# HISTORY AND MANAGEMENT OF SIREX WOOD WASP IN PINE PLANTATIONS IN NEW SOUTH WALES, AUSTRALIA

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## ABSTRACT

Sirex wood wasp (*Sirex noctilio* Fabricius (Hymenoptera: Siricidae)) is one of the most important insect pests of *Pinus radiata* D. Don in Australia. Forests NSW manages over 195 000 ha of *P. radiata,* and is the largest pine grower in Australia. Sirex was first detected in New South Wales in 1980 at Albury, and within 10 years was established in the pine-growing areas of Hume (Tumut), Monaro (Bombala), and Macquarie (Bathurst) regions. It reached northern region (Walcha) in 1997 and spread slowly up to Tenterfield, 25 km south of the Queensland border, by 2002. Although sirex emergence holes were observed in several trees in a plantation near Casino in 2002, no larvae or adults were seen, and no further evidence of sirex was observed, so we do not believe it has established in this area. The northward spread of sirex was assisted by the large pine-growing regions around Tumut, Bathurst, Walcha, and Glen Innes, and smaller private plantations and woodlot and windbreak plantings. Sirex is expected to reach the *P. radiata* plantations in south-eastern Queensland, and the southern-pine plantations in coastal north-eastern New South Wales, by 2008. Sirex management in this State began in 1981, consisting of releases of biological control agents, surveillance, and silvicultural regimes, and continues today. The sirex nematode, *Beddingia* (=*Deladenus*) *siricidicola* Bedding, provides the most effective control of sirex in New South Wales. Of the six species of parasitoid wasps released in the State since 1980, *Ibalia leucospoides* Hochenwarth and *Megarhyssa nortoni* (Cresson) are the only ones regularly detected in sirex-struck trees. *Ibalia leucospoides* and *M. nortoni* have been detected in all pine-growing regions in New South Wales, with *I. leucospoides* having the highest level of parasitism. Damaging outbreaks of sirex in New South Wales, where more than 3% of trees in an area are killed, have mainly been confined to localised areas less than 200 ha, in unthinned stands with trees 10–25 years old, where a biological control programme was not conducted for several years, or in snow-damaged areas. *Pinus radiata* is the species most susceptible

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to sirex, although a heavy infestation in *P. taeda* Linn. observed near Walcha was the first record of this species as a host of sirex in Australia. The annual sirex management programme in Forests NSW, consisting of biological control, forest health surveillance, and silvicultural treatment, has reduced the economic impact of this potentially damaging pest in New South Wales.

**Keywords**: tree mortality; sirex spread; biological control; nematodes; parasitoids; trap trees; surveillance; *Sirex noctilio*; *Pinus radiata.*

## INTRODUCTION

The wood wasp, *Sirex noctilio,* is one of the most important insect pests of *Pinus radiata* in Australia. Native to Eurasia and northern Africa, *S. noctilio* was accidentally introduced into Tasmania and detected there in 1951 (Gilbert & Miller 1952). It then spread to the mainland and was detected in Victoria in 1961 (Irvine 1962) and southern New South Wales and South Australia by 1980 (Neumann & Minko 1981; Eldridge & Simpson 1987; Eldridge & Taylor 1989). Sirex has not been detected in Queensland or Western Australia, although susceptible hosts are grown in these states.

Although sirex is able to kill relatively healthy pine trees, suppressed trees, such as those in unthinned stands and trees that are drought stressed, are more susceptible to attack (Neumann & Minko 1981; Haugen *et al.* 1990). The susceptible age class is said to be between 10 and 25 years (Haugen *et al.* 1990). *Pinus radiata* is highly susceptible (Haugen *et al.* 1990) and is the most important softwood species planted in Australia (Wood *et al.* 2001). Forests NSW manages over 205 000 ha of exotic *Pinus* plantations, including 195 000 ha of *P. radiata* and 10 000 ha of *P. elliottii* Engelm., *P. taeda*, and *P. elliottii* × *P. caribaea* Morelet hybrids. Observations overseas indicate that *P. taeda* and *P. radiata* appear to be equally susceptible to sirex, while *P. elliottii* appears more resistant (Iede *et al.* 1998; Maderni 1998; Penteado *et al.* 1998). Sirex has not previously been observed in *P. taeda* in Australia, and the susceptibility of the *P. elliottii* × *P. caribaea* hybrids in Australia is currently being determined (King *et al.* 2004).

The significant pest status of sirex was soon realised once the wasp had established in the southern states of Australia, with significant mortality over a wide area observed in Tasmania (Madden 1975, 1998), Victoria (Neumann & Minko 1981), and South Australia (Haugen 1990; Haugen & Underdown 1990). The biology and behaviour of *S. noctilio* have been detailed previously (Morgan & Stewart 1966; Taylor 1978, 1981; Neumann & Minko 1981; Madden 1988). Briefly, eggs are oviposited into trees that have low sap pressure, along with a phytotoxic mucus and a wood-decay fungus carried by sirex. Trees drilled by sirex soon die from the combination of the mucus and fungus. Larvae feed on the fungus and tunnel through the white-rotted infected wood and, during summer and autumn when fully formed, the adult sirex bores out of the tree.

Control of sirex is achieved by the use of a combination of silvicultural and biological measures (Neumann *et al.* 1987; Eldridge & Taylor 1989; Morgan 1989; Haugen *et al.* 1990). Silvicultural treatments can maintain the health and vigour of trees (Eldridge & Taylor 1989; Haugen 1990). By managing plantations optimally (e.g., timing selective thinning to sustain tree vigour and restricting pruning and thinning-to-waste outside the wasp flight season) the risk to pine plantations from sirex attack can be greatly reduced. Selected parasites have been imported into Australia from Europe and North America to assist in the control of sirex. The most effective of these is the nematode *Beddingia* (=*Deladenus*) *siricidicola* (Neotylenchidae), which infects sirex larvae rendering the adult wasp sterile (Bedding 1967, 1972; Bedding & Akhurst 1974; Neumann & Minko 1981). Several parasitic wasps were also introduced into Australia to help control sirex, including *Ibalia leucospoides* (Ibaliidae), *Megarhyssa nortoni* (Ichneumonidae), two species of *Rhyssa* (Ichneumonidae), and *Schlettererius cinctipes* (Cresson) (Stephanidae) (Taylor 1976).

It has been 25 years since sirex was first detected in New South Wales and a review of this important pest is warranted. This paper discusses the history of sirex in New South Wales, including the spread of the wasp, the damage it has caused, and the management programme implemented and its effectiveness. Information has been collated mainly from data in internal Forests NSW reports that have not previously been published.

## METHODS

### Pinus Plantations in New South Wales

Commercial plantations of *P. radiata* managed by Forests NSW are concentrated around Tumut on the south-west slopes (Hume Region), Bombala in the south-east, Moss Vale in the Southern Highlands and Queanbeyan east of the Australian Capital Territory (Monaro Region), Bathurst west of Sydney (Macquarie Region), and Walcha and Glen Innes on the Northern Tablelands (Northern Region) (Fig. 1). The southern-pine plantations (*P. elliottii, P. taeda, P. elliottii* × *P. caribaea* hybrids) are located around Coffs Harbour and Casino in the north-east (Northern Region) (Fig. 1). There are moderate-sized areas of private plantations in Hume Region, and smaller private plantations in Monaro, Macquarie, and Northern Regions, mostly *P. radiata,* and small private plantings of southern-pine species in the north-east in Northern Region.

### Distribution of Sirex in New South Wales

Aerial surveys (using fixed wing aircraft and helicopters) and ground surveys were undertaken in the majority of plantations in New South Wales annually from 1981

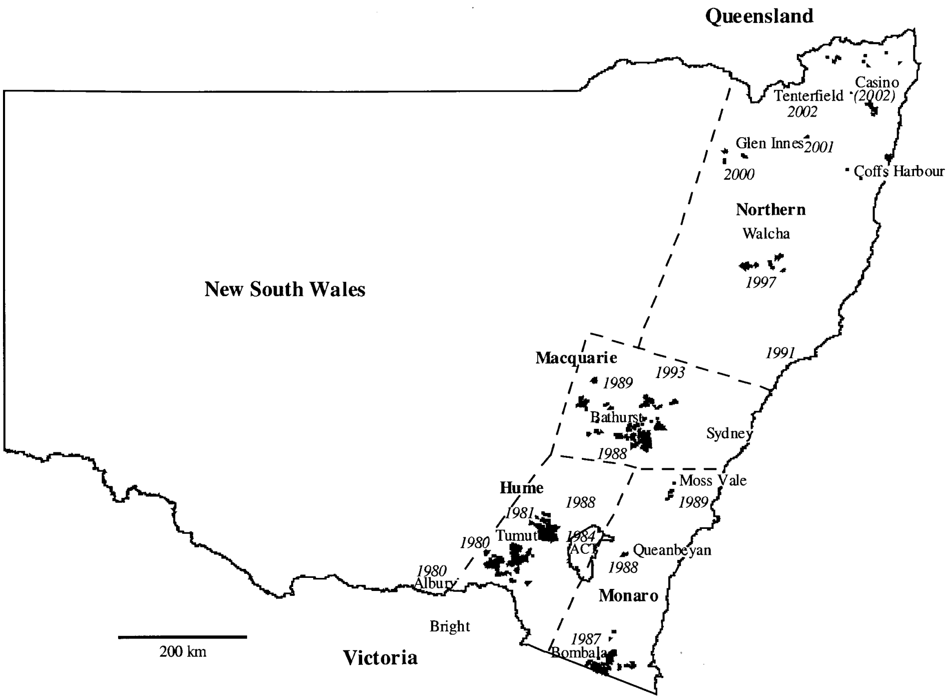


FIG. 1–Map of New South Wales showing distribution of pine plantations (■ ), Forests NSW softwood Regional boundaries (– – –), and spread of *Sirex noctilio* from 1980 to 2005 (year detected in italics; year in parentheses indicates detection but not subsequent establishment).

onwards to detect the establishment and spread of sirex. Surveys of private plantations, woodlots, and windbreak plantings throughout New South Wales were also conducted, although more sporadically. Mortality observed during aerial surveys was checked on the ground to confirm whether sirex was the cause. Early-detection trap trees were also used to detect the spread of sirex into new areas. Because of these detailed surveys, we concluded that any detection of sirex in a State Forest indicated that it had established in that area within that year or 1–2 years previously.

## Damage by Sirex to Pinus radiata Plantations

Once sirex had established in an area, aerial surveys by fixed wing aircraft and helicopter were used to locate and record dead and dying trees within plantation areas, and determine the distribution and relative intensity of damage within a compartment. Accurate ground surveys by trained personnel followed aerial location to determine the proportion of dead or dying trees associated with sirex for each affected compartment. The number of trees surveyed to obtain an accurate assessment of a stand varied depending on variation in aspect and topography within a compartment and the levels of sirex-induced mortality. Several transects through a compartment covering 250–500 trees were normally sufficient. We categorised damage levels based on the following criteria: once sirex had established in an area, infestations resulting in less than 1% of tree deaths were considered "low", 1–3% tree deaths were "moderate", and greater than 3% tree deaths a "severe" infestation (National Sirex Co-ordination Committee 2002).

Prior to 1987 most surveillance was conducted by staff from the Keith Turnbull Research Institute in Victoria with assistance from Forests NSW Softwoods Regional staff. From 1987 this task was conducted and managed by Forests NSW Research and Development Division, in conjunction with the Softwoods Regions. More systematic and intensive surveys were conducted from 1996 after the creation of the Forest Health Survey Unit (FHSU) at Forests NSW Research and Development Division.

## Biological Control Programme

Sirex parasitoids were released into areas soon after sirex was first detected. All parasitoids were supplied by the Forests Commission of Victoria (now Department of Sustainability and Environment). The success of establishment of parasitoids in a region was monitored by examination of insect emergences from billets from naturally struck trees and trap trees. The use of trap trees for biological control of sirex, described by Haugen *et al.* (1990) and the National Sirex Co-ordination Committee (2002), commenced in New South Wales in the summer of 1982–83. This involved the treating of *P. radiata* by the basal stem application of a sub-lethal dose of the herbicide Dicamba, as described by Neumann *et al.* (1982), using a formulation and application system developed for non-commercial thinning of *P. radiata* (Minko 1981). Sirex are attracted to these "stressed" trees for oviposition sites and eventually kill the trees. The trap trees were felled at the conclusion of the flight season, checked for the presence of sirex larvae, and subsequently inoculated with the nematode *B. siricidicola*. Where possible, naturally struck trees were also identified and inoculated with nematodes. Once inoculated, nematode "positive" females emerge and disseminate into the natural population (Bedding 1993). This method has been highly successful in attracting sirex female wasps and parasitoids during the flight season, and thus allows for the ready detection of new incursions, the monitoring of sirex populations, and inoculation with the parasitic nematode.

Initially, trap tree establishment in New South Wales was sporadic, with no trap trees established in some areas in Hume Region in some years. However, after significant damage observed in Hume in the late 1980s trap trees were established annually in the majority of pine-growing regions in New South Wales from 1989, with the overall aim to facilitate nematode release in infested plantations and for early detection of sirex in plantations not known to be infested. Trap trees are located in unthinned stands in the most susceptible age-class (generally 10–20 years old). The intensity of trap trees in an area depends on the infestation level, with more trap tree plots established in areas where sirex is at severe levels (National Sirex Co-ordination Committee 2002).

Evaluation to determine the establishment, distribution, and population levels of the biological control agents is an essential process for implementing an effective control programme (Haugen 1990). In New South Wales since 1989 nematode inoculation and evaluation have continued annually in all regions where sirex has become established, following the procedures of Haugen *et al.* (1990) and the National Sirex Co-ordination Committee (2002). Forests NSW has monitored and evaluated the sirex biological control programme utilising trap trees, collecting billets, and dissecting the emerging wasps. Nematode parasitism percentages have been determined for the “natural” sirex population as well as for the biological control inoculation programme. This has allowed the effectiveness of nematode inoculation techniques and background nematode parasitism to be determined, as well as the levels of parasitoid wasps as they emerge from the billets.

## RESULTS

### Distribution of Sirex in New South Wales

The “spread” of sirex through New South Wales from 1980 to 2005 is shown in Fig. 1. Sirex was first detected in private plantings of *P. radiata* near Albury, in southern New South Wales, in April 1980 (Eldridge & Taylor 1989). Albury is directly north of the major pine-growing regions of Bright and Myrtleford in north-east Victoria, where sirex had been established since 1976 (Neumann *et al.* 1987). The first record of sirex in a State Forest in New South Wales was in the Hume Region in September 1980 in Murraguldrie State Forest (80 km north-east of Albury), although it is likely that the infestations discovered at Albury and Murraguldrie State Forest were 2 years old (E. Taylor unpubl. data). Within 1 year, sirex was detected in the majority of State Forests in Hume Region (E. Taylor unpubl. data).

In May 1984 sirex was first detected in the *P. radiata* plantations in the Australian Capital Territory (E. Taylor unpubl. data), which are approximately 100 km to the east of Hume Region. By 1985, sirex had been detected in the majority of plantations in the Territory.

Adult wasps were captured in Monaro Region (Coolangubra State Forest), approximately 180 km south-east of Hume Region, during the flight season of

1986–87, although infested trees were not located until 1988–89. In 1988 sirex was detected at Tallaganda State Forest, east of the Australian Capital Territory (Monaro Region), but had been known to occur in private plantations in the area prior to this period. In the same year sirex was also confirmed from woodlot and windbreak plantings around Young, 100 km north of Tumut.

In 1988 sirex was also detected in private plantations south of Bathurst (Burraga) in Macquarie Region west of Sydney, and it is likely that the wasp had been in the area for at least 2 years. It was later detected in State Forests in this area, and by late 1989 was well established in Macquarie Region. As a result of the early-detection trap tree programme, sirex was detected in the pine plantations around Moss Vale (Monaro Region), 125 km north-east of the Australian Capital Territory, in 1989. In 1991 sirex was found in a single *P. elliottii* trap tree at Raymond Terrace north of Sydney on the central coast of New South Wales. These plantings are approximately 210 km north-east of Bathurst. No further detections were made from this area, indicating it was a rare event. In 1993–94 sirex was confirmed in a private plantation at Running Stream just north of Bathurst, and is likely to have been in the area for 1–2 years.

Further annual surveys and a continuation of the early-detection trap tree programme did not show any change in sirex distribution in New South Wales from 1995 to 1996. However, sirex was detected in a trap tree in the *P. radiata* plantations south of Walcha (Nundle State Forest) on the Northern Tablelands (Northern Region) for the first time in January 1997, and in adjacent State Forests and private plantations within 2 years. During regular forest health surveillance in September 2000, sirex was observed in *P. radiata* at Mount Topper State Forest west of Glen Innes, although from the presence of old emergence holes in killed trees it is suspected the wasp had been there for at least 1 year before detection. Large numbers of sirex were also observed emerging from *P. taeda* in private plantations south of Walcha during these surveys. This was the first record of sirex from *P. taeda* in Australia. While *P. radiata* was also affected in this plantation, *P. patula* Scheide & Deppe, *P. pinaster* Ait., and *P. ponderosa* Laws were not affected although these species are known to be susceptible to sirex (Browne 1968; Smith 1978; Spradbery & Kirk 1978).

In October 2001, sirex larvae were detected in trap trees located in Mount Mitchell State Forest east of Glen Innes, approximately 100 km south of Queensland. In winter 2002, sirex emergence holes were observed in a private plantation at Tenterfield, 25 km south of the Queensland border. We observed emergence holes in both recently killed trees and trees that had been killed in the previous 1–2 years, indicating that sirex had established in the area. This is the most northerly detection of sirex to date in New South Wales, and indeed Australia. In the same year, we observed emergence holes, from the previous years' flight season, in a *P. taeda* plantation north of Casino. Only a few trees were attacked, and we could not find evidence that sirex had been in the area prior to 2001, such as emergence holes in trees that had been dead for more than 1 year. There is no indication that sirex has established in this area, with no further observations of emergence holes, larvae, or adults from these plantations in following years. Further surveys and observation of plantations and trap trees from 2003 to 2005 have revealed no more evidence of sirex from the plantations around Casino.

## Damage to Pinus radiata Plantations by Sirex

Since the establishment of sirex in New South Wales, there have been relatively few outbreaks rated as severe (i.e., greater than 3% incidence) (Table 1). While levels of tree mortality were generally low during the first years after establishment, during the late 1980s there was a general build-up of sirex in several State Forests in Hume Region (Table 1, Fig. 2). This was directly related to a reduction in the biological control programme, delayed thinning, and severe snow damage in many areas in 1985 (R. Eldridge, unpubl. data; D. Hobson, pers. comm). In Buccleuch State Forest, cumulative levels of mortality ranged from 1 to 4% (average 2%) in 1987, 1 to 19% (average 10%) in 1988, and 1 to 28% (average 12%) in 1989, based on surveys of the same 19 compartments each year (Fig. 2). The majority of compartments were overdue for thinning, and had many trees damaged by snow, and the biological control programme did not continue in Buccleuch after 1982. In Bago State Forest (Blowering), cumulative levels of mortality ranged from 1 to 8% (average 4%) in 1987 and 1 to 37% (average 11%) in 1988 and 1989, based on annual surveys of the same 16 compartments (Fig. 2). Biological control was not conducted in this forest from 1985 to 1986, but continued from 1987 onwards. Also, compartments in Blowering State Forest are all on steep terrain and were snow damaged, with thinning delayed in many compartments until 1988 due to access problems. In contrast, Green Hills State Forest experienced levels of mortality less than 2% from 1987 to 1989 (14 compartments) (Fig. 2) because the biological control programme was more consistently applied in this area, and there was less stress on trees associated with delayed thinning. By 1988, over 2000 ha in Hume had been severely damaged by sirex (Table 1), after which a concerted effort was made by Hume Region to reduce sirex levels. This included nematode inoculation of naturally struck trees, as well as trap trees, and distribution of inoculated billets throughout affected plantations. The subsequent crash in the sirex population was quite dramatic (D. Hobson pers. comm.).

Soon after sirex was detected in Macquarie Region several State Forests had severe levels of damage, including Dog Rocks, Mt Macquarie, Pennsylvania, and Mount David. Most of this damage was greater than 5% incidence, and covered a large area (over 1500 ha). There were also more localised areas (<10 ha each) of moderate to severe damage in many State Forests. Dog Rocks State Forests had very high levels

TABLE 1–Sirex-related mortality in *Pinus radiata* plantations in New South Wales. Data collection from 1981 to 1995 by regional and research staff, 1996–2005 by the Forest Health Survey Unit. Damage of 1% or less not reported here.

| Year | Region | State Forest | Area affected (ha) | Age-class | Mortality (%) |
|---|---|---|---|---|---|
| 1988 | Hume | Regional mean | 3041 | – | <2 |
| 1988 | Hume | Regional mean | 1190 | – | 2–10 |
| 1988 | Hume | Regional mean | 1118 | – | >10 |
| 1991 | Macquarie | Dog Rocks | ~50 | | 10 |
| 1991 | Macquarie | Mt Macquarie | ~250 | | 15 |
| 1991 | Macquarie | Pennsylvania | ~500 | | >5 |
| 1992 | Macquarie | Mt David | ~250 | | 1–5 |
| 1992 | Macquarie | Mt David | ~250 | | >5 |
| 1992 | Macquarie | Mt Macquarie | ~250 | | >5 |
| 1992 | Macquarie | most State Forests | <10 ha each | | 1–5 |
| 1994–95 | Macquarie | Dog Rocks | 62 | – | 32 |
| 1994–95 | Macquarie | Dog Rocks | 90 | – | 29 |
| 1996 | Hume | Green Hills | 428 | 1975 | 3 (old*) |
| 1996 | Hume | Green Hills | 170 | 1983 | 25 (old) |
| 1996 | Hume | Bago | 65 | 1971 | 3 |
| 1996 | Macquarie | Dog Rocks | 67 | 1967 | 3 (old) |
| 1996 | Macquarie | Dog Rocks | 146 | 1967 | 3 (old) |
| 1996 | Macquarie | Dog Rocks | 20 | 1971 | 3 (old) |
| 1996 | Macquarie | Mt Macquarie | 60 | 1966 | 20 (old) |
| 1996 | Macquarie | Mt Macquarie | 70 | 1969 | 10 (old) |
| 1996 | Macquarie | Pennsylvania | ~200 | 1960s | 5 (old) |
| 1996 | Macquarie | Sunny Corner | 60 | 1970 | 2 (old) |
| 1996 | Macquarie | Sunny Corner | 16 | 1962 | 5 (old) |
| 1996 | Macquarie | Sunny Corner | 17 | 1968 | 2 (old) |
| 1996 | Macquarie | Canobolas | 33 | 1962 | 2 |
| 1996 | Macquarie | Lowes Mount | 145 | 1981 | 3 |
| 1996 | Monaro | Belanglo | 16 | 1972 | 3 (old) |
| 1996–98 | Hume | Maragle | 64 | 1985 | 25 (over 3 years) |
| 1998 | Hume | Buccleuch | 115 | 1985 | 3 |
| 1998 | Monaro | Meryla | 54 | 1979 | 3 |
| 1998 | Monaro | Wingello | 38 | 1974 | 3 |
| 1999 | Macquarie | Essington | 15 | 1985 | 4 |
| 1999 | Macquarie | Lidsdale | 8 | 1981 | 3 |
| 1999 | Macquarie | Vittoria | 17 | 1986 | 2 |
| 1999 | Monaro | Coolangubra | 75 | 1980 | 3 |
| 1999 | Monaro | Coolangubra | 187 | 1981 | 2 |
| 1999 | Monaro | Pericoe | 55 | 1984 | 5 (old) |
| 2000 | Hume | Buccleuch | 220 | 1990 | 3 |
| 2000 | Hume | Buccleuch | 196 | 1990 | 3 |
| 2000 | Macquarie | Pennsylvania | 190 | 1987 | 3 |
| 2001 | Hume | Buccleuch | 96 | 1990 | 3 |
| 2001 | Hume | Buccleuch | 260 | 1990 | 2 |
| 2002 | Hume | Buccleuch | 50 | 1988 | 2 |
| 2002 | Hume | Carabost | 50 | 1989–91 | 1.5 |
| 2003 | Macquarie | Pennsylvania | 36 | 1987 | 2 |
| 2003 | Macquarie | Pennsylvania | 28 | 1992 | 2 |
| 2004 | Hume | Buccleuch | 90 | 1992 | 2 |
| 2004 | Hume | Buccleuch | 37 | 1993 | 2 |
| 2004 | Hume | Buccleuch | 67 | 1994 | 3 |

* "old" damage indicates tree had been killed by sirex 1–3 years prior to survey

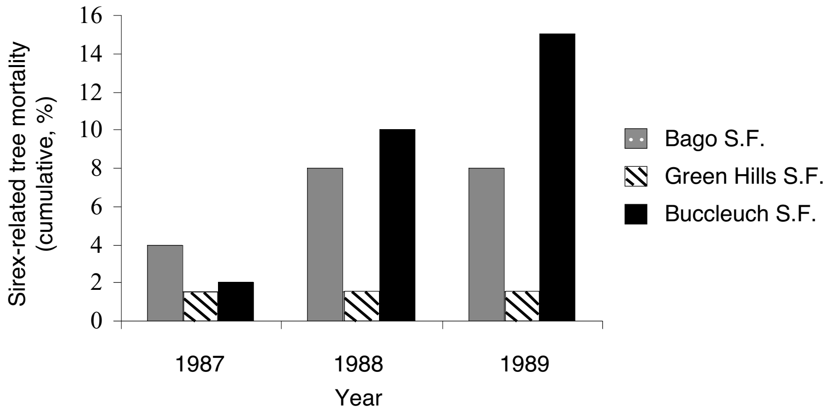


FIG. 2–Cumulative mortality associated with sirex from annual surveys of three State Forests in Hume Region from 1987 to 1989.

of damage in 1994–95, exceeding 25% incidence in two compartments totalling 152 ha.

The Forest Health Survey Unit has accurately mapped and quantified levels of sirex damage in New South Wales annually since the winter of 1996. Since then the majority of sirex observations have been mortality of suppressed trees at levels considerably below 1%, with few severe outbreaks (Table 1). Predominantly old sirex damage from previous years was observed during the 1996 surveys, with around 3% in many areas at Macquarie, Hume, and Monaro Regions, and higher levels of old damage (up to 20%) in several State Forests in Hume and Macquarie Regions. Macquarie Region reported cumulative levels of mortality at 30% in one State Forest in 1995 (based on evidence of old damage). Although the biological control programme had been in place in this region, thinning had been delayed, and adjacent unthinned private plantations had high levels of sirex.

From 1996 onwards, sirex-related tree mortality was generally restricted to one or a few compartments in a year, with generally not more than 200 ha affected per State Forest. There were only low levels of new sirex damage observed in 1996. Two State Forests in Macquarie Region had new sirex damage at 2–3% in 1996; these were less than 200 ha in area. A localised outbreak of sirex caused significant mortality in a 13-year-old plantation in southern Hume Region in 1996 (approx 65 ha), where up to 25% of the trees died over several seasons.

While no significant sirex mortality was observed in New South Wales plantations in 1997, several State Forests in Hume, Macquarie, and Monaro had up to 3% mortality from sirex in 1998 and 1999 after a prolonged drought period, with areas affected less than 200 ha each. In 2000, several compartments in northern Hume Region had up to 3% of 10-year-old trees die in an area of approximately 300 ha.

Mortality continued the following year with a further 3% of trees killed by sirex, and also in an adjacent compartment. This area has a reported low site quality and lower rainfall (J. Alston pers. comm.). In 2000, 190 ha in Macquarie Region sustained 3% mortality from sirex. Low levels of mortality (1–3%) were observed in several State Forests in Hume and Macquarie Regions from 2002 to 2004, with less than 100 ha in each forest. Surveys in 2005 revealed minor damage from sirex.

The majority of sirex mortality observed from 1996 to 2005 in New South Wales plantations was in the most susceptible age-class (>10 years) in unthinned compartments. However, mortality was also observed in suppressed trees ranging from 30 years to as young as 7 years old.

## Biological Control Programme

Sirex parasitoids were first released into Murraguldrie State Forest and Carabost State Forest (Hume Region) in 1980 (Taylor 1981), after which they were regularly released from 1980 to 1989 throughout Hume Region (Table 2). The most commonly released parasitoids were *Ibalia leucospoides* with over 18 000 released, followed by *Megarhyssa nortoni* with over 4000 released in Hume Region. *Schlettererius cinctipes*, *Rhyssa persuasoria* (Linneaus), and *R. hoferi* Rohwer were released in low numbers from 1980 to 1984 in Hume Region, but subsequent release was sporadic due to difficulty in rearing these species in the laboratory. In 1988–89, roughly 1000 *I. leucospoides* and 50 *M. nortoni* each were released in forests around Oberon (Macquarie Region) and Moss Vale and Bombala (Monaro Region), being the only species of parasitoids released in these regions. No parasitoids were released in Northern Region.

Emergence data for the parasitic wasps for Hume, Macquarie, and Northern Regions are shown in Tables 3 to 5. *Ibalia leucospoides* was by far the most

TABLE 2–Releases of parasitoids during summer in Hume Region from 1980–81 to 1988–89.

| | *Ibalia leucospoides* | *Megarhyssa nortoni* | *Rhyssa persuasoria* | *Rhyssa hoferi* | *Schlettererius cinctipes* |
|---|---|---|---|---|---|
| 1980–81 | 6765 | 490 | 123 | | |
| 1981–82 | 3871 | 588 | 54 | | 251 |
| 1982–83 | 4508 | 244 | 79 | 42 | 46 |
| 1983–84 | 666 | 383 | | 36 | |
| 1984–85 | 1721 | 7 | | | |
| 1985–86 | | 401 | | | |
| 1986–87 | 700 | 74 | | | |
| 1987–88* | | | | | |
| 1988–89 | 100 | 1850 | | | |
| Total | 18,331 | 4037 | 256 | 78 | 297 |

* No figures for 1987–88

common parasitoid recorded, emerging in moderate to large numbers in most years in Hume and Macquarie Regions. *Megarhyssa nortoni* emerged in low numbers in

TABLE 3–Emergence data from billets in Hume Region from 1988–89 to 2003–04

| - | | Sirex | | Parasitoids* | | | |
|---|---|---|---|---|---|---|---|
| | | Female +ve (%) | Male +ve (%) | Ib | Mn | Rh | Sc |
| 1988–89 | TT† | – | – | – | – | | |
| | NST‡ | 70 | 60 | | | 1 | |
| 1989–90 | TT | – | 25 | – | – | | |
| | NST | 97 | 98 | | | | |
| 1990–91 | TT | – | – | – | – | | |
| | NST | – | 78 | | | | |
| 1991–92 | TT | – | 33 | 742 | 0 | | |
| | NST | – | – | | | | |
| 1992–93 | TT | 89 | 84 | 706 | 0 | | |
| | NST | 93 | 98 | | | | |
| 1993–94 | TT | 82 | 82 | 83 | 0 | | |
| | NST | – | – | | | | |
| 1994–95 | TT | 63 | 74 | 807 | 23 | | |
| | NST | – | – | | | | |
| 1995–96 | TT | 87 | 77 | 746 | 18 | | |
| | NST | 26 | 42 | | | | |
| 1996–97 | TT | 100 | 93 | 303 | 0 | | |
| | NST | 100 | 83 | | | | |
| 1997–98 | TT | 23 | 64 | 55 | 1 | | |
| | NST | – | – | | | | |
| 1998–99 | TT | 96 | 84 | low | 0 | | |
| | NST | 0 | 5 | | | | |
| 1999–00 | TT | 90 | 75 | mod | low | | |
| | NST | – | – | | | | |
| 2000–01 | TT | 51 | 36 | 847 | 46 | | |
| | NST | – | – | | | | |
| 2001–02 | TT | 45 | 84 | 5 | 0 | | |
| | NST | – | – | | | | |
| 2002–03 | TT | 61 | 53 | 205 | 3 | | 1 |
| | NST | 74 | 90 | | | | |
| 2003–04 | TT | 75 | 78 | 178 | 2 | | |
| | NST | – | – | | | | |

* Ib = *Ibalia leucospoides*
Mn = *Megarhyssa nortoni*
Rh = *Rhyssa hoferi*
Sc = *Schlettererius cinctipes*
† TT = trap tree
‡ NST = naturally struck tree
– = no data available

Hume and Macquarie Regions, and not in all years. Both *I. leucospoides* and *M. nortoni* emerged from trap tree billets and naturally struck trees soon after sirex was detected in Northern Region, but were not observed again for several years. *Ibalia leucospoides* and *M. nortoni* appear to spread in tandem with sirex, being detected with or soon after sirex is established in a region. Very low numbers of *S. cinctipes* were detected in Hume Region in the early 1980s (data not shown),

TABLE 4–Emergence data from billets in Macquarie Region from 1990–91 to 2003–04

| | | Sirex | | Parasitoids* | |
|---|---|---|---|---|---|
| | | Female +ve (%) | Male +ve (%) | Ib | Mn |
| 1990–91 | TT† | 39 | 24 | | |
| | NST‡ | 1 | 1.5 | | |
| 1991–92 | TT | 70 | 72 | 1760 | 15 |
| | NST | – | – | | |
| 1992–93 | TT | 83 | 82 | 3421 | 82 |
| | NST | 24 | 39 | | |
| 1993–94 | TT | – | – | – | – |
| | NST | – | – | | |
| 1994–95 | TT | – | – | – | – |
| | NST | – | – | | |
| 1995–96 | TT | 87 | 92 | 244 | 87 |
| | NST | 68 | 73 | | |
| 1996–97 | TT | 80 | 71 | 329 | 28 |
| | NST | 95 | 82 | | |
| 1997–98 | TT | 91 | 87 | 761 | 17 |
| | NST | 58 | 61 | | |
| 1998–99 | TT | 77 | 80 | 822 | 22 |
| | NST | 18 | 18 | | |
| 1999–00 | TT | 82 | 45 | 1567 | 16 |
| | NST | 85 | 50 | | |
| 2000–01 | TT | 76 | 34 | 1600 | 26 |
| | NST | 78 | 24 | | |
| 2001–02 | TT | 60 | 5 | 318 | 14 |
| | NST | 67 | 6 | | |
| 2002–03 | TT | – | – | – | – |
| | NST | – | – | | |
| 2003–04 | TT | 86 | 61 | 431 | 16 |
| | NST | 83 | 67 | | |

* Ib = *Ibalia leucospoides*
Mn = *Megarhyssa nortoni*
† TT = trap tree
‡ NST = naturally struck tree
– = no data available

TABLE 5–Emergence data from billets in Northern Region (Northern Tablelands plantations) from 1996–97 to 2003–04

| | | Sirex | | Parasitoids* | |
|---|---|---|---|---|---|
| | | Female +ve (%) | Male +ve (%) | Ib | Mn |
| 1996–97 | TT† | | | low-mod | very low |
| | NST‡ | | | | |
| 1997–98 | TT | 82 | 63 | – | – |
| | NST | 0 | 0 | | |
| 1998–99 | TT | 83 | 71 | 0 | 0 |
| | NST | – | – | | |
| 1999–00 | TT | 63 | 54 | – | – |
| | NST | – | – | | |
| 2000–01 | TT | – | – | – | – |
| | NST | – | – | | |
| 2001–02 | TT | 70 | 68 | – | – |
| | NST | – | – | | |
| 2002–03 | TT | 70 | 73 | 75 | 8 |
| | NST | 55 | 50 | | |
| 2003–04 | TT | 51 | 69 | 0 | 0 |
| | NST | 100 | 100 | | |

* Ib = *Ibalia leucospoides*
Mn = *Megarhyssa nortoni*
† TT = trap tree
‡ NST = naturally struck tree
– = no data available

often proximal to original release sites, and they were not recorded again in the same areas for almost 20 years. There was only a single detection record of *R. hoferi* in New South Wales. Although it was released, no *R. persuasoria* has been detected in the State.

Sirex emergence data from billets collected in Hume Region from 1988–89 to 2003–04, showing percentage of wasps infected with the nematode, are given in Table 3. In most years from 1988–89 to 1998–99 the percentage of infected wasps from trap trees was between 75 and 95%, indicating that the inoculation procedures were working well. However, from 2000–01 to 2002–03 these dropped down below 60%. Staff at Research & Development Division immediately set about remedying the problems with in-field training and quality assurance testing of the various procedures of trap tree establishment and nematode inoculation. It was concluded that trap tree establishment had been less than optimal, with trees not dying in some instances. Old chemical was partly to blame. Because of the low level of nematode-positive females, and the “green” trap trees, a concerted effort was made to find naturally struck trees, and these were then inoculated with nematodes. In 2003–04 the percentage infected wasps was back over 75%, indicating the problem had been corrected; future emergence data will be carefully monitored.

In Macquarie Region (Table 4) the percentage of nematode-positive wasps in trap trees was generally above 75%, indicating that inoculation procedures were working well. In Northern Region (Table 5), the percentage of nematode-positive wasps from trap trees was generally below 75%, indicating that inoculation procedures need to be reviewed.

The percentages of positive wasps in naturally struck trees in all three Regions (Tables 3–5) were not consistent, with low percentages in some years and high in others. This is of concern, and indicates that contrived dissemination of the nematode via trap trees is required.

## DISCUSSION

Sirex has now been established in New South Wales for over 25 years. The spread from Albury north was most likely facilitated via the large areas of contiguous commercial *P. radiata* plantations around Tumut (Hume Region) and the Australian Capital Territory, private woodlot and windbreak plantings around Young (100 km north of Tumut), commercial plantations near Moss Vale (Monaro Region), and private plantations south of Bathurst to Macquarie Region. It is clear that amenity trees and shelterbelts assisted this spread (R. Eldridge & J. Simpson unpubl. data). The spread of sirex into south-eastern New South Wales (Bombala) may have been instigated from sirex-affected plantations around Tumut or from north-east Victoria (Neumann 1985). The spread from Macquarie Region north also appears to have been assisted by small private plantings, as there are no large plantations between Bathurst and Walcha, either State or privately owned. Once sirex had reached the Walcha plantations (Northern Region) it spread further north, reaching plantations around Glen Innes by 2001 and Tenterfield by 2002. In 2002 it was detected (as emergence holes) in a commercial plantation near Casino. However, no further emergence holes were detected by 2005, nor were any wasps or larvae observed, indicating that it has not established in this area. We believe it is possible that unmated females reached these plantations in 2000–01, but since they were unfertilised only male wasps emerged and a breeding population was not established. Further evidence is required to confirm establishment in the area.

Sirex is indigenous, but not economically important, in the Mediterranean region (southern Europe, North Africa, and Turkey) (Hall 1968), which experiences dry warm summers and cool moist winters, similar to the majority of the pine-growing regions of south-eastern Australia (Kirk 1976). Sirex is now well-established in the majority of these areas in Australia (i.e., Tasmania, South Australia, Victoria, and southern and central New South Wales) that experience similar climatic conditions, the exception being Western Australia. The isolation of plantations in Western Australia by the Nullabor Plain means that sirex could become established only through a separate overseas introduction or through traffic of infested material within Australia. Sirex is also established in the Northern Tablelands of New South Wales, which experience a more even distribution of rainfall during summer and winter (Bureau of Meteorology 2005) with higher summer temperatures and lower winter temperatures due to altitude and distance from the coast. This area lies in the zone of transition from the dominantly summer maximum rainfall areas of northern Australia to the dominantly winter maximum rainfall areas of the south (Hobbs *et al.* 1977).

The pine plantations in north-eastern New South Wales around Casino are within 100 km of the coast in an area that experiences warm moist summers due to monsoonal influences and dry winters, with a higher average humidity than the Northern Tablelands or areas further south (Bureau of Meteorology 2005). There are moderately sized plantations in the areas around Casino that are planted with species susceptible to sirex (i.e., *P. taeda*). However, the higher summer rainfall within these coastal plantations may be limiting the establishment of sirex in these areas. Recent studies have examined the susceptibility of hosts planted in the summer-rainfall areas of north-eastern New South Wales and Queensland (*P. caribaea* and *P. elliottii* × *P. caribaea* hybrids), and the effect of climate on the spread of sirex. *Pinus elliottii* × *P. caribaea* hybrids have proved to be susceptible to sirex (J. King unpubl. data), as is *P. taeda*, indicating that host is not a limiting factor for the establishment of sirex in sub-tropical Australia. Climate-matching studies (using CLIMEX) have shown that climate is also not a limiting factor (Carnegie *et al.* in press). Furthermore, sirex has established in the summer-rainfall areas of South Africa, and is causing significant damage in *P. patula* plantations (Carnegie *et al.* in press).

Eldridge & Taylor (1989) calculated the natural spread of sirex in New South Wales at approximately 4 km per year, and predicted sirex would reach the pine-growing regions of southern Queensland by 2008. As sirex is currently approximately 100 km from the pine plantations just over the Queensland border, we support the prediction of Eldridge & Taylor (1989): based on its current rate of spread, host availability, and results of climatic analysis, sirex is expected to reach *P. radiata* plantations in southern Queensland (Stanthorpe) by 2008. The climate in this area is similar to that in which sirex has established in other parts of Australia. We also believe that sirex is likely to establish in the southern-pine plantations around Casino over the next few years. However, the lower susceptibility of the majority of plantations in this area and south-eastern Queensland, compared to *P. radiata,* is likely to slow its spread further north.

Sirex has not caused the extensive mortality over large areas in New South Wales that was seen in Tasmania (Madden 1975, 1998), Victoria (Neumann & Minko 1981), and the Green Triangle (Haugen 1990; Haugen & Underdown 1990). This is due mostly to the implementation of the Sirex Management Strategy (Haugen *et al.* 1990) in New South Wales, including detailed forest health surveillance and biological control. One of the major problems in the Green Triangle that led to the severe outbreaks of 1986–87 was the failure of the monitoring programme to adequately quantify sirex impact or the change in sirex populations in specific compartments or areas (Haugen 1990).

Data from aerial and ground surveys, such as level of sirex damage and spread of the wasp, are used to efficiently locate trap trees for the biological control programme. Forests NSW has implemented a rigorous forest health surveillance programme that quantifies sirex impact and spread, and highlights areas where further trap trees for nematode inoculation are required. The programme involves Softwoods Regional staff who manage the plantations, as well as staff from Research and Development Division who provide technical expertise. Trap trees are also located in areas where sirex has not yet been detected. The aim of these is for early detection of sirex into a new area which can subsequently be monitored by regional staff.

Outbreaks of sirex usually occur only in conditions that are adverse to pines, such as those experienced during prolonged drought and in stands overdue for thinning (Neumann & Minko 1981), and can be exacerbated or stimulated when stands are damaged by snow or wind. Since trees under severe physiological stress are the most at risk of sirex attack, one of the most effective control strategies is to maintain good stand vigour and health (Eldridge & Simpson 1987). By managing plantations optimally, such as timing selective thinning to sustain tree vigour and restricting pruning and thinning-to-waste until outside the wasp flight season, the risk to pine plantations from sirex attack can be greatly reduced. However, market forces or difficult terrain sometimes lead to delays in thinning programmes. The majority of significant sirex-related deaths in New South Wales can be related to delayed thinning or pruning operations carried out in summer during the sirex flight season. There have been several instances in New South Wales where recently pruned trees have been killed by sirex. High levels of mortality (5–6%) in southern Tasmania in recent years have also been associated with summer pruning (D. Bashford pers. comm.).

Few areas where significant levels of sirex were observed in New South Wales in the past 25 years had continued mortality over several years, the exception being localised areas in Hume Region. Outbreaks in these forests declined after 3 years, either naturally or due to the thinning and biological control programmes implemented by Forests NSW. Neumann & Minko (1981) reported that when localised outbreaks of sirex occur they usually decline naturally due to the absence of suitable hosts (i.e., stressed trees).

"A key factor to reducing the risk of a sirex outbreak is to release the biological control agents well before sirex populations reach outbreak levels" (Haugen 1990). Evaluation of the biological control programme, to determine the establishment, distribution, and population levels of the biological control agents, is an essential process for implementing an effective control programme (Haugen 1990). Although initially sporadic, the nematode inoculation and evaluation programme has continued annually in all regions in New South Wales where sirex has become established. Forests NSW has monitored and evaluated the sirex biological control programme utilising trap trees, collecting billets, and dissecting the emerging wasps. Nematode parasitism percentages have been determined for the "natural" sirex population as well as for the biological control inoculation programme. This has allowed the effectiveness of nematode inoculation techniques and background nematode parasitism to be determined, as well as the levels of parasitoid wasps as they emerge from the billets. A high level of female sirex wasps are infected with the parasitic nematode *B. siricidicola.* The low levels of significant mortality in New South Wales can be attributed to this continued programme and monitoring.

During the late 1980s it became apparent that levels of infected females emerging from inoculated trees had reduced significantly in south-eastern Australian plantations, from greater than 95% down to less than 30% (Haugen & Underdown 1993). Investigations of inoculation procedures revealed the likely cause to be a reduction in the infective capacity of nematode cultures reared in the laboratory. In 1990, investigations indeed revealed that the infectivity of the cultured nematode strain, originally imported from Hungary, had significantly decreased (Calder & Bedding 2001). In New South Wales, only plantations in the southern Regions (Hume, Monaro, and Macquarie), where sirex was detected prior to 1991, were inoculated with the "defective" nematode strain, with all subsequent inoculations throughout New South Wales now using the highly infective Kamona strain. This nematode is removed from storage in liquid nitrogen and assessed periodically by CSIRO to ensure that its infectivity is being maintained at a high percentage. To date, all tested nematode strains supplied to CSIRO from New South Wales (i.e., from Hume, Macquarie, and Northern Regions) have shown excellent infectivity comparable to the Kamona strain (Calder & Bedding 2001), suggesting the Kamona strain has the capacity to replace the "defective" strain in New South Wales. In Tasmania, increased sirex damage in recent years has been linked to the defective strain, and attempts are under way to increase the proportion of the Kamona strain (D. Bashford pers. comm.). Attempts are being made in south-eastern Australia to flood the "defective" nematode train with the Kamona strain.

Of the parasitoids released and detected in New South Wales, *I. leucospoides* is the most well-established, which is similar to that reported for other areas in south-eastern Australia (Neumann & Morey 1984; Haugen 1990; Neumann *et al.* 1993; Phillips 2002). Analysis of emergence data from 1996 to 2002 in New South Wales shows that *I. leucospoides* has a much higher level of parasitism (over 99%) than *M. nortoni* (I. Hides unpubl. data). In the Green Triangle, over 99% of parasitism in 1986–87 was associated with *I. leucospoides* (Haugen 1990). Similar levels of parasitism were observed in north-eastern Victoria, with *I. leucospoides* being by far the most successful parasitoid, and *S. cinctipes* and *M. nortoni* the only other parasitoids observed (Neumann & Morey 1984; Neumann *et al.* 1993). In Tasmania, Taylor (1981) observed that parasitoids will not prevent sirex spread, but will slow it and help prevent a rapid population increase during periods such as drought where stressed trees are more susceptible to attack. Neumann & Morey (1984) stated that "the nematode is clearly superior to any of the parasitoids as a biological control of sirex".

The majority of sirex outbreaks in New South Wales have been in unthinned stands, in the age-class range from 10 to 25 years, and in localised areas (<200 ha), with the majority of outbreaks having occurred in *P. radiata.* The biological control programme in New South Wales, and annual forest health surveillance, have resulted in an acceptable level of control of sirex within Forests NSW pine plantations. The use of trap trees and annual surveillance has increased the detection of sirex in New South Wales, enabling control programmes to be implemented before sirex reaches outbreak levels. However, little sirex management is conducted in private plantations in New South Wales. Continued forest health surveillance, biological control, and silvicultural management of susceptible stands will help reduce the pest potential of sirex in New South Wales, and indeed Australia.

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