Forest Ecology and Management 381 (2016) 134–143

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Minimizing the disruptive effect of *Ips grandicollis* (Coleoptera: Scolytinae) on biocontrol of *Sirex noctilio* (Hymenoptera: Siricidae)

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ARTICLE INFO

Article history:
Received 2 May 2016
Received in revised form 15 September 2016
Accepted 17 September 2016
Available online 24 September 2016

Keywords:
Biological control
Invasive species
Pinus radiata
Bark beetles
Siricidae
Trap trees

ABSTRACT

Sirex noctilio Fabricius (Hymenoptera: Siricidae) is an invasive wood wasp that can cause significant tree mortality to *Pinus*. Trees treated with herbicide are used to attract *S. noctilio* to oviposit and are the means by which the nematode biocontrol agent, *Deladenus* (=*Beddingia*) *siricidicola* Bedding (Nematoda: Neotylenchidae), is introduced into the pest population. In Australia, these trap trees are also attacked by the invasive bark beetle, *Ips grandicollis* Eichhoff (Coleoptera: Curculionidae; Scolytinae). This study investigated the effect of herbicide dose and timing of application on subsequent attractiveness of trap trees to *S. noctilio* and *I. grandicollis*. Two replicated trials were conducted concurrently in two major pine growing regions of Australia. Trees in southern New South Wales and South Australia were treated in a factorial manner with two doses of glyphosate on two dates (December and January) along with an untreated control. In both locations, *S. noctilio* attacked January-treated trees sooner after herbicide application compared to December treatments. *Ips grandicollis* attacked December-treated trees sooner compared to January treatments. January treated trees were best in attracting *S. noctilio* before *I. grandicollis* attack—irrespective of herbicide dose—in South Australia, but not in New South Wales. Numbers of emerging *S. noctilio* and those parasitized by nematodes were negatively correlated with the number of days trap trees were infested by *I. grandicollis*. In New South Wales, herbicide application to trap trees in January (mid-summer) best promotes *S. noctilio* biocontrol by minimizing colonization by *I. grandicollis*, but this was not as clear-cut in South Australia.

1. Introduction

The wood wasp, *Sirex noctilio* Fabricius (Hymenoptera: Siricidae), is one of the most important pests of *Pinus radiata* D. Don (Pinales: Pinaceae) plantations and other pine species (Haugen and Underwood, 1990; Carnegie and Bashford, 2012; Slippers et al., 2012). *Sirex noctilio* has established and spread in exotic pine plantations throughout the Southern Hemisphere (Slippers et al., 2012) and into planted forests in North America (Hoebeke et al., 2005; de Groot et al., 2006). Significant outbreaks and damage have occurred where it has invaded. In South America, *S. noctilio* causes up to 70% mortality in plantations of exotic pine (Iede and Zanetti, 2007). In South Africa, *S. noctilio* infestations in *P. radiata* can cause 10–35% tree mortality in 12–13-year-old stands (Hurley et al., 2012). In North America and Canada, *S. noctilio* invasions are recent with up to 18% infestation rates recorded in exotic pine plantations (Dodds et al., 2010). In Australia, significant outbreaks in the Green Triangle (south-eastern South Australia to south-western Victoria) in the late 1980s resulted in death of over five million trees and a substantial effort and expense to control the outbreak (Haugen et al., 1990; Haugen and Underwood, 1990).

Sirex noctilio adults are ephemeral and usually univoltine, generally emerging in early summer through to early autumn (Neumann and Minko, 1981). The timing of egg hatching varies between regions but mainly occurs between mid-spring and late autumn (Taylor, 1981; Hurley et al., 2008). Mating takes place soon

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http://dx.doi.org/10.1016/j.foreco.2016.09.023
0378-1127/

after emergence, following which, females take flight to locate a tree for oviposition (Madden, 1974). Adult *S. noctilio* females are attracted to stressed or weakened trees (Neumann and Minko, 1981; Ryan and Hurley, 2012). The female explores the bole with her antennae and probes the sapwood with her ovipositor when a potential host tree is located (Madden, 1981; Hayes et al., 2015). In young trees, oviposition usually occurs along the entire stem but is concentrated between 3 m and 14 m above ground in older trees (Madden, 1981). Resin beading and dripping is a key symptom of attack (Madden, 1974; Zondag and Nuttall, 1977; Smith et al., 2008; Ryan, 2011; Ryan et al., 2013). *Sirex noctilio* introduces a venom (noctilisin) and the obligate symbiotic fungus, *Amylostereum areolatum* (Chaillet ex Fries) Boidin (Basidiomycotina: Amylostereaceae) into the wood during oviposition. The venom causes tree stress by blocking translocation thus, attracting *S. noctilio* to oviposit (Madden, 1977; Bordeaux et al., 2014). The fungus colonizes the wood, metabolising it into easily absorbed lignocellulosic compounds for the developing *S. noctilio* larvae (Madden, 1981; Bordeaux and Dean, 2012; Thompson et al., 2014).

Management strategies for *S. noctilio* include forest surveillance to identify areas requiring biocontrol (Carnegie and Bashford, 2012) and silvicultural techniques to reduce stand density and susceptibility to attack (Neumann et al., 1987; Haugen et al., 1990; Carnegie and Bashford, 2012). A number of parasitic wasps are used for biocontrol (Haugen and Underwood, 1990) of which two species—*Megarhyssa nortoni* (Cresson) (Hym.: Ichneumonidae) and *Ibalia leucospoides* Hochenwarth (Hym.: Ibaliidae)—are established and effective in Australia (Carnegie et al. 2005; Collett and Elms 2009). However, biocontrol using the nematode, *Deladenus* (= *Beddingia*) *siricidicola* Bedding (Nematoda: Sphaerulariidae) (Bedding, 1984; Blinova and Korenchenko, 1986) is the most important method of managing *S. noctilio* in Australia (Bedding, 2009; Haugen et al., 1990) and is a component of the more methodologically diverse management programs in South America and South Africa (Hurley et al., 2008, 2012; Slippers et al., 2014). There have been suggestions that variation in nematode infection levels (e.g. South Africa, Hurley et al., 2008) is a result of evolution of resistance in *S. noctilio* populations or reduced virulence in *D. siricidicola* in the different regions where the nematode is used as a biocontrol agent (Slippers et al., 2012). For instance, the Kamona strain (used in Australia) is incompatible with the *S. noctilio* population in South Africa. Of the *D. siricidicola* strains tested in Australia, Kamona has been optimal (Bedding, 2009; Carnegie and Bashford, 2012). Thus, *S. noctilio* from different geographical areas may be controlled best by other strains of *D. siricidicola*.

Trap trees are an effective means of monitoring and introducing the biocontrol nematode into the target *S. noctilio* population (Neumann et al., 1987; Bedding and Iede, 2005) and are also a detection tool for the wood wasp (Madden, 1981). While the use of trap trees is labour intensive and costly, this approach is effective in detecting *S. noctilio* at low densities (Taylor, 1985; Zylstra et al., 2010; Carnegie and Bashford, 2012). Current practice for the biocontrol of *S. noctilio* in Australia involves treating trap trees with 1 mL per 10 cm of stem circumference with either dicamba 500 g/L or glyphosate 360 g/L (Neumann et al., 1987; National Sirex Coordination Committee, 2007). A group of 8–12 trees (a trap tree plot) is treated with herbicide in early summer (December) to cause tree stress but not immediate tree death, thereby making them attractive for *S. noctilio* oviposition. The trees are felled from mid-autumn (April) to mid-winter (July) and cultured nematodes are inoculated into the wood (Neumann et al., 1987; National Sirex Coordination Committee, 2007). Nematode inoculation is generally preceded by sighting of resin beads followed up with dissection of a sample of trees to confirm presence of larvae inside the wood. Where the larvae are present, the remaining trap trees within the vicinity are inoculated with nematodes (Neumann et al., 1982; National Sirex Coordination Committee, 2007; Carnegie and Bashford, 2012) where the mycetophagous form feeds on the *S. noctilio*-associated fungus, *A. areolatum* (Caetano et al., 2016). Later, the entomopathogenic nematodes enter the developing *S. noctilio* larvae and migrate to the host's ovaries where they invade the eggs rendering them sterile (Bedding, 1972; Bedding and Akhurst, 1974; Bedding and Iede, 2005). Adult females later emerge and oviposit 'packets' of nematodes, thereby disseminating the biocontrol agent into new trees (Bedding, 1972; Bedding and Akhurst, 1974). The ability of the nematodes to infect *S. noctilio* is largely dependent on compatibility of the nematode strain with the local *S. noctilio* population (Hurley et al., 2008; Slippers et al., 2014).

Recent observations in Australia indicate decreased parasitism of *S. noctilio* by *D. siricidicola* and a need to optimize trap tree establishment (Carnegie and Bashford, 2012). Competing insects and microorganisms have been implicated in reduced attractiveness of trap tree to *S. noctilio* and variable trap tree efficiency (Zylstra et al., 2010; Ryan et al., 2012; Yousuf et al., 2014a). In North America, trap trees were found to be heavily colonized by bark beetles and longhorn beetles after herbicide treatment (Zylstra et al., 2010; Ryan, 2011; Ryan et al., 2012). Over the last decade in Australia, the exotic bark beetle *Ips grandicollis* Eichhoff (Coleoptera: Curculionidae) has been detected in trap trees (Carnegie and Loch, 2010; Carnegie and Bashford, 2012; Gitau et al., 2013) with up to 99% of trees attacked in some regions (Gitau et al., 2013). *Ips grandicollis* was detected in South Australia in the 1940s (Morgan, 1967) and has now established in major pine growing regions in New South Wales, Victoria, southern Queensland and Western Australia (Eldridge, 1983; Morgan, 1989; Elliott et al., 1998; Carnegie and Bashford, 2012; Gitau et al., 2013).

Attack of trap trees by *I. grandicollis* can have adverse implications for the biocontrol of *S. noctilio*. Recent studies by Yousuf et al. (2014a) showed that a competitive interaction between *A. areolatum* and the fungus associated with *I. grandicollis*, *Ophiostoma ips* (Rumbold) Nannfeldt (Pezizomycotina: Ophiostomaceae), within trap trees leads to reduced parasitism of *S. noctilio* by *D. siricidicola.* This was partly because *O. ips*-infested wood dries more quickly, preventing nematode migration. Further, *O. ips* rapidly colonizes wood after being introduced by *I. grandicollis* and this can exclude subsequent growth of *A. areolatum* that is essential for nematode and *S. noctilio* larval development. Despite these known fungal-associate-related phenomena, there is limited information on the extent to which the infestation of trap trees by *I. grandicollis* impacts on the suitability of wood for nematodes development. The objective of this study was to investigate the effects of timing of herbicide application and herbicide dose on attack of trap trees by *S. noctilio* (desirable) and *I. grandicollis* (undesirable). It has been postulated that trap trees become unattractive for oviposition by *S. noctilio* if *I. grandicollis* attacks them first (Carnegie and Loch, 2010; Carnegie and Bashford, 2012). Therefore, we assessed which of the two pests attacked trap trees first, regardless of whether the other attacked the same tree later. Further, we investigated the effect of dose and timing of herbicide application on the attack of trap trees by *I. grandicollis* and consequences on *S. noctilio* emergence and parasitism by *D. siricidicola.*

2. Materials and methods

2.1. Study sites and experimental design

Two trials were conducted: one in Tumut, plantations situated 785 m above sea level in southern New South Wales, Australia (35.3047°S, 148.2228°E) and the second trial in the Adelaide Hills, plantations situated 685 m above sea level in South Australia