Chapter 19
Sirex, Surveys and Management: Challenges of having *Sirex noctilio* in North America

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Abstract Since 2004, when the Sirex woodwasp, *Sirex noctilio*, was first discovered in North America, there have been intensive efforts to survey and determine the area infested and to assess management options. In this chapter we review the history of survey efforts in Canada and the USA from 2005 to 2009 and the challenges facing these surveys. Next we describe the significant differences between North America and the Southern Hemisphere (where this insect is a serious pest) in forest types, natural disturbance regimes, competing insects and disease, and forest management methods and how they affect surveys and management. We review the logistical issues of landscape and forest diversity, ownership, and access that affect the implementation of surveys, and biological issues of native siricids and other associated insects and diseases that complicate the use of trap trees and traps. We discuss the challenges of using silviculture and biological methods in North America to control *S. noctilio*. We conclude that management of *S. noctilio* will not be easy and must be multifaceted. The diversity, heterogeneity and complexity of North America's natural forests in terms of natural enemies and competing insects and diseases, may be a problem for survey efforts, but also a solution for management. Finally, the situation in North America is unique, allowing many interesting questions on invasion biology, community ecology, and management of an invasive species in native pine communities to be addressed.

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B. Slippers et al. (eds.), *The Sirex Woodwasp and its Fungal Symbiont: Research and Management of a Worldwide Invasive Pest*, DOI 10.1007/978-94-007-1960-6_19,

19.1 Introduction

Sirex noctilio F. (Hymenoptera: Siricidae) was first detected in North America during a 2004 exotic species survey in New York state, USA (Hoebeke et al. 2005). This insect had been high on the exotic species target lists in Canada and the United States for a number of years because it has caused widespread economic losses in pine plantations in the Southern Hemisphere and also because the extensive areas of pine forests of North America are classified as high-risk (Haugen 1999; Borchert et al. 2007). It is of considerable concern because it is capable of establishing and flourishing in the prime industrial pine forest regions in the southern and western U.S. and over much of the boreal forest in Canada (Carnegie et al. 2006; Yemshanov et al. 2009a).

Despite the carefully considered risk assessments, the real impact of *S. noctilio* to pine in North America is still unknown and debatable. There are significant differences between the North American pine ecosystems and the Southern Hemisphere pine forests, where both pine and *S. noctilio* have been introduced. It is reasonable to expect that the impact will vary across the continent and that *S. noctilio* will cause different levels of tree damage and economic impact in areas where management, landscape heterogeneity, and tree species vary. Given the uncertainty, the rapid survey response to discovery of *S. noctilio* in North America has been prudent in regarding this as a serious risk requiring substantial effort to detect and delimit the area of infestation.

In this chapter, we review the general approaches and issues surrounding the survey for this insect in Canada and the USA. We then describe the types of forests where *S. noctilio* has already been found and the types of forests where it may be found, and could cause significant economic and ecological impact. We conclude by presenting many of the unique challenges facing survey and management efforts in North America.

19.2 Detection in North America

19.2.1 Agencies Involved in Detection and Delimitation Efforts in Canada and the United States

Both provincial/state and federal agencies are involved in detection efforts for *S. noctilio* in North America. The Canadian Food Inspection Agency (CFIA) is charged with protecting food, animals, and plants and has legislative authority to regulate invasive species in Canada. The companion agency in the USA is the United States Department of Agriculture (USDA), Animal and Plant Health Inspection Service (APHIS) and it is charged with safeguarding American agriculture and natural resources. The Canadian Forest Service (CFS) and USDA Forest Service (USFS) provide scientific support and expertise to the regulatory agencies when forest pests

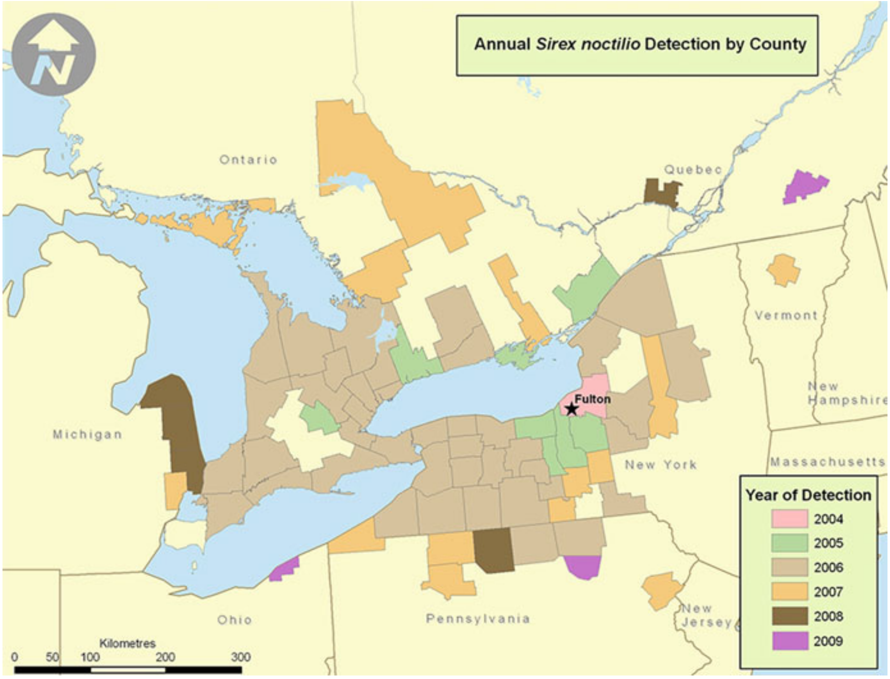

Fig. 19.1 Known distribution of *Sirex noctilio* in North America by county as of January, 2010

are involved. These federal agencies in Canada and the USA work closely with their provincial and state departments of agriculture and forestry to detect and respond to invasive species. International agreements under the North America Plant Protection Organization (NAPPO) facilitate cooperation between Canada, Mexico, and the USA when addressing plant health concerns, including invasive forest pests (NAPPO 2005).

19.2.2 Annual Surveys

Both Canada and the USA have annual exotic or invasive alien species surveys that use traps baited with bark beetle pheromones and/or host volatiles (CFIA 2006; USDA 2006). Traps are typically placed in "high-risk" areas (e.g., ports of entry, warehouse districts, forests adjacent to urban areas) to increase the likelihood of detecting an exotic species early during its establishment phase. On 7 September 2004, an individual *S. noctilio* female was captured in an exotic species survey trap placed in Fulton, New York (Hoebeke et al. 2005), an area that has limited industrial activity, and is 16 km inland from the port city of Oswego on Lake Ontario (Fig. 19.1). This was not the first time an adult *S. noctilio* female was found in North America.

In 2002, warehouse workers in Bloomington, Indiana found *S. noctilio* (Hoebeke et al. 2005). Trapping surveys around the warehouse in Indiana found no further evidence of *S. noctilio* establishment. Detections of Siricidae larvae in wood packaging materials and dunnage at North American ports have also been common (Ciesla 2003).

19.2.2.1 2005 Surveys

In response to the initial discovery in 2004, ground-based visual surveys for *S. noctilio* symptoms in red (*Pinus resinosa* Ait.) and Scots (*P. sylvestris* L.) pine stands occurred during the spring of 2005 in the USA. This effort resulted in the location of three suspect stands that were later confirmed positive for *S. noctilio* through either larval DNA analyses (Nathan Schiff, USDA Forest Service, personal communication, 2005) or rearing from infested logs. After confirmation of a breeding population of *S. noctilio* in New York, APHIS and the USFS worked together with the New York State Department of Agriculture and Markets and the New York State Department of Environmental Conservation to initiate a survey to delimit the infestation. Various types of traps (multiple-funnel, log, sticky panel traps) were placed in pine stands surrounding Oswego and Fulton, New York. Survey points about 32 km from Oswego were quickly found to be positive for *S. noctilio* and the trapping area was subsequently expanded with some traps out as far as 112 km. Other regional exotic bark beetle and woodborer survey traps were also screened for *S. noctilio*. Following confirmation of established populations in New York, a survey of 36 sites in Ontario across Lake Ontario from Oswego was conducted by CFS, CFIA and the Ontario Ministry of Natural Resources (de Groot et al. 2007a). During the 2005 survey, four Canadian and four U.S. counties were identified as having *S. noctilio* (Fig. 19.1). The combined results from Canadian and USA surveys suggested that a population of *S. noctilio* was established over a large geographic area covering portions of central New York and southern Ontario, and probably had been present for some time.

19.2.2.2 2006 Surveys

In the fall of 2005, APHIS organized a Sirex Science Panel that included members from APHIS, USFS, CFS, several universities, and international scientists (Bedding et al. 2006). The overall charge of the Sirex Science Panel was to provide science-based answers to questions posed by the U.S. State/Federal multi-agency Sirex Management Team, regarding such topics as pest biology, survey methods, and management options, and to recommend a *S. noctilio* response for the USA. A Sirex Management Team composed of scientists and regulatory officials from both state and federal U.S. agencies used information from the Sirex Science Panel report to create a national plan for *S. noctilio* population delimitation, and develop possible management options. A very similar structure of science and management teams with international participation was set up in Canada (de Groot et al. 2007b). One of the major initiatives to come from these meetings was the decision to conduct a more intense delimiting survey to define the *S. noctilio* population extent in both countries and to work in collaboration.

During the initial *S. noctilio* surveys in 2005, different lure and trap combinations were used in Canada and the USA. To produce comparable results between the two countries, the same traps and lures were used in 2006. While little data existed on trap/lure efficacy for *S. noctilio*, multiple-funnel and panel intercept traps baited with a 70:30 ratio of alpha-pinene:beta-pinene (Synergy Semiochemical 85 g ultra high release sleeve, alpha-pinene was 75%(+), beta-pinene was ~95% (−) or Pherotech 178 g ultra high release sleeve, alpha-pinene was 75% (+) and 25% (−), beta-pinene was nearly 100% (−)) were chosen as survey tools. This lure was based on findings by Simpson and McQuilkin (1976) that alpha- and beta-pinene elicited antennal responses from *S. noctilio* females. Propylene glycol was used with a wet-cup as a collection liquid for all surveys.

In the USA, a systematic survey grid (40 or 58 km^2) covered most of New York, parts of northern Pennsylvania, and western Vermont. Pine stands were prioritized for trap placement within each grid, with available host data used to assist in locating pine areas within a heterogeneous landscape. In some cases, traps were placed in non-host forest types. In addition to the systematic survey, high risk stands of stressed pine in other eastern U.S. states were surveyed using the same trapping methodology. Instead of using a systematic grid survey, the CFS and CFIA opted for a targeted approach in Ontario and Quebec, focusing on placing survey traps in high-risk Scots pine stands that showed symptoms of moderate decline. Survey traps were typically placed 10–20 m inside the stands, compared to the perimeter placement common in USA surveys.

Results from 2006 indicated that a widespread *S. noctilio* population was established in North America. Canadian surveys found *S. noctilio* in 17 counties in the province of Ontario and in the USA, 20 New York counties and two Pennsylvania counties were positive for the insect (Fig. 19.1).

19.2.2.3 2007 Surveys

The 2006 Canadian and American *S. noctilio* surveys provided a better picture of the distribution in North America. However, there were concerns that the western and northern population boundaries were not successfully delimited. This was in part because of the limited number of traps placed in these areas, but also because of doubts that the lure (a 70:30 ratio of alpha- and beta-pinene) was effective at capturing *S. noctilio* at endemic population levels. Ongoing studies by APHIS and their collaborators to provide a better attractant were inconclusive and consequently the same lure was used in 2007. The survey efforts shifted north in Canada with traps placed throughout most of northern Ontario, where forestry is important to the economy and where there are very extensive natural stands of jack pine, *P. banksiana* Lamb. Surveys also continued in Quebec and intensified in New Brunswick and Nova Scotia in eastern Canada. In the USA, *S. noctilio* delimitation efforts intensified in the west and south of New York, with a significant effort placed in Midwestern states (e.g., Michigan) where red pine is a more prominent commercial species and jack pine is present. Many states outside the delimitation survey area also conducted detection surveys of high-risk sites.

Traps in both countries were typically placed along the perimeter and in sun-exposed locations. Trap trees were also added as a survey tool in the USA. These trap trees were girdled in the spring, had a multiple-funnel trap placed on each tree to collect adults, and were examined for *S. noctilio* signs and symptoms over the course of the season.

Four additional counties or districts were found infested in Ontario in 2007 (Fig. 19.1). As in 2006, no *S. noctilio* were found east of Ontario. Several counties were added in New York and Pennsylvania, further expanding the known population south in the USA. One county in Vermont and two counties in Michigan expanded the known distribution east and west, respectively. Only one female *S. noctilio* was captured in Vermont and three in Michigan, so further delimitation efforts were planned for 2008.

19.2.2.4 2008 and 2009 Surveys

Sirex noctilio survey efforts in 2008 and 2009 continued to target high-risk sites for trapping in areas adjacent to positive finds from previous years. Canadian survey efforts focused on Quebec and northern Ontario. No new finds of *S. noctilio* were found in 2008 or 2009 in Ontario despite intensive efforts to survey the area north of the positive finds from 2005 to 2007 (Fig. 19.1). *Sirex noctilio* was first found in the province of Quebec in 2008 near La Chute about 75 km northwest of Montreal and about 100 km northeast of the closest known infestation in Ontario. In 2009, *S. noctilio* was found in one additional area about 95 km southeast of Montreal (Fig. 19.1). Survey efforts in the USA expanded slightly southward during 2008 with more effort along the northern border of Maryland and continued surveys in Midwest, Mid-Atlantic, and northeastern states. Vermont was intensively surveyed with traps placed throughout the state and trap trees deployed at locations adjacent to where *S. noctilio* was detected in 2007. The 2008 survey efforts in the USA resulted in one additional county in Pennsylvania and two in Michigan (Fig. 19.1). In 2009, survey efforts in the northeast were reduced while trapping in Maryland and the Midwest continued. Survey efforts in 2009 yielded an additional county in Pennsylvania and a new state record in Ohio where one *S. noctilio* specimen was captured. These findings only slightly altered the *S. noctilio* footprint determined from previous year survey efforts (Fig. 19.1).

19.3 North American Forests at Risk

Sirex noctilio has been problematic in countries where pine is grown intensively under pure even-aged silvicultural systems (Rawlings 1955; Haugen et al. 1990; Iede et al. 1998; Maderni 1998; Carnegie et al. 2005; Hurley et al. 2007). Southern

Hemisphere countries produce pine over large landscapes, where other than age variation, forests are generally homogeneous. The impact of *S. noctilio* on North American forests will vary with forest type, natural history of pine species present, natural disturbance regimes, competing insects and disease, and stand management regimes.

The forests of the northeastern USA and southern Canada, where *S. noctilio* is currently present, are much more diverse, both in species composition, landscape patterns, stand management plans, and uses (Foster and Aber 2004). The landscape of this area is heterogeneous with a mix of agricultural fields, urban areas, and forests forming a complex matrix of land types and uses. Much of the forest area in Ontario and the USA is managed according to a multiple-use ethic, with watershed and ecosystem protection, recreation areas, and timber production as common shared objectives. Forest management practices vary from excellent to nonexistent, with considerable areas receiving insufficient silvicultural attention since stand establishment.

Successful *S. noctilio* reproduction has occurred in eastern white (*Pinus strobus* L.), red, jack, and Scots pine in this area. Typical hard (yellow, or two and three needle pines including, red, jack and Scots) pine stands where *S. noctilio* has been found to date (2009) are dense, overstocked plantations with mortality due to overcrowded growing conditions. The poor growing conditions have been compounded by poor site quality, including a hard pan layer (a dense layer of soil, residing usually below the uppermost topsoil that is largely impervious to water), which has led to suppressed and dead trees. Winter ice storms and wind damage are common occurrences that further stress trees making them susceptible to bark beetles and other biotic organisms (Ryall and Smith 2005; Ryall et al. 2006). Interestingly, there have been several other invasive alien insects found throughout much of the same area, most notable is *Tomicus piniperda* (L.) (Coleoptera: Scolytidae) (Morgan et al. 2004; Haack 2006) creating a potential synergy between bark beetles debilitating trees (Czokajlo et al. 1997) and setting them up for mortality from *S. noctilio*. In addition to these factors, numerous native insects, especially wood and bark insects, and root and foliar diseases have taken advantage of the stress in these unthrifty stands (Whitney 1988; Klepzig et al. 1991, 1995; Erbilgin et al. 2002; Erbilgin and Raffa 2002). All these factors make it difficult to determine if *S. noctilio* is the primary cause of tree decline, or if it is amongst the suite of secondary insects and diseases that occur after a tree has been predisposed and weakened by other factors to attack.

Native pines, including eastern white and red, frequently occur in small patches dispersed across the landscape, while jack pine grows in much larger stands (often pure, fire-origin) in northern portions of Ontario. Scots pine, an introduced tree from Europe and the native host of *S. noctilio*, grows in small plantations dispersed throughout the landscape. This was once a popular Christmas tree, but there are now many abandoned plantations in eastern North America that are overstocked and serve as prime sites and hosts for *S. noctilio*. In Ontario, pine forests cover about 27 million ha (CFS 2001). In Michigan, New York, Pennsylvania, and Vermont approximately two million ha of forests are in pine or pine-mixed forests (Frieswyk and Widmann 2000; McWilliams et al. 2007; Hansen and Brand 2006; Alerich and Drake 1995).

Eastern white pine (a five-needle pine) is one of the most important economic species in eastern North America and is used for lumber, furniture making, veneer, log cabin timbers, and pulpwood. Natural eastern white pine stands are usually intermixed with other conifer and hardwood tree species, but pure stands do occur on the landscape. Commercially planted eastern white pine stands are managed either under even-aged or uneven-aged silvicultural regimes and have rotation ages between 90 and 120 years (Barrett 1995). While the potential impact of *S. noctilio* on eastern white pine is not currently understood, several biological factors could increase this tree's susceptibility to attack. Both white pine blister rust (caused by the fungus *Cronartium ribicola* J.C. Fischer: Rabenh.) and white pine weevil (*Pissodes strobi* Peck) attack eastern white pine in different parts of its range and can reduce vitality in trees, likely increasing their attractiveness and/or susceptibility to *S. noctilio*. Limited data suggest that eastern white pine is a suitable host for *S. noctilio* in North America (K. Zylstra, USDA APHIS, personal communication, 2008) and synergy with native and exotic organisms is a concern.

Red pine was widely planted for soil conservation, wind breaks, and reforestation efforts throughout northeastern USA and southern Ontario. As a commercial species, red pine is used for lumber, poles, log cabin timbers, railroad ties, and pulpwood. Often planted in areas to aid in soil stabilization after farm abandonment in the early twentieth century, red pine now suffers from being planted on poor quality sites, and overstocked growing conditions. Typically, red pine is found in pure or almost pure stands. Red pine rotation ages vary, but 60–90 years is common with some longer rotations of 100–150 years for large sawtimber stands (Ek et al. 2007). In the Midwestern USA, red pine is more intensively managed and is an important economic species with more than 758,000 ha planted in this forest type. Few biotic agents cause losses in red pine, but fungal diseases such as Armillaria root rot (Whitney 1988) and other diseases may stress stands and open up resources for *S. noctilio*. Red pine decline has been described in the Midwestern USA and is a function of interactions between insects and fungi (Klepzig et al. 1991).

Jack pine grows extensively in northern Ontario and throughout much of the vast boreal forest in Canada, where it is an important economic species, but in the northeastern USA it usually occurs in small isolated stands. In the Midwestern USA, jack pine is an important economic species and also provides habitat for the endangered Kirtland's warbler (Walkinshaw 1983). With a rotation of between 40 and 70 years, jack pine is primarily used for pulpwood, rough lumber, and pallet production. Jack pine is a fire-dependent species that is naturally regenerated through stand-replacing fires and often grows on poor sites (Benzie 1977; Rouse 1986). These stands are typically pure jack pine that develop into single-aged forests, thin themselves naturally, often have high basal areas, and could provide suitable habitat for *S. noctilio* in this region. In addition, biotic agents (e.g., *Choristoneura p. pinus* Freeman, *Neodiprion* spp., stem rusts) may also stress jack pine, opening resources for *S. noctilio* colonization (Cross et al. 1978; Wilson and Averill 1978; Gross 1992; Conway et al. 1999).

Surveys of infested stands in Ontario and New York during 2006–2009 indicated that *S. noctilio* behaved similarly to endemic populations documented in the Southern

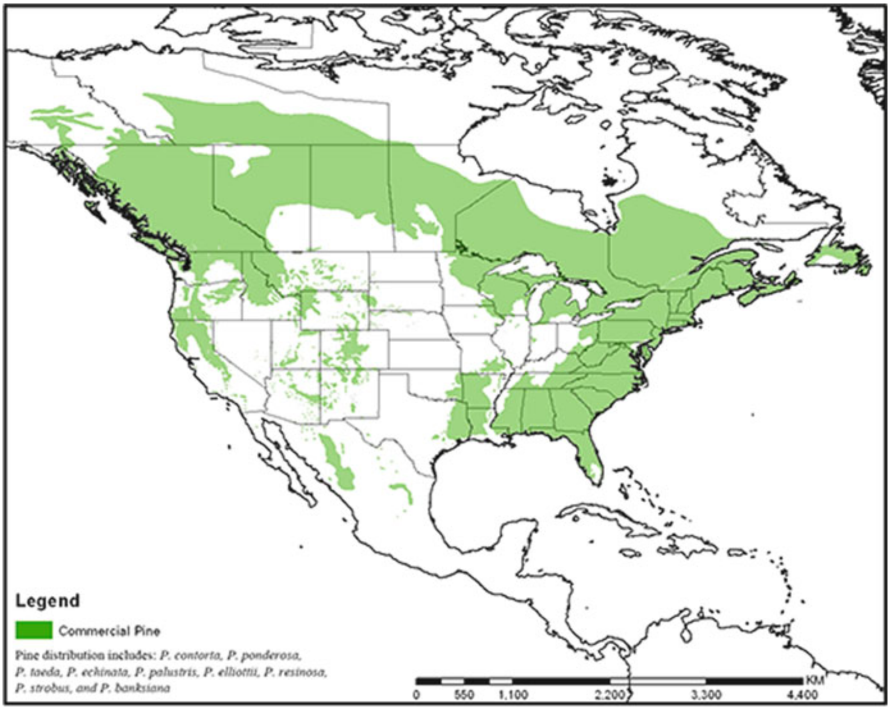

Fig. 19.2 Combined distribution of commercially important pine species in North America

Hemisphere (Jackson 1955; Neumann and Minko 1981; Neumann et al. 1987). Stands where *S. noctilio* has been located in North America are overstocked and generally in poor condition. At the individual tree scale, *S. noctilio* appears to be concentrating attacks on suppressed trees. Trees with smaller live crown ratios, smaller average diameters, and reduced incremental growth were generally more often attacked than more vigorous, larger trees with relatively healthy crowns (Dodds et al. 2010). Some larger apparently vigorous co-dominant trees in these stands were also attacked, but less frequently than smaller trees. *Sirex noctilio* had more of an impact in Scots pine stands compared to red pine stands in terms of percentage of trees attacked and basal area lost (Dodds et al. 2010). Interestingly, many overstocked red pine stands with larger over-story trees (> 30 cm dbh) and no overtopped trees are free of *S. noctilio*. These trees growing under overstocked conditions, sometimes with two times the recommended basal area and small live crown ratios, are not being exploited by *S. noctilio* at this point in the invasion.

The current area of infestation is within central North America, and represents only a small portion of pine forests on the continent. The other regions of concern are the southeastern USA, western North America, and eastern Canada, where pines are grown either under intensive silvicultural regimes or occur naturally in stands that may be more susceptible to *S. noctilio* attack (Fig. 19.2). Wildfire, bark beetle infestations, and insect-caused defoliation are common disturbances in many pine ecosystems in North America and likely would open resources for *S. noctilio* colonization causing interesting, yet problematic synergies. Conversely, well-established insect communities, containing potential competitors (both arthropod and fungal), predators, and parasitoids, may aid in keeping *S. noctilio* populations regulated or at low levels. Impact can be measured at several different levels using different criteria, but perhaps most significant will be the impact of *S. noctilio* in the southeastern pine forests, which are very important to the economy of this region.

Forest management in the southeastern USA varies with ownership type, ranging from intensively managed plantations to unmanaged natural areas. Loblolly pine (*Pinus taeda* L.), longleaf pine (*P. palustris* Mill.), shortleaf pine (*P. echinata* Mill.), and slash pine (*P. elliottii* Englem.) are important species throughout the southeastern region and several are known *S. noctilio* hosts (Haugen and Hoebeke 2005). Loblolly pine is the most common species in the southeastern USA and grows from southern New Jersey south to central Florida and west to eastern Texas (Baker and Langdon 1990). Loblolly pine is dominant on about 11.7 million ha and makes up over one-half of the standing pine volume in the southeastern U.S. (Baker and Langdon 1990). Many of these stands are overstocked and could provide excellent habitat for *S. noctilio*. Loblolly pine often grows in conjunction with other tree species, including hardwoods and other southeastern pines. Longleaf pine is an endangered ecosystem that occurs primarily in southeastern coastal areas. Because of the dramatic reduction in area of longleaf pine ecosystems, the USA Biological Survey listed this ecosystem as the third most endangered in the USA (Noss et al. 1995). Fire is a critical component of longleaf pine ecosystems and restoration efforts (Brockway et al. 2005) could result in trees stressed and attractive to *S. noctilio* infestation. Disturbance is common in southeastern forests, with abiotic factors such as fire and windstorms, and biotic factors such as insects and disease influencing forest structure, successional pathways, and possibly in the future the vulnerability to *S. noctilio*.

Like the southeastern USA, several known *S. noctilio* hosts grow over large areas in the western USA and Canada. Lodgepole (*Pinus contorta* Dougl.: Loud.) and ponderosa (*Pinus ponderosa* Dougl.: Laws.) pines are the primary economic pine species in the west and both are widely distributed across the landscape. Lodgepole pine forests cover an estimated 26 million ha in western North America (Lotan and Critchfield 1990). Lodgepole pine (like jack pine) often grows in almost pure stands that grow after stand-replacing fires. These stands either are left to self-thin or are mechanically thinned for timber production. Ponderosa pine has a large range that occurs throughout western North America from southern Canada south to Mexico. While often found in pure stands, ponderosa pine can also be found in mixed stands with other conifer species (Franklin and Dryness 1988). Fire is also important to ponderosa pine ecosystems and currently there is a movement to restore fire regimes into stands (Covington et al. 1997; Lynch et al. 2000; Allen et al. 2002). While most trees survive fire events, stand stress occurs, opening resources that are exploited by bark beetles (Breece et al. 2008) and might also be utilized by *S. noctilio*.

Bioeconomic analyses and simulation models of *S. noctilio* impacts on timber supply and harvesting in eastern Canada indicate that economic losses will vary significantly depending on the complex interactions among insect spread, tree mortality and adaptations of harvest schedules and approaches (Yemshanov et al. 2009a). In another simulation study, Yemshanov et al. (2009b) provided maps of the potential distribution of *S. noctilio* in North America over a 30 year time horizon based on the combination of three risk scenarios (high, medium and low) with two entry potential scenarios (entry from ports only and ports plus existing infestations). These and other modeling approaches are useful to provide advance warning of the potential impact of *S. noctilio* and no doubt will be improved as we continue to collect data from infested areas on the actual impact and ecological reasons why *S. noctilio* populations increased and decreased in areas.

In summary, there are vast areas of pine in North America that range from natural forests to intensively managed plantations. Within these forests, pest and forest management may range from nonexistent to the use of active and proactive measures. Furthermore, there exists a wide range of insect and disease communities present in these forests. While it is difficult to predict how *S. noctilio* will respond to these communities, it is likely that it will be significantly different from what has been recorded in the Southern Hemisphere. From a positive perspective, the native insects and fungi and natural enemies may help regulate *S. noctilio* populations. Conversely, the possible synergies and combined cumulative effects of native pests and *S. noctilio* damage are disconcerting. It is prudent to expect significant impact and to prepare strategies and tactics for the management of *S. noctilio* in these regions.

19.4 Survey Challenges in North America

Surveying for *S. noctilio* in North American forests has presented several unique challenges not encountered in other parts of the world where introductions have occurred. These challenges can be divided into two major components: (1) logistical issues of landscape and forest diversity, ownership, and access, and (2) biological issues of native siricids and other associated insects and diseases that complicate the use of trap trees and traps baited with attractants.

19.4.1 Logistical Issues

Pine forests in North America vary from small to large pine plantations, pure stands originating after mild to severe fire or wind disturbance events, to mixed conifer or mixed hardwood forests where the proportion of pines can vary. Coupled with this, is that ownership of the forests can reside with provincial, state, or federal governments, small to large forest industrial companies, or with private persons or family owners. Road access to pine forests can range from non-existent or poor (especially in much of the government-owned forests in the boreal region in Canada), to excellent, particularly in the rural areas of southern Canada and much of the eastern USA. Land ownership may also prohibit or restrict access to the site and the establishment of trap trees or even placement of removable traps. For example, on some publicly owned land, the use of herbicides is prohibited, thus effectively precluding the use of trap trees. Determining ownership of private land requires time to search land registry records and then tracking the owners, some who may live considerable distances away. Overlaid on this mosaic is the information on tree and stand attributes (e.g., age, species composition, basal area, vitality), which can vary depending on ownership and location. This presents a further challenge of determining high-risk sites where survey efforts should be prioritized.

Some of these logistical challenges can be mitigated by working closely with the various agencies responsible for forest management and forest health. In Canada and the USA, there are several organizations that already have co-operative arrangements in place to assess forest health conditions. By working with people who have local knowledge, suitable sites for *S. noctilio* surveys can be tentatively identified. Once potential sites have been identified, a field inspection is required to further assess the health of the stand. If the site is deemed suitable, then the owner has to be located, and consulted, and either verbal or written permission obtained. This hierarchal process is time-consuming, costly, and is further complicated by the biological issues inherent to North America.

19.4.2 Biological Issues

In comparison to the Southern Hemisphere countries where *S. noctilio* has become invasive, the pine forests of North America are complex ecosystems consisting of mostly native species with well-developed arthropod, plant and disease communities that influence stand structure, tree growth, vitality, and mortality. On the other hand, the exotic pure pine plantations in the Southern Hemisphere typically have few pine-killing insects and diseases present (Neumann 1979; Neumann and Marks 1976). Consequently, identifying and attributing tree mortality to *S. noctilio* is much easier and definitive in the Southern Hemisphere than it is in North America. Visual inspection of trees for round exit holes (signs) of adult *S. noctilio*, is not only difficult to do in the first place, but is confounded in North America because several native species of Siricidae are also present (Smith and Schiff 2002), and several species of Cerambycidae (e.g., *Monochamus notatus*, *M. scutellatus*) make similar sized round exit holes (Wilson 1975; Drooz 1985). Resin beads, typically formed after the bark and wood have been penetrated by the ovipositor of female *S. noctilio*, are often natural occurrences on eastern white pine or occur after infection by white pine blister rust or other agents. To date, in North America, we have not observed the classic pine needle wilting and drooping symptoms that are seen in the Southern Hemisphere. What is seen is a general chlorosis and browning of the needles, but there are several diseases (e.g., *Diplodia pinea* blight), insects, and abiotic stressors that can also show the same symptoms. Not only do these factors that produce similar signs and symptoms complicate any ground inspections, they essentially rule out any chance of rapid aerial or remote sensing techniques being successful in unequivocally identifying the presence of *S. noctilio* on the landscape. Surveying for visual symptoms is thus limited to ground based methods, but this requires good training and experience to distinguish damage by *S. noctilio* from the many other possibilities and is time-consuming (Iede et al. 1998). It also requires numerous trained staff that can be mobilized to cover large areas, a capacity that is not present in Canada or the USA. For these reasons, and other practical considerations, surveys in Canada and the USA have relied on traps baited with host volatiles, and to a very limited degree on trap trees.

Trap trees have been the primary survey method for *S. noctilio* management in most regions of the Southern Hemisphere. Essentially, a tree is injected with an herbicide so that the tree becomes stressed and thus attractive to *S. noctilio* (Neumann et al. 1982). A significant challenge to the use of herbicides in North America is the complex of wood and bark boring insects already present in forests that will also utilize these trees. Many of these insects and diseases are active before or during the same time as *S. noctilio*. Thus, unlike in the Southern Hemisphere where trees can be injected with herbicide at least 3 months in advance of the *S. noctilio* attack period (Neumann et al. 1982), timing of an herbicide application is much more critical and has a much smaller window of opportunity in North America. A three or more month window simply will not be an option in North America, but creating a stressed tree more quickly over a narrower time frame is possible (Zylstra et al. 2010). This narrower window also constrains the application of the trap tree method where there are limits to the number of field crews that can establish trap trees. It is possible that trap trees may simply not be as effective in North America as in the Southern Hemisphere because of these biological and logistical constraints.

Forest insect surveys in North America rely widely on the use of traps that emit insect attractants. Most often, these attractants are insect pheromones, which in the majority of cases have proved to be very efficient in detecting incipient populations of a specific insect species (e.g., gypsy moth). To a much smaller degree, attractants based on host-associated odors are used for insect surveys, and usually where a survey for a general group of insects is required, or where the pheromone has not been identified. The discovery of *S. noctilio* in North America was in a trap that contained both pheromones and host volatiles, including alpha-pinene, ipsdienol, cis-verbenol, and 2-methyl-3-buten-2-ol. Although portable insect traps baited with attractants can have their own limitations, they can offer some distinct advantages in cost, ease of use, and earlier detection of populations. Mainly for this reason, traps baited with attractants have been used extensively in North America.

A formidable challenge to the use of traps is that lures and trapping methods for *S. noctilio* are still in the early stages of development. While a contact sex pheromone has been identified for *S. noctilio* (Böröczky et al. 2009), a long-range sex pheromone more useful for detection purposes has not yet been identified, and may not exist. Consequently, lure development has focused on the use of host attractants, which may be used by *S. noctilio* during host finding and selection. The current lure combination of alpha- and beta-pinene are compounds that are common to other trees and thus also attract numerous other wood-boring species. While these collections provide opportunities to survey for other insects along with *S. noctilio*, sorting through these samples is laborious and expensive.

Research to develop lures is time consuming and expensive. There are also practical and statistical constraints in the number of treatments (chemicals, blends and release rates), layout of traps, and replications possible in field experiments where low numbers of insects are often captured, especially in forests. Furthermore, little is known about effective methods to trap siricids, which can present difficulties in evaluating attractants. In general, an important component of the development of a trap-based detection program for insects is the design and placement of the trap itself. Attractive chemicals placed in an ineffective trap may result in poor trap catches, and conversely, a well-designed trap, baited with unattractive chemicals or incorrect release rates may also result in poor trap catches. Several trap types were tested in North America in an attempt to determine the optimal trap for *S. noctilio* surveys. Several variations of sticky traps (panel, drainpipe, log) and flight intercept (funnel, panel intercept, aerial malaise) traps were tested in research trials (Dodds and de Groot, unpublished). At the same time, Canada and the USA split their operational survey traps between panel intercept and 12-unit multiple-funnel traps. Data from these research trials were inconclusive, but similar numbers of *S. noctilio* were captured in funnel and panel intercept traps in the operational survey. This same pattern was seen in both the Canadian and USA surveys where almost equal numbers of *S. noctilio* were captured in the two trap types. Consequently, surveys rely on either multiple-funnel or panel intercept traps.

Competition between volatiles emanating from stressed trees in a stand adds another variable in a survey plan. Severely stressed stands that are typical of the habitat for *S. noctilio* in North America will release a full and complex blend of host volatiles, which most likely out-compete simple traps baited with a few compounds. Because of this, surveyors might be more inclined to deploy traps in stands that are not in overly poor condition where volatile-baited traps would be more apparent. However, we know little about *S. noctilio* behavior in stands with a range of susceptibility and the presence of this insect in "healthy" stands. Whatever approach is taken it is important to understand that a host volatile baited trap is unlikely to attract insects over trees that emanate stress volatiles. In some stands in Canada and the USA, traps baited with alpha- and beta-pinene failed to capture *S. noctilio* even though they were readily seen in the heavily infested stands (de Groot and Dodds, personal observations, 2006), resulting in false negatives.

The current approach taken in Canada and the USA has been to target stressed or moderately stressed pine stands for trap placement. While this is subjective, placing traps near a potential source of insects or potential habitat increases the likelihood of detection. On a landscape level, traps have been placed in or adjacent to potential habitat patches (i.e., stressed pine stands). At the stand level, placement has varied from interior placement to stand edges. Systematic surveys have resulted in traps being placed first in a hard pine stand, second another pine, and third conifer stands.

The presence of native Siricidae further complicates survey and detection efforts. In Canada and the USA, there are 23 species/subspecies of Siricidae (Schiff et al. 2006). In eastern North America, three other *Sirex* species have been collected (*S. edwardsii* Brullé, *S. juvencus* (L.), *S. nigricornis* F.) and all have been captured in *S. noctilio* detection traps. Although some native siricids can be distinguished with the naked eye, one species, *S. juvencus* is very similar to *S. noctilio* and requires examination under the microscope to identify it. Although there have been two recent keys to the Siricidae in North America (Smith and Schiff 2002; Schiff et al. 2006), this group is under revision again, which will result in some synonymy of species and recognition of new species (H. Goulet, Canadian National Collection of Insects, Agriculture and Agri-Food Canada). Therefore, all specimens from the survey must be kept for future examination. While adult *Sirex* species can be differentiated by morphological characteristics, molecular techniques must be implemented to distinguish larval specimens and would help with closely related and similar appearing adults. Molecular barcoding techniques based on sequence data from the mitochondrial COI gene has recently been developed to distinguish individual siricid species (Wilson and Schiff 2010). The technique has also been shown to be useful for larval identification and successfully used to confirm the presence of *S. noctilio* in suspect trees found in New York (N. Schiff, personal communication, 2005).

In summary, there are several interesting and formidable logistical and biological challenges that face the implementation of a survey for *S. noctilio* in North America. Notwithstanding these constraints, the surveys for *S. noctilio* since detection in 2004 have been remarkable in that this insect has been detected over a wide area with limited tools and knowledge. Many improvements are needed, perhaps no more so than in the development of better attractants, knowledge of where traps should be placed, and understanding the limits (efficiency) of detection with these methods.

19.5 Management Challenges in North America

The management of *S. noctilio* in the Southern Hemisphere is based on three pillars: (1) survey to monitor population levels, (2) silvicultural control by maintaining tree vitality and stand health, and (3) biological control through the introduction of a parasitic nematode, *Deladenus* (=*Beddingia*) *siricidicola* (Bedding 1974; Bedding and Akhurst 1974; Neumann 1979; Haugen 1990; Neumann et al. 1987), and to a lesser degree insect parasitoid populations (Hurley et al. 2007). Attempts at eradication have failed where it has been tried on a large scale (Neumann et al. 1987; Haugen et al. 1990), and it certainly is not an option in North America given the very large area of infestation (Fig. 19.1). The application of pesticides, either contact or systemic, also presents very significant economic, practical, and environmental impediments so their use can also effectively be ruled out. In North America, then, the apparent options are silviculture and biological control. Before these two control methods can be implemented, an assessment on the natural level of control (real or expected) by native mortality agents, economic damage attributed to *S. noctilio*, environmental impact, and cost/benefit analysis of pest management techniques must be conducted.

19.5.1 Silviculture

To maintain overall forest health, intermediate silvicultural treatments are commonly recommended as a stand management tool in North America. Similar stand management practices would also be beneficial for reducing the effects of *S. noctilio* on North American pine stands (Dodds et al. 2007). Treatments focused on increasing residual tree vitality to increase host tree defenses and simultaneously remove potential habitat (i.e., suppressed trees) could reduce the impact *S. noctilio* may have in a stand. Stand treatments, such as thinning from below as a part of a timber stand improvement treatment could be helpful for increasing residual tree vitality (Dodds et al. 2007). Because many of the trees growing in these overstocked stands have small live crown ratios and have been growing very slowly for many years (Dodds et al. 2010), it is unknown how well they will respond to silvicultural treatments. However, preliminary results from a stand thinning study in New York suggest that thinning stands in relatively poor condition does reduce the impact of *S. noctilio* in these forests (K. Dodds, unpublished data). If trees are beyond a point where thinning will help stand health, other options such as salvage and cutting followed by replanting, or converting off-site planted pine stands back to hardwoods should be considered.

Several native North American forest insects can reach epidemic populations where economic and ecological damages can be widespread and severe. Insects likely to interact with *S. noctilio* as populations spread include problematic species like defoliators (e.g., *Choristoneura p. pinus*, etc.), as well as several bark beetle species (e.g., *Dendroctonus ponderosae* Hopkins, *Dendroctonus frontalis* Zimmermann). Active stand management is currently suggested for these species and management recommendations are in line with what would be suggested for *S. noctilio*. Forest stand management focused on improving the overall vitality of trees could reduce stand susceptibility to numerous pests at once, increasing the attractiveness of such measures for landowners.

Forest stand management objectives in North America, however, are often driven by considerations other than tree health. Intermediate stand treatments are often not economically viable and are therefore either delayed or ignored. Market values and conditions or costs of treatments may preclude proactive actions, even though they are desired. Unfortunately, many stands in the currently known infested area lack a management plan, are owned by absentee landowners who know little about silviculture or the conditions in their forests, or landowners that have no desire or means to manage their forest. Consequently, many stagnant pine stands remain on the landscape with no hopes of increasing the overall health in the stand. Perhaps concern over *S. noctilio* damage in a stand will move concerned landowners to consider thinning to maintain forest health and reduce damage not only from *S. noctilio*, but native species as well.

19.5.2 Biological Control

In addition to *S. noctilio* living amongst and competing with other wood-boring insects, all its major parasitoids are known to be naturally present in North America (Cameron 1962; Kirk 1974, 1975). Field-based observations and laboratory rearing suggest that indigenous parasitoids are successfully locating and parasitizing *S. noctilio* eggs and/or larvae (Long et al. 2009, P. de Groot and co-workers, unpublished). Competition with woodborers and parasitism by indigenous parasitoids needs to be evaluated and done so across different pine ecosystems to determine the level of natural control already present. Against this background, we can then determine if further augmentation of parasites or the introduction of the parasitic nematode is warranted and where.

In New Zealand, the nematode *D. siricidicola* was found along with *S. noctilio* (Zondag 1969) and probably came with the original or possible subsequent introductions of *S. noctilio*. Fortunately, this introduction was of a strain that parasitized the eggs. Not all strains of *D. siricidicola* are parasitic or result in 100% parasitism (Bedding and Iede 2005), and the current commercial strain is a result of extensive screening and proper culturing to ensure high levels of control. When the original screening work took place, many localities were examined in Europe to find the best strain.

In 2006, work was initiated in Canada and the USA to determine if the nematode was present, and if so, what levels of parasitism existed and how pervasive it was in the populations. In Canada, the nematode has been found and identified as *D. siricidicola* (Yu et al. 2009). This task was complicated by the fact that a morphologically similar species, *D. wilsoni* Bedding, is present in North America (Bedding and Akhurst 1978). Considerable taxonomic expertise is required to distinguish species. Further work is ongoing in Canada and the USA to develop molecular tools to help identify the juvenile form. Early and very preliminary data in Canada suggests that the strain found to date may have low virulence (de Groot et al., unpublished). If so, then at least in Canada, a considerable effort may be required to displace the low virulent strain with the commercial strain that has higher efficacy. This “swamping out” of the natural strain is similar in many respects to the situation in Australia where a “defective strain” developed in the culturing process and had to be replaced by a more virulent strain (Bedding and Iede 2005).

While the nematode has been very effective in Australia, there have been some early problems in South America, and more recently in South Africa (Hurley et al. 2007; Hurley et al. 2008) in establishing populations and getting the desired level of control necessary to minimize *S. noctilio* damage. It is reasonable to expect that there will be some early “start-up” problems with the application of nematodes in North America as well.

One issue that can be easily overlooked, yet is critical to the success of the nematode controlling an ascending population of *S. noctilio*, is that early detection is imperative. In Australia, the recommended objective is to detect *S. noctilio* in a locality before any plantation reaches 0.1% annual Sirex-associated mortality, which is about 1–2 trees per ha in an un-thinned stand in Australia (Haugen et al. 1990) and about 2–3 trees in North America. In the Southern Hemisphere, early surveillance and establishment of trap-trees are used in conjunction with a biocontrol program. Field observations from surveys in Canada and the USA suggest that the current trapping systems do not detect populations at these low levels.

19.6 Conclusions

Sirex noctilio is clearly well-established in North America. Surveys to continue to detect and then delimit the infested area are ongoing and despite the numerous obstacles and challenges, new areas of infestation have been discovered every year. Continued research on development of new survey tools is urgently needed to be effective within the various forest types in North America.

Management of *S. noctilio* will not be easy and must be multifaceted. The diversity, heterogeneity and complexity of North America's natural forests in terms of natural enemies and competing insects and diseases, may be a problem for survey efforts, but also a solution for management, at least in some areas. Diverse pre-existing communities of natural enemies, as well as the potential use of *D. siricidicola* as a biological control agent, stand management to improve individual stand vitality, and the implementation of quarantines to slow the spread of *S. noctilio* may reduce or limit the impact of this insect in North America. Because of the complexities of managing an insect over large areas and diverse habitats, pragmatic and adaptable plans will have to be developed to fit the needs of a given forest type or ecosystem.

Much remains to be observed and discovered about *S. noctilio* in North America. The situation in North America is unique, allowing for many interesting questions to be addressed on invasion biology, community ecology, and management of an invasive species in native pine communities that have not been previously addressed elsewhere. Only through continued national and international collaboration at the research and operational levels, will solutions and further understanding of *S. noctilio* biology and management in North America be achieved.

Acknowledgements This chapter summarizes the efforts of many individuals and agencies involved with *S. noctilio* detection and survey efforts in North America. In the USA, federal and state departments of agriculture and natural resources participated in various aspects of delimitation and detection efforts. Response to the *S. noctilio* detection relied upon the efforts of many people, including Ethan Angell and Bob Mungari (New York State Department of Agriculture & Markets); Jerry Carlson (New York Department of Environmental Conservation); Dennis Haugen, Noel Schneeberger, and Robert Rabaglia (U.S. Forest Service); and Leon Bunce, Vic Mastro, Yvonne DeMarino, and Lynn Evans-Goldner (APHIS PPQ). In Canada, Rob Favrin and Troy Kimoto (CFIA) and Pierre Therrien (Quebec Ministry of Natural Resources and Wildlife) and Taylor Scarr (Ontario Ministry of Natural Resources).

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