand basal area 20 m² ha', good sites. (b) Diameter= 50 cm DBHOB.

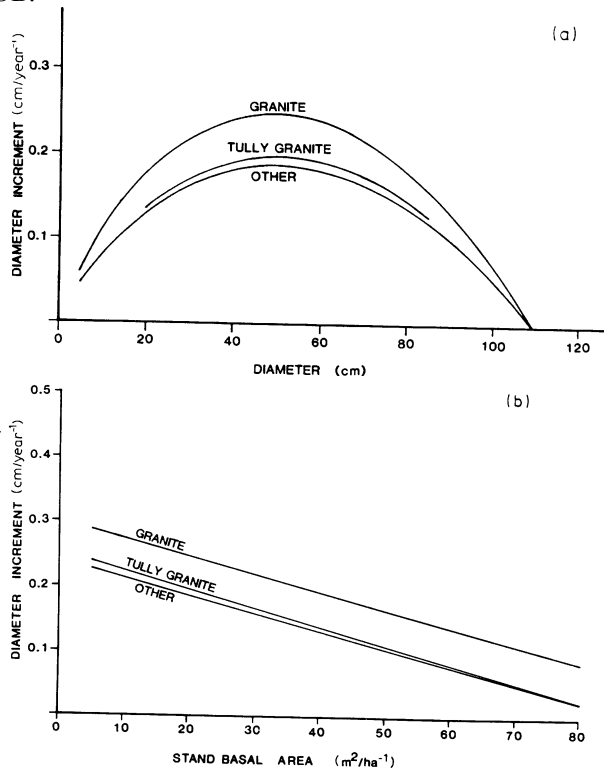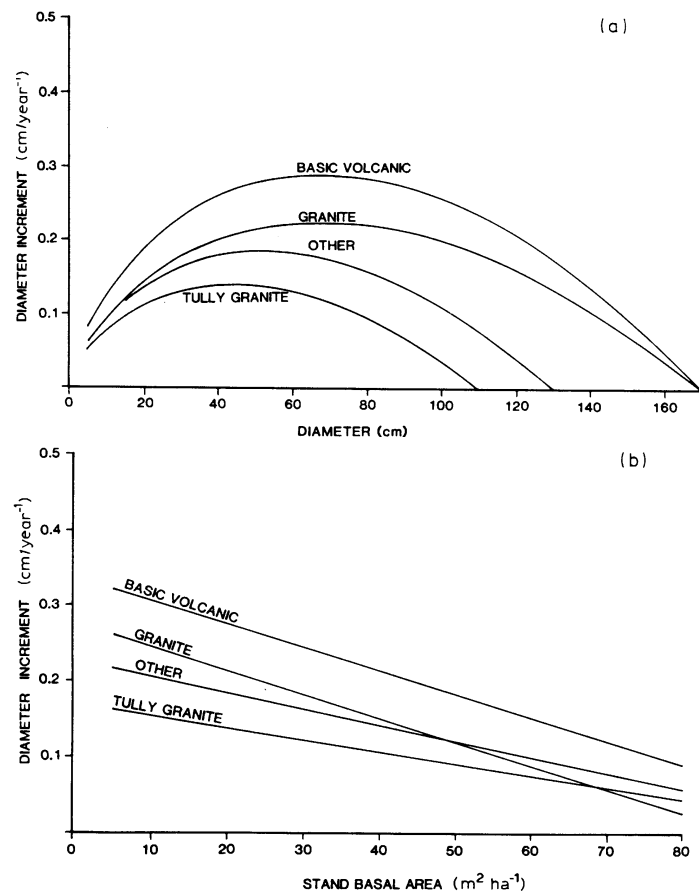**Fig. 6**. Diameter increment of growth-group 4. (a) Stand basal area 20 m² ha⁻¹, all sites. (b) Diameter= 50 cm DBHOB.

Fig. 7. Diameter increment of growth-group 5. (a) Stand basal area 20 m^2 ha^{-1}, all cites. (b) Diameter= 50 cm DBHOB.

MORTALITY

Several approaches to predicting mortality have been described, but most have been developed for monospecific stands and are not suited for modelling rainforest stands. Stand-density approaches (Reineke,1933; Yoda et a1.,1963) indicate only the residual stocking and give no indication of which trees die. Individual-tree competition approaches including threshold increment (Newnham, 1964) and limiting competition methods (Mitchell, 1969) fail to account for mortality not induced by competition (e.g. pests, diseases, cyclones). Hamilton (1974, 1980) proposes the use of logistic functions for predicting mortality. Many authors favour a function incorporating tree size and predicted increment (Buchman, 1979; Ek and Monserud, 1979; Hann, 1980; Buchman et al., 1983), but a more robust approach is Hamilton and Edwards' (1976) logistic function which predicts mortality from tree size and stand density:

$$P = 1/(1+exp[g(D, SBA)])$$

where *g(D, SBA)* is some function of stem diameter and stand basal area. Inspection revealed that this function was linear with respect to stand basal area, and asymptotic or quadratic in diameter. Linear regression was used to fit the following relationships:

$$P_1 = 1 / (1 + exp(5.899 - 6.039/D - 0.008392\ SBA))$$
$$P_2 = 1 / (1 + exp(4.379+0.1010D-0.0007908D^2-0.01477\ SBA))$$
$$P_3 = 1 / (1 + exp(5.261-5.838/D))$$
$$P_4 = 1 / (1 + exp(5.331 - 2.802/D - 0.004500\ SBA))$$
$$P_5 = 1 / (1 + exp(4.894 -1.764/D))$$

where P_i is the annual probability of mortality within growth-group i, D is diameter (cm, breast high or above buttress, over bark) and SBA is stand basal area (m^2 ha^{-1} of stems exceeding 20 cm diameter) .

These functions are illustrated in Fig. 8. The mortality trend suggested for growth-group 2 contrasts strongly to that of the other growth groups, but is not inconsistent with findings of other workers (e.g. Buchman et al., 1983).
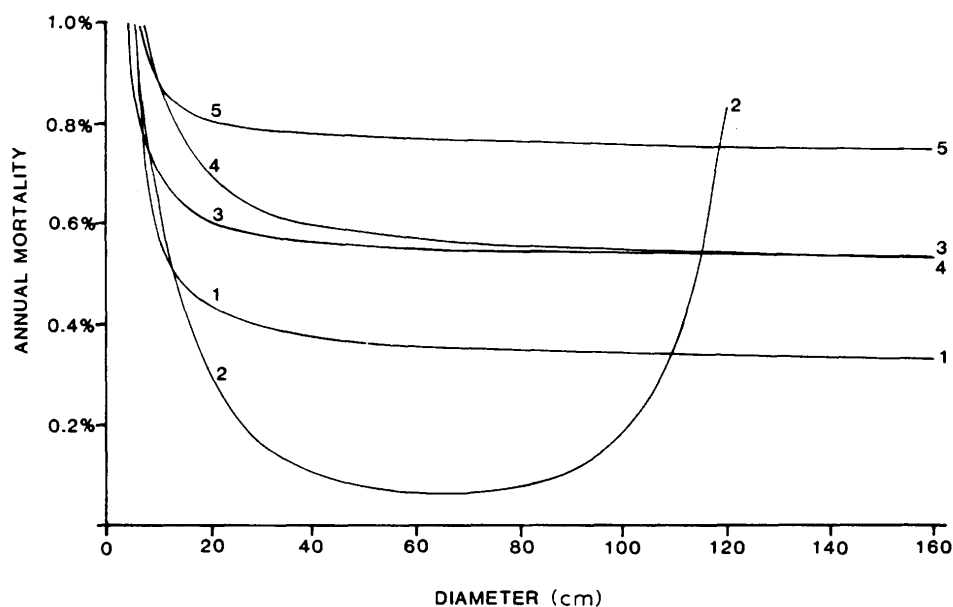

Fig. 8. Predicted mortality assuming 20 m^2 ha^{-1} basal area.

RECRUITMENT

The model requires the estimation of recruitment by species groups. The irregular nature of recruitment suggests a stochastic function, but efficient yield prediction requires a deterministic model. In order to ensure reliable estimates of recruitment it is appropriate to use a deterministic function to predict the total recruitment, and apportion it amongst the species groups. More sophisticated approaches such as those of Botkin et al. (1972) and Shugart et al. (1980) are possible if spatial information is available and a stochastic approach is acceptable. However, the requirements of the present application (efficient yield prediction utilizing existing inventory data) exclude these approaches.

Size of recruits

Existing inventory data were collected over an extended period and include several measurement practices. In particular, the minimum size for measurement of stems has varied between 3 and 20-cm diameter. Thus recruitment must be predicted at 20-cm diameter.

The model has been designed to allow full utilization of all available inventory data, irrespective of the minimum size measured. This is achieved by marking the lower limit of measurement with a 'ghost' stem in each growth group, and prediction of recruitment for any growth group is only activated when the marker (or ghost stem) attains 20 cm diameter.

Amount of recruitment

Graphical inspection of the data suggested that recruitment was linearly related to stand basal area and correlated with site quality. The total amount of recruitment was predicted as:

$N = 5.466 -0.06469\ SBA +1.013\ SQ$

where N is the number of recruits (stems ha^{-1} year^{-1} at 20 cm diameter), SBA is stand basal area (m' ha $^{-1}$ of stems exceeding 20-cm diameter), and SQ is 1 on good sites and 0 on poor sites. On average, recruitment does not exceed 6.5 stems ha^{-1} year^{-1}, and does not occur where stand density exceeds 100 and 85 m^2 ha^{-1} basal area on good and poor sites, respectively.

Composition of recruitment

It is important to correctly predict the composition of recruitment by growth group, as it determines the predicted growth rates and may influence stand basal area. Logging and volume groups only become important once the recruited stems reach commercial size, and at this stage warning messages are printed to caution the user against placing too much reliance upon results derived from stands comprising a significant proportion of predicted recruitment.

The composition by growth groups can be predicted in two ways. One approach is to allocate recruits to growth groups according to the current stand composition. Although the stand composition will be a major determinant of the composition of seedlings, this approach ignores stand density, a major factor determining recruitment through its affect on light intensity. An alternative approach is to predict the proportion of recruitment in each growth group by some function of stand condition. Stand basal area, composition and site quality may all influence the composition of recruitment, but no relationship between composition of recruitment and soil parent material could be detected. As a proportion (of total recruitment) is being predicted, it is appropriate to use a logistic function (Hamilton, 1974):

$P_i = 1 - 1 / (1 + exp\ [\ h\ (SBA,\ B_i,\ SQ)]\ )$

where P_I is the proportion of the total recruitment as growth group i, and h (sBA, B_i, SQ) is some linear function of total stand basal area, basal area of growth group i and site quality. It is necessary to use the basal area of each growth group rather than the number of stems as some inventory data are derived from horizontal point sampling (sampling with probability proportional to size) (Husch et al., 1982, p. 220) in which the presence or absence of a single small stem may give rise to a large difference in the estimated number of stems.

The following functions were derived by linear regression:

$P_1 = 1 - 1 / (1 + exp(-2.407 -0.005608\ SBA +0.01105B_1 +0.00464B_1\ SQ)\ )$

$P_2 = 1 -1 / (1 + exp(-2.572 -0.006756\ SBA +0.11800B_2 -0.06434B_2\ SQ)\ )$

$P_3 = 1 - 1 / (1 + exp(-1.761-0.008240\ SBA -0.08076B_3 +0.16610B_3\ SQ)\ )$

$P_4 = 1 - 1 / (1 + exp(-2.440 -0.010609\ SBA +0.16470B_4 -0.06230B_4\ SQ)\ )$

$P_5 = 1 - 1 / (1 + exp(-0.655 -0.024960\ SBA +0.10630B_5 - 0.02621B_5\ SQ)\ )$

where P_i is the proportion of the total recruitment as growth group i, SBA is stand basal area ⟨m^2 ha^{-1} of stems exceeding 20-cm diameter), B_1, B_2, ..., B_5 are the basal areas of growth groups 1 to 5, respectively, and SQ is 1 on good sites and 0 on poor sites.
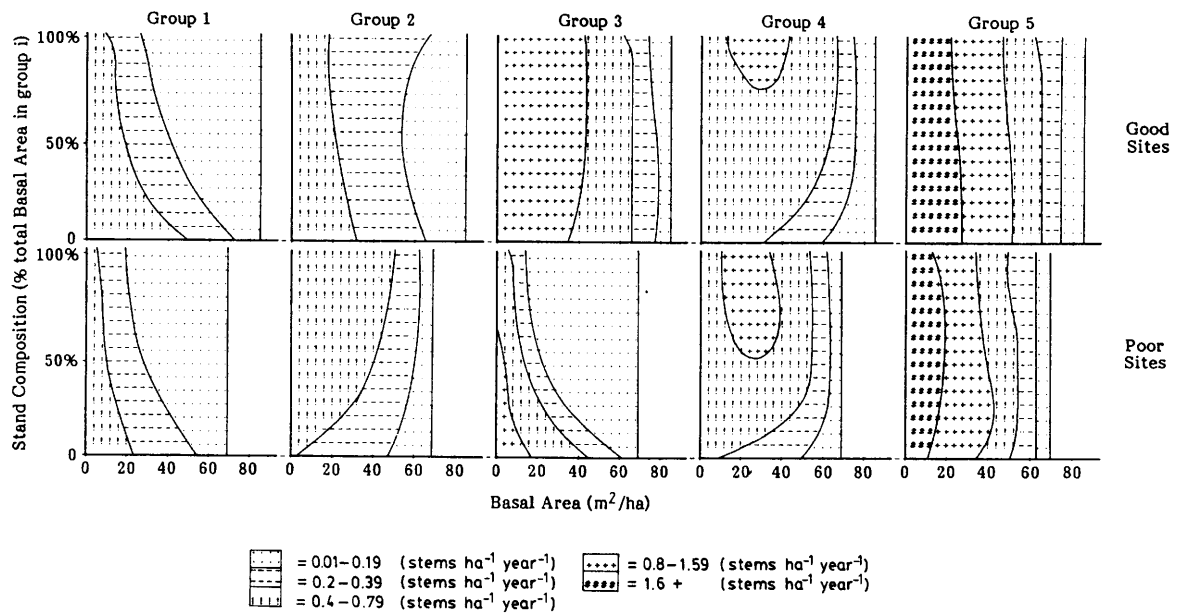
Fig. 9. Recruitment at 20-cm DBH (stems ha^{-1} year^{-1}) .

To ensure that these estimated proportions summed to exactly 1.0, the proportions were standardized:

$Pi = Pi / (P_1 + P_2 + P_3 + P_4 + P_5)$

Figure 9 illustrates how recruitment varies in response to changing stand composition and density.

Logging groups may be allocated to recruits according to the composition of the corresponding stand fraction, based on numbers of stems rather than basal area, to ensure that useless veteran trees do not exert a disproportionate effect.
Thus, for example, if it is determined that 5% of the growth-group 1 stems in the existing stand are useless (logging-group *9),* then *5%* of the predicted growth-group 1 recruits will be assigned to that category.

A similar procedure can be followed to determine the volume group. However, this is greatly simplified as volume group is usually uniquely determined by logging group and growth group.

DISCUSSION

Formal validation of the model has not yet been attempted, but inspection reveals that the model forecasts stand dynamics generally in accordance with available data and expectations, even over very long intervals.

Strengths of the model

This growth model represents a considerable advance on previous rainforest yield prediction models (Higgins, *1977;* Bragg and Henry, *1985).* Important advances include the identification of growth groups based on growth characteristics, the recognition of the influence of stand density on all aspects of stand dynamics, the explicit identification of a maximum attainable size, an attempt to quantify the site productivity (by site classification and identification of soil parent material), and the recognition that stand composition may influence the composition of recruitment. The advantage in recognising a maximum attainable diameter is that it ensures that

diameter increments cannot be overestimated for the larger trees being modelled, thus ensuring a robust model.

The model distinguishes stems actually measured during inventory from - those predicted by the model as recruitment. This serves to warn the user of diminishing precision of forecasts during long simulations. A weakness inherent in many other approaches, particularly stand-table projection approaches (e.g. Adams and Ek, *1974)* and matrix approaches (e.g. Usher, *1966)* is that predicted recruitment is not distinguished and the user is not explicitly warned of unrealistically long projections.

Weaknesses of the model

A number of weaknesses in the growth model can be identified. Five growth groups were identified largely on the basis of growth characteristics, except for the non-commercial group necessary for practical reasons. Ideally, growth groups should be formed solely on the basis of growth rate, growth pattern and regeneration strategy, as commercial criteria may be accommodated in the volume and logging groups. However, practical difficulties limit the extent to which this can be done. Existing resource inventory data contain the specific identity of all commercial and potentially commercial species, but most of the noncommercial species are simply identified as miscellaneous (MIS). In future inventories, it may be possible to identify some additional species or species groups, but it is considered impossible to reliably identify all non-commercial species during resource inventory. A viable solution may be to identify a number of groups of non-commercial species according to their growth habit.

It has long been recognised that the productive potential of any forest depends upon, among other factors, the site productivity. Soil parent material has been recognised as an important factor for some time (Anonymous, 1981; Nicholson et al., 1983; Bragg and Henry, 1985), but reflects only part of the site factors. The good/poor site classification introduced here represents a first attempt to assess site productivity. Its scope is greatly restricted by its relatively subjective nature, and by the presence of only two classes. More research is required to establish a more objective and quantitative assessment procedure.

The model assumes that the merchantability of stems does not change over time. Thus, if a stem was deemed merchantable at the time of inventory, then it is assumed to remain merchantable throughout the simulation. Although it seems reasonable that this should hold for the majority of stems, insufficient data exist to confirm or reject this assumption.

Prediction of recruitment at 20-cm diameter is less than desirable from a modelling viewpoint, but is necessary to enable forecasts using all available inventory data.

Some of the functions employed are somewhat simplistic, but these generalizations are imposed by the available data. For example, the mortality functions allow no interaction between stand basal area and tree size. Such interaction may exist, but cannot be detected in the data currently available. In order to detect any such subtle interactions, more data must be collected.

Implications of the model

The model indicates that rainforest can be managed for timber production using selection logging over long periods, without significantly altering the species

composition of the stand. This is consistent with previously published findings (Anonymous, 1983b; Caulfield, 1983).

The model also enables an objective evaluation of the tree-marking guidelines. These are used by field staff to ensure consistently high standards of forest management, and encompass several objectives including maintaining the diversity, and increasing the productivity of the forest (Anonymous, 1981b). To facilitate this analysis, we assume that the primary objective of forest management is to maximize timber volume production, that the standing basal area of the forest is held relatively constant over time, and that there is no social time preference (i.e. future volumes are not discounted). Table 8 indicates the sizes that trees should attain in order to achieve the maximum mean annual volume increment (MAI). These optimum sizes are dependent upon the diameter growth pattern and the mortality rate. Table 8 identifies two limits, the retention limit which assumes no mortality, and the cutting limit which assumes average mortality. Trees should generally be allowed to exceed the cutting limit, and should only be felled below this limit when death is imminent. Trees of outstanding vigour or of dominant status which are unlikely to die before the next logging should be retained until they reach the retention limit.

Table 8 presents strategies which maximize volume increment of individual trees, and take no account of the premium paid for large logs. A similar analysis to indicate maximum-value production would favour even larger cutting and retention limits. However, some of the assumptions made in compiling Table 8 are untenable. The standing basal area is not constant, and volume production is not the only objective of forest management; many other important considerations are also taken into account (Anonymous, 1981b). Some of the combinations of growth group, soil parent material and site quality given in Table 8-do not occur in the field. Nonetheless, the sizes indicated in Table 8 serve as a useful guide to silvicultural decisions.

TABLE 8. Diameter at which volume growth is maximized

Growth group	Soil parent material	Site class	Diameter (cm DBH or DAB) for max, volume MAI				
			Retention limit	Cutting limit (incl. mortality)			
				SBA 20 (m^2/ha)	SBA 30 (m^2/ha)	SBA 40 (m^2/ha)	SBA 60 (m^2/ha)
1	BV	Good	128	95	87	77	44
		Poor[b]	128	60	40[a]	40	40
	TG	Good	110		84	80	66
		Poor	110	76	69	58	40
	Others	Good	128	105	101	96	82
		Poor	128	93	85	73	40
2	CG, Ac	All	143	108	105	101	92
	TG	All	116	96	93	89	77
	Others	All	143	106	103	99	88
3	CG, Ac	Good	109	71	64	54	40
		Poor[b]	109	40	40	40	40
	TG	Good	108	73	69	64	48
		Poor	108	56	47	40	40
	Others	Good	109	81	77	73	59
		Poor	109	66	58	45	40
4	CG, Ac	All	101	66	60	53	40
	TG	All	101	58	49	40	40
	Others	All	101	55	47	40	40

[a]40-cm diameter is the minimum merchantable size.
[b]These combinations do not occur in the field.

CONCLUSION

This model has provided an objective basis for appraising management decisions, and for determining the sustainable yield and allowable cut of Queensland's northern rainforests.

Careful selection of component functions has ensured a robust model which provides realistic forecasts for a diverse range of forest types and inventory data. Standard analytical techniques including graphical inspection, weighted linear regression and inspection of residuals were used in developing the model.

This approach may be applicable to other mixed species forests, particularly rainforests in other tropical countries.

ACKNOWLEDGEMENTS

REFERENCES

Adams, D.M. and Ek, A.R., 1974. Optimizing the management of uneven-aged forest stands. Can. J. For. Res., 4: 274-287.

Anonymous, 1972. 1: 250 000 Geological series - Explanatory notes. Australian Government Publishing Service, Canberra, A.C.T.

Anonymous, 1979. A generalized forest growth projection system applied to the Lake States region. USDA For. Serv. Gen. Tech. Rep. NC-49,96 pp.

Anonymous, 1981a. Rainforest increment studies. Queensl. Dep. For. Res. Rep., 3: 63-64. Anonymous, 1981b. Timber production from North Queensland's rainforests. Position paper issued by the Queensland Department of Forestry, Brisbane, Qld., 28 pp.

Anonymous, 1983a. Nomenclature of Australian timbers. Australian Standard 2543-1983, Standards Association of Australia, Sydney N.S.W., 62 pp.

Anonymous, 1983b. Rainforest Research in North Queensland. Position paper issued by the Queensland Department of Forestry, Brisbane, Qld., 52 pp.

Boland, D.J., Brooker, M.I.H., Chippendale, G.M., Hall, N., Hyland, B.P.M., Johnston, R.D.,

Kleinig, D.A. and Turner, J.D., 1984. Forest Trees of Australia (4th Edition). Nelson-CSIRO, Melbourne, Vic., 687 pp.

Botkin, D.B., Janak, J.F. and Wallis, J.R., 1972. Some ecological consequences of a computer model of forest growth. J. Ecol., 60: 849-872.

Bragg, C.T. and Henry, N.B., 1985. Modelling stand development for prediction and control in tropical forest management. In: K. Shepherd and H.V. Richter (Editors), *Managing* the Tropical Forest. Papers from a workshop held at

Gympie, Qld., Australia, 11 July-12 August 1983. Development Studies Centre, Australian National University, Canberra, A.C.T., pp. 281-297.

Buchman, R.G., 1979. Mortality functions. In: A generalized forest growth projection system applied to the Lake States region. USDA For. Serv. Gen. Tech. Rep. NC-49, pp. 47-44.

Buchman, R.G., Pederson, S.P. and Walters, N.R., 1983. A tree survival model with application to species of the Great Lakes region. Can. J. For. Res., 13: 601-608.

Canonizado, J.A., 1978. Simulation of selective forest management regimes. Malay. For., 41: 128142.

Caulfield, C., 1983. Rainforests can cope with careful logging. New Sci., 99 (1373): 631.

Clutter, J.L., Fortson, J.C., Pienaar, L.V., Brister, G.H. and Bailey, R.L., 1983. Timber Management: A Quantitative Approach. Wiley, New York, 333 pp.

Ek, A.R. and Monserud, R.A.,.1979. Performance and comparison of stand growth models based on individual tree and diameter class growth. Can. J. For. Res., 9: 231-244.

Francis, W.D. and Chippendale, G.M., 1981. Australian Rain-Forest Trees (4th Edition). Australian Government Publishing Service, Canberra, 468 pp.

Hamilton, D.A., 1974. Event probabilities estimated by regression. USDA For. Serv. Res. Pap. INT-152,18 pp.

Hamilton, D.A., 1980. Modelling mortality: a component of growth and yield modelling. In: K.M. Brown and F.R. Clarke (Editors), Forecasting Forest Stand Dynamics. Proc. Workshop, 2425 June 1980, School of Forestry, Lakehead University, Thunder Bay, Ont., pp. 82-99.

Hamilton, D.A. and Edwards, B.M., 1976. Modelling the probability of individual tree mortality. USDA For. Serv. Res. Pap. INT-185, 22 pp.

Hann, D.W., 1980. Development and evaluation of an even- and uneven-aged ponderosa pine/Arizona fescue stand simulator. USDA For. Serv. Res. Pap. INT-267, 95 pp.

Havel, J.J., 1980. Application of fundamental synecological knowledge to practical problems in forest management. II. Application. For. Ecol. Manage., 3: 1-29.

Higgins, M.D, 1977. A sustained yield study of North Queensland rainforests. Queensland Department of Forestry, Brisbane, Qld., 182 pp. (unpublished).

Husch, B., Miller, C.I. and Beers, T.W., 1982. Forest Mensuration (3rd Edition). Wiley, New York, 402 pp.

Hyland, B.P.M., 1982. A revised card key to the rainforest trees of north Queensland. CSIRO, Melbourne, Vic.

Leary, R.A., 1980. A design for survivor growth models. In: K.M. Brown and F.R. Clarke (Eds), Forecasting Forest Stand Dynamics. Proc. Workshop, 24-25 June 1980, School of Forestry, Lakehead University, Thunder Bay, Ont., pp. 62-81.

Mitchell, K.J., 1969. Simulation of the growth of even-aged stands of white spruce. Yale Univ. Sch. For. Bull. 75, 48 pp.

Newnham, R.M., 1964. The development of a stand model for Douglas fir. Ph.D. thesis, University of British Columbia, Vancouver, B.C., 201 pp.

Nicholson, D.I., Henry, N.B., Rudder, E.J. and Anderson, T.M., 1983. Research basis of rainforest management in North Queensland. Paper presented at XV Pacific Science Congress, Dunedin, New Zealand, 1-11 February 1983, 23 pp.

Preston, R.A. and Vanclay, J.K., 1988. Calculation of timber yields from north Queensland rainforests. Queensl. Dep. For. Tech. Pap. 47, 19 pp.   -

Reed, K.L., 1980. An ecological approach to modelling the growth of forest trees. For. Sci., 26: 3350.

Reineke, L.H., 1933. Perfecting a stand density index for even-aged stands. J. Agric. Res., 46:627638.

Shugart, H.H., 1984. A Theory of Forest Dynamics: The Ecological Implications of Forest Succession Models. Springer, New York, 278 pp.

Shugart, H.H., Mortlock, A.T., Hopkins, M.S. and Burgess, LP., 1980. A computer simulation model of ecological succession in Australian subtropical rainforest. ORNL 1407, Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN.

Usher, M.B., 1966. A matrix approach to the management of renewable resources, with special reference to selection forests. J. Appl. Ecol., 3: 355-367.

Vanclay, J.K., 1983. Techniques for modelling timber yield from indigenous forests with special reference to Queensland. M.Sc. Thesis, Univ. of Oxford, 194 pp.

Vanclay, J.K., 1988. A stand growth model for cypress pine. In: J.W. Leech, R.E. McMurtrie, P.W. West, R.D. Spencer and B.M. Spencer (Editors), Modelling Trees, Stands and Forests, Proc. Workshop, August 1985, Univ. of Melbourne. Univ. Melbourne Sch. For. Bull. 5, pp. 310-332.

Webb, L.J. and Tracey, J.G., 1967. An ecological guide to new planting areas and site potential for hoop pine. Aust. For., 31: 224-240.

Webb, L.J., Tracey, J.G., Williams, W.T. and Lance, G.N., 1971. Prediction of agricultural potential from intact forest vegetation. J. Appl. Ecol., 8: 99-121.

Yoda, K., Kira, T., Ogawa, H. and Hozumi, K., 1963. Self thinning in overcrowded pure stands under cultivated and natural conditions. J. Biol. Osaka City Univ., 14: 107-129.