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Review of the ecology and control of the introduced bark beetle *Ips grandicollis* (Eichhoff) (Coleoptera: Scolytidae) in Western Australia, 1952–1990

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SUMMARY

This paper reviews and collates historical material, previously unpublished, relating to *Ips grandicollis*, hereafter called *Ips*, in pine plantations in Western Australia. Within 10 years of being discovered, *Ips* was distributed in nearly all plantations. *Ips* initially caused concern to foresters because it introduces blue stain fungi to felled logs. Attack of felled logs by *Ips* is retarded by cool weather. Low temperatures also increase the length of the larval phase of the life cycle. Available data indicate that logs of radiata pine are more attractive to *Ips* than those of pinaster pine.

By 1970 the coincidence of a severe drought and canopy closure of many hectares of radiata pine plantations in the Blackwood Valley led to outbreaks of *Ips*, resulting in some feeding attacks. Subsequent droughts in 1972, 1979 and 1987, combined in some instances with inadequate disposal of thinning slash, led to further outbreaks. The balance of local evidence available indicates that *Ips* is a secondary pest of the pine.

From 1984 to 1990, Western Australia participated in a national scheme to establish biological control agents (insect predators and parasitoids) to help minimize future *Ips* outbreaks. Only the parasitoid *Roptrocerus xylophagorum* (Hymenoptera, Pteromalidae) has established in Western Australian plantations, where an average rate of parasitization of *Ips* of *c.* 5 per cent was recorded in 1990.

INTRODUCTION

Ips grandicollis (Eichhoff) (hereafter *Ips*) was first recorded in Western Australia in September 1952. Western Australia and South Australia are the only parts of Australia where *Ips* and pines have coexisted for more than three decades.

Although research into *Ips* commenced in Western Australia in 1955, the amount of effort allocated has been limited and only one scientific paper has been published (Rimes 1959). During 1966–1979 S.J. Curry[1] carried out surveys, none of which were published. A search of files of the Department of Agriculture and of the Forests Department revealed existing records of data collected to be fragmentary. Nonetheless, studies of *Ips* in South Australia (Morgan 1967, 1989) and Victoria (Neumann and Morey 1984) complement this information.

This review organizes existing facts and information into two time frames. The period 1952 to 1982 included the important necessary steps of documenting the spread of *Ips* through the south-west of Western Australia, elucidating its life history, and devising operational techniques for limiting the damage that outbreaks may cause to the pinewood resource. The second phase, 1984 to 1990, involved a biocontrol program carried out in conjunction with the *Ips* Project Management Committee (Australian Forestry Council), and the formulation of a prescription for the introduction of biocontrol agents into pine plantations managed by the Department of Conservation and Land Management (CALM).

THE INSECT: DISTRIBUTION, HABITAT AND SEASONAL ACTIVITY

Description

See Wood (1982: pp 699–701) for a full diagnosis.

Distribution in Northern Hemisphere

According to Wood (1982), *Ips* ranges over most of the eastern half of North America, from southern Manitoba and Quebec to Florida, and Mexico and Central America.

[1] Forest Entomologist, Department of Agriculture, Western Australia from 1964 to 1984.

Introduction to Australia

The species was first recorded in Australia, at Wirrabara in South Australia, in 1943 (Morgan 1967).

Distribution in Western Australia

In 1952 *Ips* was recorded only in Collier and Somerville plantations near Perth. The species is presumed to have reached Western Australia through shipment of infested material to Fremantle. It is not known whether such material came from South Australia or directly from North America.

By 1954 *Ips* was found in the Gnangara, Scaddan, Mudros and Greystone plantations near Perth as well as in metropolitan timber yards, but not in plantations further south. In 1962 *Ips* was present in all plantations except Boranup. By 1968, Curry recorded it in all plantations except two comparatively isolated ones south and east of Pemberton and Manjimup respectively. It has since reached these and has been recorded further east at Albany (see map in Abbott 1985).

Habitat

The main breeding habitat of *Ips* is fresh slash material (either from felled or wind blown material) and recently felled logs (Rimes 1959). Standing trees damaged by fire, lightning or weakened by drought are also attacked (see also below). In Western Australia attack has been recorded on eight species of pine. Neumann (1987) records attack on 10 species of pine in Australia and Wood (1982) lists 16 *Pinus* species which are attacked in North America. Both adults and larvae feed on the inner bark tissues of conifers. Wood felled for more than one year becomes too dry to sustain *Ips*.

Life cycle

The following account is condensed from Rimes (1959), Morgan (1967), and Neumann and Morey (1984). Two types of attack on trees may be found. Only males can initiate the breeding attack, whereas either sex can initiate the feeding attack.

In the *breeding* attack, the male enters the inner bark (cambium) and constructs a nuptial chamber. Both the initial attraction of females and the aggregation of the population are mediated through the production of pheromones. A female later enters and constructs an egg gallery from the chamber. Mating occurs, after which the female constructs lateral galleries into which eggs are laid. Eggs hatch in 7–12 days, depending on temperature. There are three[1] larval instars, each lasting 5–9, 6–10, and 6–10 days. Each larva produces a mine more or less perpendicular to the brood gallery. (If the bark is removed, the overall pattern of tunnels resembles an engraving in the sapwood.) Upon maturation a pupal chamber is formed and metamorphosis occurs. The freshly hatched adults bore to the outside of the wood, making an exit hole. Bark thickness influences larval survival, as thicker bark ensures a higher moisture content of cambium and this promotes survival. The fastest period from oviposition to emergence is *c.* 45 days in South Australia, in contrast to 60 days in Victoria. In South Australia 4–5 generations per year are recorded, whereas only 4 occur in Victoria.

In the *feeding* attack no nuptial chamber or brood galleries are constructed. Instead, the phloem, cambium and outer sapwood of live trees, recently killed trees and freshly felled logs are damaged. Such an attack is often found in the branches and upper bole during February and March.

SEASONAL ACTIVITY

Aims and Methods

A detailed study of seasonal activity in four plantations close to Perth was carried out by S.J. Curry during 1966 and 1967. Pinaster pine (*Pinus pinaster*) was studied at Collier in compartments 12 (planted 1932), 21 (1933) and 23 (1934), Somerville 51 (1940) and 57 (1945), Greystones 11 (1950) and Beraking 1 (1955). Radiata pine (*P. radiata*) was also studied at Greystones and Beraking. Collier and Somerville plantations no longer exist, having been replaced by the suburbs of Bentley and Murdoch to the south of Perth. Greystones and Beraking are on the Darling Plateau 30–45 km east of Perth.

The stated objective of this study was to relate seasonal variation in attack of pine logs by *Ips* to rainfall and humidity, and in particular to establish whether *Ips* is dormant during winter. Two trees were felled in each compartment each month for one year from May 1966. Each tree was cross cut into two 3 m (10 feet) logs and any lateral branches were removed though the crown was left intact. The two logs were placed on old logs so that they were off the ground and could easily be rolled over for inspection.

Logs in Collier compartment 12 were interfered with by firewood collectors; subsequently observations were transferred in July 1966 to compartment 21. Logs were examined within one week of felling and thereafter at fortnightly intervals (Collier, Somerville) or monthly intervals (Greystones, Beraking) for one year. Entry and exit holes were counted and marked with a cork borer and crayon at each inspection. Unfortunately, the diameter of the logs is not recorded in the files, nor is the sampling unit specified unequivocally. Therefore it is not possible to express these parameters in absolute terms. Comparisons between plantations are consequently not possible.

The period between felling and first recorded attacks, and the period between felling and first recorded emergences at the Collier and Greystones

[1] Morgan (1967) recorded four instars. This is now known to be in error, based on head capsule widths of some 'giant' larvae. There are only three moults to the pupa from hatching (F. D. Morgan, personal communication).

compartments has been examined in relation to mean maximum temperature during these periods. Weather data from Perth and Kalamunda, the nearest temperature recording centres, were used.

RESULTS AND DISCUSSION

Dormancy

Ips beetles were inactive from May until late August in all plantations. Dormant beetles were found in old galleries beneath the bark of logs (produced by the last autumn generation in logs then freshly felled) and dead standing trees. *Ips* may also overwinter as larvae or pupae.

Onset of Attack

Attack was recorded as soon as two days after felling, or as late as 64 days after felling (Table 1). A significant inverse relationship was found between mean maximum temperature and the number of days after felling before attack began (Fig. 1).

Emergence of New Generation of Beetles

This took place from November to January for the logs felled in May (autumn), whereas the process took only 15–30 days from logs felled during summer. It is possible that some of the records of <30 days represent re-emergence of attacking adults and not emergence of their brood. There is a strong inverse relationship between number of days from felling to emergence of adults and mean maximum temperature for that period (Fig. 2). Even if the six lowest points are omitted (for the reason just discussed), the strong inverse relationship remains (Fig. 2).

A 15-day generation length in February and March is twice as fast as recorded by Rimes (1959), and implies that a maximum of nine generations between May and April of the following year is possible. However, Rimes (1959) suggested that there could be 6–8 generations per year. This large number of generations per year explains why, under suitable conditions, *Ips* can reach outbreak levels rapidly.

The total number of adult *Ips* emerging from the felled logs shows no uniform seasonal pattern (Table 2): large numbers can emerge during the subsequent 1–15 months from logs felled in any month. Presumably this variability reflects differences in the numbers of *Ips* available to attack freshly felled logs (perhaps related to differences in silvicultural treatment such as thinning, slash management and stand basal area), as well as differences in the frequency of attack, ambient temperature and bark thickness.

A noticeable implication from the data pertaining to the two plantations containing both pine species (Table 2) is that many more *Ips* emerged from the logs of radiata pine. This may indicate that this species is a more attractive host than pinaster. Confirmation of any host preference would require specifically designed controlled field and laboratory studies.

Some anecdotal data available on file indicate that although greatest activity occurs from September to May, unseasonal conditions can extend or inhibit this. For example, *Ips* was still active in June 1967 north of Perth but not so near Mundaring which is wetter and cooler. In November 1968 unseasonal cool weather reduced activity near Perth. Curry considered that activity was usually much less in the south of Western Australia where winters are cooler and wetter. These anecdotes agree with the inverse relationship demonstrated in Figure 1 between time from attack and temperature.

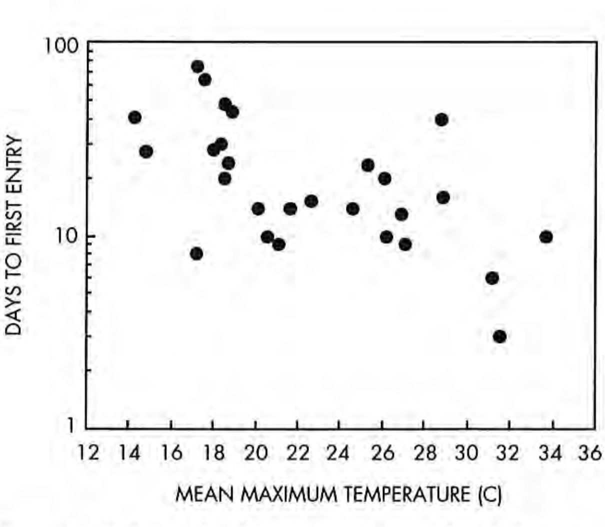

Figure 1. Relationship between number of days before adult Ips *attack freshly-felled logs of pinaster pine and mean maximum air temperature. Data pertain to Collier and Greystones plantations. Least squares best-fit regression:* $\log Y = 2.08 - 0.0366X$ ($r^2 = 0.36$, $P = 0.001$).

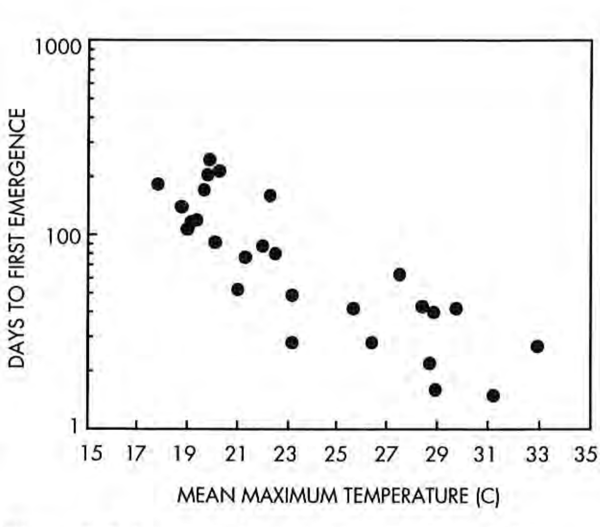

Figure 2. Relationship between number of days before adult Ips *emerge from freshly-felled logs of pinaster pine and mean maximum air temperature. Data pertain to Collier and Greystones plantations. Least squares best-fit regression:* $\log Y = 3.42 - 0.0647X$ ($r^2 = 0.71$, $P = 0.001$).

TABLE 1

Periods between felling of test logs and first emergence of adult *Ips* in 1966–67, based on dates of felling, first recorded attack by beetles and first emergences of progeny.

GREYSTONES													
Date of felling (day/month)	18/5	16/6	14/7	10/8	15/9	13/10	8/11	1/12	10/1	6/2	7/3	4/4	2/5
PINASTER													
Attack first recorded	27/5	27/7	10/8	13/10	13/10	27/10	1/12	10/1	16/1	9/2	20/3	19/4	1/6
(days)	9	41	27	64	28	14	20	40	6	3	13	15	30
Emergence first recorded	16/1	16/1	1/12	16/1	1/12	1/12	10/1	10/1	6/2	21/2	4/4	2/5	2/11
(days)	243	214	140	159	77	49	63	40	27	15	28	28	184
RADIATA													
Attack first recorded	27/5	10/8	27/7	13/10	13/10	27/10	10/1	10/1	16/1	21/2	20/3	19/4	1/6
(days)	9	55	13	64	28	14	63	40	6	15	13	15	30
Emergence first recorded	1/12	1/12	16/1	16/1	16/1	16/1	10/1	10/1	6/2	7/3	2/5	16/5	3/10
(days)	197	168	186	159	123	95	63	40	27	29	56	43	154

BERAKING													
Date of felling (day/month)	17/5	16/6	14/7	10/8	15/9	13/10	8/11	1/12	10/1	6/2	7/3	4/4	2/5
PINASTER													
Attack first recorded	7/6	27/7	30/8	15/9	13/10	27/10	1/12	10/1	6/2	21/2	20/3	19/4	16/5
(days)	21	41	47	36	28	14	23	40	27	15	13	15	14
Emergence first recorded	1/12	1/12	1/12	8/11	8/11	1/12	1/12	10/1	6/2	7/3	4/4	5/7	1/10
(days)	198	168	140	90	54	49	23	40	27	29	28	31	154
RADIATA													
Attack first recorded	30/5	10/8	15/9	27/10	13/10	1/12	1/12	10/1	6/2	21/2	20/3	19/4	4/7
(days)	13	55	63	78	28	49	23	40	27	15	13	15	64
Emergence first recorded	1/12	8/11	1/12	10/1	10/1	10/1	1/12	10/1	6/2	21/2	4/4	5/9	3/10
(days)	198	145	140	153	117	89	23	40	27	15	28	154	154

COLLIER (all pinaster)														
Date of felling (day/month)	13/5	15/6	12/7	9/8	13/9	11/10	9/11	6/12	3/1	7/2	7/3	4/4	2/5	6/6
COMPT 12/21														
Attack first recorded	23/5	–	29/8	29/8	21/9	25/10	2/12	22/12	25/1	13/2	9/3	8/4	–	–
(days)	10	–	48	20	8	14	23	16	22	6	2	4	–	–
Emergence first recorded	–	–	9/11	9/11	9/11	2/12	22/12	12/1	9/2	9/3	6/4	18/5	–	–
(days)	–	–	120	92	57	52	43	37	37	30	30	44	–	–
COMPT 23														
Attack first recorded	23/5	29/8	29/8	29/8	21/9	25/10	2/12	22/12	12/1	17/2	17/3	18/4	15/6	30/6
(days)	10	75	48	20	8	14	23	16	9	10	10	14	44	24
Emergence first recorded	2/12	2/12	9/11	9/11	2/12	2/12	22/12	22/12	25/1	21/3	18/4	30/6	28/8	22/9
(days)	203	170	120	92	80	52	43	16	22	42	42	87	118	108

SOMERVILLE (all pinaster)														
Date of felling (day/month)	16/5	14/6	12/7	9/8	6/9	12/10	9/11	7/12	11/1	7/2	7/3	4/4	2/5	20/6
COMPT 51														
Attack first recorded	26/5	12/7	25/8	25/8	13/9	26/10	29/11	30/12	24/1	13/2	15/3	6/4	31/5	8/9
(days)	10	28	44	16	7	14	20	23	13	6	8	2	29	80
Emergence first recorded	10/11	10/11	10/11	10/11	10/11	29/11	30/12	11/1	8/2	8/3	22/3	4/5	13/7	22/9
(days)	178	149	121	93	65	48	51	35	28	29	15	30	72	94
COMPT 57														
Attack first recorded	26/5	24/8	13/9	24/8	12/10	26/10	24/11	30/12	24/1	13/2	15/3	20/4	4/5	–
(days)	10	71	63	15	36	14	15	23	13	6	8	16	2	–
Emergence first recorded	10/11	10/11	10/11	10/11	10/11	24/11	30/12	30/12	8/2	8/3	30/3	4/5	31/5	–
(days)	178	149	121	93	65	43	51	23	28	29	23	30	29	–

– not recorded or no data

TABLE 2

Number of adult beetles emerging from logs felled at different dates 1966–7.

GREYSTONES													
Date of felling (day/month)	18/5	16/6	14/7	10/8	15/9	13/10	8/11	1/12	10/1	6/2	7/3	4/4	2/5
Pinaster (up to 3 Aug 1967)	480	472	320	524	516	668	733	815	3007	2300	2710	1078	0
Radiata (up to 3 Aug 1967)	1451	1707	2402	1463	989	1522	2198	869	1492	3433	51	1022	0
BERAKING													
Date of felling (day/month)	17/5	16/6	14/7	10/8	15/9	13/10	8/11	1/12	10/1	6/2	7/3	4/4	2/5
Pinaster (up to 14 June 1967)	876	1335	593	884	566	971	787	1014	1020	1119	2100	0	0
Radiata (up to 14 June1967)	4244	1770	1990	2319	2219	1940	1733	1766	3039	3619	1596	0	0
COLLIER (all pinaster)													
Date of felling (day/month)	13/5	15/6	12/7	9/8	13/9	11/10	9/11	6/12	3/1	7/2	7/3	4/4	
compt 12/21 (up to 18 May 1967)	–	–	2116	1984	2270	847	665	358	192	223	142	2	
compt 23 (up to 4 May1967)	682	1224	1695	1964	1612	582	804	1519	1715	94	159	0	
SOMERVILLE (all pinaster)													
Date of felling (day/month)	16/5	14/6	12/7	9/8	6/9	12/10	9/11	7/12	11/1	7/2	7/3	4/4	
compt 51 (up to 31 May 1967)	3303	2539	3039	2126	3085	1981	2991	3936	2571	5306	1478	143	
compt 57 (up to 18 May 1967)	1816	1298	2520	1249	3082	1729	2560	2647	2476	5212	2739	515	

THE HOST TREE: PINES AND THEIR SILVICULTURE IN WESTERN AUSTRALIA

At the end of 1990, the area of Government-owned pine plantations in Western Australia was 68 408 ha, comprising radiata pine (57 per cent), pinaster pine (42 per cent) and other species (<1 per cent). Radiata pine is grown in the cooler and wetter parts of the south-west and pinaster pine is grown on the sandy soils of the Swan Coastal Plain. Radiata pine therefore tends to be grown where topography is relatively steep and on relatively fertile soils tending to be shallow and stony.

A regular annual planting program began in 1922 at Ludlow and Mundaring, although little was achieved during 1939 to 1945 (Foresters' Manual 1964). The area planted increased rapidly from about 7000 ha in 1953 (Fig. 3). Initially pinaster pine was the preferred species for planting (Table 3).

The silvicultural systems applied to pine plantations have been explained in detail in the various editions of the Foresters' Manual (1927, 1952, 1964, 1973, 1981) and in the Pine Management Guide (CALM 1985). For both species, early management of plantations (up to 1970) was extremely conservative, mainly because there was no market for early thinnings. Up to then, the closing of the canopy was achieved at 6–7 years after planting depending on the site (Foresters' Manual 1954). In 1970 a new prescription was implemented, in order to produce high quality timber on a short rotation by heavy, early thinning and high pruning of crop trees. The stand was reduced to its final crop stocking early in the rotation. For radiata pine the first thinning was to be carried out before the stand reached 20 m (*c.* 10 years after planting) to ensure wind stability.

Delayed thinning and subsequent overstocking causes instability and susceptibility to windthrow, reduced diameter growth rates and, in extreme cases, death from drought (Hopkins 1971; McKinnell 1971; Butcher and Havel 1976; McGrath *et al.* 1990).

THE INTERACTION: *IPS*, BLUE STAIN FUNGI, DROUGHT AND PINE DEATHS

Pinaster Pine

Prior to 1970 *Ips* was considered a problem in the metropolitan plantations in its role as a vector of blue stain fungi, particularly *Ophiostoma* (syn. *Ceratocystis*) *ips* (Rumb.) Nannf., into logs stored on the ground (E. Hopkins[1], personal communication; see also Rimes 1959 and Stone and Simpson 1987). This infection discolours sapwood, thereby degrading wood and depreciating its market value.

Extensive drought deaths of pinaster pine on sands of the Swan Coastal Plain occurred after severe droughts in 1949–50 and 1976–77. During 1950–51 there were many investigations at Gnangara into the causes but there was no mention of insects or *Ips* in

[1] Dr E. Hopkins, formerly of Forests Department and Department of Conservation and Land Management, Western Australia.

TABLE 3

Planting history of the two major pine species in state plantations in South-Western Australia, to 1990.

	PERCENTAGE OF HECTARES PLANTED BY YEAR SHOWN					
SPECIES	1939	1964	1970	1980	1990	TOTAL AREA PLANTED (ha)
			ha			
RADIATA PINE	3.6	15.1	27.1	62.1	100.0	39 062
PINASTER PINE	10.8	32.0	53.2	81.8	100.0	29 346

Compiled from Annual Reports of the Forests Department of Western Australia and CALM.

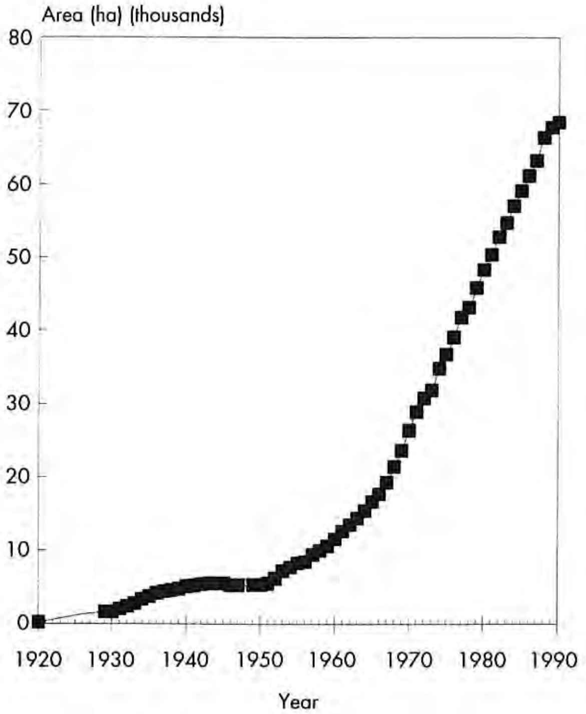

Figure 3. Area under pine plantation (Government-owned) in South-west Western Australia, 1920–1990.

particular. Deaths in Somerville plantation in February 1961 were thought to have been caused by moisture limitations in the shallow, limestone soils (yellow sands). However, for the first time *Ips* was suspected to have contributed. This plantation had suffered tree mortality in fertile (though shallow) sites over limestone at about 7–10 years of age. This corresponded with canopy closure and full utilization of the site. The disorder was known as Autumn Brown Top and was common until thinning was introduced in the late 1960s (Hopkins, personal communication).

In June 1976, 4 per cent of 9-year-old pinaster in a recently (April–May) thinned plantation at Yanchep experienced heavy attack by *Ips*. During 1977–78 there was wholesale collapse of older, dense, healthy plantations; *Ips* was present on most of these trees as well as on less healthy ones (Butcher[1], personal communication). Trees started dying from late May 1977. All of these instances involved drought in overstocked stands. Also relevant is that pinaster pine, by virtue of its mode of branching, is vulnerable when first pruned at age 6–7 years. This pruning may nearly ring-bark the tree, and if done in summer may result in its death.

Thus, in conclusion, no evidence was found on file to support the speculation that *Ips* infestation resulted in mortality of pinaster pine. However, the blue stain fungi associated with *Ips* are primary pathogens of pine as they disrupt the movement of water to the crown.

Radiata Pine

Significant mortality of radiata pine and feeding attacks by *Ips* were first recorded in 1970, and then in 1973, 1980 and 1987–88. These events occurred primarily in overstocked stands and/or on sites susceptible to drought. Most of these stands and sites occur in the Blackwood Valley. Bridgetown, situated in this valley, has a long term (1887-1990) average annual rainfall of 837mm. In the period 1929-1990 yearly rainfall has been below average 33 times, with the five driest years being 1940 (509 mm), 1969 (547 mm), 1972 (586 mm), 1979 (596 mm) and 1987 (555 mm): 1940 may be disregarded because there was no plantation then in the Blackwood Valley, only isolated trees. In addition, *Ips* was probably not present then. In 1969 well below average rainfall coincided with canopy closure in many of these plantations (Butcher and Havel 1976).

The 1970 and 1973 summers each followed a dry winter. Up to three-quarters of the 13 to 14-year-old trees in overstocked plantations near Nannup died, mostly from the top down. *Ips* attack of these usually followed the dying tissue down the tree. A small,

[1] T. Butcher, Research Scientist, Department of Conservation and Land Management, Como.

unspecified, proportion of trees was attacked at the base, and these died more quickly due to *Ips* attack. Curry (unpublished reports) doubted these would have survived even in the absence of this attack. The worst affected stands were recorded on north-facing slopes.

In April 1970, 1900 radiata trees were examined in three plantations near Nannup. It was found that 12 per cent were attacked by *Ips* in the lower 3 m (10 feet) of stem visible above ground level. Of the 30 per cent of the 1900 trees which were green and as yet not noticeably affected by drought, fewer than 1 per cent were attacked by *Ips*.

In the summer of 1973 *Ips* attack of green, apparently healthy, trees was recorded following thinning of 8 to 9-year-old plantations at Lewana. In the youngest plantation, thinned in the dry spring of 1972, 11 per cent of the standing trees were attacked by *Ips* during summer following their breeding in the slash. These trees generally died from the base up after *Ips* ring-barked them. In the older plantations, thinned and pruned over summer, more than 30 per cent of the standing trees died over the following year, after *Ips* attack in early autumn. Similar observations were made in Mungalup (planted 1957) and Wellington (1961–62) plantations near Collie during the summers of 1970–71 and 1971–72 (Shedley[1], personal communication).

Attack of living trees was also reported in plantations at Mundaring and Harvey. In March 1973 *Ips* was recorded attacking live trees in plantations near Collie, Nannup and Mundaring. These were either recently thinned 5 to 9-year-old stands or (at Collie) an unthinned 9-year-old stand. In February 1980 a feeding attack by *Ips* was recorded on 8-year-old trees in Murray plantation near Dwellingup. This plantation is on steep, rocky slopes and had been progressively thinned and pruned since November 1979.

In May 1988 Morgan[2] inspected a 17-year-old stand in Ferndale plantation which had experienced drought and wind damage in December 1987. Large populations of *Ips* were present; some trees had dead tops with *Ips* breeding in the lower bole and others still with green tips had *Ips* attack in their boles. One tree was felled and revealed that a feeding attack had occurred to the mid-crown level and all branches had been attacked by *Ips*. Breeding had then progressed further down with the most recent breeding in the lower bole.

During 1988 a broadscale survey of Blackwood Valley radiata pine plantations was carried out by McGrath *et al.* (1990), following dry winters of 1986 and 1987. The presence/absence of *Ips* exit holes at breast height was recorded on each tree sampled. The percentage of trees with evidence of *Ips* presence was 0.4 per cent (live trees), 3.3 per cent (trees showing tip death) and 70.9 per cent (dead standing trees). A graph of the proportion of basal area in each plot infested by *Ips* plotted against the proportion of basal area showing drought stress symptoms (tip death or dead) clearly indicates that the proportion of trees infested with *Ips* does not exceed the proportion of the basal area showing drought stress symptoms. This relationship supports the widely held view that *Ips* is not generally a cause of crown dieback or death of pines.

The mechanism of the interaction between the adult beetle and the host tree was investigated by Witanachchi and Morgan (1981) in South Australia. Resistant trees prevent continued boring of beetles through the bark by exuding resin in the phloem. In contrast, susceptible trees do not respond (this also explains why felled logs or recently dead trees are readily infested). During drought, particularly on sites with shallow soils, on upper slopes and ridges and facing north-east (McGrath *et al.* 1990), presumably the resin defence system of trees is insufficient to repel *Ips*, as are subsequent hypersensitive reactions of host tissues (see Fernandes 1990).

CONTROL OF *IPS* 1952–1982

Early research evaluated the efficacy of insecticides such as BHC, DDT, Chlordane, Dieldrin, Aldrin and NaPCP (Pirrett *et al.* 1953). Strips of pinaster pine stands at Gnangara were sprayed in May 1953 to examine whether *Ips* beetles could be killed and if further attack could be prevented. A complementary study of logs sprayed with insecticide was also conducted. Both studies concluded in December 1953. Neither study was successful because of faulty experimental design and non-quantitative recording of infestation. However, the authors' impression was that the sprayed strips were less heavily infested than the untreated slash. They concluded:

> It appears abundantly clear that spraying other than of logs is impracticable and it would definitely be desirable to remove slash from the Plantation floor. It is realised that this is much too costly an operation, therefore the risk of a large reservoir of beetles in this slash turning to live trees on exhaustion of slash feeding stocks must be taken for the present. However, close watch should be kept, particularly on unthrifty trees and should attack occur, these and several other trees should be felled to attract the beetles and gradually reduce their numbers by exhaustion as is done in some parts of Europe.

These authors also suggested that trucks working unaffected plantations should not be allowed into affected plantation or timber yards or conversely, vehicles operating in infested areas should be kept out of unaffected plantations or thoroughly cleaned before entering them.

In 1957–58, a further experimental study was made

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of protecting logs with insecticide (Rimes 1959). Such protection was not implemented in plantation management. About the same time it was realized that appropriate silvicultural techniques would minimize damage to plantations. Rimes (1959 and unpublished) recorded that *Ips* is not a primary pest of pines in Western Australia, i.e. healthy trees are not susceptible to attack, though if damaged by fire or other means entry could be made and reproduction could occur. Dead branches of healthy trees provide suitable breeding sites. The prompt removal of felled trees, within 12 to 24 hours, was recommended. Bark removal at the time of felling would make the log unattractive to *Ips*, but this was considered uneconomic. In practice, the policy adopted was to remove the logs from thinning within a few weeks in the summer and autumn months.

Curry reported that prescribed low intensity fire could kill *Ips* living in slash, but only where the bark was charred. Removal of slash was probably more effective in the long term as it removed the habitat required by *Ips*. Unfortunately, fire is of limited use as a silvicultural technique because of the sensitivity of pine trees to fire. The policy in Western Australia is generally to exclude fire from radiata pine plantations and surround them with fuel-reduced buffers. However, in pinaster pine plantations older than 20 years, fuel reduction is easily carried out, and appears to reduce *Ips* populations (McKinnell[1], personal communication).

The findings of the early 1970s showed that either the combination of a dry winter with the presence of recent prunings and thinnings on the plantation floor or of a dry winter with overstocked plantations resulted in heavy infestation of trees with *Ips*. The risk of drought and ensuing tree mortality is particularly great on shallow soils on steep, rocky slopes, shallow soils and on north-facing slopes.

Because *Ips* is active from September to May, pruning and thinning of stands during this period should ideally be avoided unless the slash can be promptly removed or mulched. Any non-commercial thinning should be restricted to the period April to August. Chemical thinning is not recommended, as it results in large numbers of dead standing trees which serve as suitable breeding habitats for *Ips*.

In summary, chemical insecticides are successful but are expensive and must be applied quickly after felling. Good silvicultural management (thinning followed by slash removal through burning or maceration) reduces the availability of breeding substrate for *Ips* and promotes healthy, vigorous trees (Neumann 1987; Morgan 1989). In Western Australia no burning is carried out in radiata pine plantations, and no maceration is carried out in pine plantations.

CONTROL OF *IPS* 1984–1990

Although the importance of thinning stands on schedule and the prompt disposal of slash is recognized as fundamental to the successful management of *Ips*, provision of biological control agents was thought to provide extra resource security (Morgan 1989). In 1981 he gained permission for the Waite Insititute of Agricultural Research to import several species of *Ips* parasitoid and predators for laboratory studies. The breeding in the laboratory of large numbers of these biocontrol agents for release was funded by the State forest services and private plantation owners. Laboratory studies showed, however, that one of these agents, the parasitoid *Roptrocerus xylophagorum*, rarely parasitized more than 5 per cent of the *Ips* population (Samson and Smibert 1986).

Roptrocerus was released under permit into several South Australian plantations in 1982, and was clearly established there by 1988 (Morgan 1989).

In Western Australia, the first releases of biocontrol agents (Table 4) took place at Gnangara in November 1984. In 1988 a prescription for release of predators and parasitoids of *Ips* in Western Australia was written, based largely on a field manual prepared by F.D. Morgan and S.A. Lawson in South Australia. Releases terminated in May 1990. *Roptrocerus* had clearly established in Gnangara by March 1985 when two adult *Roptrocerus* wasps emerged from caged billets. In 1988 *Roptrocerus* adults were detected in Gnangara and Ferndale plantations and also in a privately owned plantation (Loc. 8476) *c.* 2 km north of Dalgarup Brook between Greenbushes and Bridgetown (Morgan, personal communication). *Roptrocerus* had never been released in the latter two plantations. To provide extra genetic diversity, more *Roptrocerus* were introduced in 1989–90 (Tables 5, 6).

In May 1990 two U.S. entomologists, W. Berisford and D. Dahlsten, visited several release sites in Ferndale plantation. They found evidence only of *Roptrocerus* having established. Furthermore, studies of caged radiata pine billets collected from Ferndale (D2) and Pinjar (compartment 27) plantations have conclusively proven that only *Roptrocerus* has established. Billets were collected from recently thinned stands in May 1990 and caged until November 1990. *Roptrocerus* was found to have parasitized on average only about 5–6 per cent of the *Ips* population (Table 7), with considerable variation between the 19 caged samples evident.

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TABLE 4

Biocontrol agents released in Western Australian pine plantations 1984-1990.

SPECIES	ORDER	FAMILY	FUNCTION ROLE
Dendrosoter sulcatus Mues.	Hymenoptera	Braconidae	North American parasitoid of *Ips* larvae
Roptrocerus xylophagorum (Ratz.)	Hymenoptera	Pteromalidae	North American parasitoid of *Ips* larvae
Thanasimus dubius (Fab.)	Coleoptera	Cleridae	North American predator of *Ips* larvae and adults
Temnochila virescens (Fab.)	Coleoptera	Trogossitidae	North American predator of *Ips* larvae and adults

TABLE 5

Numbers of biocontrol agents sent to, and released in, Western Australia (adult males, females, larvae, eggs).

YEAR	*Dendrosoter*		*Roptrocerus*		*Thanasimus*				*Temnochila*			
	M	F	M	F	M	F	LARVAE	EGGS	M	F	LARVAE	EGGS
1984/5	120	329	194	325	150	150						
1987/8								60	60			
1988/9			153	1425			414		84	111	3620	500
1989/90	40	428	878	1223	137	150	8	3137	70	100	4	12005
TOTAL NO. SENT	169	757	1225	2973	287	300	422	3137	214	271	3624	12505
TOTAL NO. RELEASED	147	663	933	1985	139	146	414	2791	?	?	2020	48104

TABLE 6

Sites where biocontrol agents were released in Western Australia, together with dates of releases and numbers released.

SPECIES	RELEASE DATES	PLANTATION	NUMBERS RELEASED	
Dendrosoter	09.01.85 – 10.04.85	Gnangara	Adults	98M, 235F
	25.04.90 – 10.05.90	Ferndale D	"	49M, 428F
Roptrocerus	28.11.84 – 10.04.85	Gnangara	"	158M, 325F
	27.01.89	Ferndale C	"	38M, 500F
	08.04.89	Balingup	"	40M, 150F
	1989	Dalgarup	Not recorded	
	28.03.90	Ferndale B	Adults	55M, 94F
	20.04.90 – 03.05.90	Ferndale D	"	567M, 625F
Thanasimus	24.09.84 – 30.04.85	Gnangara	"	132M, 132F
	11.01.89	Ferndale C	Larvae	140 1st instar
	27.01.89 – 17.03.89	Southampton	"	274 " "
	10.01.90 – 25.04.90	Ferndale B	Eggs	3806
			Adults	5M, 6F
	28.03.90 – 03.05.90	Ferndale D	Eggs	785 1st Instar
			Adults	2M, 8F
Temnochila	21.12.88 – 08.04.89	Ferndale C	Larvae	1460 1st Instar
				100 mature
			Adults	69M, 91F
			Eggs	300
	1988	Pinjar	Adults	50M, 60F
	03.03.89	Balingup	Larvae	300 1st Instar
			Adults	10M, 20F
	17.03.89	Southampton	Larvae	160 1st Instar
	1989	Dalgarup	Eggs	Not recorded
	05.01.90 – 25.04.90	Ferndale B	Eggs	4068
		Ferndale D	Adults	7
			Eggs	442+

TABLE 7

Abundance of *Ips* beetles and *Roptrocerus* wasps emerging from caged billets of pine (U, M and L refer to billets taken from upper, middle or lower bole).

PLANTATION	SPECIES	TYPE AND NO. OF BILLETS PER CAGE	NO. *Ips* PER 10^3 cm^2 OF BARK	NO. *Roptrocerus* PER 10^3 cm^2 OF BARK	% PARASITIZATION
PINJAR	Pinaster	U4	89.8	7.5	8.4
		U7	27.3	1.9	7.0
		U7	89.8	8.3	9.2
		U8	27.7	1.3	4.7
		U7	28.6	2.1	7.3
		U6	25.9	2.9	11.2
		M4	55.6	1.3	2.3
		Means	43.2	3.2	6.3
FERNDALE	Radiata	U4	10.3	0	0
		U6	5.5	0.9	16.4
		U3	12.6	1.7	13.5
		U5	29.2	0.3	1.0
		U4	35.7	0.7	2.0
		U4	11.6	0.1	0.9
		U4	13.5	0.4	3.0
		U/M 5/1	10.7	1.6	15.0
		M5	9.4	0.1	1.1
		M3	14.6	0.6	4.1
		M3	18.0	0.4	2.2
		L2	7.4	0.2	2.7
		Means	14.9	0.6	5.2

REFERENCES

Abbott, I. (1985). Forest entomology research in Western Australia. *Technical Report, Department of Conservation and Land Management, Western Australia* No. 2.

Butcher, T.B. and Havel, J.J. (1976). Influence of moisture relationships on thinning practice. *New Zealand Journal of Forestry Science* 6, 158–170.

CALM (1985). Pine Management Guide (Central Region). Department of Conservation and Land Management, Western Australia.

Curry, S.J. (unpubl.). Monthly reports, 1967–85 (incomplete).

Fernandes, G.W. (1990). Hypersensitivity: a neglected plant resistance mechanism against insect herbivores. *Environmental Entomology* 19, 1173–1182.

Foresters' Manual (1927). Part iv. Afforestation. *Bulletin of the Forests Department of Western Australia.* 39, 70–96.

Foresters' Manual (1952). Part iv. Afforestation with pines (South-west). *Bulletin of the Forests Department of Western Australia* 58.

Foresters' Manual (1964). Pamphlet No. 5. Afforestation with pines (South-west). *Bulletin of the Forests Department of Western Australia* 58.

Foresters' Manual (1973). Pamphlet No. 5. Afforestation with pines. *Bulletin of the Forests Department of Western Australia* 58.

Foresters' Manual (1981). Part 16. Pine Plantations. Forests Department of Western Australia.

Hopkins, E.R. (1971). Early responses to thinning in stands of *Pinus pinaster*. *Forests Department of Western Australia. Research Paper*, No. 6.

McGrath, J.F., Ward, D.J. and Davison, E.M. (1990). Pine deaths in the Blackwood Valley plantations: a recurrent problem. Internal Report, CALM.

McKinnell, F.H. (1971). Commercial thinning in Radiata pine. *Forests Department of Western Australia. Research Paper*, No. 2.

Morgan, F.D. (1967). *Ips grandicollis* in South Australia. *Australian Forestry* **31**, 137–155.

Morgan, F.D. (1989). Forty years of *Sirex noctilio* and *Ips grandicollis* in Australia. *New Zealand Journal of Forestry Science* **19**, 198–209.

Neumann, F.G. (1987). Introduced bark beetles on exotic trees in Australia with special reference to infestations of *Ips grandicollis* in pine plantations. *Australian Forestry* **50**, 166–178.

Neumann, F.G. and Morey, J. (1984). Studies on the introduced bark beetle *Ips grandicollis* (Eichhoff) in Victorian radiata pine plantations. *Australian Forest Research* **14**, 283–300.

Pirrett, P., Van Noort, A.C. and Harding, J.H. (1953). Control of *Ips grandicollis* in *Pinus pinaster* plantations in Western Australia. Unpublished.

Rimes, E.D. (1959). The bark beetle in Western Australia pine forests. *Journal of Agriculture Western Australia* **8**, 353–355.

Samson, P.R. and Smibert, J. (1986). Preliminary studies on the efficiency and establishment of *Roptrocerus xylophagorum* [Hym. : Torymidae], a parasitoid of *Ips grandicollis* [Col. : Scolytidae], in Australia. *Entomophaga* **31**, 173–182.

Stone, C. and Simpson, J.A. (1987). Influence of *Ips grandicollis* on the incidence and spread of blue stain fungi in *Pinus elliottii* billets in north-eastern New South Wales. *Australian Forestry* **50**, 86–94.

Witanachchi, J.P. and Morgan, F.D. (1981). Behaviour of the bark beetle, *Ips grandicollis*, during host selection. *Physiological Entomology* **6**, 219–223.

Wood, S.L. (1982). The bark and ambrosia beetles of North and Central America (Coleoptera: Scolytidae), a taxonomic monograph. *Great Basin Naturalist Memoirs* **6**, 1–1359.