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ABSTRACT

'New England Dieback' is defined in this study as a particular group of symptoms of living trees and 'New England Tree Mortality' as the premature death of native trees in rural areas on the New England Tablelands.

Dieback was investigated in 1977 using a road survey, by questioning owners of 15 randomly chosen rural properties between Walcha and Glencoe and by making observations in 30 plots established on the 15 properties. Some plots were re-examined in 1979 to assess tree death rates for the 1977-79 period. In a further experiment, tree crowns were protected from leaf grazing insects for 18 months by application of systemic insecticide.

Symptoms defined as New England Dieback — crown defoliation, secondary shoot development and death of primary and secondary shoots — were found to be the main symptoms of tree decline. Premature death of trees was shown to be strongly associated with high levels of dieback. Based on these findings it was suggested that, under the stress of repeated defoliation, trees may die due to gradual depletion and eventual exhaustion of the energy reserves necessary for crown regeneration.

All 590 live trees examined (20 species of *Eucalyptus* and *Angophora floribunda*) were defoliated to some extent but *E. nova-anglica* and *E. blakelyi* were significantly more defoliated than other species. Significant trends of increasing defoliation with decreasing levels of dominance and maturity were found for non-epicormic defoliation but not for epicormic defoliation. Tree density was found to have a significant effect on some aspects of dieback but a non-significant effect on others. Dieback was independent of most site, land management and stand characteristics but higher levels were found on northerly aspects, in depressions and on poorly drained sites.

Significant recovery of tree crowns occurred on trees treated with insecticide. Based on this finding and observations made during the survey, insects were implicated as the main defoliating agents. It was concluded that repeated defoliation by leaf grazing insects was a major factor in the dieback and premature death of native trees on the New England Tablelands during the period of these investigations.

INTRODUCTION

Decline of native trees on pastoral land is now well recognised as a major problem affecting large areas of eastern Australia. (Old *et al.* 1981; Oates *et al.* 1981). It is particularly severe on the New England Tablelands where striking changes to the landscape (Figure 1) have been caused by the premature death of large numbers of native trees during the last decade (Anon 1979; Mackay 1978).

The New England Tablelands is situated in the north east of New South Wales (31.1 to 29.9 °S, 150.9 to 152.0 °E) (Figure 2). Elevation is at a maximum of around 1200 m in the east and falls steadily to about 600 m in the west. Mean annual rainfall ranges from 750 mm in the west to about 2000 mm in the east with the driest three monthly period from March to May and the wettest from November to January. Mean annual temperature for much of the area is around 14°C and frosts are common, ranging from about 20 per year at the lowest altitudes to around 60 at the highest altitudes.

Tree cover has been substantially and progressively changed during the period since European settlement (circa 1830) by the partial clearing of native woodlands and forests to an open woodland formation suitable for grazing. However, within this grazing zone numerous, isolated residual or regrowth stands of trees in woodland or forest formation also occur.

Native tree dieback on the New England Tablelands is not a new phenomenon (Boyd 1965) but an upsurge in its severity during the early 1970s and the public concern which followed led the Government of New South Wales to establish a Working Group in 1976 which was to investigate and report to the Minister on the problem.

During early meetings of the Working Group it became clear that very little reliable information was available on New England Dieback (as it became known). This was true not only of the aetiology and epidemiology of the disease but also of the very basic information which is necessary to establish a satisfactory diagnosis — such as major disease symptoms and the spatial and temporal distribution of affected trees. To provide some of this information the Forestry Commission of N.S.W., acting as a member of the Working Group, undertook a broadscale survey of the region in 1977 and a follow-up investigation in 1979. Broad conclusions of this work formed the basis of a report to the Minister in 1979 (N.S.W. Parliament 1979) and were also published in an extended abstract in 1981 (Clark *et al.* 1981). Since then information on New England Dieback has become available from a number of other studies commenced in the late 1970s (Williams and Nadolny 1981; Roberts and Sawtell 1981; Ford 1981; Trenbath and Smith 1981; Duggin 1981; Richards 1981; Sinden *et al.* 1982).

The purpose of this paper is to describe the 1977-79 investigations conducted by the Forestry Commission and to present the data and analyses from which the published conclusions were reached. A supplementary study, to evaluate the effectiveness of protecting trees from insect grazing by the application of systemic insecticide, is also described.

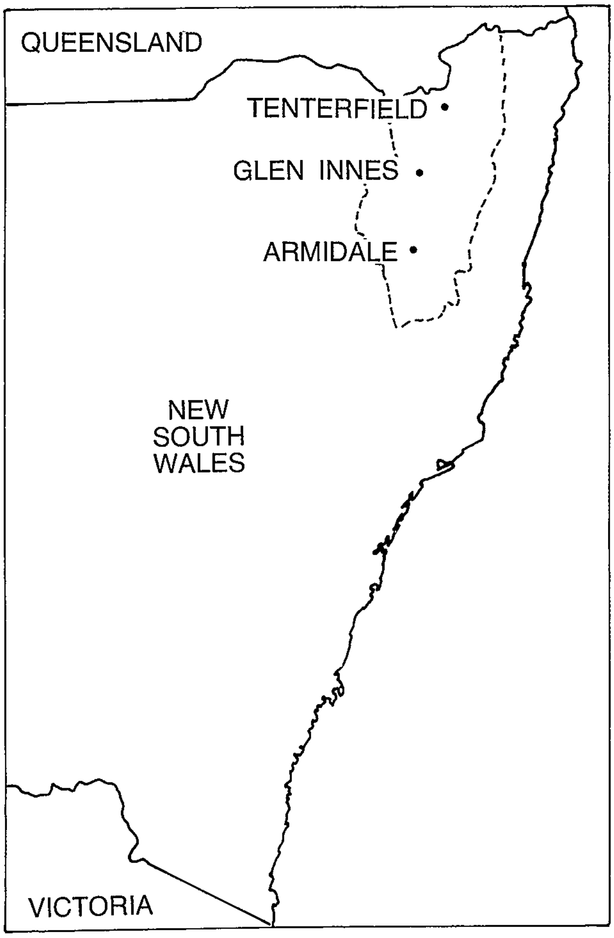


Figure 2. Location of the New England Tablelands.

DEFINITIONS AND STUDY RATIONALE

Because the term 'dieback' has been applied in different ways, confusion may arise when it is applied without definition. Podger (1981) describes the different applications as:

- the individual symptom — "progressive dying back from the tips of twigs, branches or tops".
- the affected tree — "progressive general deterioration often ending in the death of trees, for which single exclusive causes have not been isolated".
- the affected forest or stand — "where the incidence of unhealthy, dying or dead trees clearly becomes greater than that which can be expected from normal tree growth and senescence".

In this paper the term 'New England Dieback' is used only to describe symptoms of individual trees:

A

B

Figure 1. Native trees in grazing country near Armidale, December, 1977. 1a, Typical symptoms of decline described in this paper as New England Dieback. 1b, Extensive death of trees described in this paper as New England Tree Mortality. (Photos, Chris Taylor.)

- extensive loss of primary crown from growing tips.

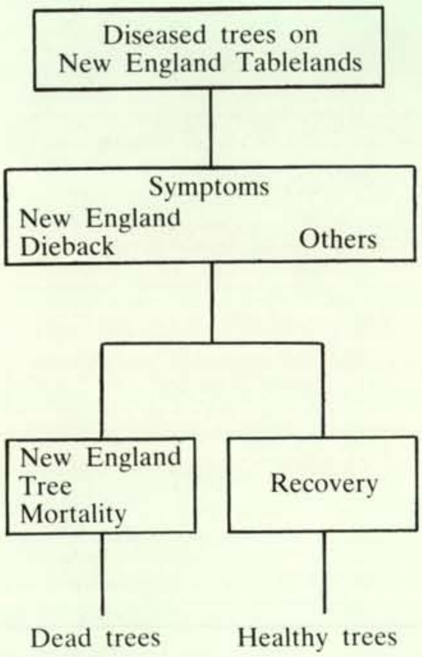
- death of leaf bearing branches.

- associated secondary shoot development.

- loss of secondary crown and associated death of secondary shoots.

The term 'New England Tree Mortality' is proposed to describe abnormally high death rates of native trees in rural landscapes on the New England Tablelands such as those which occurred on a number of occasions during the 1970s.

The various phenomena are summarised in the following diagram:



Using this definition of terms, the objectives of the Forestry Commission investigations were:

- To examine the relationship between New England Dieback and various tree, site and landuse factors.

- To evaluate the relationship between New England Dieback (i.e. symptoms on living trees) and tree mortality.

Four broad directions were followed to achieve these objectives:

- The collection of general observations on land management, and on New England Dieback and Mortality from the owners of randomly chosen landholdings.

- Quantitative assessment of New England Dieback and a range of tree, site and landuse factors in a series of plots established on the selected landholdings.

- Evaluation of the tree, site and landuse factors associated with Dieback by statistical analysis of the plot data.

- Re-examination of a sample of plots two years after the initial survey to assess the death rate of trees during the intervening period and determination of those characteristics associated with high death rates.

A supplementary study, to assess whether dieback can be effectively controlled by protecting trees from insect grazing, was established because of the high level of insect defoliation observed during the initial investigation carried out in 1977.

METHODS

Broadscale Survey

To assess the broad distribution of dieback a road survey was carried out in February 1977. Most main and secondary roads were travelled on the New England Tablelands and surrounding country to the south and west. The incidence of dieback in forest or woodlands visible from the moving vehicle was scored for severity on an arbitrary scale of absent, moderate or severe.

The overall distribution of dieback affected areas obtained from these road transects (Figure 3) showed the problem was most severe on grazing land between Walcha and Tenterfield, was generally on land above 800 m and was bounded on the east by the forested gorge country. It was also evident that dieback trees were primarily seen in landscapes which had been partially cleared for grazing.

Based on the results of this survey, a zone between Walcha and Glencoe was selected for more detailed study, which was carried out in March and April 1977. This 5000 km^2 area was subdivided into 15 equal-sized rectangles and a point randomly located within each of the subdivisions (Figure 4). The landholding encompassing the selected point was then considered as a unit and each manager interviewed and questioned about period of ownership or management; clearing history; land use history (general type of industry pursued, fertilizer usage, stocking rates, pasture species changes); value of tree cover; tree management practices; dieback history; observations on mistletoe, scarabaeid larvae and miscellaneous insect pests; burning-off practices; effects of stock on tree seedlings and coppice.

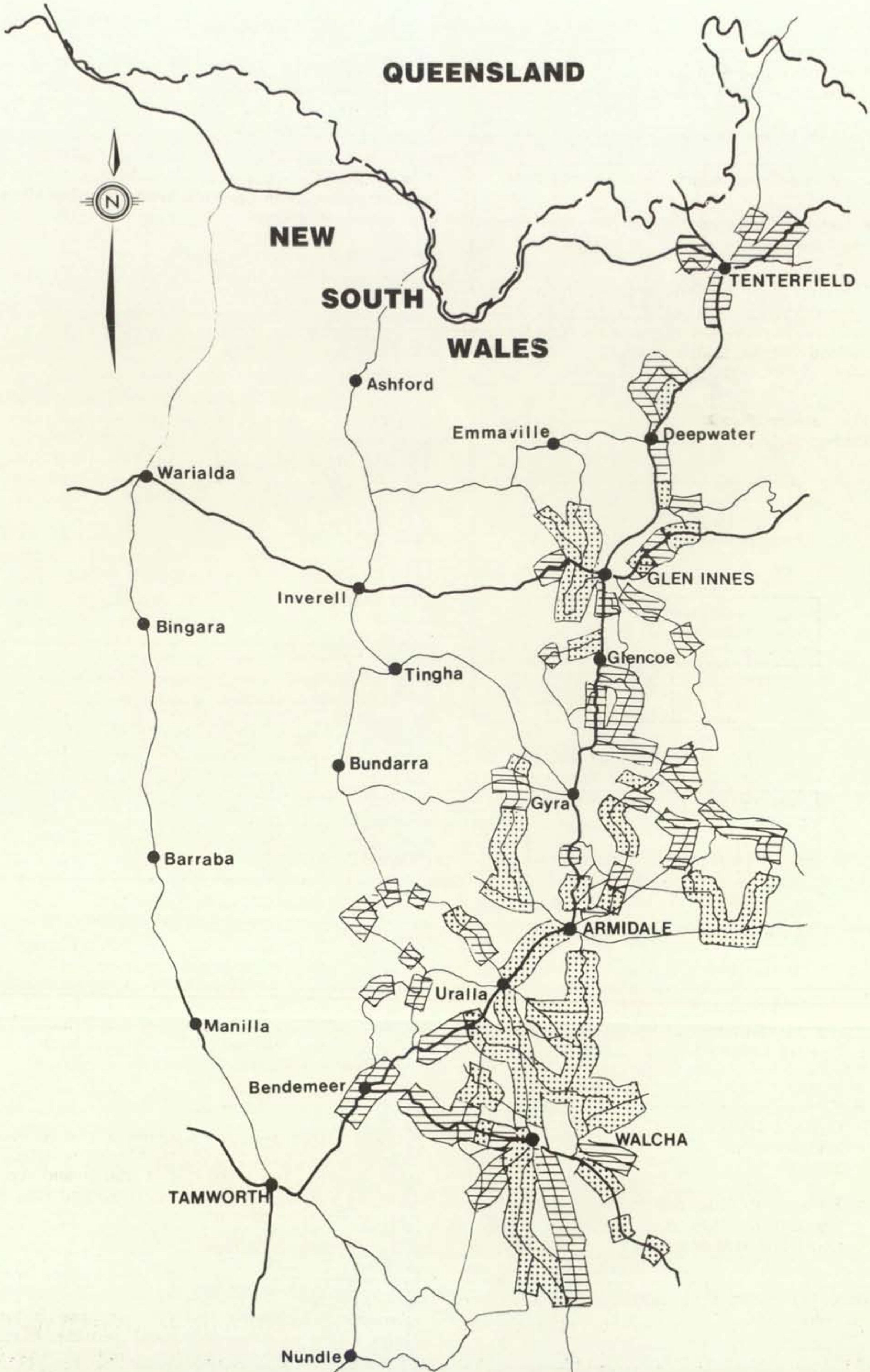


Figure 3. Road survey of dieback carried out in February 1977. All roads shown (solid lines) were travelled and the incidence of dieback scored as absent (blank) moderate (cross hatched — not to scale) and severe (dotted — not to scale). Border between Queensland and N.S.W. is shown as a dashed line.

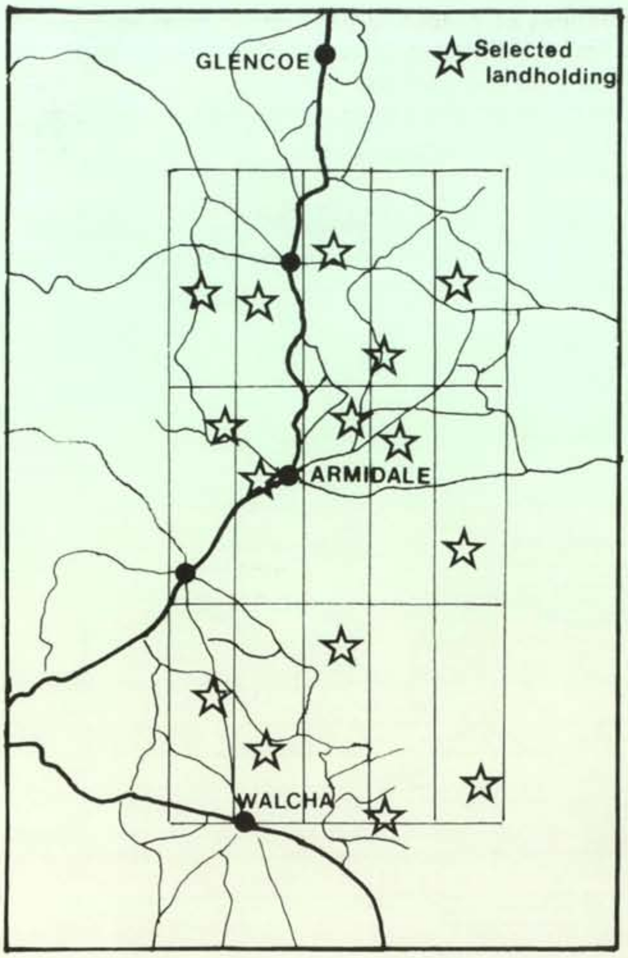


Figure 4. Location of landholdings selected by stratified random sampling of the area indicated (large rectangle) between Walcha and Glencoe.

For more detailed quantitative analysis two circular plots were established in each of the 15 selected landholdings. In determining the location of plots, timbered areas of each landholding were first sub-divided into two broad tree density strata — either dense stands (closed or almost closed canopy) or scattered or open stands of trees down to a minimum density of 5 trees ha^{-1}. One plot was then randomly located within each stratum. This further stratification was introduced to ensure that a wide range of tree densities was sampled by the 30 plots.

Young trees were regarded as part of the tree population when their diameter at breast height over bark (DBHOB) was 5 cm or greater. If it was found, after on-ground examination of a random plot location, that the tree density was below 5 tree ha^{-1}, or the stocking markedly non-uniform, or the species composition atypical of the landholding, the plots were relocated. Because of the wide range of tree densities encountered (10 to 2500 trees ha^{-1}) plot size was varied from 0.01 ha to 1.0 ha so that 10 to 25 trees were included in each plot. Thus, a stratified random sample of the native tree population in pastoral landscapes was obtained in 30 plots, covering a range of tree densities and sites.

The trees and plots were examined for a number of characteristics (Table 1). Crown condition was assessed independently by two observers using binoculars. In making the assessment, the ultimate branchlets of each crown were considered to belong to one of two groups depending on their origin. If they had clearly arisen from a recent branch epicormic shoot they were placed into Group A. The remaining ultimate branchlets were regarded as part of the original crown and placed into Group B. For each crown the following factors were estimated and recorded:- the proportion of ultimate branchlets in Group A, (U); defoliation of ultimate branchlets in Group A, (E); the defoliation of ultimate branchlets in Group B, (D). These crown condition factors were then used in combination to give an estimate of whole crown defoliation (W) such that:

TABLE 1. Characteristics of trees and plots examined in survey.

Individual tree characteristics	Plot characteristics
	Site Factors
• Species	• Aspect
• DBHOB (cm)	• Slope
• Height (m)	• Slope position (depression, slope, ridge top)
• Crown condition*	• Geology
• Maturity class (sapling, pole, mature, overmature)	• Drainage (poor, otherwise)
	Land Management Factors
• Dominance class (dom., co-dom., sub-dom., suppressed, woodland**)	• Fertilizer (used, not used)
• Vigour (vigorous, static, declining, dead)	• Pasture species (natural or introduced)
• Occurrence of mistletoe	• Cultivation (cultivated, not cultivated)
	Stand Factors
• Cause of recent tree death, poisoning and ringbarking; other	• Understorey (absent, present)
	• Stand vigour (vigorous, static)
	• Stand density (stocking & basal area)
	• Seedlings (all plants less than 5 cm DBHOB were counted by species)

* See text for details of these measurements.
** Woodland — while not a dominance class, this classification was included here for convenience.

$$W = \frac{D(100 - U) + EU}{100}$$

where D = percent defoliation of the original crown

U = proportion of epicormics (percent)

E = percent defoliation of epicormics

Least square multiple linear regression analysis was used to assess the effect of the various tree, site, land management and stand factors on dieback.

The crown condition factors, D, E and U and the composite factors W and (W + U)/2 were all regarded as indices of dieback and each was used as the dependent variable in separate analyses of the data. Pooled individual tree data from all plots were used to assess the effects of species, dominance, maturity and density on dieback. To assess the effect of site, land management and stand factors, plot mean values of the five alternative dependent variables were used in the analyses.

To assess the relationship between dieback and subsequent tree mortality, eight plots which contained predominantly the most common tree species were revisited in June 1979. The trees which had died in the intervening period, i.e. since the previous assessment in 1977, were noted. For these dead trees the level of dieback measured in 1977 was compared with the 1977 dieback scores for the trees still living by 1979.

Insecticide Experiment

Three plots, containing predominantly the most severely dieback affected species — *E. nova-anglica* and *E. blakelyi* were selected for the insecticide experiment. In each plot six pairs of trees were chosen after matching for species, crown condition and height. One tree in each pair was selected at random for treatment and the other left untreated.

The treatment trees were injected with the insecticide monocrotophos according to procedures outlined by Hadlington (1971). Treatment was carried out in November and December 1977, February 1978 and again in December 1978. Assessments of crown condition were made on each occasion, and a final assessment was made in June 1979.

RESULTS AND DISCUSSION

1. General Observations

The landholdings (properties) on which the plots were established had typically been managed as pastoral operations for more than 50 years. Almost all managers had kept records of stock numbers and production, fertilizer applications, shearing numbers and rainfall. The properties had been cleared or thinned by the late 1920s to parkland stocking levels. From then until the area was aerially photographed (1961-71) most of the dead timber had been removed by tractors. However, there had been some further tractor cleaning-up operations of old ring-barked and dieback areas on some properties. Removal of seedlings and suckers had become unnecessary on superphosphate treated areas.

Until about 1970 merino sheep grazing had been the normal industry. Since then there had been a small increase in cross-bred sheep numbers and a large increase in cattle numbers.

Superphosphate, applied at a rate of 125 kg ha^{-1} an^{-1} had been used over large areas on most of the properties from 1960 to 1973, with additional superphosphate being applied to cultivated paddocks. Sometimes sulphur-fortified superphosphate and occasionally molybdenum-superphosphate had been used. Very little superphosphate had been spread between 1975 and 1977, the period during which the government ceased to pay a bounty on the use of superphosphate.

Stocking rates had been 1.9-2.5 sheep ha^{-1} before 1960. Sheep numbers had doubled subsequent to the use of superphosphate. From 1970 to 1977 the sheep population had stabilized or dropped to cope with increased cattle numbers. Whereas before 1950, properties had carried about 98% sheep and 2% cattle, in 1977, they were carrying 90% sheep and 10% cattle. Since 1965, sections of the properties had generally been sown for improved pasture on cultivated soil (typically 20-30% of the area). Pastures had been sown by air on unploughed ground on only 5 of the 15 properties.

Blackberry (*Rubus* spp.) spraying on a small scale using 2,4,5-T had been carried out on almost all properties. No other wide-spread use was made of weedicides, or insecticides (except on the stock).

The trees were utilized by the farmers as a source of timber for fencing and rough buildings, for stock shade and shelter, and pasture shelter. Aesthetic values associated with the trees were generally recognised but the farmers could not place their trees in a meaningful economic context. They did not protect regeneration from stock damage, nor replace dead trees, nor grow trees to replace those which were over-mature. In some instances species liable to die were selectively removed and those suitable for fencing timber retained. Wind break planting in paddocks was unusual, but some had been established around homesteads, *Pinus radiata* and *Cupressus torulosa* being the preferred species used. There was a distinct tendency to leave clumps of natural timber for stock shelter; many of these actually were regrowth stands which had developed after clearing in the early part of the century.

The managers generally held the opinion that New England Dieback had only been serious for three to five years prior to the survey. A few stated that it had also appeared for a period many years previously. Some stated that mistletoe was a significant killer of trees on their properties while others said it was not an important factor. About 60% of the managers knew of the existence of scarabaeid larvae as pests and about 50% of these had had problems with these insects in their pastures. Almost all had experienced plagues of other pasture insects in recent years.

Burning-off of native pasture to kill regeneration and provide green grass in early spring had been a normal procedure until it became the general practice to sow pastures and use superphosphate. Concomitantly with this and the resulting higher stocking rates, coppice and seedlings had disappeared from the paddocks. The general opinion was that the sheep and cattle consume this type of growth for "roughage". When it is no longer available, the animals often go into nearby timber stands and eat the bark of standing timber, frequently ringbarking and killing the trees thus used.

A number of general observations could be made based on the conditions of the sampled plots:

- Tree deaths appeared to be associated with repeated defoliation of the tree crowns.

- All eucalypts in the region visited had been defoliated to some extent and insects appeared to be the main defoliating agents.

- No dead or almost dead trees which had retained their leaves intact were observed.

- Some species appeared more susceptible to defoliation than others. For example, *Eucalyptus nova-anglica* was very susceptible and *E. caliginosa* far less so.

- Heavy mistletoe infestations appeared in very restricted areas only — particularly where the climate was somewhat drier than is normal for the area, such as immediately north of Armidale.

- New England Dieback occurred both in places which were fertilized with superphosphate, and in unfertilized areas.

- In the seedling-sapling-pole size tree classes, a negative relationship appeared to exist between tree height and the extent of defoliation.

- Various species exhibited different modes of refoliation after heavy and/or repeated defoliation. For example, *E. nova-anglica* usually established epicormic growth further back down the crown than the other species and few shoots grew from the outer branchlets. On the other hand, after defoliation *E. viminalis* developed a flush of epicormics on the fine outer branchlets. Subsequent defoliation resulted in the regrowth retreating to larger branches in the crown.

TABLE 2. Number of plots in each site and landuse category.

Slope (°)		
0-5	5-15	>15
16	13	1

Geology*			
1	2	3	4
6	2	19	3

Drainage	
Poor	Otherwise
3	27

Fertilizer treatment	
Fertilized	Not Fertilized
21	9

Pasture Ground Cover (%area)		
<50	50-80	>80
3	8	19

Aspect (°)			
0-90	91-180	181-270	271-360
12	9	9	0

Pasture species	
Near natural	Improved
20	10

Tree density (number ha^{-1})			
<30	31-150	151-300	>300
5	9	6	10

Occurrence of Understorey	
Present	Absent
14	16

Slope position		
Ridge	Mid slope	Depression
5	23	2

Cultivation	
Cultivated	Not Cultivated
3	27

* Geologic categories:- 1 — Upper Permian granitoid rocks; 2 — Tertiary basalt; 3 — Lower Permian and Carboniferous metamorphosed sediments; 4 — Lower Permian tuffs and porphyries.

TABLE 3. Distribution of live and dead trees in the various plots in 1977, according to species.

Species	Total	Live trees	No. of plots with species	Dead Trees		
				Evidence of dieback	Unknown** causes	Poisoning ring-barking
Eucalyptus caliginosa	167	119	9	9	15	24
Eucalyptus macrorhyncha	111	106	6		1	4
Eucalyptus nova-anglica	62	54	4	7	1	
Eucalyptus blakelyi	56	42	7	13		1
Eucalyptus laevopinea	45	45	2			
Eucalyptus viminalis	38	34	6	4		
Eucalyptus albens	29	29	1			
Eucalyptus acaciiformis	25	25	3			
Eucalyptus amplifolia	24	24	1			
Eucalyptus stellulata	23	22	1		1	
Eucalyptus melliodora	21	15	7		1	5
Eucalyptus moluccana	19	19	2			
Eucalyptus pauciflora	12	12	2			
Eucalyptus andrewsii	11	11	2			
Angophora floribunda	8	8	3			
Eucalyptus radiata	7	7	1			
Eucalyptus dalrympleana	6	6	3			
Eucalyptus obliqua	4	4	1			
Eucalyptus bridgesiana	4	4	2			
Eucalyptus cameronii	3	3	1			
Eucalyptus saligna	1	1	1			
TOTALS	676	590		33	19	34

* Trees in this category had evidence of extensive secondary shoot development and defoliation.

** Many trees placed into this category had been dead for three or more years. Consequently dieback symptoms were no longer clearly recognisable.

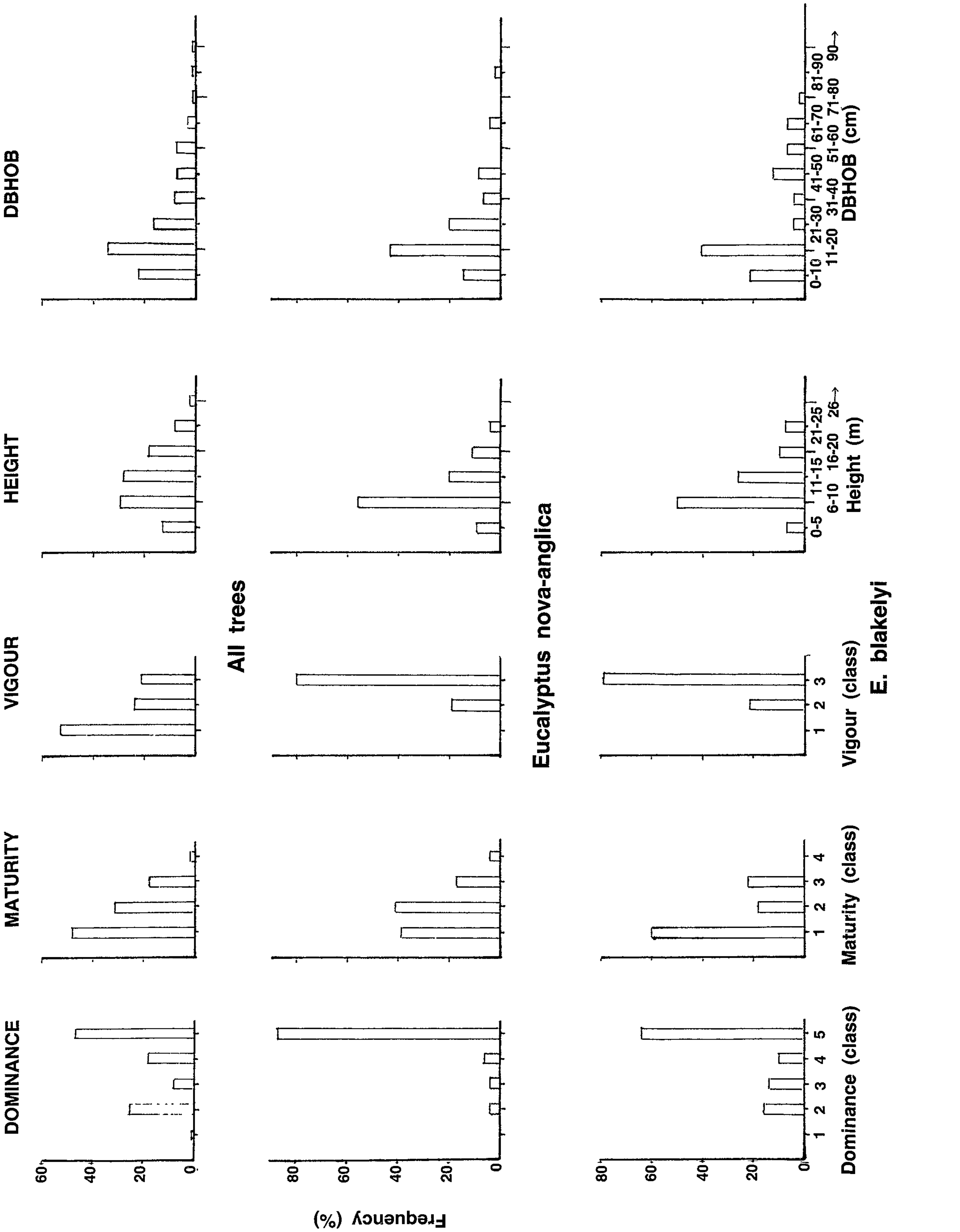
2. Broadscale Survey

General Site and Tree Characteristics

Most plots were on gentle to moderate slopes, were well drained and were not cultivated (Table 2). About two thirds of the plots were on soils derived from metamorphosed sediments, had received some application of fertilizer and had unimproved pastures. A wide range of tree densities was represented (10 to 2500 trees ha^{-1}; basal area 1.5 to 34.2 m^2 ha^{-1}) and about half the plots had an established understorey. Mean plot tree height ranged from 7 to 24 m (overall mean 13.4 m) and mean plot tree diameter from 9 to 54 cm (overall mean 28.2 cm DBHOB).

The 30 plots contained a total of 676 living and dead trees comprising 20 *Eucalyptus* species and one species of *Angophora (A. floribunda)* (Table 3). Nine species occurred in three or more plots, five in two plots and seven in one plot only. There was no species common to all plots. Eighty-six (12.7%) of the 676 trees were dead. Thirty-four of these (5.0%) had been poisoned or ringbarked during land clearing and timber getting operations and 52 (7.7%) had died from other causes; of the latter, 33 showed clear evidence of dieback prior to death (defoliation and extensive secondary shoot development). Such trees were found in only 4 of the 21 species, *E. blakelyi* being most severely affected with a rate of 23% (Table 3), followed by *E. nova-anglica* and *E. viminalis* each with 11% and *E. caliginosa* with 5%, this species being, however, strongly represented in the group of trees which had deaths from unknown causes.

A number of the characteristics of the examined trees (dominance, maturity, vigour, height and diameter) have been summarized diagrammatically in Figure 5 for all trees, and for two of the most severely affected species — *E. nova-anglica* and *E. blakelyi*. The histograms show that individuals in the total sample of trees were about equally divided between those in woodland formation and those in forest. Stands of trees with closed or almost closed canopy were classified as forest and more open stands with scattered trees as woodland. Since the proportion of the tree population occurring as forest on the selected holdings was usually smaller than the proportion occurring as woodland, the equal distribution between forest and woodland in the sample shows it was biased (deliberately) in favour of the higher density stands. Most trees in forest formation were classified as either co-dominant or suppressed and about 75% of all trees were in the lower order maturity categories of sapling and pole.



Dominance classes: 1 dominant; 2 co-dominant; 3 sub-dominant; 4 suppressed; 5 woodland.
Maturity classes: 1 sapling; 2 pole; 3 mature; 4 over-mature.
Vigour classes: 1 vigorous; 2 static; 3 declining.

Figure 5. Frequency distributions of dominance, maturity, vigour. height and DBHOB for the full sample of 590 trees and for *Eucalyptus nova-anglica* (54 trees) and *E. blakelyi* (42 trees).

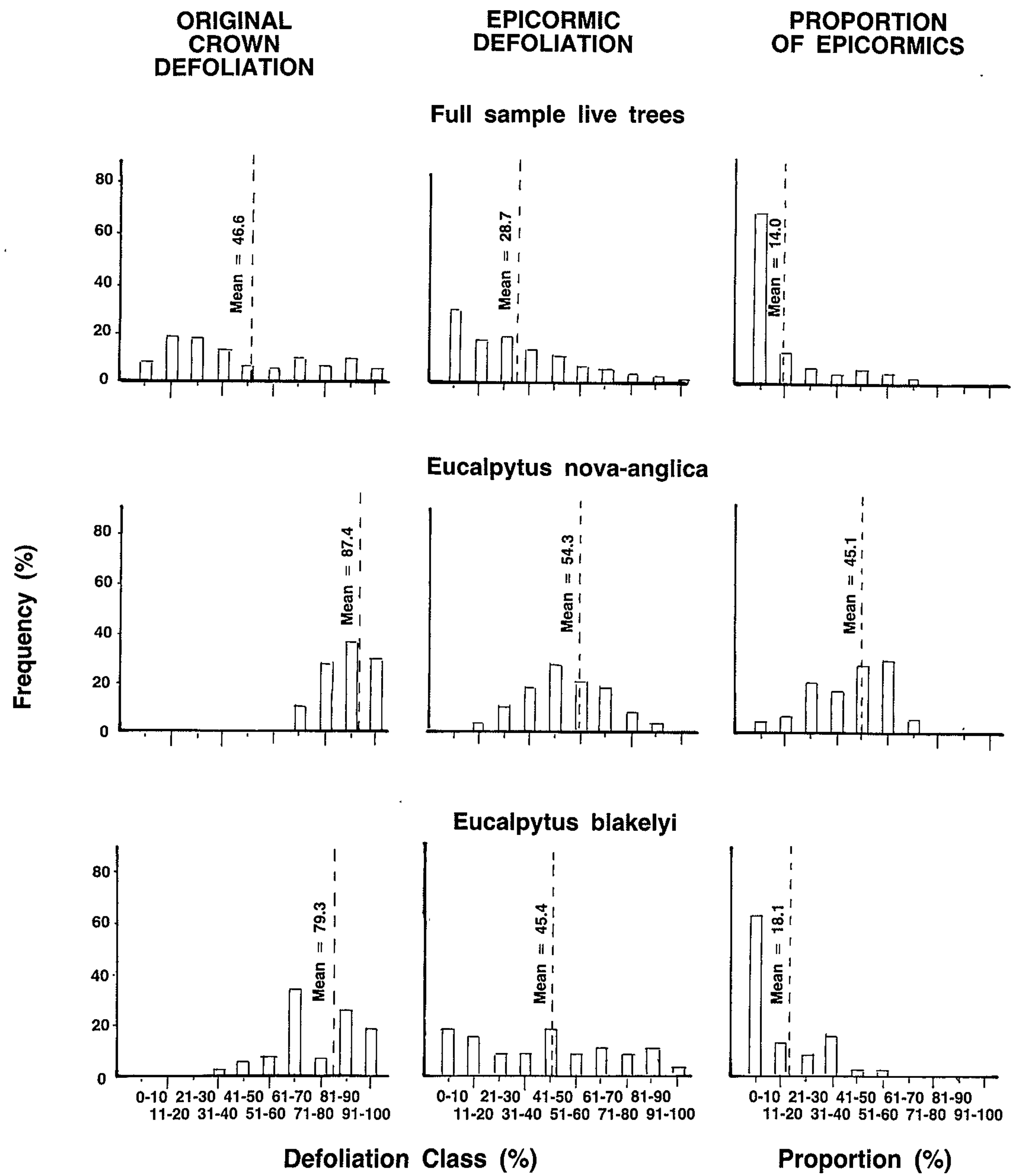


Figure 6. Distribution of crown defoliation indices for the full sample of live trees and for *Eucalyptus nova-anglica* and *E. blakelyi*.

Clear differences were apparent between some of these general findings in the complete tree sample and those for *E. nova-anglica* and *E. blakelyi.* Both species occurred predominantly in woodland formations and all individuals were classified as either static or declining in vigour (Figure 5).

All trees examined were defoliated to some extent but the level of defoliation was highly variable (Figure 6). Sixty percent of living trees had recent branch epicormic shoots and the defoliation of these shoots was about half the original crown defoliation. *E. nova-anglica* and *E. blakelyi* were severely defoliated compared with the total tree sample (Figure 6). *E. nova-anglica* crowns also had considerably higher proportions of epicormic shoots than those of either *E. blakelyi* or of the total sample of trees.

Statistical Analysis of Tree Data

It was clear from a preliminary examination of the information collected that detailed analysis of both individual tree data and plot characteristics was constrained by several factors. First, the sample contained very few of the total possible combinations of the tree and plot factors being considered. For example, if the influences on individual tree dieback were likely to be dominance (5 levels), maturity (4 levels), species (10 levels), tree density (say 4 levels) and differences between plots (30 levels) 24 000 combinations are possible. In the sample the number of combinations available was 590. Second, many of the measurements were qualitative rather than quantitative. For example, fertilizer and understorey are only recorded as present or absent. When present, no quantities were recorded for these two factors. It was, therefore, not possible to discern quantitative trends. Third, the indices of dieback were quantitative estimates expressed as percentages. Fourth, some of the factors included were probably related e.g. slope position and drainage, pasture species and cultivation.

Given these constraints the approach adopted was to use a method which allowed for missing or poorly distributed information. In addition, we regard the statistical analyses as giving indications of broad trends only — trends which may then be used to develop hypotheses on causal relationships and in the design of future studies.

To analyse individual tree data least squares multiple linear regression was used. Analyses of variance were generated by fitting multiple linear regression models, expressing variation in the dieback indices D, E, U, W and (W+U)/2 in terms of the measured factors (dieback indices are defined under 'Methods'). All models included the main factors — species, plots, dominance, and maturity, as well as the higher order interaction term plots x species. In addition, the data were analysed using models which included tree density expressed both as trees ha^{-1} and BA ha^{-1}. For this analysis it was necessary to allocate the same density to all trees within a specific plot. All analyses were repeated using angular transformations of the five dieback indices.

Because of the large number of missing combinations of species with other factors, only those species occurring in at least three plots were considered individually. This reduced the number of species in the analysis to nine with the remaining species being placed into an 'others' category.

An example of an analysis of variance (for original crown defoliation) is shown in Table 4. The high significance for the full model and the coefficient of determination indicate an extremely low probability that the effect of the full model in explaining variation of D could have arisen by chance. The full model was therefore able to provide very good predictions of D. The significance levels for the individual terms in the model indicate whether the

TABLE 4. Analysis of variance of original crown defoliation (D) generated by fitting a multiple linear regression model in terms of the factors: tree density, plots, species, dominance, maturity and the interaction term plots x species.

Source of Variation	Degrees of Freedom	Mean Square	F-Ratio	Significance
Full model	66	4691.3	19.1	**
Tree density (trees ha^{-1})	1	605.2	2.5	NS
Plots (P)	28	1714.3	7.0	**
Species (S)	9	2458.1	10.0	**
P X S	21	1273.8	5.2	**
Dominance	4	1490.7	6.1	**
Maturity	3	1531.0	6.2	**
Residual	523	245.9		
TOTAL	589			

Coefficient of determination 70.6%

NS — not significant, * — significant at 5% level
** — significant 1% level.

TABLE 5. Significance levels for the main factors on five indices of dieback. Data derived from analyses of variance from five independent multiple linear regression models. Regression coefficients positive except where indicated.

Factor	Dieback Index				
	D	E	U	W	$\frac{W+U}{2}$
Full model	**	**	**	**	**
Density (trees/ha⁻¹)	NS	* (-)	** (-)	NS	* (-)
Plots (P)	**	**	**	**	**
Species (S)	**	**	**	**	**
PXS	**	*	**	**	**
Dominance	** (-)	NS	* (-)	** (-)	** (-)
Maturity	** (-)	NS	NS	** (-)	NS
Coefficient of Determination (%)	70.6	57.8	61.1	70.0	72.5

NS — not significant, * — significant at 5% level, ** — significant at 1%. D = original crown defoliation, E = epicormic defoliation, U = proportion of epicormics, W = whole crown defoliation.

effect of the factor (in explaining variation of D) could have arisen by chance, after variation due to all other factors in the model had been removed. For example, after variation due to all other factors had been removed there was a very low probability that the effect of dominance, in explaining variation of D, could have arisen by chance. Thus, after accounting for the effects of species and plots, tree dominance and maturity had a highly significant effect on D.

In similar analyses for the other indices of dieback, the main factors, plots, species, and plots x species were all highly significant (Table 5). Actual probability values are shown in the Appendix. The results were substantially unchanged with angular transformations of dieback indices.

To determine the manner in which significant effects such as species, dominance and maturity were operating, least squares or adjusted means were calculated and compared. These adjusted means allowed for the non-uniform distribution of dieback scores among factor classes. For example, if species A was represented in the sample predominantly in the dominance classes 1 and 2 and species B predominantly in classes 3 and 4, a direct comparison of overall species means would be confounded by any dominance effects. Factor means calculated in the analysis were adjusted to allow for these differences and could therefore be compared directly.

The variation in whole crown defoliation among species is illustrated in Table 6.

TABLE 6. Adjusted mean whole crown defoliation index (W) by species.

Species	Adjusted mean	Number of observations
Eucalyptus caliginosa	37.5	119
Eucalyptus macrorhyncha	32.8	106
Eucalyptus nova-anglica	66.8	54
Eucalyptus blakelyi	57.3	42
Eucalyptus viminalis	36.4	34
Eucalyptus acaciiformis	28.7	25
Eucalyptus melliodora	31.4	15
Angophora floribunda	54.0	8
Eucalyptus dalrympleana	39.2	6
others	36.4	181

All species showed high levels of defoliation but *E. nova-anglica, E. blakelyi* and *A. floribunda* had considerably higher levels than other species. The differences were significant for the former two species but not for *E. floribunda.* This was probably due to the relatively small number of trees of the species in the sample. Similar results were obtained for the other dieback indices.

Dominance and maturity did not have significant effects on all dieback indices (Table 5) but in those cases where they were significant, decreasing levels of dieback were associated with increasing levels of dominance and maturity. To illustrate this trend adjusted means for W by dominance and maturity classes are shown in Table 7. Values for the 'over mature' and 'dominant' classes are included for completeness although these results should be treated with caution because of the small number of observations in each case.

TABLE 7. Adjusted mean whole crown defoliation (W) by dominance and maturity classes.

		Adjusted mean	Number of Observations
Dominance	Dominant	34.6	7
	Co-dominant	40.4	148
	Sub-dominant	44.2	53
	Suppressed	49.2	104
Maturity	Sapling	46.5	292
	Pole	42.5	182
	Mature	36.8	105
	Over-mature	42.5	11

An interpretation of these results can be made based on the model of dieback initiation and development proposed by Landsberg and Wylie (1983). The central mechanism of their model is the triggering of leaf-eating insect population expansion and associated increased levels of defoliation, by an increase in the nitrogen content of leaves. The authors cite literature indicating that increased nitrogen content can be associated with increasing water stress of trees. Under dry climatic conditions the most highly stressed individuals are likely to be those in the lower levels of dominance since these individuals are at a competitive disadvantage to dominant and co-dominant trees. Therefore, if these most stressed trees develop higher leaf nitrogen levels than the dominants and co-dominants they are likely to be preferentially defoliated by insects. Similarly it is likely that the lower orders of maturity (saplings and poles), being less well established than mature trees, would be more susceptible to environmental stress.

Tree density was a poor estimator of variation in original crown defoliation (D) and whole crown defoliation (W). However, it was significant in explaining epicormic defoliation (E), (W+U)/2 (an estimate of whole crown defoliation with a weighting for the proportion of epicormic shoots) and highly significant in explaining the proportion of epicormic shoots (U). The level of epicormic foliage reflects, to some degree, the severity of crown damage due to a previous episode of defoliation. At the time of the initial defoliation, crowns would have been classified as predominantly original crown. Thus, it is likely there was a density effect at that time but no density effect on foliage of similar origin at the time of the survey.

Two possible explanations for this apparent disparity were considered. First, at the time of the survey it is likely that non-epicormic or 'original crown' foliage had experienced a different history of defoliation from that of the recent branch epicormic foliage. Differences which probably occurred in conditions during the defoliation episodes of non-epicormic foliage, such as in climate, tree stress levels and defoliation agents (e.g. different species or groups of insects), would have increased the overall variability of defoliation and may have masked tree density effects.

A second possible explanation is associated with the high levels of epicormic foliage which would have been present on trees near the time of the survey. This foliage is higher in nutrients and is grazed preferentially by insects (Landsberg and Wylie, 1983) and may have reduced grazing pressure on non-epicormic foliage. Consequently, in less dense stands where the highest levels of epicormic shoots and epicormic defoliation were found, defoliation of non-epicormic foliage may have been reliatively low.

Although tree density effects were observed in the survey for the defoliation of epicormic shoots and the extent of epicormic foliage, our finding that tree density had no significant effect on whole crown defoliation tended to conflict with casual observation. The reason for this conflict is the predominance of the two most severely defoliated species (*E. nova-anglica* and *E. blakelyi)* in low density stands. Under these circumstances casual observation may indicate that tree density is important in determining levels of defoliation. However, our analysis assessed the effect of density on whole crown defoliation independently of effects due to species, dominance, maturity and plots. The calculated adjusted mean value of W for woodland stands was 42.0% — a value which lies in the middle of the range observed for trees in forest formations (see dominance class values in Table 7). This result reflected a tendency for the most severely defoliated species (usually in woodland) to exhibit high levels of W when present in forest formations and, conversely, for the least defoliated species (usually present in forest formation) to show low levels of defoliation when present in woodland.

An interesting result was the absence of significant trends in epicormic defoliation with changing levels of dominance and maturity. This might be explained by the higher levels of nutrients in epicormic foliage compared with original crown foliage. These relatively high levels are probably independent of dominance or maturity class. Under these circumstances trends of defoliation with maturity or dominance would not occur.

Statistical Analysis of Plot Characteristics

Analyses of individual tree data indicated highly significant differences between plots for all dieback indices when variation due to species, dominance, maturity and density was removed. In an attempt to determine the significance of site, landuse and stand characteristics in explaining this between plot variation, a similar analysis to that described for the individual tree data was carried out relating mean plot dieback index to site, landuse and stand characteristics. Limitations of the data, as discussed in the previous section, and the small number of plots in relation to the number of factors being considered, restricted the value of the analyses to indicating broad trends only. Furthermore, it was not possible to include species in the model because of the number of plots with more than one species. Consequently, observed significant effects may have been partly due to species differences.

TABLE 8. The influence of plot characteristics in five indices of dieback. Data derived from analyses of variance from five independent multiple linear regression models. Significance levels of regression coefficients are indicated; coefficients positive except where indicated.

Characteristic	Dieback Index				
	D	E	U	W	$\frac{W+U}{2}$
Full Model	*		*	*	*
Aspect	*				
Slope					
Geology			*		
Drainage			**		
Fertilizer					
Pasture Species					
Ground Cover					
Cultivation					
Understorey					
Slope Position	*	**	* (-)	**	*
Tree density class (trees ha^{-1})					
Tree density class (BA ha^{-1})					
Coefficient of determination (%) (21 degrees of freedom)	90.1	88.2	91.8	89.4	90.2

* significant at 5% level — ** significant at 1% level — Non significant effects shown blank.

A summary of the analysis of variance tables from the five multiple linear regression models (Table 8) showed aspect explained a significant part of the variation of D (percent defoliation of original crown) with plots in the north-east sector being more defoliated than those with southerly aspects.

Geology was significant for U (proportion of epicormics) with plots on tuffs and porphyries showing the highest levels followed by plots on basalt, granite and sedimentary rocks. The highest levels of U were also significantly associated with poorly drained plots and with those in the lower density stands (trees ha^{-1}). Slope position was a significant factor in explaining variation of all indices but U, with plots in depressions more defoliated than mid-slope and ridge top plots although the full model for E was not significant. Probability values from which the significance levels in Table 8 were derived are shown in the Appendix.

None of the other factors — slope, fertilizer, pasture species, ground cover, cultivation, understorey, tree density (BA ha^{-1}) — were significant in any model. With limitations of the data and analysis these factors may of course have had some effects which were undetected. However, we concluded it was unlikely that any of these factors had a *strong* influence on levels of dieback.

Tree density was important only in explaining variation of the level of epicormic shoots in plots (U), which paralleled findings of the individual tree analysis. Furthermore, the tendency for epicormic defoliation (E) to be independent of the various factors measured, apart from slope position. was confirmed by the analysis of the full model, which was not significant.

While slope position was significant in four of the five models, the result should be treated with caution because of the small numbers of plots in the categories ridge (5) and depression (2) (see Table 2). Similarly, drainage was represented by 3 plots defined as 'poorly drained' and 27 as 'otherwise'. However, since drainage and slope position are probably related and all models have one of these as significant, further consideration of these factors would be justified in future studies. No obvious reasons were evident during the survey for the high levels of dieback on lower slopes and in depressions.

The significance of geology was regarded as an equivocal result because of low numbers of plots in 2 of the 4 geology categories (Table 2). However, the result for aspect (highest levels of dieback on north facing slopes) may have been caused by higher levels of moisture stress on northerly aspects and consequent increased levels of leaf nitrogen as discussed by Landsberg & Wylie (1983).

TABLE 9. Number of live trees in 8 plots containing the most common tree species in 1977 and in the same plots when revisited in 1979.

Species	No. of live trees 1977	1979	Tree deaths during the period 1977-1970 (%)	Number of plots with species
Eucalyptus nova-anglica	42	24	43	3
Eucalyptus caliginosa	32	25	22	2
Eucalyptus blakelyi	27	18	33	3
Eucalyptus viminalis	19	16	16	2
Eucalyptus stellulata	19	18	5	1
Eucalyptus pauciflora	12	12	0	2
Eucalyptus melliodora	8	7	13	1
Angophora floribunda	7	6	14	2
Eucalyptus macrorhyncha	7	7	0	1
Eucalyptus dalrympleana	6	6	0	3
Eucalyptus acaciiformis	2	2	0	1

Relationship between tree dieback and mortality

On the eight plots revisited in 1979, 22% of trees which were living in 1977 had died. The highest death rates recorded were for *E nova-anglica, E. blakelyi* and *E. caliginosa* (Table 9).

During this period trees were stressed first by heavy insect defoliation during the summer of 1977/78 and then by drought in the following summer which persisted until the time the plots were re-examined. The condition of dead trees suggested that individuals had died throughout the two year period.

The trees which were found to be alive in 1979 and those which had died during the period 1977-1979 were grouped separately. For these two groups, frequency distributions of 1977 scores for the five dieback indices, D, E, U, W and (W+U)/2 were compared. The index U (proportion of epicormics) was significant at the 0.025 probability level while the other indices were all highly significant ($p<0.01$). Figure 7a illustrates the trends using the data for whole crown defoliation index (W).

Thus, trees which had died in the period 1977 to 1979 had significantly higher scores for dieback indices than those which remained alive. The trend was also strongly reflected in the death rate between 1977 and 1979 for trees with progressively higher defoliation indices in 1977 (Figure 7b).

It was concluded from these results that the abnormally high death rates of native trees on the New England Tablelands (defined in this paper as New England Tree Mortality) were strongly associated with symptoms of severe defoliation and secondary shoot development (defined as New England Dieback).

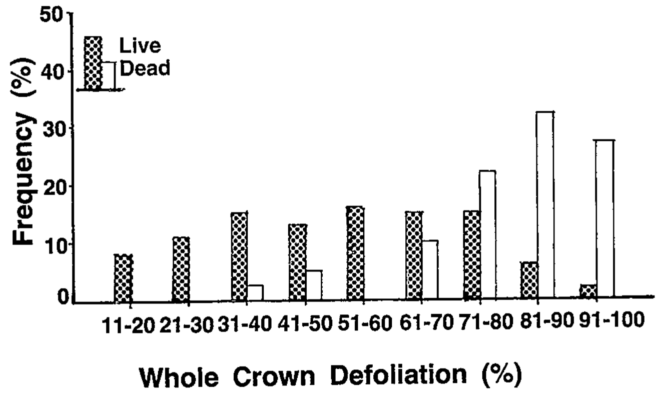


Figure 7a. Distribution of 1977 whole crown defoliation indices (8 re-surveyed plots) for both dead and live trees in 1979.

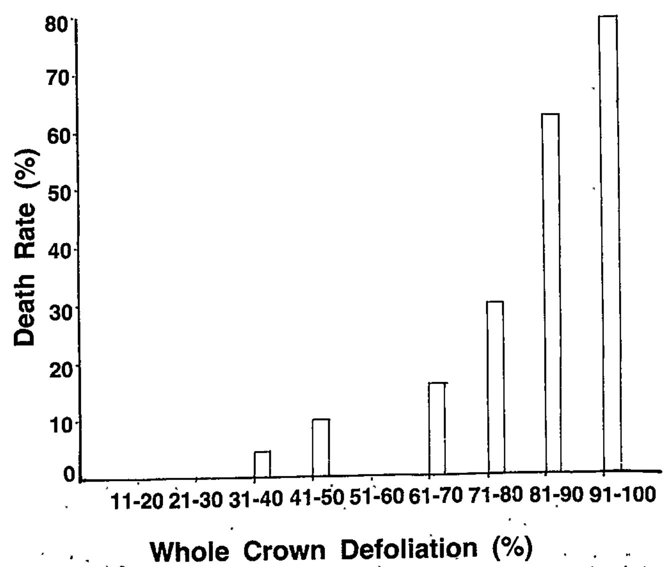


Figure 7b. Distribution of death rate between 1977 and 1979 in relation to 1977 whole crown defoliation indices (8 re-surveyed plots).

Repeated defoliation by either insects or animals, has been associated with tree death in previous Australian studies. Gall (1978) noted that koala grazing was killing trees in the Tucky Nature Reserve in northern N.S.W. Bamber and Humphreys (1965) showed that native tree deaths which followed prolonged and severe repeated defoliation by Psyllids or Phasmids in coastal and tableland locations in N.S.W. could be attributed to the inability of trees in such situations to build up sufficient reserve carbohydrates to produce and maintain a new crown. They demonstrated that repeated manual defoliation of *Angophora costata* trees (at 2 monthly intervals) led to their death in about 18 months. This process gradually depleted the sapwood starch reserves until insufficient remained to supply the energy required to form new shoots. At this stage the trees died. This may also be the mechanism of tree death on the New England Tablelands.

3. Insecticide Experiment

Results of the insecticide experiment are shown in Figure 8. At the first measurement (15.12.77) none of the trees had been treated and there was no significant difference in the crown condition of trees planned for treatment and control trees. For the three subsequent comparisons treated trees were significantly less defoliated ($p<0.01$) than untreated trees (Figure 9).

The different numbers of observations (n) for the measurements were due to the different timing of the first treatment on one plot and its forced abandonment between the third and fourth measures, due to ringbarking by cattle. Since the plot was treated three weeks before the other two plots, which gave it protection during a period of high insect grazing pressure, its results were excluded from the first measurement means.

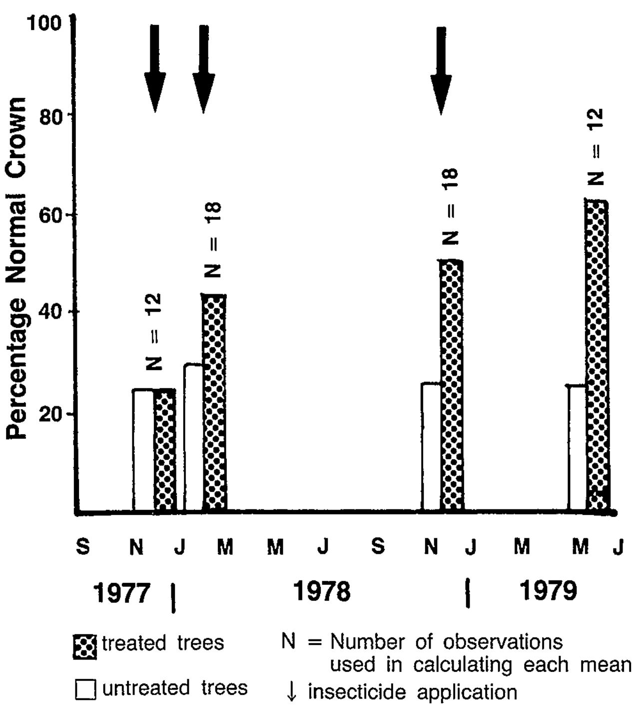


Figure 8. Mean crown condition for treated and untreated trees in the systemic insecticide experiment.

The initial improvement of control trees between the first and second measures may have been due to some protection being provided by the close proximity of treated trees. However, observations made in the plots during that time indicated the recovery may also have been due to a decline in the very heavy leaf grazing pressure by scarabaeids which had occurred during the two to three weeks preceding the first treatment.

Overall, the experiment demonstrated the importance of insects as defoliating agents and confirmed observations made during the main survey. The results have been reinforced by a further experiment established on properties around Glen Innes in 1978 by E. E. Taylor (pers. comm) in which 106 trees (*E. viminalis, E. blakelyi, E. nova-anglica* and *E. melliodora*) were treated regularly for the five years to the end of 1983. One percent of these trees died during the period, which included a severe drought, compared with 32% of 364 untreated trees in close proximity to the treated trees.

SUMMARY AND CONCLUSIONS

In this study two aspects of rural tree decline on the New England Tablelands were considered separately. These aspects were:

- symptoms of poor health displayed by living trees.
- death rates of native trees.

The symptoms investigated and defined as New England dieback were crown defoliation, death of primary shoots and secondary shoot development. No other widespread symptoms of ill health were encountered during the survey either during detailed examination of plot trees or from casual observation of the general tree population. Mistletoe was an important symptom in highly localised areas only. No trees were seen which had died with normal crowns. All dead trees which still retained evidence of their crown condition at the time of death (fine branchlets were lost from dead trees in 12-18 months) had been defoliated to some extent and many also had secondary shoots. Thus, it was concluded that symptoms defined as New England Dieback were the predominant symptoms of rural tree decline on the New England Tablelands.

By re-examining a sample of trees 2 years after the initial assessment it was shown that trees with high levels of dieback were more likely to die than those with low levels. Thus, a link between particular symptoms of living trees and high tree death was established.

Based on these findings a plausible mechanism of tree death is exhaustion of energy reserves by continuous high demands to regenerate foliage. Under further defoliation pressure trees die because they have insufficient energy available to re-establish their crowns.

Defoliation to varying degrees was evident on all 590 live trees examined in the plot survey and 60% had recent branch epicormic shoots. Two species — *E. nova-anglica* and *E. blakelyi* — were significantly more affected by dieback than all other species.

Significant trends of increasing defoliation with decreasing levels of dominance and maturity were evident for non-epicormic foliage. A possible explanation of this result is that higher stress levels on the less dominant and less mature trees render them more attractive to insect defoliators.

By contrast, there were no significant trends found for the level of epicormic defoliation with dominance and maturity classes suggesting that the relatively high nutrient status of this foliage is probably unaffected by the dominance or maturity level of the tree on which it occurs.

There was no consistent effect of tree density on dieback. Non-epicormic defoliation was independent of tree density but levels of epicormic defoliation and the proportion of epicormic shoots increased significantly with decreasing tree density. We conclude that while it is likely tree density has a definite influence on some aspects of the dieback phenomenon it also appears to have little influence on others.

Dieback was independent of most site factors recorded during the survey. Only three factors — slope position, drainage and aspect — were important, with the highest levels of dieback on northerly aspects, in depressions and on poorly drained sites. Because of limitations imposed by the data we regard these results as providing indications of factors to consider in future studies only, rather than as firm conclusions.

Insects were implicated as the main defoliating agents from detailed observations on individual trees made during the plot survey and from the significant crown recovery of trees protected from insect grazing by application of systemic insecticide. Based on these findings, observations of patterns of defoliation and previously demonstrated casual relationships, we concluded that repeated defoliation by insects was a major factor in the decline and premature death of native trees on the New England Tablelands at the time of this study.

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Figure 9. Crown recovery due to protection from insect grazing in the insecticide experiment.
A. Tree No. 8 *(Eucalyptus blakelyi)* at the time of first treatment showing a much reduced and entirely epicormic crown and extensive death of ultimate branchlets.
B. Tree No. 8 after 18 months of insecticide treatment showing a nearly normal crown.
C. Tree No. 6 *(Eucalyptus blakelyi)* at the commencement of the experiment showing similar symptoms to tree No. 8 at the same time. This tree (No. 6) was not treated.
D. Tree No. 6 after 18 months without treatment. Very few leaves remained and most ultimate branchlets were dead.

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APPENDIX

Probability values (%) from which significance levels in Tables 5 and 8 were derived.

Table 5 (see main text).

Factor	D	E	U	W	$\frac{W+U}{2}$
	Dieback Index				
Full model	$<5x10^{-4}$	$<5x10^{-4}$	$<5x10^{-4}$	$<5x10^{-4}$	$<5x10^{-4}$
Density (trees/ha^{-1}	12	2.4	$2.0x10^{-1}$	31	1.1
Plots (P)	$<5x10^{-4}$	$<5x10^{-4}$	$<5x10^{-4}$	$<5x10^{-4}$	$<5x10^{-4}$
Species (S)	$<5x10^{-4}$	$3.2x10^{-1}$	$<5x10^{-4}$	$<5x10^{-4}$	$<5x10^{-4}$
P x S	$<5x10^{-4}$	4.5	$2.4x10^{-1}$	$<5x10^{-4}$	$<5x10^{-4}$
Dominance	$9x10^{-3}$	11	4.4	$5.9x10^{-2}$	$<5x10^{-4}$
Maturity	$3.7x10^{-2}$	61	15	$3.0x10^{-2}$	9.3

Regression analyses based on 590 data sets with 66 degrees of freedom for full model.

Table 8 (see main text).

Factor	D	E	U	W	$\frac{W+U}{2}$
	Dieback Index				
Full model	3.8	6.5	2.1	4.7	3.7
Aspect	4.1	13	34	5.7	8.5
Slope	13	5.3	48	13	23
Geology	50	52	3.9	75	26
Drainage	43	64	$9.7x10^{-1}$	96	16
Fertilizer	92	18	68	78	99
Pasture Species	83	94	33	98	67
Ground Cover	66	27	31	76	51
Cultivation	56	51	12	83	38
Understorey	52	85	28	94	59
Slope Position	1.3	$9.8x10^{-1}$	17	1.0	2.3
Tree density class (trees/ha^{-1})	8.3	24	4.2	21	7.6
Tree density class (BA/ha^{-1})	12	22	91	7.6	28

Regression analyses based on 30 data sets with 21 degrees of freedom for full model.