Ecological Implications of Insect Pests in Jarrah and Karri Forests

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Abstract

Unlike most forested parts of the world, the hardwood forests of Western Australia did not experience insect outbreaks until 30 years ago, even though these forests have been commercially logged for up to 80 years.

This paper reviews what is known and what is not known about the three most important forest insect pests and their impact on conservation values and stand dynamics and productivity. These pests are: *Perthida glyphopa*, jarrah leafminer (Lepidoptera, Incurvariidae); *Uraba lugens*, gumleaf skeletonizer (Lepidoptera, Noctuidae); and *Tryphocaria acanthocera*, bullseye borer (Coleoptera, Cerambycidae).

Current research is summarized under five broad headings, and 12 additional high priority research requirements are briefly discussed.

INTRODUCTION

No serious insect problem was reported in jarrah (*Eucalyptus marginata*) forest until the early 1960s, when the feeding of jarrah leafminer (Table 1) caused extensive defoliation of jarrah crowns east of Manjimup. This infestation has gradually extended west and north, and at present occurs as far north as Collie.

A second problem arose in 1983 when outbreaks of gumleaf skeletonizer were first recorded in jarrah forest between Nannup and Walpole. Infestation by this species expanded within this region until 1985. It then declined and from 1989 has not been of concern.

The only insect problem known in karri (*E. diversicolor*) forest concerns the bullseye borer, the larvae of which bore within the bole of karri. Foresters became aware of this problem in 1967.

The relative importance of these species is shown by the most recent reliable estimates of areas infested: jarrah leafminer, 420 000 ha in 1976; gumleaf skeletonizer, 240 000 ha in 1986 (0 ha infested in 1991); bullseye borer, not known but probably not exceeding the area of even-aged regenerated karri stands (currently 40 000 ha). Leafminer infests 56 per cent of the high quality jarrah forest.

The maximal extent of recent infestations by leafminer and by skeletonizer is marked in Figure 1.

This paper updates Abbott (1985), and reviews and summarizes knowledge about these three insect species, discusses their impact in the forest, outlines current research conducted by CALM, and concludes with a catalogue of urgent research needs.

PAST RESEARCH AND CURRENT KNOWLEDGE

The three major insect pests in jarrah and karri forests have not been given the same degree of research attention. The oldest problem, jarrah leafminer, has been studied longest (CSIRO 1962 - 1988, Forests Department and CALM 1967 and 1984 to the present).

Jarrah leafminer

The CSIRO studies have yielded a detailed body of information on life history (Wallace 1970; Mazanec 1980, 1983, 1984a, b; Mazanec and Justin 1986), population biology (Mazanec 1978, 1981), natural enemies (Mazanec 1987, 1988a, 1990a, b), resistant trees (Mazanec 1974, 1985), chemical control (Wallace 1966), and the short term impact of infestation on wood increment (Mazanec 1974).

Table 1

TAXONOMIC DETAILS FOR INSECT SPECIES IN THE ORDER MENTIONED IN THIS PAPER

Venacular Name	*Latin Binomial*	*Order*	*Family*
Jarrah leafminer	*Perthida glyphopa*	Lepidoptera	Incurvariidae
Gumleaf skeletonizer	*Uraba lugens*	Lepidoptera	Noctuidae
Bullseye borer	*Tryphocaria acanthocera*	Coleoptera	Cerambycidae
-	*Diadegma* sp.	Hymenoptera	Ichneumonidae
-	*Chrysonotomyia* sp. C	Hymenoptera	Eulophidae
Leafblister sawfly	*Phylacteophaga froggatti*	Hymenoptera	Pergidae
Autumn gum moth	*Mnesampela privata*	Lepidoptera	Geometridae
'Cup moth'	*Doratifera quadriguttata*	Lepidoptera	Limacodidae
-	*Liparetrus* spp.	Coleoptera	Scarabaeidae
-	*Chrysophtharta amoena*	Coleoptera	Chrysomelidae
-	*Paropsisterna elliptica*	Coleoptera	Chrysomelidae
'Spitfires'	*Perga* spp.	Hymenoptera	Pergidae

The extent of infested forest was mapped by the Forests Department in 1964-1967 and in 1983, and by CSIRO in 1968-1976 and 1980. These maps, drawn to a common scale, are included in Abbott (1987).

The involvement of the Forests Department in leafminer research has until recently been minimal. Van Didden (1967) showed that an experimental aerial spraying of jarrah stands was ineffective and uneconomic. Since 1984 research has concentrated on measuring damage levels near Manjimup and Collie, relating these to environmental factors, and quantifying medium term impact on crown condition and wood increment (Abbott unpublished).

Information on silvicultural control and the cause(s) of the outbreak is less comprehensive and more speculative. The approach used in the CSIRO study involved sampling the abundance of larvae after they had ceased feeding, and expressing this variable in relation to a defined area of jarrah canopy. The abundance of moths emerging from soil has also been measured relative to a defined area of the forest floor. Studies in the same stands over several years have been used to assess the impact of prescribed low intensity fires, logging, clearing, and annual variation in rainfall on relative abundance of final instars and/or moths.

The approach used in the CALM research involved marking newly developing leaves each November (or as soon as the petiole is long enough to hold a tag) since 1984 in 20 stands within a 50-km radius of Manjimup. This research was extended in November 1987 to 20 stands within a 40-km radius of Collie. For each stand, damage caused to leaves by leafminer is expressed as a percentage of fully expanded leaf area. Multiple regression analyses were used to correlate this variable with environmental factors such as stand basal area, years since previous fire, years since previous logging, average annual rainfall, percentage forest cover and soil texture.

During 1983-1987 J. Hall of CALM estimated the extent of browning caused by leafminer in each jarrah crown in 15 plots north-east of Manjimup. Some of these trees experienced crown scorch during autumn burning during the study period.

Life history (Table 2)

Moths emerge and fly during the day. They are weak fliers. At night or during cold wet days they seek shelter in the litter. Almost all eggs are laid on the lower surface of jarrah leaves (Wallace 1970), at 14-22°C in diminishing light or overcast conditions (Mazanec 1986). The longevity of moths averages 10 days in the laboratory.

The caterpillar stage (within the leaf) lasts 160 days. After feeding finishes (instar 4), the caterpillar falls to the ground within a case, generally around midnight, to avoid predation by ants (Mazanec 1980). It then burrows 1-2 cm

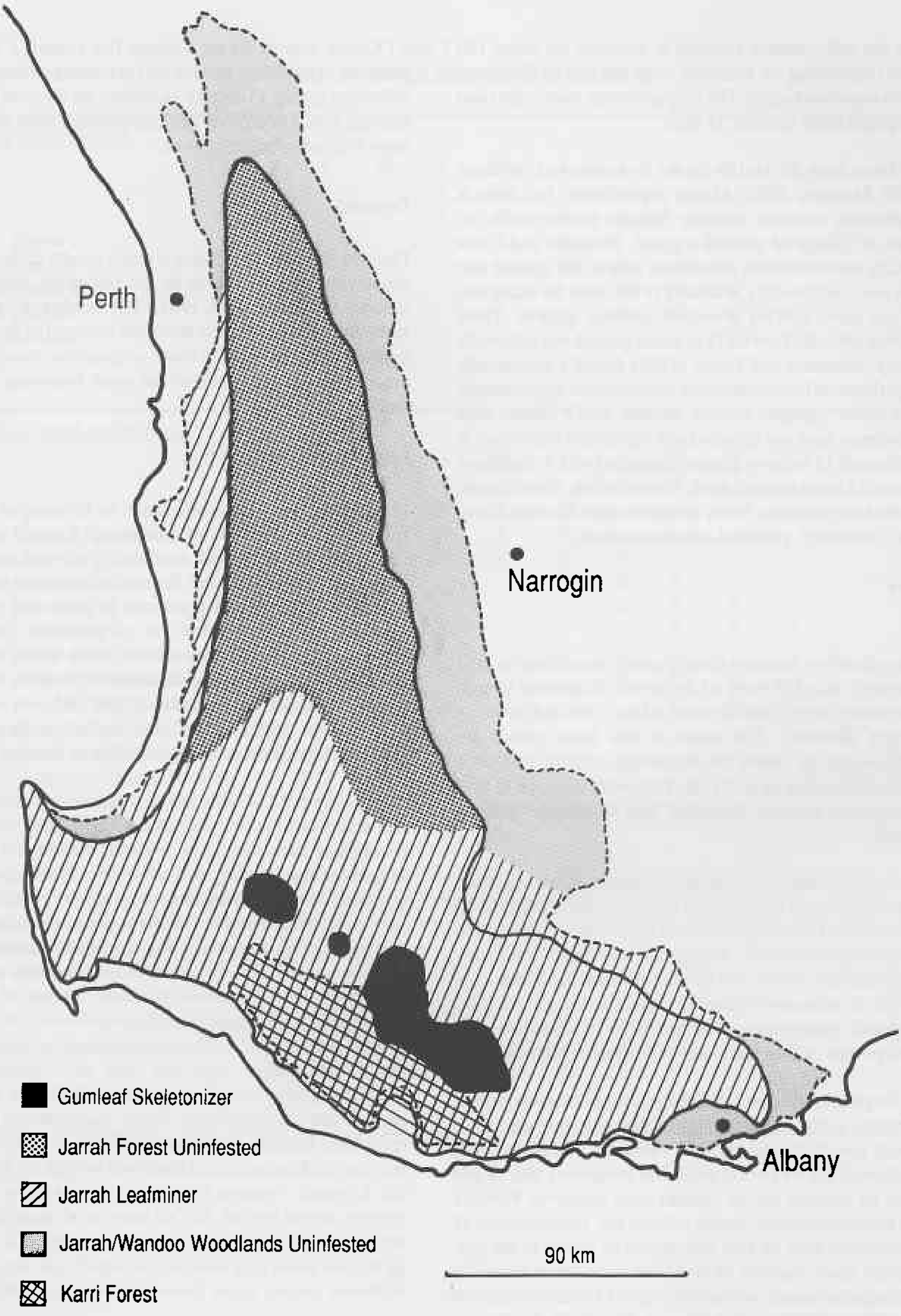

Figure 1.

Maximal extent of recent outbreaks of leafminer and skeletonizer in jarrah forest and woodland.
There has been no forestwide survey of leafminer outbreaks since 1983.
Since 1989, gumleaf skeletonizer has not been in outbreak.

into the soil, where it remains in diapause for about 150 days (depending on latitude), until the end of February, when pupation begins. The prepupal stage lasts 2 days and the pupal stage another 35 days.

Most eggs are laid in leaves 6-months-old (Wallace 1970; Mazanec 1986; Abbott unpublished) but there is conflicting evidence whether females prefer crowns of trees or foliage of ground coppice. Newman and Clark (1925) noted heaviest infestation nearer the ground and this was confirmed by Wallace (1970), with the exception of one stand lacking abundant advance growth. There infestation in the crowns 12 m above ground was extremely heavy. Mazanec and Justin (1986) found a statistically significant difference between infestation in upper canopy and lower canopy. CALM studies in 12 stands near Manjimup have not detected any significant difference in infestation 12 m above ground compared with 1-2 m above ground (Abbott unpublished). Nevertheless, where female moths have a choice, lower levels are used for oviposition first (Mazanec[1], personal communication).

Fire

Prescribed low intensity fires in spring, depending on their intensity, may kill most of the larvae diapausing in soil. But adults (moths) can disperse at least 1 km and probably farther passively. The result is that burnt stands are recolonized by moths the following autumn (Mazanec 1980, 1981). For up to 2 years following this type of fire, many more eggs are deposited than in adjacent unburnt stands.

Spring burning rejuvenates the forest crown, resulting in production of more leaves on which females prefer to oviposit the following autumn. These females then have a wider choice of leaves. Damage to individual leaves may not attain the 40 per cent threshold which the human eye perceives as brownish tinge in the forest canopy (Abbott, personal observation). The presence of abundant new foliage thus dilutes the effect of leafminer infestation.

Regression analyses of damage to tagged leaves (ground coppice) at 40 locations in the central and southern jarrah forest found 26 per cent of variation in damage was accounted for by period since fire (negative) and 14 per cent by average annual rainfall (also negative). Perhaps the latter correlation simply reflects the concentration of oviposition sites on few new leaves in stands in the low rainfall zone. Surveys of stands recently burnt in spring and adjacent stands not burnt for up to 11 years indicate no significant increase of leafminer density in the former (Abbott, unpublished).

Crown scorch during autumn fire caused a notable decrease in leafminer infestation (percentage damage) the following spring (Table 3). However, by the next spring, damage levels could not be distinguished from adjacent trees with unscorched crowns.

Drought

Drought (particularly during winter) results in decreased production of new leaves in the following spring and summer (Mazanec 1980, 1981). The number of eggs laid in the following autumn is therefore low, and so the leaves available should receive more oviposition, resulting in more damage and therefore obvious browning of the canopy.

Logging and regeneration

Logging followed by regeneration or thinning of stands results in rejuvenation of remaining foliage, perhaps responding to increased availability of soil moisture (Mazanec 1980, 1981); this favours oviposition. Advance growth is released and continues to grow and provide plentiful foliage suitable for oviposition. Detailed behavioural studies (Mazanec and Justin 1986) indicate that logging by itself should disfavour oviposition, because gravid females require subdued light and cool weather (<20°C). The abundance of new leaves (i.e. those with suitable oviposition sites) may be the true limiting factor.

Wallace (1970), using broad-scale surveys, concluded that severe infestations were usually associated with open country, or with natural or artificial clearings. He then suggested that logging and other silvicultural practices which tend to open up the forest may require modification. Mazanec (1980) examined this hypothesis more closely by measuring stand basal area at 42 places within the leafminer outbreak zone and at 38 places in non-outbreak areas in November 1978. The averages were 30 and 38 m^2ha^{-1} respectively, a statistically significant difference. However, recent research by CALM near Manjimup has shown that neither stand basal area nor time since logging are significant predictors of leaf damage by leafminer, but that rainfall zone is significant. These discrepancies can be reconciled because the difference between outbreak and non-outbreak areas in stand basal area very likely describes the difference between stands experiencing low or high average annual rainfall. Recent surveys of stands recently logged and adjacent stands either never logged or logged up to 100 years ago indicate no significant increase in leafminer density in the former (Abbott, unpublished).

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[1] Z. Mazanec, CSIRO Division of Entomology, Floreat W.A.

Table 2

LIFE CYCLES OF THREE PEST FOREST INSECTS

JARRAH LEAFMINER

	J	F	M	A	M	J	J	A	S	O	N	D
adult				X	X							
egg				X	X							
{instar 1					X	X						
{instar 2						X	X					
caterpillar {instar 3							X	X				
{instar 4							X	X	X	X		
larva in case in soil	X	X							X	X	X	X
prepupa		X	X									
pupa		X	X									

GUMLEAF SKELETONIZER

	J	F	M	A	M	J	J	A	S	O	N	D
adult		X	X									
egg		X	X	X	X	X						
{instar 1 (G)				X	X	X						
{instar 2 (G)					X	X	X					
{instar 3 (G)						X	X	X				
{instar 4 (G)							X	X	X			
{instar 5 (G)								X	X	X		
caterpillar {instar 6 (S/G,1head capsule)						X	X	X				
{instar 7 (S/G,2head capsules)							X	X	X			
{instar 8 (S/G,3head capsules)								X	X	X		
{instar 9 (S,4head capsules)	X	X								X	X	
{instar 10 (S,5head capsules)	X	X										X
{instar 11 (S,6head capsules)	X	X										X
pupa	X	X										

S = solitary phase

G = gregarious phase

S/G = some caterpillars are solitary, others are gregarious.

BULLSEYE BORER

	J	F	M	A	M	J	J	A	S	O	N	D
adult	X	X										X
egg	X	X										X
larva (instars unstudied) 2 years }	X	X	X	X	X	X	X	X	X	X	X	X
}	X	X	X	X	X	X	X	X	X			
pupa										X	X	

Table 3

EFFECT OF CROWN SCORCH DURING AUTUMN FIRES ON SUBSEQUENT INFESTATION OF LEAFMINER IN JARRAH CROWNS.

Plot No.	*Recent fire history*	*No trees*	*% of jarrah crowns infested [a] with leafminer in Spring*				
			1983	*1984*	*1985*	*1986*	*1987*
501	Spring 1980	15	18.7	21.0	16.7	35.0	17.3
505	Autumn1983	48	22.7	27.5	38.8	68.1	40.6
506	Autumn 1985[b]	31	32.9	27.3	22.4	26.3	22.6
557	Spring 1984	17	86.8	65.3	43.5	36.2	37.1
558	Spring 1984	15	95.0	76.7	65.7	62.3	60.8
559	Autumn 1986	16	93.8	92.5	69.4	53.1	82.2
		not scorched				*69.2*	*87.5*
		scorched				*2.5*	*66.3*
560	Spring 1984	20	92.5	59.8	43.0	50.3	59.0
561	Autumn 1986	25	88.0	64.6	51.6	6.0	11.6
		not scorched				*15.5*	*14.0*
		scorched				*0.0*	*11.1*
562	Spring 1981	27	55.0	52.8	57.2	42.4	42.8
564	Spring 1984	12	87.5	70.0	64.6	70.8	68.8
565	Autumn 1986	36	76.7	74.6	73.5	71.0	64.2
		not scorched				*75.2*	*68.8*
		scorched				*50.0*	*40.8*
566	Autumn 1986[b]	27	94.4	60.4	60.7	54.8	61.9
567	Spring 1984	13	96.2	47.3	38.5	55.4	61.2
618	Spring 1983	14	94.6	43.6	63.9	66.8	66.1

[a] at least 20 per cent of crown brown, caused by leafminer

[b] no crowns were scorched by this fire

Outbreaks

The occurrence of outbreaks of leafminer may be modelled in three ways (Fig. 2; Ridsdill-Smith[2] personal communication). Model 1 may apply to stands near Manjimup (infested for more than 20 years) whereas model 3 certainly would apply to Collie region (infested for 5-10 years). Model 2 is not supported by CSIRO data.

Reasons for a non-outbreak stand being transformed into an outbreak stand are not clear. Single factor explanations are not supported by the history of human use and management of the forest. Thus, fire was used by Aborigines; many areas near Collie and Manjimup were cut-over in the 1920s, yet these were free of outbreaks until recently. The outbreaks beginning east of Manjimup were recorded around farms near Lake Muir in the 1870s (Mazanec, personal communication). Yet the surrounding jarrah forest remained free of outbreaks until the 1960s.

Severe leafminer infestation itself promotes further infestation, because severely damaged leaves are shed in October instead of the normal January-February period (Mazanec 1980). This premature abscission contributes to an abundance of new leaves suitable for oviposition the following autumn.

Site

It is commonly observed that sandy sites in the southern jarrah forest consistently have browner canopies than upland sites. Sandy sites may result in more stress than

[2] J. Ridsdill-Smith, CSIRO Division of Entomology, Floreat W.A.

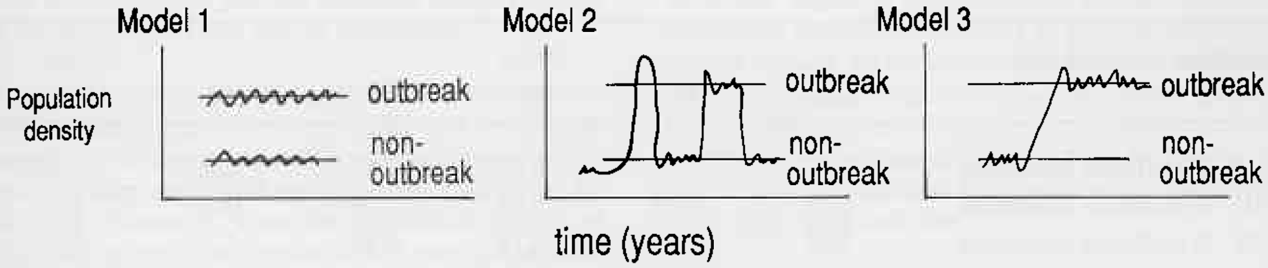

Figure 2.
Three models of how outbreaks of pest insect species may occur

Model 1 suggests that population density increases to outbreak levels then fluctuates somewhat about a mean density but not falling to non-outbreak levels over considerable periods of time (e.g. the Greenhouse Whitefly, F.D. Morgan, personal communication).

Model 2 shows typical periods of outbreak and non-outbreak varying in intensity and duration (e.g. Ips bark beetles, Sirex woodwasp).

Model 3 is in effect the early stage of Model 1.

lateritic sites, though the occurrence of the former in valleys contradicts this. Outbreaks were recorded in woodland (not forest) near Perth, Bunbury and Albany over 70 years ago (Newman and Clark 1925) - these are sandy sites.

One of the major obvious differences between the northern and southern jarrah forests is the more extensive gravelly soils in the former. The absence of leafminer from much of the northern jarrah forest may be related to this textural difference, given that the insect pupates in the soil. However, an experiment in the northern jarrah forest showed that gravelly surface soils are no impediment to larval penetration (Mazanec 1980).

Resistance

Not all jarrah are infested by leafminer to the same degree. Wallace (1970) termed individuals with only slight damage 'resistant' and those severely damaged 'susceptible'. Within outbreak areas, the crowns of resistant trees appear green whereas those of susceptible trees are brown. At low levels of infestation, the two types may be best distinguished (Mazanec 1980) by the abundance of aborted mines (containing dead larvae) and the scarcity of cutouts (made by fully developed larvae after they exit from their mines) within leaves of resistant jarrah.

CSIRO studies indicate that about 25 per cent of jarrah trees are resistant to larval feeding by leafminer (Mazanec 1974, 1980). One tree is known to be resistant to egg development and another tree is known to resist both oviposition and egg development (Mazanec 1985). This last tree differs from all other trees studied in its leaf anatomy; it also lacks tannin in its palisade tissue.

Analysis of data collected by CALM Inventory Branch suggests that none of the 406 jarrah trees assessed was strictly resistant to leafminer (Table 4). Yet Mazanec (1974) found that *c*.25 per cent of jarrah were 'resistant' to leafminer. This discrepancy can be reconciled by inferring that Mazanec tolerated the presence of some cutouts in crowns when he classified trees as resistant. These data imply that infestation by leafminer of tree crowns up to 20 per cent was the criterion subconsciously applied in the CSIRO study (Table 4). This yields an overall proportion of 'resistant trees' in these plots of 0.22, close to the figure quoted by Mazanec (1974, 1980).

Using this criterion, there is great variation among stands north-east of Manjimup in the proportion of jarrah 'resistant' to leafminer infestation (Table 5). Most stands had considerably less than 10 per cent of trees resistant. These plots also show that very few of the supposed resistant trees were in fact resistant each year between 1983 and 1987. This again highlights the incorrectness of equating 'absence of leafminer infestation' with 'resistance to leafminer infestation'.

Table 4

VARIOUS CRITERIA FOR RECOGNIZING JARRAH RESISTANT TO LEAFMINER INFESTATION IN CALM INVENTORY PLOTS IN THE SOUTHERN JARRAH FOREST

Proportion of jarrah with	*1983*	*'84*	*Spring '85*	*'86*	*'87*	*Grand Mean*
0 % leafminer infestation [a]	0	0	0.003	0.13	0.003	0.001
≤10 % leafminer infestation	0.09	0.03	0.05	0.19	0.21	0.11
≤20 % leafminer infestation	0.15	0.16	0.15	0.30	0.32	0.22
≤30 % leafminer infestation	0.27	0.33	0.29	0.44	0.44	0.35
≤40 % leafminer infestation	0.27	0.47	0.43	0.53	0.53	0.45
Total No. trees	323	373	375	375	374	

[a] Recognized as browning of jarrah crowns.

Table 5

SPATIAL VARIATION IN PROPORTION OF JARRAH 'RESISTANT' IN SPRING 1985 TO LEAFMINER INFESTATION Assuming ≤20 per cent infestation of each crown by leafminer as the criterion of 'resistance'

Plot No.	*Total No. trees*	*No. trees 'resistant'*
501	16	12
505	49	9
506	33	24
557	17	3
558	15	0
559	17	0
560	20	2
561	68	4
562	28	0
564	16	0
565	37	1
566	29	0
567	14	1
618	16	1
Total	375	57

Natural enemies

Mazanec (1987) recorded 10 species of Hymenoptera as parasitoids of the immature stages of leafminer. Parasitoids were more common in one plot within the northern jarrah forest (non-outbreak) compared with two plots in southern jarrah forest (outbreak). Relative mortality of feeding larvae was greater in non-outbreak than in outbreak situations.

Much is known (Mazanec 1988a, b, 1990a, b) about the basic biology of these parasitoids. Most species fluctuate markedly in numbers from year to year. A key factor analysis (Mazanec unpublished) indicates that these parasitoids are unlikely to prevent outbreaks. Most species have several generations per year and so require an alternative host during October to April when leafminer is within the soil. This is not available, so most of the parasitoids could never attain consistently high densities from year to year.

The two univoltine species are *Diadegma* sp. and *Chrysonotomyia* sp. C. The former is very rare but is not specific to leafminer, whereas the latter can be abundant, but is specific to leafminer (Mazanec, personal communication). Both species are internal parasitoids of larvae.

The most promising species, *Chrysonotomyia* sp. C, is apparently adversely affected by fire. Mazanec (1988a) found it present at high densities in the Meribup fire exclusion area (last burnt in 1962) in comparison with two stands experiencing the normal prescribed fire regime. Percentage parasitization by this species varies directly over the range 23-48 per cent with both annual variation in leafminer abundance and air temperature.

A systematic survey by CALM research staff in October 1987 of jarrah stands between Collie and Dwellingup found many examples of jarrah leaves with aborted mines, resulting from successful parasitoid control north of the outbreak. However, when the population density of leafminer increases as a result of increased oviposition, often helped by immigrating female moths, there is usually no proportional increase in parasitization (Mazanec 1988b). Birds also have minor impact because none irrupt during outbreaks and the local populations soon become satiated with leafminer larvae (Mazanec 1988b).

Key factor analysis

Mazanec (personal communication) has found that the main k factor in the life table of jarrah leafminer is natality. Once leafminer is present, the major cause of year to year variation in density is change in the abundance of leaves younger than six months.

Gumleaf skeletonizer

Since 1983 information has been gathered by the Forests Department and CALM on distribution of moderately and severely defoliated stands (1983, '84, '85 and 86), life cycle and hosts (Strelein 1988a), and damage levels in jarrah crowns and ground coppice, and development of a suitable method for sampling caterpillars (Abbott unpublished). This sampling has served to document the decline in skeletonizer density since 1987 (Farr[3], personal communication).

In the bulk of the forest there is only one generation each year (Table 2). The moth is nocturnal, does not feed, is a poor flier, and is probably shortlived. It mates in February and March and the female then lays her eggs in a series of parallel rows, usually on the underside of a leaf 1-4 months old. The eggs hatch from April to June and the small caterpillars feed together on the same leaf until about August. This gregarious phase lasts until about October when the caterpillars become largely solitary (2 or 3 per leaf) and more mobile, often using silken threads to cross to the other trees.

Caterpillars in the gregarious phase confine their feeding to the green leaf matter of the leaf, leaving patches of the brown network of veins. Those in the solitary phase are more voracious: they also eat smaller veins and frequently leave only the midrib and irregular portions of the lamina.

In stands of forest where caterpillars are dense, browning of crowns begins in late November to late December (depending probably on weather). In any case crowns are at their thinnest by the end of January when nearly all caterpillars pupate. Pupation occurs in cocoons spun by the caterpillars; these cocoons are placed on the branchlets near the leaves the caterpillars have been feeding on, in branch forks, or under bark flakes on large branches or the upper trunk, or in leaf litter.

Between January 1986 and January 1988, foliage from crowns of 45 jarrah poles, piles or trees (within a 50-km radius of Manjimup) was collected every 3 months and sorted for all individuals of invertebrate species present (Abbott, unpublished). The immediate environment of these 45 jarrah was quantified, as follows: basal area, proportion of jarrah present, years since previous fire, years since logging and average annual rainfall. The number of caterpillars expressed in terms of oven-dry leaf weight varied directly with rainfall. Thus, in contrast to leafminer, skeletonizer is more abundant in jarrah stands receiving higher rainfall. No significant statistical association between type of forest management and degree of infestation was found (Abbott unpublished).

Unlike leafminer, skeletonizer can feed on many eucalypt species, including karri, marri (*E. callophylla*), and wandoo (*E. wandoo*).

Strelein (1988a) and Abbott (1990) have circumstantial evidence that the extent of skeletonizer outbreaks since 1983 is greatest following dry, warm winters. However, it is not known whether this could be caused by annual variations in rainfall and minimum temperature acting directly on skeletonizer caterpillars or indirectly through parasitoids or predators or even the host tree.

Very few skeletonizer caterpillars occur on ground coppice (i.e. jarrah no taller than 1-2 m) (Abbott unpublished).

No jarrah poles, piles or trees resistant to skeletonizer feeding have yet been found. Even jarrah resistant to leafminer is susceptible to feeding by skeletonizer. During the past outbreak there was an urgent need for forest managers to arrange systematic searches for jarrah resistant to skeletonizer feeding. These searches are best carried out during January within skeletonizer outbreaks so that jarrah with green crowns would be obvious.

The only previously recorded outbreak of skeletonizer occurred in spring 1947 between Calingiri and Cowaramup. So few details are now available that it is uncertain whether the northern jarrah forest was affected by this outbreak.

[3] J. Farr, CALM Research Centre, Manjimup, W.A.

The most recent outbreak in the southern jarrah forest began in 1982, resulting in widespread browning of crowns in January 1983. Some 90 000 ha of jarrah forest between Nannup, Greenbushes and Walpole were affected. One year later the infested area covered 230 000 ha. In January 1985 and 1986 the extent of outbreak was 300 000 ha and 240 000 ha respectively. Maps showing the maximum annual extent of the outbreak (in January) have been produced for 1983, 1984, 1985 and 1986 (see Abbott 1987). The outbreak has since declined (Abbott 1990).

In January 1986 the severity of infestation by skeletonizer was quantified by crownometer in two stands near Yornup, based on 200 random observations in each stand. Crown cover was 66 per cent in the outbreak and 54 per cent in the non-outbreak stand. The proportion of brown jarrah foliage was 60 per cent and 2 per cent respectively, and that of brown marri foliage was 7 per cent and 0 per cent.

Bullseye borer

The life history (Table 2) of this insect was elucidated by Clark (1925) in a study done mainly on marri near Mundaring. Interestingly, although recording six eucalypt species as hosts, Clark did not include karri. Voutier (unpublished) studied aspects of the biology of this species in karri from 1983 to 1985, and found several differences from Clark's study, particularly the presence of 'frass ejection vents' along the bole, where the larva empties out the contents of its tunnel. Infestation was found to be widespread throughout the karri forest and have the capacity to inflict severe structural damage to young vigorous karri regeneration.

Borer damage is also associated with brown wood, i.e. heartwood, which develops rapidly into decayed wood (Donnelly, unpublished), and with kino exudation from frass ejection vents (Voutier, unpublished). Interestingly, Clark (1925) vigorously disputed that this borer was the main cause of kino veins in marri.

In 1986 R. Smith (CALM Research Division) studied the association between internal borer damage and external symptoms on karri trees, and statistical analysis showed that the association was significant. These data revealed that infestation of karri regeneration began sometime between 10 and 14 years of age. In 1987, Smith surveyed 30 stands of karri regeneration, and recorded on a sample of 50 trees in each stand five indications of external damage caused by bullseye borer, dominance status, bole length, stem diameter and bark thickness at breast height. Stand age, years since the last fire, coupe size, site type, average annual rainfall, stand basal area, proportion of marri present and distance to nearest non-regenerated karri forest were also recorded for the stand.

Most bullseye borer damage is associated with proximity to mature karri stands, sites where karri is a minor component before regeneration, small coupe size and site susceptibility to drought (Abbott *et al.* in press).

ECOLOGICAL IMPLICATIONS

The impact of pest insect species on the ecology of jarrah and karri forest has been measured for only a few attributes, namely biomass of other crown-dwelling invertebrates, condition of jarrah crowns, wood increment, and mortality of jarrah.

It was fortunate that leafminer outbreaks developed in W.A. decades after methods of organic chemical control became commercially available in the 1940s and had been enthusiastically adopted in North America and Europe to control insect outbreaks. By the 1960s it was widely appreciated that insecticides have adverse environmental and evolutionary consequences, including water pollution, contamination of birds and mammals feeding on affected insects, extensive mortality of non-target insects, and evolution of resistance by pest insects to chemicals, which counteracts their efficacy. Insecticides have not been used to reduce leafminer outbreaks.

Conservation values

It is reasonable to hypothesize that stands with insect-damaged crowns would offer fewer feeding sites, less food and fewer suitable oviposition sites for other invertebrates compared with stands in which most of the foliage comprising the canopy is green.

In the southern jarrah forest, samples have been collected (9 sampling dates over 2 years x 45 trees) from jarrah both unaffected and affected to varying degrees by gumleaf skeletonizer caterpillars. These samples have been sorted to species level, and the biomass of each species has been estimated from a body length/oven-dry mass regression based on a representative sample of species. Biomass of each sample is expressed relative to oven-dry mass of foliage in the sample.

A graph (Fig. 3) showing the biomass of all invertebrates (excepting skeletonizer) in relation to the biomass of skeletonizer caterpillars in the same sample clearly shows that there is no significant relationship. Similar graphs were prepared for Coleoptera, Araneae, Hemiptera, other Lepidoptra, Hymenoptera, Diptera, other leaf chewers,

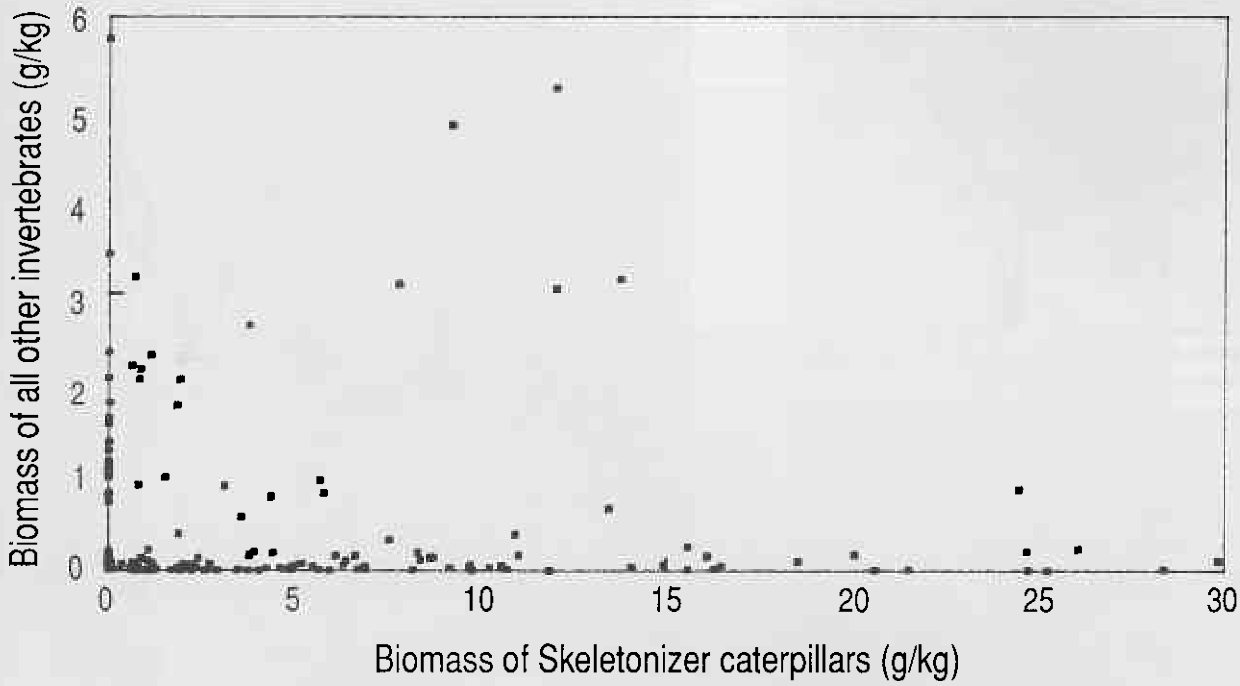

Figure 3.

Biomass of all invertebrates (kilogram oven-dried/kilogram foliage oven-dried) graphed against biomass of skeletonizer caterpillars (same units) in samples collected from crowns of jarrah poles in the southern jarrah forest during 1986-1988 (N=405).

parasitoids, and predators. None showed any significant correlation. Therefore, skeletonizer has not caused any measurable deterioration in the microhabitat of the hundreds of other indigenous/endemic invertebrate species living in jarrah crowns.

Stand dynamics and productivity

Assessment of whether jarrah crowns are deteriorating in width, depth and leaf density

In 1970 a questionnaire (M. Wallace, CSIRO, unpublished) asked foresters at Manjimup whether leafminer attack affected the forest canopy and general tree vigour in any viable way and whether any visible change was confined to jarrah leafminer infested areas only.

Most foresters circularized believed that permanent damage resulted from jarrah leafminer infestation. They noted that where defoliation had only recently begun, crown deterioration had not reached the severity of old infestations. Deterioration appeared rapidly within 5-10 years. Photographs of selected jarrah crowns (Fig. 4) best show the extent of this deterioration.

These conclusions are supported by studies on inventory plots rating the condition of the crown of selected codominant and subdominant jarrah resistant or susceptible to leafminer. C. Ward (CALM Research Division) used a modified version of an Index (Grimes 1978) based on visual estimates of leaf density, contribution of epicormic branches to foliage and the incidence of dead branches. The index ranges from 0 (tree dead) to 24 (see Appendix).

Resistant poles in high and low quality jarrah forest had above average (=12) indices of crown condition (Table 6). The deterioration in crown condition caused by leafminer was greatest in codominant poles in low quality forest (44 per cent), followed next by codominant poles in high quality forest (35 per cent). Crowns of subdominant poles deteriorated least (19 per cent). These data, when combined with those in Table 7, indicate that diameter under bark (d.u.b.) increment would be zero when the crown condition index has a value of 9-10 or below.

CALM policy concerning thinning of jarrah stands is that all resistant trees are retained regardless of size, position or quality (Bradshaw 1987).

The conditions of the crowns of tagged jarrah poles was assessed in 1988 on plots established by Mazanec (personal

Figure 4a Crown of healthy mature jarrah pole. Crown condition index = 23

Figure 4b Crown suffering from recent insect infestation. Crown condition index = 14

Figure 4c Crown showing early signs of degradation. Crown condition index = 13

Figure 4d Crown showing severe degradation. Crown condition index = 10

Figure 4e Detail of crown showing severe degradation. Crown condition = 12

Figure 4f Full extent of pest insect impact on jarrah crowns is obvious when seen from afar. High quality forest

Figure 4g Full extent of pest insect impact on jarrah crowns is obvious when seen from afar. Low quality forest

Table 6

MEAN INDEX OF CROWN CONDITION FOR CODOMINANT AND SUBDOMINANT JARRAH POLES IN HIGH AND LOW QUALITY STANDS IN THE SOUTHERN JARRAH FOREST

Stand quality	*Crown condition*			
	Codominant		*Subdominant*	
	Resistant	*Susceptible*	*Resistant*	*Susceptible*
High (9 plots)	17.5	11.3	15.6	12.7
Low (6 plots)	17.0	9.5	16.2	13.1

Table 7

MEAN D.U.B. INCREMENT (cm y^{-1}) SHOWN BY CODOMINANT AND SUBDOMINANT JARRAH POLES IN HIGH AND LOW QUALITY STANDS IN THE SOUTHERN JARRAH FOREST

Stand quality	*d.u.b. increment*			
	Codominant		*Subdominant*	
	Resistant	*Susceptible*	*Resistant*	*Susceptible*
High (9 plots)	0.23	0.11	0.19	0.15
Low (6 plots)	0.16	0.04	0.14	0.06

communication) in 1967. The two plots in high quality forest were free of leafminer outbreaks in 1968 whereas the two plots in low quality forest had experienced outbreaks for at least 5 years (Mazanec, personal communication). Poles were selected in 1968 on the basis of having a perfect crown (Mazanec, personal communication), equivalent to 24 in the rating scheme used in 1988 (Appendix).

Resistant trees (as designated by Mazanec) in all plots showed remarkably similar declines in crown index (-24.2 to -29.6 per cent, average -26.8 per cent) over the 21-year period (Table 8). This presumably is caused mainly by drought. Fire was not a factor as one plot had experienced no fire since 1962 (Table 8).

Susceptible trees (as designated by Mazanec) showed an average crown decline of -40.5 per cent (range -30.4 to -46.3 per cent) during the 21-year period (Table 8). Comparison of the crown condition of susceptible and resistant poles in each plot shows that the average difference is 18.2 per cent (range 8.2 - 28.3 per cent), i.e. leafminer outbreaks over two decades are responsible for nearly 20 per cent of the deterioration in jarrah crown condition.

Outbreaks of leafminer reached Collie district between 1975 and 1983. A comparison in 1987 of jarrah plots within the outbreak zone, with those to the north of the outbreak shows that poles in high quality forest experienced most deterioration in crown condition (Table 9). Poles in low quality forest had similar crown condition irrespective of location with respect to outbreaks, perhaps a legacy of past wildfires. Similar relationships were found for diameter under bark (d.u.b.) increment (Table 9).

Table 8

MEAN INDEX OF CROWN CONDITION IN 1988 FOR JARRAH POLES IN HIGH AND LOW QUALITY STANDS IN THE SOUTHERN JARRAH FOREST. ALL TREES IN 1967 HAD INDEX VALUE = 24.

Stand quality	*Crown condition*	
	Resistant	*Susceptible*
High		
Diamond	18.2 (13)	16.7 (12)
Marranup	16.9 (14)	14.1 (15)
Low		
Boyicup	18.0 (2)	12.9 (9)
Cessna	17.2 (10)	13.8 (10)

NOTE: (1) All but 6 of the 85 trees assessed in 1988 had subdominant crowns.

(2) Year when last burnt: Diamond (Spring 1973), Marranup (Spring 1985), Boyicup (Autumn 1981), Cessna (Spring 1962).

Table 9

MEAN INDEX OF CROWN CONDITION AND MEAN D.U.B. INCREMENT (cm y^{-1}) FOR CODOMINANT AND SUBDOMINANT JARRAH POLES IN HIGH AND LOW QUALITY STANDS IN COLLIE DISTRICT (NOVEMBER 1987).
All jarrah were classified as susceptible to leafminer.

Stand quality	*Codominant*		*Subdominant*	
	Crown index	*d.u.b. increment*	*Crown index*	*d.u.b. increment*
High				
- in outbreak zone (4 plots)	13.6	0.11	14.3	0.15
- not in outbreak zone (3 plots)	19.4	0.40	19.3	0.51
Low				
- in outbreak zone (3 plots)	14.2	0.11	16.7	0.07
- not in outbreak zone (3 plots)	14.2	0.07	17.4	0.16

NOTE: Outbreaks of leafminer reached these plots between 1975 and 1983.

Wood growth

It has long been recognized that leaf-eating insects reduce the growth rate of Australian forests (Jacobs 1955).

Short-term effect of leafminer on wood growth
Mazanec (1974) assessed the short-term impact of leafminer on diameter increment by measuring the diameter (over bark) of 58 resistant trees and an equal number of susceptible trees on four sites near Manjimup from 1967 to 1971.

One site, Diamond, had very low levels of leaf damage (not specified by Mazanec 1974, but certainly <40 per cent, Mazanec personal communication), and a comparison of the diameter increments of resistant and susceptible trees there showed no appreciable difference. However, the other three sites experienced 'severe' leaf damage (i.e. 60 per cent of the average leaf area of susceptible jarrah was damaged by leafminer, Mazanec personal communication), so that the annual loss of diameter increment per susceptible tree at these sites ranged from 64-79 per cent (mean 71 per cent). The annual loss of diameter increment per tree (susceptible and resistant jarrah combined) varied from 49-61 per cent (mean 54 per cent). Thus, within severely infested forest, diameter increment of the jarrah component is about half of its value in non-outbreak forest (Mazanec 1974).

Mazanec (1974) estimated that 400 000 ha (25 per cent) of State jarrah forest was affected by moderate to heavy leafminer infestation (i.e. an average of 40 per cent of leaf area damaged). The loss in wood growth over such a large area is of concern.

The four plots just mentioned were a subset of seven plots established by Mazanec in 1969 in which 20 trees were tagged. An additional four plots were established in 1980.

Medium and long-term effects of leafminer on wood growth
Medium-term effects have been assessed on a selection of inventory jarrah plots in Manjimup, Pemberton and Nannup Districts. Most of these plots were first measured in 1961 or 1971. C. Ward (CALM Research Division) visited 15 plots, selected codominant and subdominant jarrah poles, noted whether they were resistant or susceptible to leafminer and remeasured diameter over bark (d.o.b.) and bark thickness. These data allow calculation of growth losses over 15-25 year periods (Table 7).

The diameter (under bark) loss in high quality stands is 52 per cent for codominant poles and 21 per cent for subdominant poles (or an average of 38 per cent). In low quality stands the comparable figures are 75 per cent and 57 per cent (66 per cent). Because future intensive silviculture will be carried out only in high quality stands, the loss in low quality forest is not relevant. To put these data on a stand basis, it is necessary to multiply by 0.75 (the proportion of susceptible trees). Assuming that average volume under bark (u.b.) production is 1 m^3 ha^{-1} per year and given that 420 000 ha of high quality jarrah forest is infested by leafminer, then the *annual* loss in wood growth caused by leafminer is about 0.38 x 0.75 x 420 000 or 120 000 m^3. Allowing for 50 per cent utilization, this amounts to a loss of more than $1m in sawlog royalty each year. These figures could be made more precise if the volume of wood produced per hectare per year by codominant and subdominant jarrah in high quality stands in the southern jarrah forest were known.

Effect of skeletonizer on wood growth
About 118 000 ha of high quality jarrah forest was infested moderately-severely by skeletonizer at the latest estimate (January 1986). Given that the proportion of jarrah resistant to skeletonizer appears << 1 per cent, then by analogy with leafminer the loss of wood growth owing to skeletonizer should be 118 000 x 0.38 or 45 000 m^3 y^{-1}. This was equivalent to about $0.35m per annum in sawlog royalty, allowing for 50 per cent utilization.

Effect of bullseye borer on wood growth
The main impact of this borer is that its tunnels within the karri bole affect the utilization of timber. However, as yet, no detailed estimates of wood loss are available.

Mortality of jarrah

Effect of chronic infestation

Leafminer outbreaks have not yet resulted in any extraordinary mortality of jarrah trees, as evidenced from 11 plots kept under long-term investigation by CSIRO. In six plots (Cessna, Boyicup, Boyicup East, Marranup, Diamond and Dingup) established in 1969, only three out of 120 trees had died by 1987; and one of these trees had never experienced much leafminer damage (Mazanec, personal communication).

In four other plots (Gold Gully, Stallard, Easter and Jubilee) established in 1980, none of the 80 trees had died up to 1987.

Combining these data, mortality owing to leafminer is 0.11 per cent per annum, i.e. 11 trees die per 10 000 trees per annum.

Dynamic processes

The intermediate (900-1100 mm p.a.) and low (<900 mm p.a.) rainfall zones cover the parts of the jarrah forest most favoured by leafminer. The most relevant watercourses include the Helena, Canning, Serpentine, Harvey, Collie, and Donnelly Rivers and Bell Brook, Bingham River, Harris River, Beraking Brook, Darkin River, Nockine Brook, and Bannister River. Though several of these streams feed into the reservoirs serving metropolitan Perth, recent related research has indicated that any forest decline over the next 20 years should not cause appreciable rises in water table or increases in water salinity (Stokes and Batini 1986).

CURRENT RESEARCH

Details of current research activities are set out in CALM's Research Division Research Plan, 2nd - 4th editions. These activities are only summarized here.

Insect ecology

Leafminer

When leafminer completes its feeding in the jarrah leaf, it cuts itself out of the leaf while remaining in a cell, which falls to the ground. Since October 1986, the presence of 'cutouts' in leaves has been recorded at predetermined sampling points in forest north of the Collie outbreak. These data allow accurate measurement of the rate of spread of leafminer populations north of the outbreak.

The level of parasitism of leafminer larvae in mines within, and to the north of, the leafminer outbreak near Collie is being assessed.

The effect of moderate intensity fire on leafminer and condition of crowns is being assessed in 240 ha of jarrah forest north of Collie which was burnt in autumn 1989. It is hoped that these fires could be used to reduce the rate of spread of the outbreak farther into the northern jarrah forest.

The effect of leafminer damage on biomass of other invertebrates in jarrah crowns is being investigated at 15 sites in Collie district.

Skeletonizer

Studies of the population dynamics of caterpillars have commenced. These will indicate between which instars most mortality occurs.

Laboratory cultures of caterpillars collected from forest are being used to detect parasitoids. The preferred site of pupation is being studied as a possible means of population control.

The impact of an autumn fire on population densities is being assessed in an area of 100 ha north-west of Manjimup.

The effect of size of the female moth on fecundity is being measured.

The northern limit of distribution in jarrah forest has recently been determined.

The occurrence of bivoltine populations and their taxonomic status is under investigation.

Bullseye borer

Studies of oviposition preferences are underway.

Monitoring levels of herbivory in jarrah forest

In 1984, an unbiased method of sampling leaves was developed (Abbott 1987). A herbarium of damaged foliage, consisting of voucher specimens on which insects were observed feeding, has been compiled. It is now possible to reliably assign most examples of damaged foliage to a particular insect species or family.

Damage levels in ground coppice jarrah in Manjimup region have been quantified annually since 1984, and since 1987 in Collie region. Damage levels in pole crowns have been measured less frequently. Damage levels in ground coppice in the Jarrahdale-Dwellingup region were measured on the 1985, 1987 and 1989 cohorts of leaves.

Variation in damage levels in terms of site and season are now well understood. Multiple regression analyses are being used to relate damage levels to environmental factors. The complexity of interacting factors makes factorial experimentation impracticable at this stage.

Research into economic injury levels has focused on manual defoliation of ground coppice jarrah. It is reasonable to expect that a threshold exists, below which damage has no impact on jarrah growth. An experiment using ground coppice in Holmes Block was set up in December 1987 to assess the interaction between proportion of foliage removed (0,25,50,75,100 per cent) and number of annual defoliations (0,1,2,3).

Monitoring potential pests

More than 20 insect species have been found damaging jarrah, marri or karri leaves. Surveillance is maintained on several species which are known outside the forest or elsewhere in Australia to occasionally cause severe defoliation. These include *Phylacteophaga froggatti, Mnesampela privata, Doratifera quadriguttata, Liparetrus* spp, *Chrysophtharta amoena, Paropsisterna elliptica* and *Perga* spp.

P. froggatti (leafblister sawfly) was introduced into Western Australia in 1978 (Curry 1981) and rapidly spread throughout the south-west. Jarrah is not attacked but marri is very susceptible to defoliation. Curiously, although the species has been recorded at Boyanup and Manjimup, it has so far not penetrated into the forest.

The remaining species listed are indigenous. Several of them are widespread in jarrah forest but never locally abundant. Life history details are collected opportunistically for each of these species.

A species of leafminer has been recorded sporadically on leaves of karri in the main karri belt. In the Porongurup Range, this species has recently caused significant damage to the foliage of karri saplings.

Mapping of outbreak areas and hazard rating of stands

The current extent of the outbreak of leafminer favours the use of remote sensing techniques to map insect damage in forests. The CSIRO Remote Sensing Group is involved in determining the spectral, temporal and spatial characteristics required of a remote sensing system to enable discrimination of insect-infested forest (Behn *et al.* 1990). One test area (Collie) is being used; results to date are promising and may lead to a practical and routine inventory system being implemented.

Any surveys must be carried out in October (for leafminer) and in January (for skeletonizer) because they depend on the recognition of brown crowns. If deferred, surveys are useless because the flush of new green leaves after insects cease feeding quickly obscures insect damage.

Hazard rating is a recognition that stands differ in their vulnerability to damage by insects. Hazard is determined by the influence of climatic, site and management factors on observed damage levels. It differs from risk, which is an assessment of the probability of spread from nearby stands experiencing insect outbreaks or after a particular forest operation. Reliable prediction of hazard and risk would enable the forest manager to judge which forest management practices should aggravate outbreaks. The aim of forest management in terms of outbreaks is to know how stands free of outbreaks can be kept in this condition, and how stands experiencing outbreaks can be manipulated to reduce damage to an acceptable level. In State forests, the aim is to reduce infestation and so promote wood growth and perfect conservation and aesthetic values, whereas in national parks and reserves the goal is to improve aesthetics and nature conservation values.

CALM is planning to map the occurrence in selected areas of the site-vegetation types devised by Havel (1975) and Strelein (1988). These maps will then be used to assess whether particular site-vegetation types associate strongly with susceptibility to infestation by leafminer or skeletonizer. Such information would allow CALM to plan to manage certain site-vegetation types differently from others.

The likely future distribution of outbreaks of leafminer and skeletonizer is not clear. Both species occur at present well north of the current area affected by outbreaks (Fig. 1). North of Dwellingup, leafminer was recorded up to 1988 at low densities in Randall, Lesley, Flynn, and Victoria forest blocks, and since that year in many forest blocks. The only records of skeletonizer north of Collie are from Illawarra, Lesley, Randall, Holmes, Clark and Proprietary forest blocks. However, outside the forest, skeletonizer occurs very widely in an area bounded by the coastline, Geraldton, Merredin and Esperance (Abbott 1987).

If the rate of expansion of leafminer outbreaks follows that experienced during the 1960s and '70s near Manjimup, then the leafminer outbreak should reach Dwellingup by 2011, Jarrahdale by 2028 and Mundaring by 2043.

Monitoring of jarrah crowns

The condition of crowns of jarrah is being monitored regularly near Collie (180 trees) and near Manjimup (45 trees). This procedure should provide early warning of any marked deterioration in crown condition or unusual mortality resulting from outbreak populations of defoliating insects.

The current inventory of jarrah forest being carried out by Inventory Branch of CALM should provide forest-wide estimates of jarrah mortality. Stands with known histories of insect outbreaks could then be compared both with each other and with stands in non-outbreak zones.

HIGH PRIORITY ADDITIONAL RESEARCH REQUIREMENTS

1. *Impact of repeated, chronic defoliation on nutrient levels in, and physiological condition of, jarrah*

A physiologist could examine small numbers of trees, within and without outbreak areas, and resistant or susceptible to defoliators, and draw precise conclusions about impacts of defoliators on the well-being of jarrah trees. Very early warning of any impending mass collapse of stands would be gained. It would also be valuable to evaluate the physiological response of jarrah to a combination of experimental intensities and repetitions of defoliation.

2. *Reasons for the initiation and continuation of outbreaks*

The outbreak of leafminer that began more than two decades ago in the southern jarrah forest had no historical precedent, since European settlement. Newman and Clark (1925) recorded that noticeable damage was confined to the 'coastal jarrah growing on the plains country', mainly near Fremantle, Bunbury, Busselton and Albany, but radiating inland ' for several miles to the base of the foothills'. They noted explicitly that no damage was recorded in the country between Torbay and Busselton or in the Darling Range forests. Outbreaks near Perth (Kings Park) were first recorded in 1914.

This historical perspective invites the question 'What initiated the 1960s outbreak in forest east of Manjimup?' Obvious perturbating factors include fire (a change in intensity, season of burning, frequency of burning or combinations of all three factors), logging, deforestation (for farming and settlement) and subtle changes in climate (rainfall, temperature, soil dryness index). Mazanec (1988b) argues that any factor that leads to the production of new leaves will lead to an increase in population of leafminer.

Associations between some of these variables and expansion of leafminer and skeletonizer outbreaks could be sought by modelling. The maps in Abbott (1987) would serve as a start. Then the more accurate maps that would be produced using remote sensing techniques would allow refinement of these models. It is hoped that these models could explain why leafminer and skeletonizer have become forest pests only within the past 25 and 5 years respectively.

3. *Search for parasitoids of leafminer and skeletonizer elsewhere in Australia*

This would complement the research completed by CSIRO on local parasitoids of leafminer and the research being done by CALM on skeletonizer parasitoids already present in the southern jarrah forest. Research interstate would ideally be covered by the CSIRO Division of Entomology and the Department of Entomology, Waite Institute of Agricultural Science, South Australia.

4. *Virological, bacteriological and/or mycological options for controlling leafminer and skeletonizer*

If research on parasitoids yields little of value, it may be necessary to study the natural importance of viruses, bacteria and fungi in killing pest insects, and to evaluate whether other viruses, bacteria and fungi should be introduced to control pest insect populations without detriment to non-pest insect populations.

In particular there is a need to examine whether aerial spraying of foliage with commercially available *Bacillus thuringiensis* would contribute to control of leafminer, without prejudicing conservation values by reducing the abundance of other invertebrates (particularly Lepidoptera) living in jarrah crowns.

5. *Selection of jarrah resistant to leafminer and skeletonizer*

A workable definition of resistance needs to be devised. Trees and regeneration immune to pest insect infestation could then be identified and retained throughout the jarrah forest. The feasibility of readily increasing the proportion of resistant trees in stands requires investigation.

It is necessary to test trees with resistant phenotypes (i.e. crowns unaffected in stands severely affected) and establish a genetic basis by collecting seed, growing seedlings and testing them in culture and within forest.

6. *Comparison of bird populations within and outside outbreak areas*

Extensive browning of jarrah crowns may lessen their suitability as habitat for insectivorous birds. Expansion of outbreak areas may result in some of these bird species declining in distribution and abundance within jarrah forest. The suitability for birds inhabiting crowns of unaffected species such as marri or yarri also needs to be assessed.

7. *Taxonomic expertise*

The taxonomy of many potentially economically important insect groups is out-of-date or confused. The major taxa are Chrysomelidae, Cerambycidae, Curculionidae, *Doratifera*, *Lyctus* and *Ochrogaster*.

This would be an ideal subject for CSIRO to service, as the Division of Entomology has the major national collection (ANIC) and the largest national group of insect taxonomists.

8. *Nitrogen fertilization and thinning of jarrah stands*

There is a need to determine whether proposed operational thinning and application of nitrogen fertilizers (during winter) will favour or disfavour leaf-feeding by leafminer and other insect species.

9. *Damage to foliage of* Eucalyptus rudis

A limited comparison in 1985 of damage by insects, fungi and other agents to the leaves of the eight eucalypt species growing in forest in the Manjimup region (Abbott unpublished) found that *E. rudis* experienced almost as much damage as jarrah. To the east of State forest *E. rudis* becomes an important component of the lower parts of the landscape and may help mitigate salinity problems in agricultural areas in the lower south-west. There is a need to investigate why *E. rudis* is attractive to insect herbivores.

10. *Impact of outbreaks on water quality*

Historical records of groundwater levels, stream flow and salinity levels in subcatchments in the northern and southern forests should be examined to determine whether leafminer infestation has produced measurable changes. These subcatchments have or should have <900 mm annual rainfall, be free of any deforestation, lack wandoo and have comparable densities of marri. Hydrologic records for the period 1940-1960 (before leafminer outbreaks) could be compared with those for the period 1960-1980, during which leafminer outbreaks have persisted. Comparisons between adjacent subcatchments in the southern jarrah forest (one severely affected by leafminer, the other not so) would also be useful but difficult.

11. *Plantations of* Eucalyptus globulus

Plans to reforest tens of thousands of hectares of farmland in the south-west could result in insect outbreaks (especially *Mnesampela privata* and Psyllid species) developing in these stands and then spreading to adjacent native hardwood forests.

Monitoring of insect populations and experimental studies of chemical, silvicultural and biological control should be an essential component of the development of these plantations.

12. *Argentine Ant*

This species, *Iridomyrmex humilis*, was accidentally introduced to Western Australia in 1941. It is a very aggressive species, eliminating most native ant species. In South Africa, displacement of seed-dispersing native ant species resulted in reduced germination of many native plant species. There is therefore a need to survey the jarrah and karri forest for Argentine ants and if necessary carry out control measures.

CONCLUSION

Factors affecting the long-term population dynamics of jarrah leafminer and gumleaf skeletonizer are poorly understood. The evidence available indicates that forest operations have not been responsible for recent outbreaks of these insects. It is not yet possible to assess the problem of bullseye borer outbreaks because old-growth karri trees have not been sampled.

From an economic perspective, insect problems in jarrah forest are probably as serious as dieback in jarrah forest caused by the fungus *Phytophthora cinnamomi*.

If pest insect outbreaks can be controlled, then the following benefits would follow: improvement in wood productivity; improvement in the condition of tree crowns, lessening the risk of death of jarrah after long periods of intense defoliation, and consequential detrimental effects on forest hydrology, conservation, and aesthetics.

The hardwood forests of south-western Australia are currently valued in excess of $1 000m (G. Malajczuk[4] personal communication). They are therefore a significant asset deserving of protection from outbreaks of injurious insects.

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APPENDIX

Assessment of jarrah crowns (based on method of Grimes 1978). The value of the index ranges from 0 to 24.

LEAF DENSITY

(exclude epicormics on bole)

9	very dense
7	dense
5	average (refers to ideal, not the stand)
3	sparse
1	very sparse
0.5	all leaves dead
0	leaves absent

If much fruit is present, increase the score by 1.

INCIDENCE OF DEAD BRANCHES

9	none present
8	< 50% of branchlets dead
7	$\geq$ 50% of branchlets dead
6	< 50% of small branches dead
5	$\geq$ 50% of small branches dead
4	< 50% of large branches dead
3	$\geq$ 50% of large branches dead
2	< 50% of primary branches dead (epicormics present)
1	$\geq$ 50% of primary branches dead (no epicormics)
0	all branches dead

CONTRIBUTION OF EPICORMIC BRANCHES TO FOLIAGE

6	no epicormics present (foliage concentrated at extremities of branches)	
5	on crown or bole	< 25%
4	on crown or bole	> 25-50%
3	on crown or bole	> 50%
2	on crown and bole	< 50%
1	on crown and bole	$\geq$ 50%
0.5	on crown and bole	100%
0	tree is dead	