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# The Recovery of Rainforest Overstorey Following Logging. I. Subtropical Rainforest

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*Abstract*

The recovery time of the overstorey trees in a subtropical rainforest in northern New South Wales has been found to increase with intensity of logging. In the case of a full utilization logging (removal of 70-80% of the basal area of the overstorey), recovery as predicted by a growth model may take longer than 200 years. However, with more selective logging (such as the 50% canopy retention method which in this study resulted in the removal of 33% of the basal area of the overstorey), the recovery time for the overstorey will be approximately 30 to 60 years. The model predicts that the major overstorey species will remain present at recovery but that there will be some changes in the relative frequencies at the time of initial recovery. Following logging, there was a significant overall increase in the tree diameter growth rate of the remaining trees, although the growth rate of an individual tree appears to bear little or no relationship to the diameter of the tree. Measurements of the basal area per hectare of the unlogged overstorey indicated that over the longer term, the net growth of the undisturbed overstorey approached zero, the growth of individual trees being balanced by mortality.

[O.D.C. 213 : 182.3 : 182.41 : 31 : (944)]

## Introduction

'The name rainforest is commonly given, not only to the evergreen forest of moist tropical lowlands .... but also to the somewhat less luxurient evergreen forests of oceanic subtropical climates in south-western China, southern Chile, South Africa, New Zealand and eastern extra tropical Australia' Richards (1952). The rainforest type which is characteristic of most of northern New South Wales has been classified as subtropical rainforest (Baur 1965) or, alternatively as complex notophyll vine forest (Webb 1978), and is regarded as the most complex forest type of the area (Hopkins *et al.* 1977).

In New South Wales, timber from this type of forest was not intensively utilized until the onset of the 1939-1945 War. The emergency created by Australia's isolation from overseas supplies of specialty timbers and the development of techniques which allowed many previously unusable species to be utilized, had the effect of markedly increasing the economic value to the nation of such forests. The problems of the post-war years necessitated the continued utilization of local timber and small but important decentralized industry based on this raw material resource was established. Accordingly, investigations concerned with the silvicultural implications of this circumstance were commenced. A number of experimental plots were established in typical subtropical rainforest in New South Wales to determine the qualitative and quantitative aspects of the recovery of stands which had undergone various logging intensities.

**Best Available Document**

One particular group of plots have been recovering long enough to yield meaningful data and this paper reports the observations made on these plots. In this paper we present a model that describes the overstorey recovery growth which enables predictions to be made regarding the time required for the forest overstorey to recover to the prelogged state after being subjected to various intensities of logging disturbance.

## Methods

In 1965 an experiment was established in an area of subtropical rainforest located in the Wiangaree State Forest in northern New South Wales to determine the regrowth of the forest following various regimes of logging intensity. Some aspects of the results from this experiment have been previously discussed by Burgess *et al.* (1975) and Shugart *et al.* (1980). Here, the data have been analysed to determine the relative growth rates of logged and unlogged stands, individual species and individual trees.

The Wiangaree State Forest covers approximately 14 000 ha adjacent to the Queensland border on the McPherson and Tweed ranges. It consists mainly of subtropical rainforest extending over an altitudinal range of 600-1200 m. Annual rainfall is *c.* 3000 mm, while the soils are kraznozems derived mostly from tertiary basalt flows. The experimental plots are located approximately 153°03′E. 28°23′S. on the Air Drop road at the head of Sheepstation Creek, at an altitude of *c.* 750 m.

Eleven plots which varied in size from 1.4 to 3.9 ha were established in 1965 in this area of relatively homogeneous forest. Three of the plots were left as unlogged controls. Five plots were logged in 1966 under differing logging regimes, the intensity of which varied from the so-called 50% canopy retention logging (which attempts to retain about half the rainforest canopy), to the logging of all trees considered merchantable at the time. The five treatments carried out in 1966 are listed in increasing order of logging intensity:

*Treatment 7.* Merchantable stems, totalling 33% of the basal area of the overstorey, were logged while retaining a nominal 50% canopy.

*Treatment 8.* As for treatment 7, but more merchantable stems, totalling 45% of the basal area of the overstorey, were logged (about 50% of the standing basal area).

*Treatment 4.* All merchantable stems greater than 61 cm in diameter (at breast height over bark), totalling 47% of the basal area of the overstorey, were logged except some seed trees; all damaged and surplus small trees were felled.

*Treatment 1.* All merchantable stems, totalling 70% of the basal area of the overstorey, were logged, and all useless stems were poisoned.

*Treatment 6.* All merchantable stems, totalling 78% of the basal area of the overstorey, were logged; useless understorey stems were removed.

The three remaining plots were scheduled for later loggings and have not been considered in this study.

At the centre of each of these plots, was located a sub-plot of 0.36 ha (60.4 m square) in which the diameters of all trees with diameter greater than 10 cm at breat height were measured. Eligible trees were identified and numbered with metal tags. Their diameters were measured in 1966, 1970, 1973, 1975 and 1980 while additional trees were measured, identified and tagged when they attained a diameter of 10 cm.

Profile diagrams from within the 0.36 ha sub-plots were also prepared in 1966 to show all trees over 6 m in height on a transect 61.1 m long and 7.6 m wide. An example of one such profile for treatment 7 (33% of basal area of the overstorey logged) is shown in Fig. 1. Trees removed or destroyed during logging have been hatched in the diagram thus indicating the height and structure of the stand and the visual effect of the logging.

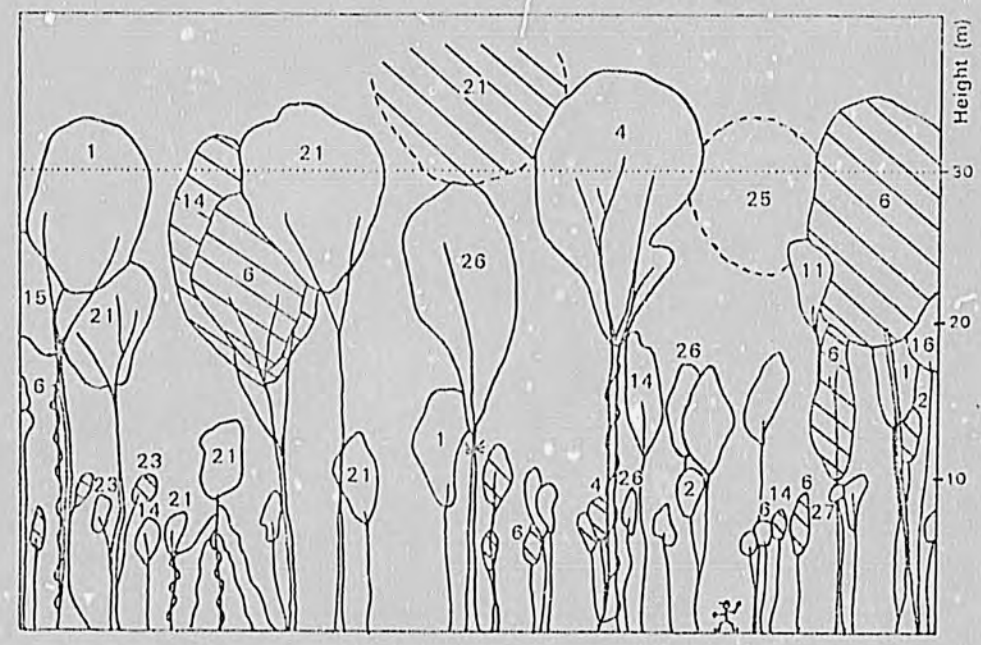


Fig. 1. Stand profile for treatment 7 (33% of the basal area of the overstorey logged). Numbers refer to the tree species as shown in Table 2.

The method used to determine the recovery time is that of developing a growth model for the overstorey advanced growth segment of the forest following logging. The method employed here is to 'grow on' this segment of the stand until the overstorey is reconstituted to pre-logging proportions.

*The Growth Model*

A growth model was developed to predict the growth of the residual potential overstorey segment of the rainforest, following logging, based on the following assumptions:

1. The overstorey is composed of trees greater than 30 m in height (see Fig. 1).
2. In the undisturbed state, the net basal area increment of the overstorey is zero when considered over an extended period of time, due to the balance of growth and mortality (see Table 5). This limit to growth is referred to as the 'equilibrium overstorey basal area'.

3. In a rainforest disturbed by logging, residual overstorey advanced growth trees respond to release from competition and hence have the potential to reconstitute the overstorey (see Table 4).

4. Overstorey recovery from logging takes place when the basal area of the reconstituted overstorey grows back to the equilibrium basal area of the undisturbed forest (see Fig. 2).

5. The net basal area growth rate of the recovering overstorey declines with time due to the increasing effects of competition and mortality. Ultimately, at recovery, the growth rate reaches zero (see Fig. 2). The decline in basal area growth rate has been taken to be logarithmic in form.

6. All overstorey and potential overstorey trees have an equal chance of mortality during the recovery period.

*Operation of the Model*

The operation of the growth model has been illustrated diagrammatically in Fig. 2.

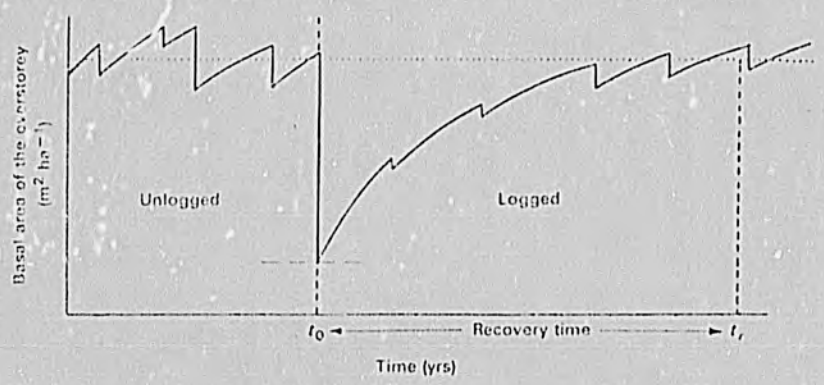


Fig. 2. The operation of the growth model showing the overstorey equilibrium basal area (. . . . . .) of the undisturbed stand, the recovery growth path following logging, and the time $t_r$ taken to reconstitute the overstorey to the undisturbed level.

Recovery growth at $t_0$ is due to the growth of the residual overstorey trees remaining after logging, together with the overstorey advanced growth trees that will grow into the overstorey as time passes. Gradual increase in competition and mortality will cause the increasing basal area to limit at the equilibrium overstorey basal area level. The time taken for this to be achieved is the recovery time $t_r$ which is determined by iterative computer process of 'growing' the stands for one year at a time until the basal area of trees in excess of 30 m in height has reached the equilibrium overstorey basal area. The recovery time, following any logging intensity, may thus be calculated using the following relationship:

$$Ba_{UL} = \sum_{1}^{n} \left\{ Ba_{t1} + \left( \frac{Ba_{t2} - Ba_{t1}}{t_2 - t_1} \times t_r \times F \right) \right\} ,$$

where $Ba_{UL}$ is the equilibrium basal area of the undisturbed rainforest overstorey; $n$ is the number of individual trees, capable of reaching overstorey dimension, necessary to

reconstitute the equilibrium basal area; $Ba_{t_1}$ is the basal area of an individual tree capable of overstorey dimension at measurement 1; $Ba_{t_2}$ is the basal area of an individual tree capable of overstorey dimension at measurement 2; $(t_2 - t_1)$ is the time interval in years between the two measurements; $F$ is the average growth measurement decline factor which accounts for competition and mortality where the pattern is such that the growth rate of the reconstituted overstorey, as measured following logging, declines to zero at recovery – this factor would be the average value of the first derivative of the basal area growth recovery curve (see Fig. 2); and $t_r$ is the recovery time for the overstorey.

*Growth Results*

The stand profiles of the combined treatment plots prior to logging showed that 16.7% of all trees were more than 30 m in height. Applying this percentage to the upper end of the diameter distribution of the trees in the unlogged plots, gave a minimum diameter at breast height over bark of 46 cm. Assuming that the height/diameter relationship in this forest is similar to that described by Tatuo Kira (1978) for South East Asian rainforests and Bernhardt-Reversat *et al.* (1978) for rainforests of the Ivory Coast, and in the absence of later height data, a tree is considered to be part of the tall forest canopy (height greater than 30 m) when its diameter reaches 46 cm.

Below the overstorey canopy trees, are found a variety of other trees containing many species which are incapable of sufficient height growth to become part of the overstorey, mixed together with immature individuals of species which are capable of growing into the overstorey. These latter individuals can recruit into the overstorey, given time and opportunity, and are defined here as 'overstorey advanced growth'. Hopkins *et al.* (1977) stated that for large gaps in the rainforest (up to 900 $m^2$), the lateral expansion of existing tree crowns cannot fill these gaps and they are invariably plugged by trees from lower strata. For the overstorey recovery model, the tree species which have been recruited from the overstorey advanced growth are those described by Floyd (1977–1981) as being capable of growing to 30 m in height and 46 cm in diameter.

The range of overstorey tree species contained by the undisturbed rainforest have been taken as being represented by the three control plots (Table 1). This is the standard to which the logged plots have been compared when 'grown on' in the growth model. This is necessary as the available data for the logged plots prior to logging are incomplete.

These three control plots differ, however, both in species composition and basal area per hectare, showing the variable nature of the forest. In general, the unlogged overstorey is dominated by the following species: corkwood, red carabeen, white booyong, yellow carabeen, black apple and prickly ash. From these plots it can be seen that the average condition for overstorey 'recovery' for this forest area is 95 trees $ha^{-1}$ of overstorey dimensions, with a total basal area averaging about 33 $m^2 ha^{-1}$. The projected species distribution of the treatments at recovery should be similar to the control plot averages shown in Table 1. When comparing Table 1 and Table 2 it should not be overlooked that there are some species absent from the overstorey in the unlogged plots which are nevertheless present in the lower strata as stems with diameter less than 46 cm and which are capable of recruitment into the overstorey. Golden sassafras, flame tree, maidens blush, pepperberry, purple cherry, red ash and red cedar are examples of

Table 1. Mean percentage of rainforest overstorey tree species in three unlogged control plots
These overstorey species are capable of height growth greater than 30 m and diameter growth in excess of 46 cm over bark.

| Common name | Botanical name | Number (% of total) | | | | Basal area (% of total) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | C1[A] | C2 | C3 | Mean | C1 | C2 | C3 | Mean |
| Black apple | *Planchonella australis* (R.Br.) Pierre | 0 | 14 | 0 | 5 | 0 | 11 | 0 | 4 |
| Black booyong | *Heritiera actinophylla* (F.M.Bail) Kostern. | 0 | 0 | 3 | 1 | 0 | 0 | 3 | 1 |
| Black myrtle | *Diospyros pentamera* (Woods & F. Muell.) | 3 | 3 | 0 | 2 | 3 | 2 | 0 | 2 |
| Bolly gum | *Neolitsea reticulata* (Meisn.) F. Muell. | 0 | 3 | 0 | 1 | 0 | 7 | 0 | 2 |
| Celery wood | *Polyscias elegans* (C. Moore & F. Muell.) Hanns | 0 | 4 | 0 | 1 | 0 | 6 | 0 | 2 |
| Corkwood | *Caldcluvia paniculosa* (F. Muell.) Hoogl. | 38 | 26 | 28 | 31 | 38 | 20 | 17 | 25 |
| Domatia tree | *Endiandra discolor* Benth. | 5 | 0 | 0 | 2 | 6 | 0 | 0 | 2 |
| Doughwood | *Euodia micrococca* F. Muell. | 0 | 0 | 4 | 1 | 0 | 0 | 5 | 1 |
| Flame tree | *Brachychiton acerifolium* F. Muell. | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Fig | *Ficus watkinsiana* F. M. Bail. | 0 | 0 | 8 | 2 | 0 | 0 | 17 | 6 |
| Golden sassafras | *Doryphora sassafras* Endl. | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Jackwood | *Cryptocaria glaucescens* R. Br. | 0 | 0 | 3 | 1 | 0 | 0 | 5 | 2 |
| Maidens blush | *Sloanea australis* F. Muell. | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Olivers sassafras | *Cinnomomum oliveri* F. M. Bail. | 0 | 0 | 8 | 2 | 0 | 0 | 6 | 2 |
| Pepperberry | *Cryptocaria obovata* R. Br. | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Pigeonberry ash | *Cryptocaria erythroxylon* Maiden et Betcha | 5 | 0 | 0 | 2 | 5 | 0 | 0 | 2 |
| Prickly ash | *Orites excelsa* R. Br. | 3 | 11 | 6 | 7 | 3 | 8 | 4 | 5 |
| Purple cherry | *Syzigium crebrinerve* (C.T. White) L. Johnson | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Red ash | *Alphitonia excelsa* (Fengl.) Benth. | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Red cedar | *Toona australis* (F. Muell.) Harms | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Red carabeen | *Geissois benthami* F. Muell. | 17 | 5 | 27 | 16 | 16 | 12 | 32 | 20 |
| Rosewood | *Dysoxylum fraseranum* Benth. | 0 | 8 | 0 | 2 | 0 | 6 | 0 | 2 |
| Saffron heart | *Halfordia kendack* Guill. | 0 | 0 | 4 | 1 | 0 | 0 | 2 | * |
| Scentless rosewood | *Synoum glandulosa* (Sm.) A. Juss. | 0 | 0 | 3 | 1 | 0 | 0 | 1 | * |
| Socket wood | *Daphnandra micrantha* (Tul.) Benth. | 0 | 3 | 0 | 1 | 0 | 2 | 0 | 1 |
| White booyong | *Heritiera trifoliata* (F. Muell.) Kosterm | 5 | 23 | 6 | 13 | 5 | 26 | 8 | 13 |
| Yellow carabeen | *Sloanea woolsii* F. Muell. | 24 | 0 | 0 | 8 | 24 | 0 | 0 | 8 |
| Total stems $ha^{-1}$ or $m^2 ha^{-1}$ | | 104 | 106 | 74 | 95 | 38.7 | 33.7 | 26.0 | 32.8 |

[A] Control plots C1, C2 and C3 as in Fig. 5.
* Present but below 0.5%.

overstorey trees in this category. These species, although absent from the control plot overstorey, all occur in the projected reconstituted overstorey of the logged plots shown in Table 2.

**Table 2.** The number and basal area of overstorey species forecast by the growth model to make up the reconstituted overstorey of 33 $m^2 ha^{-1}$ basal area at the time of recovery

| Overstorey species | Number (% of total) | | | | | | Basal area (% of total) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Treatment: | [A] 7 | 8 | 4 | 1 | 6 | Mean | 7 | 8 | 4 | 1 | 6 | Mean |
| 1. Black apple | 1 | 0 | 3 | 1 | * | 1 | * | 0 | 6 | 1 | * | 1 |
| 2. Black booyong | 8 | 3 | 6 | 4 | 10 | 6 | 14 | 3 | 6 | 3 | 20 | 9 |
| 3. Black myrtle | 0 | * | * | 0 | 3 | 1 | 0 | * | * | 0 | 2 | * |
| 4. Bolly gum | 3 | 0 | 0 | 0 | 0 | * | 3 | 0 | 0 | 0 | 0 | * |
| 5. Celery wood | 0 | 0 | 0 | 0 | 3 | * | 0 | 0 | 0 | 0 | 2 | * |
| 6. Corkwood | 21 | 15 | 23 | 11 | 19 | 18 | 15 | 12 | 26 | 10 | 14 | 16 |
| 7. Domatia tree | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8. Doughwood | 8 | 0 | 0 | 0 | 0 | 2 | 8 | 0 | 0 | 0 | 0 | 2 |
| 9. Hare's tree | 0 | 3 | 0 | 3 | 0 | 1 | 0 | 3 | 0 | 6 | 0 | 2 |
| 10. Figs | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 11. Golden sassafras | 2 | 10 | 5 | 13 | 19 | 10 | 2 | 9 | 4 | 10 | 14 | 10 |
| 12. Jackwood | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 13. Maidens blush | 0 | 3 | 0 | 5 | 0 | 2 | 0 | 2 | 0 | 4 | 0 | 1 |
| 14. Olivers sassafras | 4 | 6 | 8 | 18 | 14 | 10 | 3 | 7 | 7 | 20 | 15 | 10 |
| 15. Pepperberry | 2 | * | 1 | 0 | 0 | 1 | 2 | * | * | 0 | 2 | 1 |
| 16. Pigeonberry ash | 2 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | * |
| 17. Prickly ash | 3 | 10 | 1 | 1 | 6 | 4 | 3 | 9 | 1 | 1 | 3 | 4 |
| 18. Purple cherry | 2 | 5 | 15 | 0 | 1 | 5 | 1 | 5 | 14 | 0 | 1 | 4 |
| 19. Red ash | 2 | 0 | 0 | 0 | 0 | * | 2 | 0 | 0 | 0 | 0 | * |
| 20. Red cedar | 0 | 0 | 3 | 0 | 0 | 1 | 0 | 0 | 5 | 0 | 0 | 1 |
| 21. Red carabeen | 12 | 12 | 20 | 3 | 11 | 12 | 11 | 15 | 19 | 2 | 10 | 11 |
| 22. Rosewood | 2 | * | 4 | 0 | 1 | 1 | 2 | * | 4 | 0 | * | 1 |
| 23. Saffron heart | 0 | 0 | 0 | 7 | 0 | 1 | 0 | 0 | 0 | 5 | 0 | 1 |
| 24. Scentless rosewood | 0 | 3 | 0 | 2 | 0 | 1 | 0 | 2 | 0 | 1 | 0 | 1 |
| 25. Socketwood | 2 | 0 | 3 | 1 | 0 | 1 | 1 | 0 | 2 | * | 0 | 1 |
| 26. White booyong | 21 | 9 | 7 | 0 | 8 | 9 | 28 | 3 | 6 | 0 | 7 | 10 |
| 27. Yellow carabeen | 5 | 21 | * | 31 | 5 | 12 | 4 | 24 | * | 37 | 9 | 15 |
| Total stems $ha^{-1}$ | 98 | 109 | 99 | 80 | 94 | 96 | | | | | | |

[A] Treatments are listed in order of increasing logging intensity as described in 'Methods' section.
* Present but below 0.5%.

The average rates of diameter growth between 1966 and 1980, grouped into size classes, for all trees greater than 10 cm in diameter for the nine major overstorey species in logged and unlogged plots are given in Table 3. The tree diameter increment has been calculated using the formula:

$$Di = \frac{1}{n} \sum_{1}^{n} \left\{ (D_2 - D_1) / 14 \right\},$$

where $Di$ is the diameter increment; $D_1$ and $D_2$ are the diameters at breast height over bark in 1966 and 1980 respectively; and $n$ is the number of trees. A summary of the

Table 3. Diameter increment (cm $yr^{-1}$) in diameter classes, for the period 1966–1980, of major overstorey species in the logged and unlogged plots

| Species | Diam. class[A] | Unlogged | | | Logged | | |
|---|---|---|---|---|---|---|---|
| | | Mean diam. (cm) | No. of trees[B] | Diam. incr.[C] (cm $yr^{-1}$) | Mean diam. (cm) | No. of trees[B] | Diam. incr.[C] (cm $yr^{-1}$) |
| Corkwood | | 34.5 | *106* | *0.16* | 34.3 | *68* | *0.24* |
| | A | | 33 | 0.10 | | 12 | 0.24 |
| | B | | 21 | 0.20 | | 22 | 0.36 |
| | C | | 21 | 0.21 | | 17 | 0.19 |
| | D | | 19 | 0.21 | | 10 | 0.20 |
| | E | | 12 | 0.07 | | 7 | 0.06 |
| Golden Sassafras | | 19.9 | *54* | *0.08* | 28.0 | *48* | *0.31* |
| | A | | 32 | 0.07 | | 13 | 0.23 |
| | B | | 18 | 0.08 | | 15 | 0.38 |
| | C | | 4 | 0.18 | | 15 | 0.32 |
| | D | | 0 | – | | 5 | 0.25 |
| | E | | 0 | – | | 0 | – |
| White booyong | | 41.3 | *33* | *0.15* | 37.8 | *28* | *0.36* |
| | A | | 8 | 0.07 | | 4 | 0.44 |
| | B | | 7 | 0.20 | | 10 | 0.54 |
| | C | | 5 | 0.14 | | 8 | 0.42 |
| | D | | 5 | 0.13 | | 4 | 0.01 |
| | E | | 0 | – | | 0 | – |
| Red carabeen | | 47.4 | *33* | *0.21* | 36.9 | *42* | *0.26* |
| | A | | 7 | 0.09 | | 7 | 0.24 |
| | B | | 3 | 0.22 | | 13 | 0.29 |
| | C | | 8 | 0.22 | | 10 | 0.27 |
| | D | | 2 | 0.57 | | 6 | 0.24 |
| | E | | 13 | 0.20 | | 6 | 0.20 |
| Prickly ash | | 33.6 | *25* | *0.22* | 31.8 | *13* | *0.44* |
| | A | | 7 | 0.08 | | 2 | 0.33 |
| | B | | 7 | 0.35 | | 5 | 0.51 |
| | C | | 5 | 0.21 | | 4 | 0.38 |
| | D | | 3 | 0.28 | | 2 | 0.49 |
| | E | | 3 | 0.22 | | 0 | – |
| Black apple | | 37.0 | *15* | *0.06* | 26.4 | *13* | *0.16* |
| | A | | 3 | 0.02 | | 3 | 0.10 |
| | B | | 4 | 0.03 | | 7 | 0.15 |
| | C | | 3 | –0.02 | | 2 | 0.12 |
| | D | | 2 | 0.04 | | 0 | – |
| | E | | 3 | 0.24 | | 1 | 0.41 |
| Yellow carabeen | | 45.7 | *14* | *0.14* | 44.1 | *28* | *0.28* |
| | A | | 3 | 0.10 | | 2 | 0.24 |
| | B | | 2 | 0.08 | | 4 | 0.41 |
| | C | | 1 | 0.22 | | 13 | 0.36 |
| | D | | 3 | 0.03 | | 4 | 0.14 |
| | E | | 5 | 0.23 | | 5 | 0.11 |
| Olivers sassafras | | 31.1 | *12* | *0.30* | 29.9 | *37* | *0.53* |
| | A | | 2 | 0.19 | | 7 | 0.42 |
| | B | | 5 | 0.37 | | 14 | 0.51 |
| | C | | 3 | 0.27 | | 11 | 0.60 |
| | D | | 1 | 0.36 | | 5 | 0.62 |
| | E | | 1 | 0.15 | | 0 | – |
| Black booyong | | 25.9 | *5* | *0.11* | 54.1 | *16* | *0.15* |
| | A | | 4 | 0.09 | | 3 | 0.15 |
| | B | | 0 | – | | 1 | 0.15 |
| | C | | 0 | – | | 4 | 0.25 |
| | D | | 0 | – | | 2 | 0.35 |
| | E | | 1 | 0.20 | | 6 | 0.02 |

[A] Diameter classes: A, 9.5–20.4 cm; B, 20.5–30.5 cm; C, 30.5–46.4 cm; D, 46.5–60.4 cm; E, 60.5 cm and over.

[B] Total number of trees for each species given in italics.

[C] The weighted mean diameter increment for each species is given in italics.

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mean diameter increment for the various size classes for these species is given in Table 4.

Table 4. Mean diameter growth (cm $yr^{-1}$) of the major overstorey species, for the period 1966–1980, in logged and unlogged forest

| Diameter class | Diameter increment (cm $yr^{-1}$) 1966–1980 | |
|---|---|---|
| | Unlogged | Logged |
| A (9.5–20.4 cm) | 0.08 | 0.27 |
| B (20.5–30.4 cm) | 0.18 | 0.39 |
| C (30.4–46.4 cm) | 0.18 | 0.33 |
| D (46.4–60.4 cm) | 0.20 | 0.27 |
| E (60.5+ cm) | 0.17 | 0.10 |
| Weighted mean diameter increment* | 0.15 | 0.31 |
| Standard deviation | 0.15 | 0.26 |

* Significantly different at the 99% confidence level.

These tables show that there was an increase in the diameter growth rate of the trees following logging, irrespective of the size of the tree. Some species in the unlogged forest grew faster than others and some species showed greater growth response than others following logging. Olivers sassafras was the fastest growing species in both the logged and unlogged plots, and together with golden sassafras and prickly ash showed the greatest diameter growth increase following logging.

The considerable variation that was observed in the growth rates of individual trees within both the logged and unlogged plots, and the wide scattering of points obtained by plotting diameter increment against diameter, are similar to the observations of Tatuo Kira (1978) and are reflected in the large standard deviation values (Table 4). The variation was sufficiently great to suggest that the growth rate of an individual tree bears little relationship to the diameter of the tree.

Examination of the data from the unlogged plots (Table 3) shows that individual trees within the overstorey continue to grow with time, indicating that for a given number of trees, the basal area per hectare of the undisturbed overstorey will continue to increase accordingly. However, Table 5 shows that for all overstorey trees the mean basal area per hectare of the overstorey of the unlogged plots has oscillated about a mean of approximately 33 $m^2 ha^{-1}$ (average of 5 measurements). This means that over the longer

Table 5. Basal area ($m^2 ha^{-1}$) of the rainforest overstorey for each of five measurement years in the three unlogged control plots

| Year | Basal area ($m^2 ha^{-1}$) | | | |
|---|---|---|---|---|
| | Plot 1 | Plot 2 | Plot 3 | Mean |
| 1966 | 40.4 | 31.9 | 21.4 | 31.2 |
| 1970 | 39.7 | 34.2 | 26.8 | 33.5 |
| 1973 | 37.7 | 34.1 | 26.4 | 32.7 |
| 1975 | 38.7 | 34.5 | 27.4 | 33.5 |
| 1980 | 36.7 | 33.7 | 28.2 | 32.9 |
| Mean | | | | 32.8 |

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term, the growth of the undisturbed canopy of the rainforest has tended to be balanced by mortality, and the overstorey basal area per hectare has oscillated around a mean value which is presumably related to the site and forest type. These data indicate that the average net growth of the overstorey over time will be zero and support the validity of assumption 2 of our growth model.

However, it can be seen from Table 5 that throughout the 14-year period, one unlogged plot had a lower basal area than the other control plots and did not oscillate but increased steadily. This difference is almost certainly due to a recent natural disturbance of some kind from which the plot is recovering. The inclusion of data from this plot has lowered what has been taken as the equilibrium value for this forest, but since natural disturbance is a normal forest occurrence and not all of the forest would be oscillating around its equilibrium value at a given time, this is considered acceptable. Table 4 shows that in accord with assumption 3 of the growth model, there was a general increased response in diameter growth in the potential overstorey trees of the logged plots. The average annual growth in diameter of trees in the logged plots being 0.31 cm compared to 0.15 cm for trees in the unlogged control plots.

*Modelling Results*

To include all the variation of growth measurements available from the data, all combinations (totalling 10 for each tree) of the 5 measurements taken over the 14 years (1966, 1970, 1973, 1975 and 1980) were used to determine the periodic annual increments for each individual tree (i.e. using measurements 1 and 2, 1 and 3 and so on to measurements 4 and 5). The periodic annual increment, *Pai*, is given by:

$$Pai = (Ba_{t_2} - Ba_{t_1}) / (t_2 - t_1),$$

where $Ba_{t_2}$ and $Ba_{t_1}$ are the basal areas of the tree at time $t_2$ and $t_1$ respectively; and $(t_2 - t_1)$ is the time in years between the two measurements. In this way, growth aberrations arising from seasonal variation, falling bark and errors in measurements have been minimized. Figure 3 illustrates the extent to which the overstorey of each logged plot (averaged over the measurement period) is required to grow to reach the growth equilibrium line which is the average of the three unlogged control plots.

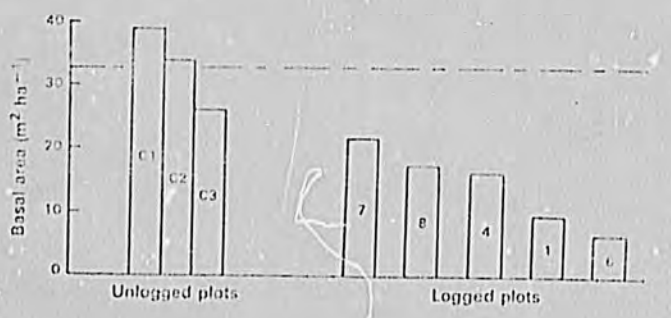


Fig. 3. The residual overstorey basal area of the experimental logged plots in relation to the mean basal area of the unlogged control plots (broken line).

The recovery time was estimated using the initial growth rate (the growth rate of the measurement period), the final growth rate (zero at growth equilibrium) and the form of the decline in growth rate as the rainforest overstorey proceeds to fulfil the recovery criteria previously discussed. Since only the total time for recovery is sought, the average growth rate decline over the total time (factor *F*) has been used in the model in place of the continually changing, declining growth rate.

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In this growth model we assume that the basal area growth rate of the developing overstorey follows the form of the function $y = \log(10 - x)$ where $y$ is the basal area increment and $x$ is the time since logging. This function was chosen as it described the accelerating decline that increasing competition and mortality could be expected to impose on the reconstituting overstorey as time passes. The net growth rate reaches a limit at zero when the equilibrium basal area is attained. This function varies between the values 1 and 0 with an approximate average value of 0.65. This implies that the average overstorey stand growth rate over the whole recovery period is 0.65 of the growth rate that was measured immediately following logging. By applying this factor to the growth rate of individual trees, mortality and increased competition during the recovery period can be taken into account in a general rather than a specific way. This method is considered to be preferable to the alternative of assigning an arbitrary value for the mortality rate and making an arbitrary choice as to which trees will die. As tree mortality is a sporadic occurrence, the 14-year measurement period is considered to be too short to allow an adequate survey of this phenomenon.

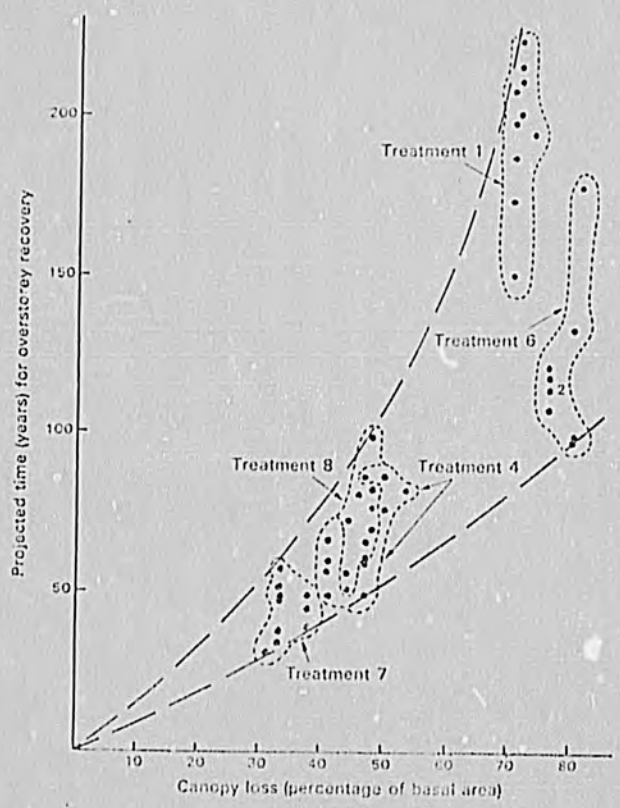


Fig. 4. Relationship between the projected time required to regrow canopy to pre-logging levels of basal area per hectare, and the percentage of the canopy basal area removed. Ten estimates of recovery for each treatment have been plotted. These represent all the possible combinations of growth increments from five measurements.

With the use of a computer program, it is possible to simulate the growth of each tree one year at a time at 65% of its initial growth rate. When the total basal area per hectare of trees greater than 46 cm in diameter reaches 33 $m^2 ha^{-1}$, an estimate of the recovery time for the reconstitution of the overstorey can be obtained. All ten recovery times for each of the treatments have been plotted in Fig. 4. The range of the estimated recovery times was as follows: treatment 1, 150 to 224 years; treatment 6, 98 to 178 years; treatment 4, 49 to 87 years; treatment 8, 51 to 99 years; and treatment 1, 31 to 58 years.

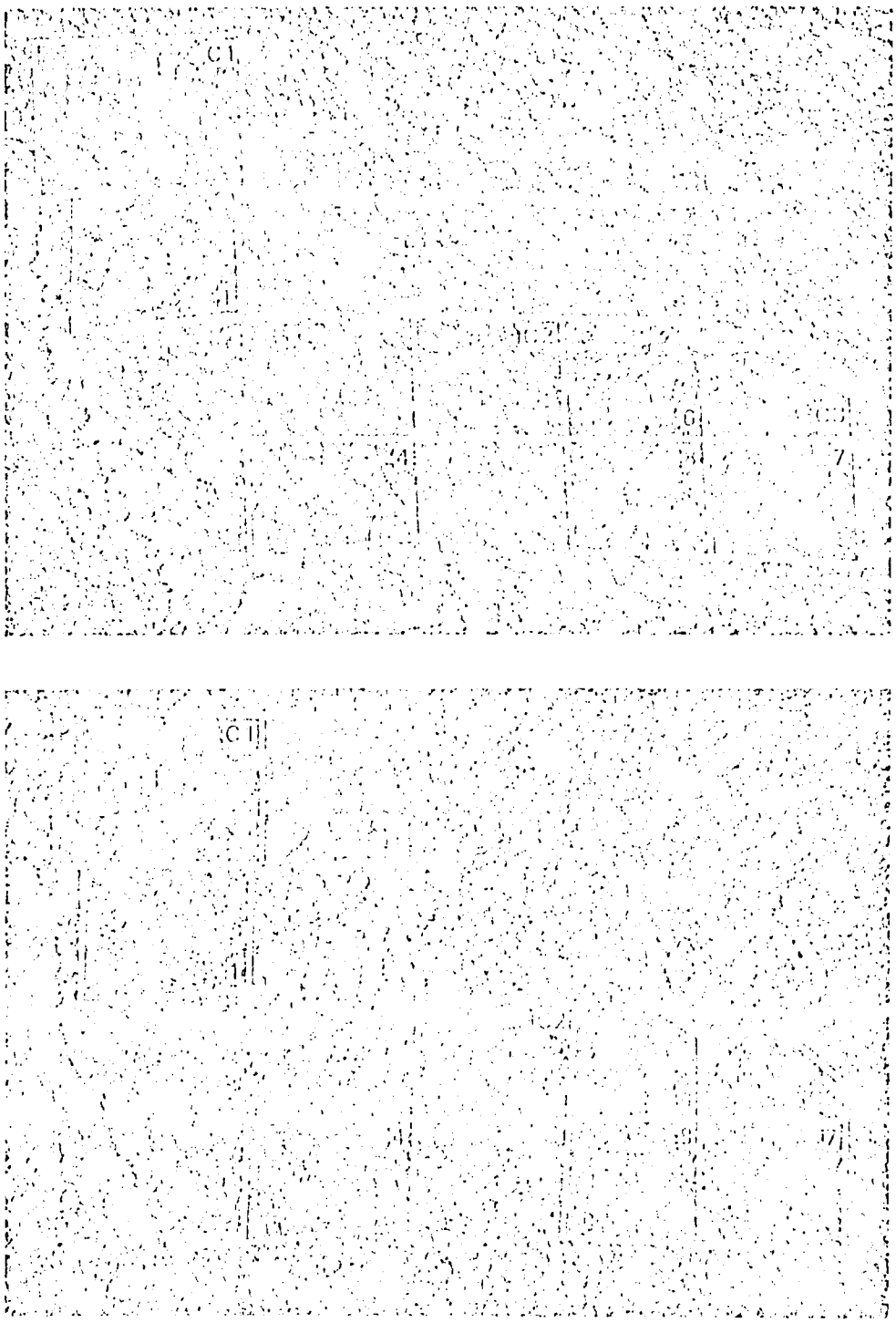


Fig. 5. (top) Aerial photograph taken in 1966, a few months after logging, of the experiment in Wiangaree State Forest. Plots C1, C2 and C3 are unlogged controls. See text for details of treatment Nos. 1, 4, 6, 7 and 8. (bottom) Aerial photograph of the same plots taken in 1981.

Thus for a light logging treatment (e.g. treatment 7 with 50% canopy retention) which results in a loss of about 33% of the overstorey basal area, the recovery time varied from *c.* 30 to 60 years. For a medium logging, e.g. treatments 4 and 8 which sustained 45–47% loss of overstorey basal area, the recovery time varied from *c.* 50 to 100 years. However, for heavy logging, e.g. treatments 1 and 6 in which up to 78% of the overstorey basal area was removed, the estimates of recovery time varied considerably due to the availability of advance growth, but showed a lower limit of *c.* 100 years with an upper limit of *c.* 220 years.

## Discussion

### *The Importance of the Overstorey*

Overstorey or canopy is invariably referred to in the description and classification of rainforest (Schimper 1903, Richards 1952, Baur 1962, Whitmore 1978). The emphasis placed here on the reconstitution of the rainforest overstorey, as an indication of recovery following logging, is based on the oft-reported view that the overstorey exercises some control over the rainforest as a whole. For example Halle *et al.* (1978) describe the overstorey canopy as the master regulator of the forest in their architectural analysis of tropical forests. Gomez-Pompa and Vasquez-Yanes (1981) say of Mexican rainforests that the overstorey confers an overall sensation of stability. Overstorey trees are responsible for creating and maintaining environmental conditions of shade and moisture which are vital to the many life forms found in subtropical rainforest (Richards 1952, Whitmore 1981). Hopkins *et al.* (1977) stated that the internal environment of rainforest is comparatively uniform, benign and predictable, partly because of the buffering action of the dense canopy. It is thus consistent to regard the overstorey as being of major importance in that it creates a 'seal' to the forest. When the forest is disturbed by an external agency such as logging, the overstorey trees are reduced in number and effect so that the visual framework of the forest is changed and the environmental 'seal' broken. In this circumstance reconstitution of the overstorey is a prerequisite of total recovery.

As a visual indication of the extent to which the overstorey can be reconstituted as time passes by the advanced growth see Fig. 5 which shows a photograph of the experimental plots taken in 1966 and another taken 15 years later in 1981.

### *Model Fitting*

*Diameter distribution.* The diameter distribution of the predicted overstorey at recovery for each treatment has been compared with the diameter distribution of the unlogged control plots (Fig. 6). Using 5-cm diameter classes, the range of the number of trees per hectare in each diameter class for the unlogged control plots was plotted (in heavy outline). The diameter distribution was then plotted for each treatment at recovery, to determine whether or not it fell inside the range indicated by the three control plots. Of the 65 points thus plotted, thirteen fell outside the unlogged range. However, five of these points were from the large tree range (110–165 cm in diameter) representing 6 trees, all but one of which were trees of this size at the time of logging. Thus only one tree in the 110–115-cm range had been projected onto a large size by simulated growth. Overall, 86% of the projected points fell inside the range of diameter

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distributions shown by the unlogged plots. It is therefore concluded that the projected reconstituted overstorey of the treatments forecast by the model is similar in diameter distribution to the unlogged controls.

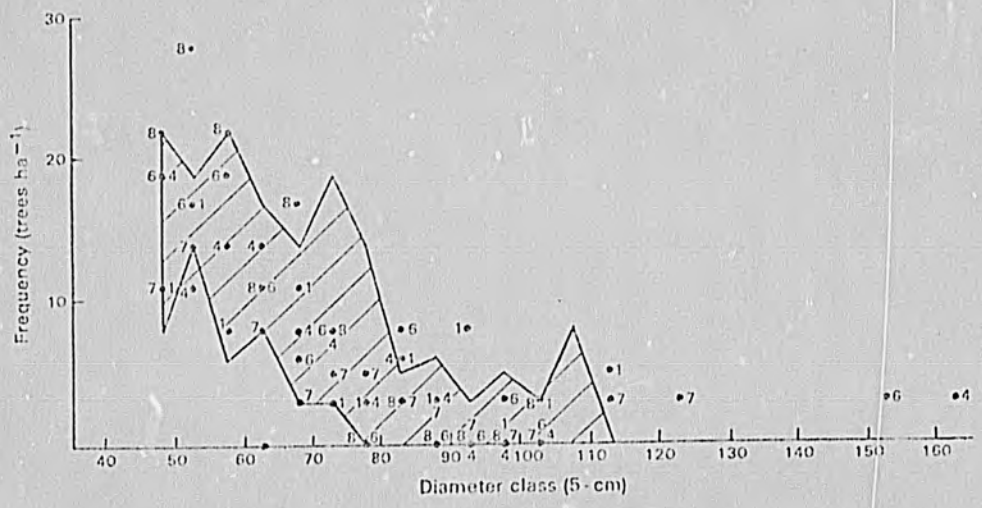


Fig. 6. The diameter distribution of the predicted overstorey at recovery compared to the actual range of diameter distributions in the three unlogged plots (shaded area). Calculations were based on 5-cm diameter classes. Numbered points indicate the forecast frequency of a diameter class at recovery for the various treatments.

*Species composition.* The growth model used in this study allowed individual trees to 'grow on' to overstorey recovery, and so provided a forecast of the composition of the new overstorey. A comparison of the unlogged overstorey (Table 1) with the projected overstorey (Table 2) suggests that the major overstorey species of the unlogged forest will continue to be the major species after recovery. That is, there will be no disappearance or severe depletion of any of the major overstorey species.

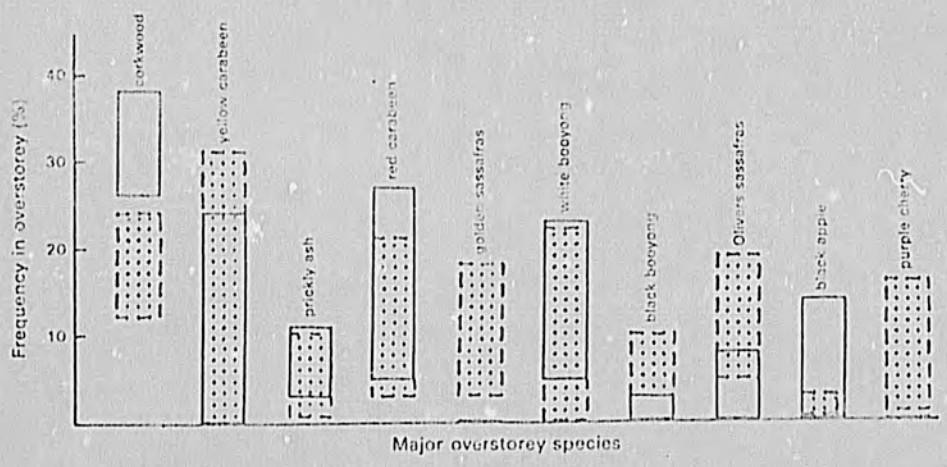


Fig. 7. Comparison of the frequency ranges of the major overstorey species in the unlogged control plots (dark outline), with the frequency ranges of those species as predicted by the model for the experimental plots (dotted areas).

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Logging may cause some alteration in the relative frequencies of the major overstorey species due to their different growth rates. For example the model indicates (see Fig. 7) that there will be a decrease in the number of corkwood trees in the overstorey (from 31% to 18%), accompanied by increased numbers of Golden sassafras (from 0% to 10%) and Oliver sassafras (from 2% to 10%). This pattern is in accord with the relative growth rates of these species; corkwood being a relatively slow grower compared to the two sassafras species.

## Conclusions

There is a significant increase in the average diameter growth rate of trees with diameter greater than 10 cm (over bark at breast height) following logging. Major overstorey species showed a mean growth rate in diameter of 0.15 cm $yr^{-1}$ in unlogged forest, compared with 0.31 cm $yr^{-1}$ in logged forest over the period 1966-1980.

The growth rate of an individual tree appears to bear little or no relationship with the diameter of the tree. There is a large variation in diameter growth rate over the whole range of diameter classes.

The basal area per hectare of the unlogged overstorey oscillated over the measurement period indicating an average upper limit to the basal area per hectare. That is, over the longer term, the growth of the undisturbed overstorey of the rainforest tends to be balanced by mortality.

The recovery time of the overstorey trees, based on basal area per hectare, increases with intensity of logging. The projected time scale forecast by the growth model is as follows: if overstorey removal is 30%, 50%, and 70-80% of the basal area per hectare, the predicted overstorey recovery times are 30 to 60 years, less than 100 years, and may be more than 200 years respectively.

There will be some changes in the relative frequencies of the major species of the overstorey at the time of initial recovery.

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