8

Invasive Root-feeding Insects in Natural Forest Ecosystems of North America

D.R. COYLE 1, W.J. MATTSON 2 AND K.F. RAFFA 1

1 Department of Entomology, University of Wisconsin, Madison, USA; 2 USDA Forest Service, Rhinelander, Wisconsin, USA

8.1. Introduction

8.1.1. Importance of belowground herbivory

Many studies have examined aboveground herbivory as it relates to primary production and nutrient dynamics (Mattson and Addy, 1975; Ritchie, 1998; Hunter, 2001a). However, studies of belowground herbivory are largely lacking (Hunter, 2001b) even though belowground productivity, albeit much less conspicuous, is comparable to aboveground productivity (Newman et al., 2006). In forests, conservative estimates indicate that fine roots (≤2 mm in diameter) alone represent 33% of global annual net primary productivity (NPP) (Jackson et al., 1997), and as much as 73% of total NPP may occur belowground in some systems (Fogel, 1985). Fine-root NPP was estimated at >2 Mg ha⁻¹ year⁻¹ in a deciduous hardwood stand in the Adirondack Mountains (Burke and Raynal, 1994), and exceeded 4 Mg ha⁻¹ year⁻¹ in sugar maple, Acer saccharum, stands in Wisconsin (Aber et al., 1985). Average belowground NPP is 7 Mg ha⁻¹ year⁻¹ in temperate forest systems (Burrows et al., 2003).

Belowground herbivory can have numerous effects at scales of individual plant roots and shoots, plant communities and ecosystems (see Blackshaw and Kerry, Seastedt and Murray, Hunter and Johnson et al., Chapters 3, 4, 5 and 9, respectively, this volume). Root feeders often decrease the belowground biomass and alter the physiology of their host plant, and may exert a significant influence on primary production (Detling et al., 1980). Stevens et al. (2002) proposed root herbivory as the leading explanation for 37% fine-root mortality in a longleaf pine, Pinus palustris Miller, stand. Consistent with this hypothesis, an insecticidal soil drench increased fine-root longevity by up to 125 days, and decreased fine-root mortality by as much as 41% in peach, Prunus persica Batsch, trees (Wells et al., 2002).
Root density and surface area are correlated with a plant’s competitive ability to gather water and nutrients (Casper and Jackson, 1997). Belowground herbivory can reduce competitive abilities, which can be particularly important at high plant density. The relationship between root herbivory and competitive ability was demonstrated in purple loosestrife, *Lythrum salicaria* L. (Nötzold et al., 1998), where *Hylobius transversovittatus* Goeze (Coleoptera: Curculionidae) delayed flowering and reduced plant height, shoot weight and total biomass. In addition, fine-root feeders can greatly alter the carbon and nutrient flow throughout a habitat (Blossey and Hunt-Joshi, 2003), as fine roots generally have the highest nitrogen concentration, an essential element for insect development (Scriber and Slansky, 1981).

Despite the importance of belowground herbivory, little is known about native species in natural systems. The majority of our knowledge of belowground herbivores is from studies of pests of turf, agriculture and plantation forests. Of these, the corn rootworm, *Diabrotica* spp. (Coleoptera: Chrysomelidae), complex is probably the most damaging root feeder in agricultural systems worldwide, costing North American farmers over US$1 billion annually (ARS, 2001). Another well-studied example involves red pine, *P. resinosa* Solander, decline and Christmas tree mortality in the midwestern USA (Rieske and Raffa, 1993; Erbilgin and Raffa, 2002). There are few well-studied rhizophagous pests in natural systems in North America, with cicadas (Hemiptera: Cicadidae) being one exception (see Hunter, Chapter 5, this volume).

### 8.1.2. Invasive species

Biological invasions constitute one of the greatest threats to native biodiversity (Gurevitch and Padilla, 2004), being partially responsible for nearly 50% of extinct or imperiled species in the USA (Wilcove et al., 1998). They cost the US economy an estimated US$120 billion annually (Pimentel et al., 2005), and may persist undetected for years before discovery (Liebhold et al., 1995; Mattson et al., 2007). Invasive plants such as kudzu, *Pueraria* spp., cost the USA nearly US$500 million annually, and salt cedar, *Tamarix* spp., can out-compete native flora, reduce the available groundwater (Hoddenbach, 1987) and reduce resident nesting bird species by >97% (Anderson and Ohmart, 1977). Invasive pathogens cost the USA an estimated US$30 billion year⁻¹. For example, the exotic fungi causing Dutch elm disease (*Ophiostoma* spp.), white pine blister rust (*Cronartium ribicola* J. C. Fisch. ex Rab) (Peterson and Jewell, 1968; Gibbs and Wainhouse, 1986), butternut canker (*Sirococcus clavigigenti-juglandacaerum* N. B. Nair, Kostichka and Kuntz) (SAMAB, 1996), chestnut blight fungus (*Cryptonectria parasitica* [Murrill] M. E. Barr) (Liebhold et al., 1995) and sudden oak death (*Phytophthora ramorum* S. Werres, A. W. A. M. de Cook) (Rizzo et al., 2002) have dramatically and irrevocably altered ecosystem structure, composition and function.

Arthropods are one of the major groups of invasive species in North America, and have had enormous economic and ecological effects. Forests
are particularly susceptible to exotic insect invasions, partially because of the vast area and diverse ecosystems they cover. There are many well-documented cases of invasive insects in US forests (Mattson et al., 1994), but, nearly all published examples are aboveground feeders. Folivores such as the gypsy moth, *Lymantria dispar* L. (Lepidoptera: *Lymantriidae*), can alter species composition of mature forests under heavy, repeated defoliation, and reduce aesthetic values of parks and urban areas (Liebhold et al., 1995). The hemlock woolly adelgid, *Adelges tsugae* Annand (Homoptera: *Adelgidae*), threatens to eliminate hemlocks from eastern US forests (Orwig and Foster, 1998). Recently, the woodwasp, *Sirex noctilio* Fabricius (Hymenoptera: *Siricidae*), was discovered in New York (Hoebke et al., 2005), subjecting several *Pinus* spp. to potential infestation and mortality.

Aboveground insects have received the vast majority of attention worldwide because they are more apparent, and their aboveground life histories make them easier to study. The number of known invasive aboveground insects dwarfs the number of invasive belowground insects. For example, www.invasive.org lists 223 invasive insect species—of which only six are belowground pests. Less than 10% of the 423 exotic phytophagous insects in North American forests are root feeders (Mattson et al., 1994, 2007). In Canada, Kimoto and Duthie-Holt (2006) list 41 exotic forest insect species, of which only four feed belowground.

Just as belowground herbivory by native insects is largely underestimated (Blossey and Hunt-Joshi, 2003), the same is likely true for invasive species. Again, our knowledge is derived mainly from cultivated systems. In North America, the major invasive root-feeding agricultural pest is the clover root curculio, *Sitona hispidulus* Fabricius (Coleoptera: *Curculionidae*), causing yield losses of nearly 1 Mg ha⁻¹ (Hower et al., 1995). The Japanese beetle, *Popillia japonica* Newman (Coleoptera: *Scarabaeidae*), feeds on more than 300 plant species in the USA and costs over US$450 million each year for control and management (Mannion et al., 2001; Potter and Held, 2002). The black vine weevil, *Otiorhynchus sulcatus* Fabricius (Coleoptera: *Curculionidae*), is a serious pest of many ornamental tree species and small fruits (Moorhouse et al., 1992). The sugarcane rootstalk borer, *Diaprepes abbreviatus* L. (Coleoptera: *Curculionidae*), has recently been found on the West Coast of North America (Grafton-Cardwell, 2005), and threatens to severely impact plant production. The sweet potato weevil, *Cylas formicarius* Fabricius (Coleoptera: *Brentidae*) (Chalfant et al., 1990), European crane fly, *Tipula* spp. (Diptera: *Tipulidae*) (Umble and Rao, 2004) and several scarabs (Coleoptera: *Scarabaeidae*) (Jackson and Klein, 2006) are also economically important invasive belowground pests in North America.

Although an insect’s economic impact often drives the research, its environmental impact can be equally important. For example, a suite of invasive root-feeding weevils (Coleoptera: *Curculionidae*) has established in the northern hardwood forests of eastern North America, and research has just begun to determine their range and impact. In this chapter, we summarize what is known so far about these insects, discuss their impacts on the northern forest ecosystems and suggest future research strategies and directions.
8.2. Invasive Root-feeding Weevils in Eastern North American Deciduous Forests

8.2.1. Species composition

A complex of nine invasive rhizophagous weevils has been found by various trapping methods in northern hardwood forests in the north-eastern and Great Lakes Regions of North America. Two of these, *Polydrusus sericeus* Schaller and *Phyllobius oblongus* L., are generally the most abundant, comprising >80% of the total weevil population (Pinski et al., 2005b; D.R. Coyle, 2008, unpublished data). The other species, in order of relative abundance, include *Sciaphilis asperatus* Bonsdorff, *Barypethes pellucidus* Boheman, *T. aristatus* Gyllenhal and *O. ovatus* L. (Pinski et al., 2005b; D.R. Coyle, 2008, unpublished data). Pitfall trapping recently yielded two additional invasive species, *Calomycterus setarius* Roelofs and *Pachyrhinus elegans* Schoenherr (Werner and Raffa, 2000), and sticky traps yielded the most recently discovered species, *Strophosoma melanogrammum* Forster (Shields et al., 2008). Only two native species have been found so far: *H. warreni* Wood via pitfall trapping (Werner and Raffa, 2000) and *Hormorus undulates* Uhier via sweepnetting.

While there is some variation in phenology, the life cycles of these species are very similar. Adults emerge in late spring and early summer. They have an obligatory pre-oviposition feeding period on the developing buds and leaves of various understory deciduous woody plants, especially seedlings and saplings of sugar maple, hop hornbeam, *Ostrya virginiana* Koch, yellow birch, *Betula alleghaniensis* Britton, basswood, *Tilia Americana* L. and various shrubs including raspberry (*Rubus* spp.). Their impact on the leaf surface area of these plants can be severe, at times approaching 100% defoliation. Mating takes place soon after emergence and oviposition occurs approximately 2 weeks later, when eggs are deposited near or into the soil. Larvae hatch in approximately 1 month and begin feeding on root tissue. Larvae overwinter in the soil, and resume feeding the following spring until they pupate in May. Larval feeding habits and host preferences are, for the most part, unknown. However, we do know that some larvae do not enter a winter diapause, particularly if snowpack prevents a deep soil freeze. Preliminary data show that even over winter, some new fine roots are produced by trees and larvae recovered during the winter months were active and increasing in weight, suggesting growth even during the winter months. Yet overall, little is known about the larval ecology and their feeding impacts on the invaded ecosystems.

8.2.2. Adult host range

Like many invasive coleopterans that feed on woody plants, including scarabs (Reding and Klein, 2007) and *Otiorhynchus* root weevils (Van Tol et al., 2004; Fisher, 2006), this suite of nine European weevils is polyphagous, feeding on many species of trees and shrubs. *P. oblongus* is known to feed on elm...
(Ulmus spp.), maple (Acer spp.), birch (Betula spp.), hop hornbeam, aspen (Populus tremuloides), willow (Salix spp.), basswood, pear (Pyrus spp.), apple (Malus spp.), various shrubs and strawberries (Fragaria spp.) (Felt, 1928; Massee, 1932; Caruth, 1936; Fields, 1974; Helsen and Blommers, 1988). Hop hornbeam and mountain maple (A. spicatum Lamarck) were preferred in laboratory trials, followed by basswood, white birch (Betula papyrifera Marshall), sugar maple, red maple (A. rubrum), aspen, poplar (Populus) and yellow birch (Pinski et al., 2005a).

P. sericeus feeds not only on many of the same aforementioned hosts, but also on oak (Quercus spp.), hazel (Corylus spp.) and alder (Alnus spp.) (Parrott and Glasgow, 1916; Frost, 1946; Simmons and Knight, 1973; Morris, 1978; Casteels and De Clercq, 1988; Gharadjedaghi, 1997). In laboratory feeding trials, yellow birch and basswood were the most preferred host species, followed by hop hornbeam, white birch, red oak (Quercus rubra), poplar, aspen, sugar maple, mountain maple and red maple (Pinski et al., 2005a).

The generalist B. pellucidus feeds on strawberry (Bomford and Vernon, 2005), raspberry (Levesque and Levesque, 1994) and grapes (Vitis spp.) (Bouchard et al., 2005). This is a widely distributed invasive weevil, and is known to feed on hosts from the plant families Anacardiaceae, Asteraceae, Fabaceae, Rosaceae, Ulmaceae, Vitaceae (Bouchard et al., 2005) and Cucurbitaceae (Barrett and Agrawal, 2004). Interestingly, B. pellucidus is an important component of salamander diets in the north-eastern USA (Maerz et al., 2005).

Sciaphilus asperatus feeds primarily on sugar maple, birch, raspberry and other trees and shrubs (Henshaw, 1888; Witter and Fields, 1977; Levesque and Levesque, 1994; Maerz et al., 2005), as well as plants in the family Apiaceae (Šerá et al., 2005). In addition, we have captured S. asperatus on hop hornbeam and basswood.

Hosts commonly consumed by both P. oblongus and P. sericeus (and presumably by S. asperatus) in the northern hardwood forest include sugar maple, red maple, hop hornbeam, elm, basswood and wild raspberry. Leatherwood, Dirca palustris L., is almost never eaten even though it is relatively common.

Few records of T. aristatus exist, but these weevils are occasionally found in northern hardwood forests (Pinski et al., 2005a). Trachyphloeus bifoveolatus, a close relative, is reported to be a common pest of grasslands (Barstow and Getzin, 1985), raspberries (Levesque and Levesque, 1994) and vineyards (Bouchard et al., 2005).

### 8.2.3. Geographic distribution

Without aggressive and systematic sampling, determining an accurate geographic range for any insect species is extremely difficult. None the less, with the help of many insect museum curators across the north-eastern and mid-western USA, and eastern Canada, we have compiled what we believe is an accurate picture of the current distribution of this suite of invasive weevils (Table 8.1). Due to the low numbers of T. aristatus and O. ovatus captured, we
Invasive Root-feeding Insects of North America

Table 8.1. Confirmed collection locations of invasive root-feeding weevils in North America. See text for references.

<table>
<thead>
<tr>
<th>Species</th>
<th>USA</th>
<th>Canada</th>
</tr>
</thead>
</table>

will focus on *P. sericeus*, *P. oblongus*, *B. pellucidus* and *S. asperatus*. Several references were also used in constructing these ranges (Arnett, 1973; O'Brien and Wibmer, 1982; Wibmer and O'Brien, 1989; Majka et al., 2007a,b) as well as the generous help from nearly 20 public and University museum curators.

*P. oblongus* was first recorded in New York, USA, in 1923 (Felt, 1928). It has been captured in eastern Canada, throughout the north-eastern USA, south to West Virginia and west to Minnesota, where it was first collected in 1990. *P. sericeus*, first discovered in Connecticut in 1934 (Britton, 1934), has been captured in every state and province bordering the Great Lakes, several north-eastern US states and in the Maritime Provinces of Canada. *S. asperatus* was first captured in Nova Scotia in 1884 (Harrington, 1891). Currently, it is well established in the north-eastern USA, and there are scattered records of its occurrence across much of southern Canada and the northern USA, including as far south as Oklahoma and North Carolina. *B. pellucidus* has the most cosmopolitan distribution of this group, having
been collected in all the Maritime Provinces of Canada and Quebec, Ontario and British Columbia. Blatchley and Leng (1916) first reported this weevil in several north-eastern states in the early 1900s. *B. pellucidus* has been recorded from nearly all states in the north-east and bordering the Great Lakes, and as far south as North Carolina and Oklahoma, and in several states west of the Rocky Mountains.

### 8.2.4. Population dynamics

We annually monitored larval populations of the soil invasive weevil complex in the Ottawa National Forest in Gogebic County of the western Upper Peninsula of Michigan from 1998 to 2007. Each November we extracted 30–40 randomly placed soil cores (6.45 cm diameter × 16 cm length) from the same 100 × 40 m quadrat of a northern hardwood forest dominated by a dense canopy of mature sugar maple (Pinski *et al.*, 2005a). Soil cores were stored in plastic bags and returned to the laboratory, where we sieved them to recover all meso-macro invertebrates, but especially weevil larvae. All larvae were counted and then saved to measure fresh and dry weights and retained in 80% ethanol for later sorting to species.

Weevil larval populations varied yearly by nearly tenfold, and ranged from 112 to 972 m⁻² (Fig. 8.1A). Their annual mean density was 571 m⁻². Larval fresh mass per square metre varied yearly and ranged almost 14-fold, from 0.52 to 7.11 g m⁻², with a 10-year mean of 3.62 g m⁻² (Fig. 8.1B). If weevil larvae are randomly distributed within the forest, then the data from our soil cores should conform to the Poisson probability distribution where the sample variance (\(v^2\)) is equal to the sample mean (\(v^2 = m\)) (Sokal and Rohlf, 1995). However, Fig. 8.2 reveals instead that sample variances were generally larger than the mean, and increased approximately as follows: \(v^2 = m + m^2/k\), where \(k = 3\), the variance equation for the negative binomial probability distribution. The parameter \(k\) is an index of over-dispersion or aggregation due perhaps to the heterogeneous distribution of larval foods and to behaviour such as egg dumping by mothers. But, should the \(k\) values be very large or very small, then the underlying data would likely represent the Poisson or the logarithmic distributions, respectively.

### 8.3. Impacts on Forest Ecosystems

#### 8.3.1. Soil processes

In order to determine the effects that root feeding is having on northern hardwood forests we need to know how much root tissue the larvae are consuming. We can estimate this quantity using larval weights from our 10-year larval sampling data (Fig. 8.1A and B). The larvae were probably only two-thirds grown in November, having yet to finish their feeding and final growth in the ensuing spring after soil temperatures permitted feeding. Assuming
Fig. 8.1. Annual estimates of (A) larval weevil density and (B) total weevil larval biomass at Taylor Lake, Gogebic Co., Michigan. The dashed line in (B) is the overall mean. Sampling was conducted in November of each year.

Fig. 8.2. Relationship between sample variance and mean of larval root-feeding weevil abundance. Sampling was conducted at Taylor Lake, Gogebic Co., Michigan, each November during 1998–2007.
that the gross efficiency of food conversion for larvae feeding on fine roots is about 5–10% (Slansky and Scriber, 1985), then average total plant consumption by November is roughly 10–20 times fresh larval mass, or 36–72 g m$^{-2}$ fresh root weight. Furthermore, assuming that fine-root net primary production averages about 200 g m$^{-2}$ dry weight in northern hardwood forests (Burke and Raynal, 1994), then weevils may be consuming up to 15% of fine-root mass after accounting for their spring feeding.

Little information is available on how root herbivory affects soil microbial communities. One approach for measuring soil microbes is phospholipid fatty acid analysis, where lipids of the microbe cell walls are removed and measured, giving an indication of the relative abundance and types of microbes present in the sample (Kao-Kniffin and Balser, 2007). As root herbivory increases, the amount of dead root tissue may increase, as roots may be severed or only partially eaten. An increased number of herbivores will result in an increased amount of frass in the soil, and Hunter (2001a) showed that elevated frass inputs to the soil can drastically alter soil microbiota. The soil microbial community is expected to respond positively to changes in amount and quantity of available organic matter.

Herbivory reduces the amount of plant material in the soil, therefore reducing the amount of plant material that will eventually die (e.g. fine-root turnover). This can induce a chain reaction of lower carbon accumulation and reduced carbon flow in an ecosystem (Cebrían and Duarte, 1995), unless grazing stimulates compensatory plant growth. Most carbon balance and nitrogen cycling models do not take root herbivory into account even though it may greatly alter the flux of carbon from naturally dying plant material into the ecosystem. In addition, few soil respiration studies include and identify inputs from soil dwelling fauna, even though this guild is an important contributor to overall soil respiration (Hanson et al., 2000). Fine-root turnover represents a large source of soil carbon accumulation, and is often nearly as high as fine-root production (McClaugherty et al., 1982). Root herbivory by weevil larvae could drastically alter this balance by accelerating root turnover, decreasing aboveground productivity and altering soil carbon fractionization pools.

Högberg et al. (2001) showed that a high proportion of plant carbon allocation is belowground, suggesting that nutrient cycling and energy fluxes through terrestrial ecosystems are larger than previously thought. Estimates of global root turnover and primary production may also be greatly underestimated (Chapin and Ruess, 2001), in part due to the paucity of data on the impact of root herbivores. More detailed, intensive and systematic measurement of the impact of root herbivores could lead to a fundamental paradigm shift in our understanding of their roles in root turnover and nutrient cycling.

8.3.2. Displacement of native fauna

In the Lake States, invasive curculionid larvae comprise between 75% and 82% of the belowground insect mesofauna (Pinski et al., 2005a,
D.R. Coyle, 2008, unpublished data). Less than 1% of the larval curculionids were from native species. Invasive weevil adults likewise dominate aboveground arthropod fauna in the understory. Considering the overwhelming proportion of larval curculionids to total fauna, and the ratio of invasive to native root weevils, we can confidently say this suite of invasive weevils is the dominant belowground and aboveground fauna in this system. This raises the question: before the weevils’ introduction to Northern America, what organisms dominated the belowground ecological niche? While it is possible that prior to the introduction of these invasive weevils there was no root-feeding guild in this ecosystem, this seems unlikely. A more probable scenario is that a native complex of root feeders was replaced by a complex of invasive species that were more efficient competitors. Some evidence supports this idea, namely the rare capture of native weevil species. Curculionid collections in insect museums throughout the range of the northern hardwood forests may hold the answer to this question. If displacement of native species occurred, we would expect the ratio of native to exotic weevils to decline precipitously with collection date. This shows the need for biological surveys that yield baseline data and studies that utilize the resources available in insect museums across North America and worldwide.

8.3.3. How are community processes and forest structure affected?

In northern hardwood forests, root feeding by weevils may reduce seedling vigour and increase mortality, reducing regeneration and eventually changing forest structure. Larval weevil feeding on fine roots may indirectly select for more grazing-tolerant plant species or genotypes, as plant tolerance likely varies among individuals. It is unknown if larval weevils feed selectively on the roots of seedlings or mature trees, or show no preference. Given few reports of physiological differences between the fine roots of mature versus young trees, it seems unlikely that larvae have major preferences between them.

Wounds caused by root feeding may result in elevated susceptibility or access to pathogens. The soil is rich in microorganisms, and part of a tree’s defences is the protective epidermis on fine roots. Root feeding damages this tissue, creating infection courts. Root feeding by larvae may weaken plants, and reduce their competitive ability to compete with other invasive species, such as pathogens or other species of plant.

Invasive root-feeding weevils could potentially predispose northern forest ecosystems to subsequent biological invasions. For example, several species of invasive plants are known to aggressively colonize forest gaps. Similarly, root-feeding curculionids could potentially predispose stands to invasive earthworms. Our sampling during 2001–2002 indicated low densities of earthworms, only 61 m⁻² (R.A. Pinski, 2002, unpublished data), compared to areas in which they have become well established, with densities of >565 m⁻² (Eisenhauer et al., 2007). More studies are needed to examine interactions between exotic earthworms and arthropod fauna (Bohlen et al.,
2004a,b). It is also possible that as earthworms become more established at these sites they could increase activities by established invasive weevils. For example, plants in areas with exotic earthworms have exhibited increased foliage nitrogen levels (Scheu, 2003) – which could increase food quality for adult weevils. Exotic earthworms can decrease fine-root biomass (Fisk et al., 2004), which could negatively impact root-feeding weevil larvae.

8.4. Conclusions

A complex of root-feeding weevils is established in North America, ranging throughout south-eastern Canada and the north-eastern USA. Rhizophagous larvae comprise a large portion of the belowground biomass and mesofauna abundance in the northern hardwood forests. They appear to have displaced much of the native fauna. We do not know how they are affecting plant ecology or nutrient cycles, and we have little information regarding their interactions with other native or invasive organisms. Additional research is needed to determine the impacts on ecosystem function, production and overall health.

Acknowledgements

We are indebted to the many systematists who provided data for this project: C. Bartlett (University of Delaware), R. Bell (University of Vermont), S. Boucher (McGill University), D. Chandler (University of New Hampshire), G. Fauske (North Dakota State University), C. Freeman (The Ohio State University), P. Johnson (South Dakota State University), S. Krauth (University of Wisconsin), D. Larson (Memorial University), C. Majka (Nova Scotia Museum of Natural History), C. O’Brien (retired, Florida A&M University), G. Parsons (Michigan State University), K. Pickett (University of Vermont), G. Setliff (University of Minnesota), L. Shapiro and K. Kim (Penn State University). This work could not have been completed without the assistance of many dedicated technicians from UW-Madison and the USDA Forest Service. Funding has been provided for this research and publication from the USDA Cooperative State Research, Education and Extension Service (CSREES Proj WI50 and WIS04969), an EPA STAR Fellowship and grant from Applied Ecological Services, Inc., to DRC, and the USDA Forest Service and UW-Madison College of Agriculture and Life Sciences.

References

Anderson, B.W. and Ohmart, R.D. (1977) Vegetation Structure and Bird Use in the Lower
Colorado River Valley. USDA Forest Service General Technical Report RM-34. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado, USA.


Erbilgin, N. and Raffa, K.F. (2002) Association of declining red pine stands with reduced...


Author Queries:

[AU1] The affiliation in chapter opening is different from the affiliation appearing in the contributors list for K.R. Raffa.

[AU2] Please provide location for the unpublished data. Also check in other occurrences.

[AU3] Bomford and Vernon, 2005 is not in the list.

[AU4] Högberg *et al.* 2001 is not in the list.