MINIREVIEW / MINISYNTHÈSE

Contrasting research approaches to managing mistletoes in commercial forests and wooded pastures[1]

Nick Reid and Simon F. Shamoun

Abstract: Many mistletoe species are pests in agricultural and forest ecosystems throughout the world. Mistletoes are unusual "weeds" as they are generally endemic to areas where they achieve pest status and, therefore, classical biological control and broad-scale herbicidal control are usually impractical. In North American coniferous forests, dwarf mistletoe (*Arceuthobium* spp.) infection results in major commercial losses and poses a public liability in recreation settings. Hyperparasitic fungi have potential as biological control agents of dwarf mistletoe, including species which attack shoots, berries, and the endophytic systems of dwarf mistletoe. Development of an inundative biological control strategy will be useful in situations where traditional silvicultural control is impractical or undesirable. In southern Australia, farm eucalypts are often attacked and killed by mistletoes (*Amyema* spp.) in grazed landscapes where tree decline and biodiversity loss are major forms of land degradation. Although long-term strategies to achieve a balance between mistletoe and host abundance are promoted, many graziers want short-term options to treat severely infected trees. Recent research has revisited the efficiency and efficacy of silvicultural treatments and selective herbicides in appropriate situations. The results of recent research on these diverse management strategies in North America and Australia are summarized.

Key words: Arceuthobium, *Amyema*, hyperparasitic fungi, biological control, selective herbicide, silvicultural and surgical control.

Résumé : Plusieurs espèces de faux-gui constituent des agents néfastes dans les écosystèmes agricoles et forestiers partout dans le monde. Les faux-guis se comportent comme des mauvaises herbes étant généralement endémiques dans certaines régions où ils agissent comme des pestes; conséquemment, la lutte biologique et l'utilisation à grande échelle des herbicides demeurent généralement impraticables. Dans les forêts conifériennes de l'Amérique du Nord, l'infection par les faux-guis (*Arceutobium* spp.) conduit à des pertes commerciales majeures et implique une responsabilité civique dans l'établissement des emplacements de récréation. Les champignons hyperparasites ont un potentiel comme agents de lutte biologique contre le faux-gui, incluant des espèces qui attaquent les tiges, les fruits et le système endophyte du faux-gui. Le développement de stratégies de lutte biologique généralisée devient utile dans les conditions où la lutte sylvicole traditionnelle est impraticable ou indésirable. Dans le sud de l'Australie, les plantations d'eucalyptus font souvent l'objet d'attaques mortelles par le faux-gui (*Amyena* spp.), dans les paysages pâturés où le déclin des arbres et la perte de biodiversité constituent des formes majeures de dégradation des terres. Bien qu'on encourage des stratégies à long terme pour assurer une balance entre l'abondance du faux-gui et de l'hôte, plusieurs éleveurs réclament des options à court terme pour traiter les arbres sévèrement infectés. Des recherches récentes ont réexaminé l'efficience et l'efficacité des traitements sylvicoles et des herbicides sélectifs dans des situations appropriées. Les auteurs résument les résultats de ces recherches récentes sur ces diverses stratégies d'aménagement, en Amérique du Nord et en Australie.

Mots-clés : Arceuthobium, *Amyena*, champignon hyperparasite, lutte biologique, herbicide sélectif, lutte sylvicole et chirurgicale.

[Traduit par la Rédaction]

Received 31 July 2008. Published on the NRC Research Press Web site at botany.nrc.ca on 9 December 2008.

N. Reid.[2] Ecosystem Management, School of Environmental and Rural Science, University of New England, Armidale, NSW 2351, Australia.
S.F. Shamoun. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, 506 West Burnside Road, Victoria, BC V8Z 1M5, Canada.

[1]This minireview is one of a collection of papers based on a presentation from the *Stem and Shoot Fungal Pathogens and Parasitic Plants: the Values of Biological Diversity* session of the XXII International Union of Forestry Research Organization World Congress meeting held in Brisbane, Queensland, Australia, in 2005.
[2]Corresponding author (e-mail: nrei3@une.edu.au).

Introduction

Mistletoes are common pests of agricultural and forest ecosystems throughout the world (Hawksworth 1983). In North America, dwarf mistletoes (*Arceuthobium* spp.) parasitize most commercially important conifers in temperate softwood forests. Along with bark beetles, dwarf mistletoes are the most important forest pests in terms of lost timber production (Hawksworth and Shaw 1984). Dwarf mistletoes cause annual timber losses of 3.8×10^6 m^3 in western Canada and 11.3×10^6 m^3 in the western United States (Hawksworth and Wiens 1996). These shortfalls in production are valued (volume loss × average price) at CDN $166 million and US $1 billion in Canada and the USA, respectively. Dwarf mistletoes also cause problems in protected areas, wildland recreation sites, and peri-urban parks and gardens in North America, owing to the danger of branch and tree fall associated with infection, witches brooms, and tree death around day-use and camping areas, along walking tracks, and near residences (Scharpf et al. 1987, 1988; Hawksworth and Johnson 1989).

In North American production forests, silvicultural management has been traditionally used to reduce dwarf mistletoe infestations. The logging to waste or salvage logging of densely infested stands and individual trees greatly reduces dwarf mistletoe seed production and spread due to the contagious dispersion of mistletoe populations (Hawksworth and Wiens 1996), and is well suited to timber production forests. Sometimes, however, silvicultural control is inappropriate, owing to affected trees being high-value species, or lack of access, or harvesting restrictions associated with environmental protection and amenity. In these circumstances, cheap alternatives that do not damage host trees but selectively control dwarf mistletoes are required.

Constraints on silvicultural options have reactivated research interest in dwarf-mistletoe management in North America (Shamoun et al. 2003). Some 60 herbicidal formulations have been tested, but none have been discovered that are sufficiently selective and that do not damage host conifers (Hawksworth and Wiens 1996). The plant-growth regulator, ethephon, defoliates dwarf mistletoes but the effects are only temporary. Thus, its use is only justifiable in limited situations (Hawksworth and Johnson 1989). Genetic resistance in conifers to dwarf mistletoes is well established (Scharpf 1987; Hawksworth and Wiens 1996). Resistance screening and resistance breeding programs are now underway in several conifer species (Shamoun and DeWald 2002). However, plant breeding is only appropriate where commercial returns and environmental considerations permit manipulation of the genetic structure of tree populations in natural forests. A final avenue attracting research interest is the exploitation of pathogenic mycobiota associated with dwarf mistletoe for biological control (Shamoun et al. 2003).

In grazing and mixed-farming areas in temperate southeastern Australia, scattered pasture trees left after broad-scale clearing of the original woodland and forest are susceptible to mistletoe infestation and may be killed (Reid and Yan 2000). Several species of loranthaceous mistletoe (*Amyema* spp.) are commonly involved, particularly the eucalypt parasites, box, and dropping mistletoe (*Amyema miquelii* (Miq.) Tiegh. and *Amyema pendula* (Spreng.) Tiegh., respectively). Scattered paddock trees are disproportionately valuable to graziers for shade, shelter, and aesthetics (Reid and Landsberg 2000), and it is often such trees that are most infected. In northern New South Wales, mistletoe (*Amyema bifurcata* (Benth.) Tiegh. and *Dendrophthoe vitellina* (F. Muell.) Tiegh.) infestation is an incipient problem in plantations of bloodwood (*Corymbia* spp.) (Carnegie et al. 2008). By contrast, mistletoes have not generally been a problem in native forests and woodlands in Australia (McKinnell et al. 1991) owing to the prevalence of natural control factors (e.g., canopy fires, arboreal marsupial herbivores, and vigorous tree competition) (Reid and Yan 2000). However, this may now be changing as a result of altered fire and logging regimes (Jurskis et al. 2005).

Unlike the North American situation, little control is undertaken of pest mistletoes in agricultural districts in southeastern Australia. Most farmers and graziers run family farms (small businesses) with limited finance and time to spend on any but the most pressing farm management issues associated with crops, pastures, livestock, plant, and infrastructure. Mistletoes threatening paddock trees are a low priority for farmers because mistletoes are only one of several causes of paddock tree loss, only occasional trees are lost to mistletoe, the ecosystem service value of scattered paddock trees is difficult to estimate directly, some ecosystem services may be more of a public than private good (e.g., dryland salinity mitigation), and there are benefits in mixed farming districts of having few or no trees in paddocks that are frequently or occasionally cultivated. The fact that there is generally too little tree cover and a lack of natural regeneration of scattered trees in grazed paddocks means that the silvicultural removal of heavily infested trees is undesirable. Although there are no data, most mistletoe management undertaken by farmers in southeastern Australia probably involves cutting out individual mistletoes, pollarding the branches of trees removing the entire crown, shooting infected branches from trees, and stem injections of 2,4-Dichlorophenoxyacetic acid (2,4-D) into host eucalypts (which are relatively immune to this chemical, unlike box and drooping mistletoe: Brown 1959; Brown and Greenham 1965).

As weeds, mistletoes are unusual in that conventional weed management approaches are generally inappropriate or ineffective. Synthetic chemical herbicide and defoliant application to aerial-stem parasites high in host canopies is problematic, owing to the difficulty of obtaining sufficient spray on target foliage using helicopter application of mistletoe-specific chemicals (Robbins et al. 1989), as well as the problem of selectively targeting mistletoe foliage when using broad-spectrum chemicals. Precise air-borne or ultralight ground-based chemical spray systems designed to operate in forest canopies have not yet been developed to solve this problem. Mistletoes are also generally endemic to the areas if not the vegetation where they are pests, meaning that classical biological control (i.e., the introduction of coadapted predators and parasitoids) is unlikely to work: the mistletoes' natural enemies are either already present but unable to exert sufficient control, owing to human influence (e.g., fire suppression, habitat rendered unsuitable), or are locally extinct (and will die out if re-introduced, owing to the threatening processes that originally caused their extinction).

Given the peculiarities and challenges presented by weedy mistletoes, it is timely to review new approaches and data to managing temperate-zone pest mistletoes in the contrasting environments of North American production forests and southeastern Australian farmland. In North America, biological control strategies are being developed as an alternative where silvicultural control is impractical or undesirable. In Australia, new research on surgical and herbicidal approaches helps refine the various options for graziers from the perspectives of efficacy and cost.

Hyperparasitic fungi for biological control of dwarf mistletoes

Mycoherbicides have been successfully developed for use in agriculture and woody weed control (TeBeest and Templeton 1985; Shamoun 2006). Some of the best-known examples include *Phytophthora palmivora* (E.J. Butler) E.J. Butler as a commercial product DeVine®, for the control of strangler vine (*Morrenia odorata* (Hook. & Arn.) Lindl.) in citrus (*Citrus* spp.) groves (Ridings 1986), and *Colletotrichum gloeosporioides* (Penz.) Penz & Sacc. in Penz. f. sp. *aeschynomene* as registered product Collego® for the control of northern jointvetch (*Aeschynomene virginica* (L.) Britton, Sterns & Poggenb.) in rice (*Oryza sativa* L.) and soybean (*Glycine max* (L.) Merr.) fields (Daniel et al. 1973). In Canada, a dry formulation of *Colletotrichum gloeosporioides* f. sp. *malvae* was registered in 1992 under the trade name BioMal® for control of round-leaved mallow (*Malva pusilla* Sm.) in field crops (Makowski and Mortensen 1992). In forestry situations, Canadian and European scientists have been investigating the potential use of a well-known primary wood invader, *Chondrostereum purpureum* (Pers.: Fr.) Pouzar, as a biological control agent for unwanted woody vegetation in conifer regeneration sites and utility rights-of-way (de Jong et al. 1990; Wall 1994; Shamoun 2000, 2006). In South Africa, another white-rot fungus, *Cylindrobasidium laeve* (Pers.: Fr.) Chamuris, has been registered and extensively tested as the biological control product, StumpOut®, for the control of introduced Australian wattles (*Acacia* spp.) (Morris et al. 1998).

Early surveys of the fungal parasites of dwarf mistletoes revealed a range of species varying in host specificity. The two most promising species for use in the mycoherbicidal control of dwarf mistletoes are the aerial shoot pathogen *Colletotrichum gloeosporioides*, and the canker fungus *Neonectria neomacrospora* (C. Booth & Samuels) Mantiri & Samuels (Shamoun et al. 2003).

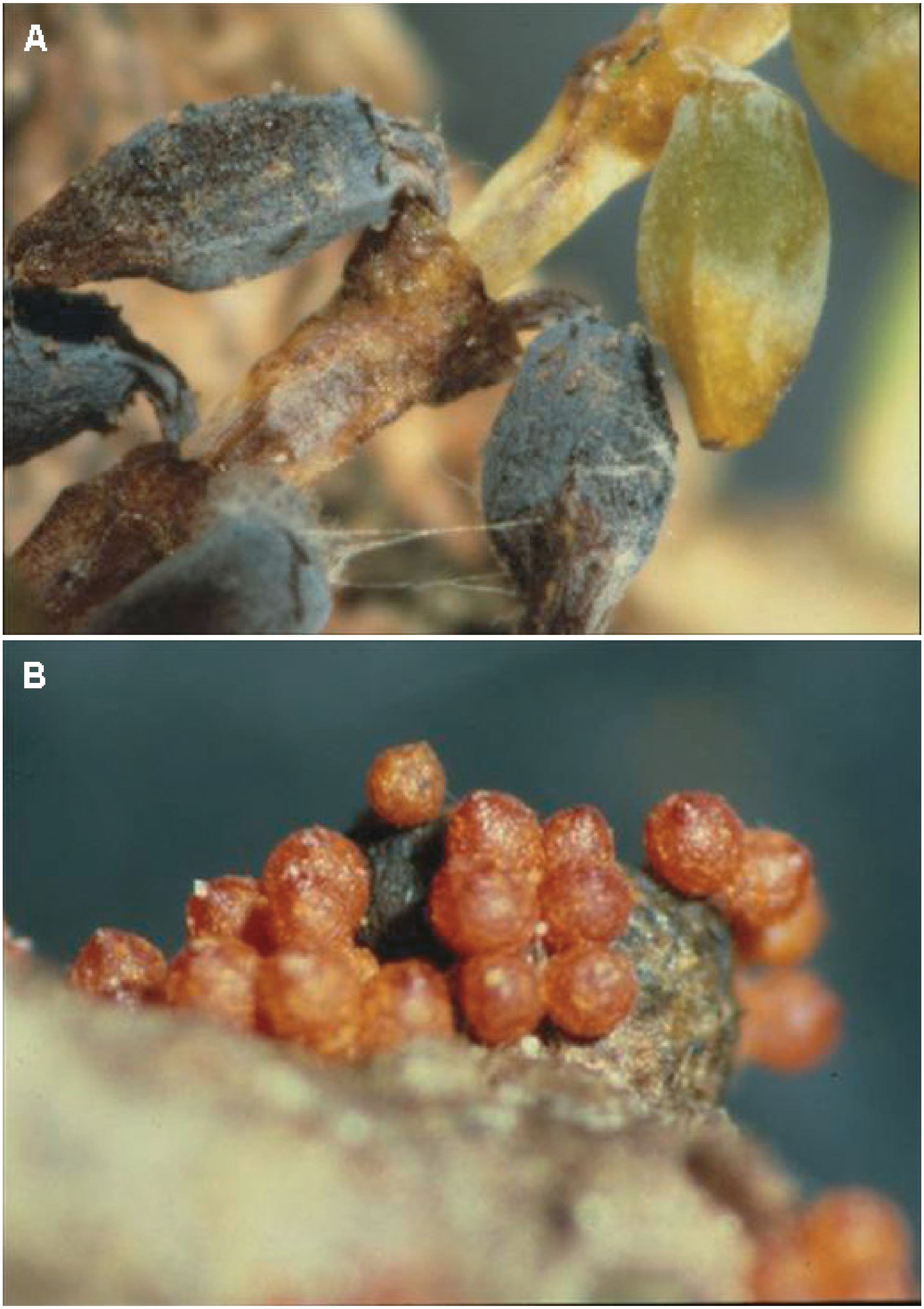
Colletotrichum gloeosporioides

Colletotrichum gloeosporioides is common and widespread on dwarf mistletoes in North America. It is currently being developed as a mycoherbicide for management of dwarf mistletoes on western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and lodgepole pine (*Pinus contorta* Dougl. ex Loud) (Shamoun et al. 2003). The fungus is easily and inexpensively cultured in the laboratory and germinates over a wide temperature range. It attacks dwarf mistletoe foliage any time after shoot emergence, disrupting shoot development and preventing reproduction (Fig. 1A). It therefore has a potentially broad application window between bud burst and the time of seed maturation. Successful field trials have been completed in British Columbia. *Colletotrichum gloeosporioides* has been commonly isolated from *Arceuthobium* spp. in the USA and the western provinces of Canada (Muir 1967; Wicker and Shaw 1968; Kope et al. 1997). Muir (1967), Kope et al. (1997) and Ramsfield et al. (1999) found *C. gloeosporioides* to be destructive to *Arceuthobium americanum* Nutt. ex Engelm. and *Arceuthobium tsugense* (Rosendahl) G.N. Jones subsp. *tsugense* (western hemlock dwarf mistletoe) in several locations in Alberta and British Columbia, Canada, respectively. Deeks et al. (2001) developed an in vitro bioassay system to test the potential use of *C. gloeosporioides* as a biocontrol agent for *A. tsugense* subsp. *tsugense*. The results of the field inoculations of a *C. gloeosporioides* formulation on *A. americanum* and *A. tsugense* subsp. *tsugense* in the interior and costal regions of British Columbia, are encouraging (Ramsfield et al. 2005; Askew et al. 2006; Askew 2007). The fungus is widespread and virulent, having successfully controlled dwarf mistletoes in several study areas. One characteristic of this fungus that makes it an attractive candidate for control use is that it successfully disrupts the vegetative shoots of *Arceuthobium*, and can attack at any stage of the life cycle after the aerial shoots appear.

Neonectria neomacrospora

Neonectria neomacrospora is a canker fungus selective for dwarf-mistletoe-infected host tissue. It has proven pathogenicity and invades dwarf mistletoe tissue without wounding surrounding host tissue. It grows rapidly in infected tissue, produces abundant spores, and reduces mistletoe shoot growth. Research is currently underway on laboratory and potential industrial methods of growing inoculum and the delivery technology for field inoculation (Rietman et al. 2004, 2005). The fungus is characterized by dark red perithecia held on stroma (Fig. 1B). Ascospores bear eight-spored asci. The conidial sporodochia (*Cylindrocarpon*) appear white, and are found most commonly on freshly cankered swellings. Funk et al. (1973) found that *N. neomacrospora* destroyed the swellings caused by western hemlock dwarf mistletoe in British Columbia. The fungus was commonly isolated from open, resinous dwarf mistletoe cankers throughout the range of *A. tsugense* subsp. *tsugense* in British Columbia in 1968–1970, and most recently in 1996–1998 (Funk et al. 1973; Shamoun 1998; Kope and Shamoun 2000). Such characteristics as selectivity for dwarf-mistletoe-infected host tissue, proven pathogenicity, ability to invade without host wounding, rapid canker and abundant spore production, and shoot growth reduction, girdling, and branch mortality, indicate its potential as a biological control agent for western hemlock dwarf mistletoe. Deeks et al. (2001) developed an in vitro method to investigate the potential use of the anamorph stage of *Cylindrocarpon cylindroides* as a biocontrol agent on callus and germinated seeds of western hemlock dwarf mistletoe. The in vitro system was sensitive enough to show that *C. cylindroides* was a more aggressive colonizer of callus and germinated seeds than *C. gloeosporioides*. Further assessment of *N. neomacrospora* as a candidate for biological control agent of western hemlock dwarf mistletoe includes improving the fungal formulation and delivery technology (Rietman et al. 2005).

Fig. 1. (A) *Colletotrichum gloeosporioides* infecting the berries and shoots of *Arceuthobium tsugense*. (B) Perithecia of *Neonectria neomacrospora* infecting basal cup and swelling (endophytic system) of *Arceuthobium tsugense*.



Integrating mycoherbicides with production forest management

Mycoherbicides are at an interesting stage of development for dwarf mistletoe control in forests managed for timber production. No commercial mycoherbicide product is currently available for dwarf mistletoe management. However, to date, a few mycoherbicides have been commercially released to manage woody vegetation in North America or Europe. The available products include Chontrol®, MycoTech®, and BioChon™, which are all based on the white-rot fungus *Chondrostereum purpureum* (Shamoun 2006). Ongoing research and development activities at the Canadian Forest Service's Pacific Forestry Centre are focused on several potential biological control candidates, including *Phoma argillacea* (Bres.) Aa & Boerema for control of weedy salmonberry (*Rubus spectabilis* Pursh.), and *Phoma exigua* Desm., and *Valdensinia heterodoxa* Peyr. for managing salal (*Gaultheria shallon* Pursh.) (Vogelgsang and Shamoun 2004; Zhao and Shamoun 2005; Sumampong et al. 2008). Research on management of dwarf mistletoes is focused on developing the technologies for mass production of *C. gloeosporioides* and *N. neomacrospora*, and efficient field-delivery systems. Simultaneous research is also required in the field and laboratory to determine the conditions under which products should be applied. Spatio-temporal and bio-economic models of dwarf-mistletoe dynamics, host impacts and the predicted effects of myocherbicidal application on mistletoe pathogenicity are required to determine when field application is warranted to achieve an economic benefit. These outputs need to be integrated with field assessments of host and mistletoe populations to develop forest management guidelines for mycoherbicidal use.

Market research

Market research has been commissioned to determine the commercial feasibility and market potential of mycoherbicides for dwarf mistletoe management in timber production forests in North America. Research and development of *Chondrostereum purpureum* (Chontrol®) to control woody regrowth in Canada took 12 years and cost CDN $3–4 million. This cost compares favourably with the US $30–40 million generally required to develop and register synthetic chemical herbicides (Shamoun 2006). Given the annual production losses of timber due to dwarf mistletoe in North America (see Introduction), there is more than sufficient market potential to justify the commercial development of one or more mycoherbicides, assuming appropriate technology can be developed to produce industrial quantities and apply the product in the field. The primary target timber species are lodgepole pine and western hemlock in British Columbia, and Douglas fir (*Pseudotsuga menziesii* (Mirbel) Franco) in the western US, as these are the largest timber markets affected by dwarf mistletoe in North America.

Managing mistletoe in eastern Australian farm eucalypts

Several mistletoe control options exist for primary producers to manage mistletoe infestation of paddock trees in eastern Australia (reviewed by Reid and Yan 2000).

Actual control options

Research was undertaken in the 1950s and 1960s into stem injection of chemical herbicides. The approach assumes the use of a chemical that is relatively harmless to the host tree but lethal to mistletoe. Although many chemicals were tested, research focused on 2,4-D owing to its relative selectivity between box mistletoe and farm eucalypts. The research wasn't widely extended, however, because of difficulties associated with determining the ideal dose under a wide range of situations (e.g., tree species, size, season of application, seasonal conditions, mistletoe infestation level). Although good levels of mistletoe control were sometimes obtained, little control of mistletoes in treated trees was achieved at other times, or some of the trees died (Brown 1959; Brown and Greenham 1965; Minko and Fagg 1989).

Surgical methods are the time-honoured approach to mistletoe control on a small scale, and remain the most common method used in rural and regional Australia. Local government shires and city councils generally use cherry pickers and their own staff to control mistletoes in parks and gardens. Tree surgeons and arborists offer commercial tree-lopping and mistletoe pruning services, but these are probably rarely used by farmers to treat paddock trees owing to the expense. Farmers and their employees are most likely to attempt mistletoe control themselves, as there is a long tradition of pollarding farm trees in southeastern Australia for drought fodder, livestock shade, and mistletoe control, as well as the cutting of on-farm timber for firewood and fencing materials, and the use of firearms for vermin control.

Potential control options

Reid and Yan (2000) speculated about several potential options that have not yet been developed for mistletoe control in farm trees. Experiments using small kerosene weed burners show that eucalypt-parasitizing mistletoes (*A. miquelii* and *A. pendula*) are killed by fire, unlike their hosts (Kelly et al. 1997). Military-style flame throwers thus have the potential to efficiently treat whole trees or stands of trees, killing the mistletoes but allowing the eucalypts to survive through epicormic resprouting. Reid and Yan (2000) also wondered about the potential of yet-to-be-developed aerial or ultralight ground-based surgical equipment or precise chemical delivery systems. Firearms using a herbicidal paint in the ammunition (similar to commercial "paint-ball" equipment) would allow precise targeting of individual mistletoes from the ground. However, such an approach might not be efficient for heavily infested farm eucalypts that support 400 individual mistletoes (Reid and Yan 2000). Several pathogenic fungi have been detected on Australian Loranthaceae (Beilharz 1997). However, no research has been conducted into the potential of fungal control of pest mistletoes on farms.

Many potential options for mistletoe control on farm eucalypts have not been investigated or developed for one principal reason: the lack of commercial incentives to undertake such R&D. Although the problem of mistletoe-induced farm tree death is widespread, it is not of sufficient importance to individual primary producers or companies to warrant significant public or private R&D expenditure. There are also potential political obstacles to publicly-funded research on the issue. Mistletoes are keystone resources for fauna, including several threatened or charismatic bird and

Table 1. Average time taken (in minutes:seconds) to pollard paddock trees and prune mistletoes from paddock trees of red stringybark (*Eucalyptus macrorhyncha*) and Blakely's red gum (*E. blakelyi*) infected with drooping mistletoe (*Amyema pendula*) and box mistletoe (*A. miquelii*), respectively.

	Prune one-third of mistletoes	Prune two-thirds of mistletoes	Prune all mistletoes	Pollard
Red stringybark	5:00a	9:48b,c	33:24b,c	4:48a
Blakely's red gum	13:24b,c	16:48c	51:00d	7:36b

Note: Times are averages for five trees for each combination of species and treatment. Different proportions of mistletoe were pruned in the one-third, two-thirds, and complete-prune treatments. Letters following the values indicate means that differed significantly (least significant difference, $p \leq 0.05$) after analysis of variance of the natural logarithm of time taken in relation to species ($F_{[1,31]} = 15.4$, $p < 0.001$) and treatment ($F_{[3,31]} = 17.4$, $p < 0.001$) with tree height as a significant covariate ($F_{[1,31]} = 8.317$, $p = 0.007$). Source: Reid and Fittler (2008).

butterfly species, in natural and modified ecosystems in Australia (Watson 2001), and so nature conservation concerns are often raised when mistletoe control is mooted (Falkingham 1997; Herring and Watson 2005). Implicit in this stance is that some mistletoe-induced tree death in rural Australia is preferable in the short-term to the unlikely potential for the widespread control of mistletoes by the farming community in the future.

Long-term mistletoe management options

While the various mistletoe control options reviewed above generally only provide short-term therapeutic solutions to saving individual or small numbers of paddock trees, long-term preventative solutions treat the putative causes of mistletoe over-abundance at farmscape scale. Reid and Yan (2000) outlined several long-term strategies designed to maintain farm mistletoe populations in balance.

First, mistletoes have probably been killing trees for millions of years, since the main species of pest Loranthaceae evolved in Australasia after the break-up of Gondwana. Trees also die for a variety of reasons, not just mistletoe infestation. Thus, a balance between recruitment and mortality is required to ensure farm trees for the future. However, paddock tree recruitment is rare or nonexistent on many farms in the high rainfall zone and wheat–sheep belt of southeastern Australia, owing to livestock grazing, periodic cultivation, and competition from fertilized pastures (Reid and Landsberg 2000).

Second, owing to the excessive loss of tree cover from many parts of the high rainfall zone and wheat–sheep belt, revegetation with trees and shrubs will be the primary means of returning adequate timber to affected farmscapes. Owing to the (at least partial) genetic basis for mistletoe–host compatibility, selection for resistance to local problem mistletoes when collecting seed from individual trees and species for revegetation purposes, will provide long-term reductions in mistletoe prevalence in planted vegetation.

Third, mistletoes are dispersed contagiously in the landscape owing to disperser behaviour and mistletoe–host compatibilities. Since eucalypt-parasitizing mistletoes can persist for decades and grow to a large size, the early treatment of small mistletoes on young trees while control is easy may avoid the build-up of difficult-to-control infection centres higher in the canopy as the vegetation matures.

Fourth, mistletoes have many natural enemies, including herbivorous arboreal marsupials, broad-tailed parrots, and the larvae of mistletoe-specific butterflies, moths, and fruit flies. Incorporating wildlife habitat design elements for native fauna in property and catchment planning, including hollows, a wide variety of nectar sources and wildlife corridors, will help to ensure healthy populations of natural control agents on farms.

Fifth, mistletoes are dependent on the host's xylem stream for nutrients and water. Any factors that reduce the over-abundance of moisture and nutrients in host trees may reduce mistletoe establishment, growth, and reproduction. Thus, creating competition between susceptible trees, reducing edges, and providing more woodlot interiors, and avoiding fertilizer use and stock camping in the root zone of host trees, should reduce mistletoe abundance.

Recent research on surgical options

Recent research has focused on the surgical treatment of farm trees for mistletoe control to provide information about the merits of pruning versus pollarding. Table 1 shows the average time taken by an experienced tree surgeon to prune and pollard two eucalypt species of differing habit in farm paddocks in northern New South Wales. Trees averaged about 50% mistletoe infection level. Single-stemmed red stringybarks (*Eucalyptus macrorhyncha* F. Muell. ex Benth.) of good form with an erect habit are quicker to prune or pollard than shorter spreading Blakely's red gum (*Eucalyptus blakelyi* Maiden) with 1–4 stems at breast height. Pollarding is quick, taking 5–7 min depending on the number of stems or lower limbs to be cut. Pruning one- or two-thirds of the mistletoe biomass from paddock trees takes from 5–15 min, on average. However, the last one-third of mistletoes costs a disproportionate amount of time to remove, as the tree surgeon has to re-position themselves several times to cut out the last few clumps.

Preliminary results on the efficacy of pruning versus pollarding are available from the same experiment described in Table 1. Fifteen months after autumn treatment and a winter–spring drought, three of the five pollarded stringybarks (mean DBH, 58 cm) and two of the five pollarded red gums (mean DBH, 64 cm) were dead. None of the pruned trees died. The host response to pruning treatments is compared with the unpruned control trees in Table 2. Pruning some or most mistletoe from both species of paddock tree improves the amount of eucalypt foliage relative to controls, with less improvement in trees with one-third of mistletoes removed, and the best response in completely pruned trees. Note that in this experiment, the crown condition of most red gums deteriorated after treatment, owing to insect attack (including untreated control trees).

Table 2. Mean change in eucalypt foliage density (%), 15 months after a tree surgeon pruned varying amounts of mistletoe from farm trees (five trees per combination of species and treatment).

	Control	Prune one-third of mistletoes	Prune two-thirds of mistletoes	Prune all mistletoes
Red stringybark	–3.0a	3.0b	7.8b	26.8b
Blakely's red gum	–15.6a	–2.2b	–10.8a	11.6b

Note: Eucalypt foliage density is an estimate of eucalypt foliar biomass, expressed as a percentage of the potential foliage capable of being supported by the woody architecture of the tree in full leaf without parasites or branch death. Letters following the values indicate means that differ significantly within each row (least significant difference, $p \leq 0.05$) after analysis of variance of the natural logarithm of change in eucalypt foliage in relation to species ($F_{[1,32]} = 18.6$, $p < 0.001$) and treatment ($F_{[3,32]} = 11.1$, $p < 0.001$). Source: Reid and Fittler (2008).

Table 3. Proportion (%) of box mistletoe foliage that remained green, 5 months after spraying with half and full label doses of several herbicides used for woody weed control (source: Reid et al. 2008).

	MCPA	Glyphosate	Garlon	DP600	Starane	Tornado*	Brushkiller
Half label dose	32.2	45.7	39.3	53.6	52.1	31.2	57.3
Label dose	21.1	42.8	25.3	30.3	42.9	16.7	45.4

*Tornado, Na salt of 2,4-D.

Recent research on herbicide options

Australian research in the 1950s and 1960s focused on the selectivity of 2,4-D between eucalypts and box mistletoe in ground spraying and stem injection trials (Greenham and Brown 1957, 1959; Brown 1959; Brown and Greenham 1965). The advent of aerial agriculture and use of helicopters for weed spraying provides an opportunity for the selective control of mistletoes in high-value paddock trees from the air. Recent research suggests that half the label dose of the sodium salt of 2,4-D (13.8 g/10 L) is as effective as several other herbicides used in woody weed control in killing 42% of box mistletoe sprayed throughout the year (Reid et al. 2008), with best results in spring and autumn. The preliminary results of this research confirm the efficacy of half the label dose of 2,4-D Na in defoliating box mistletoe to the extent likely to permanently suppress and eventually kill sprayed plants (Table 3). The research also confirms the relatively benign impact of 2,4-D Na on Blakely's red gum and yellow box (*Eucalyptus melliodora* Cunn. ex Schauer) saplings, in comparison with other herbicides with similarly severe effects on box mistletoe (Reid et al. 2008).

Discussion

Several points emerge from this review of recent advances in approaches to mistletoe management in timber production forests and sparsely wooded grazing lands in North America and south-eastern Australia, respectively. Economics not only dictate the choice of control techniques, but also the direction of current R&D in managing pest mistletoes in these different environments. In North America, where production losses attributable to dwarf mistletoe exceed US $1 billion annually, biotechnological R&D approaches are being used to engineer biocontrols designed to inundate pest populations with large quantities of locally occurring pathogen. While scientifically elegant, these approaches require extensive laboratory and field development trials and are relatively expensive. By comparison, in southeastern Australia, and despite the fact that the replacement value of farm trees is counted in the billions of dollars (Reid and Landsberg 2000), the occasional loss of paddock trees to problem mistletoes at farm scale is an insufficient priority to attract major investment by agricultural R&D funding organisations. Accordingly, low-cost surgical methods are most commonly used by farmers, if mistletoe control is undertaken at all. There is also continuing interest in developing effective methods to apply selective chemicals cheaply. Given the financial pressures on family farms in southeastern Australia, surgical methods are likely to continue to be favoured for short-term control, in the absence of proven cheap alternatives reliant on chemicals, fire or other means.

Ideally, long-term preventative measures for managing mistletoes in balance in productive landscapes in southeastern Australia might be widely adopted. However, the significant cost of such measures where they require special interventions without collateral benefits, are likely to see only sporadic adoption. The difficulty in establishing the direct, short-term worth of paddock trees to farmers means that long-term preventative measures will most likely be adopted with mistletoe in mind only when they offer farm and catchment managers additional advantages over and above the potential for a balance between mistletoe and wildlife populations (natural control agents). The difficulty in "proving" the value or worth of long-term preventative measures through landscape experimentation, given the low priority afforded pest mistletoes and paddock tree survival, is a significant impediment to adoption.

The research on mycoherbicides in North America may have unexpected application in managing pest mistletoes in other parts of the world. Low-specificity fungi that attack a wide variety of mistletoes (Loranthaceae and Viscaceae) or other plants may be too dangerous to release in areas beyond their natural distribution for fear of widespread and damaging impacts. However, there may be less risk in introducing fungi of intermediate host specificity beyond their natural range to control pest mistletoes in particular situations. The technology to produce industrial quantities of fungal inoculum and deliver it affordably may also be readily applied to fungal candidates for selective mycoherbicides to control mistletoes and other weeds elsewhere in the world.

Acknowledgements

Nicholas Reid thanks Jim Fittler, Ajoy Kar, Kàren Zirkler-Forge (Southern New England Landcare Ltd., Armidale, N.S.W.), and various landowners for technical and logistic assistance, as well as John and Annette Cassidy (Merilba Partnerships), Meat & Livestock Australia (North Sydney, N.S.W.), and the University of New England (Armidale, N.S.W.) for research funds to support his mistletoe research. Simon Shamoun thanks Grace Sumanpong, Sue Askew, Lea Rietman, Shannon Deeks, Holly William, Tod Ramsfield, Chery Konoff, John Leaky, Ed Wass, Forest Innovation Investment, Forest Renewal B.C., Science Council B.C., the Canadian Forest Service, and Forest Sciences at the University of British Columbia for supporting his research.

References

Askew, S.E. 2007. Assessment of *Colletotrichum gloeosporioides* as a biological control agent for hemlock dwarf mistletoe (*Arceuthobium tsugense*). M.Sc. thesis, Department of Forest Sciences, The University of British Columbia, Vancouver, B.C.

Askew, S.E., Shamoun, S.F., and van der Kamp, B.J. 2006. Development of a biological control strategy to mitigate hemlock dwarf mistletoe in retention silviculture systems: *Colletotrichum gloeosporioides* – western hemlock dwarf mistletoe pathosystem. B.C. J. Ecosyst. Manag. **7**: 23–29.

Beilharz, V. 1997. Fungal pathogens of mistletoes in Victoria. Vic. Nat. **114**: 162–163.

Brown, A.G. 1959. Mistletoe control on a large scale. J. Aust. Inst. Agric. Sci. **25**: 282–286.

Brown, A.G., and Greenham, C.G. 1965. Further investigations in the control of mistletoe by trunk injections. Aust. J. Exp. Agric. Anim. Husb. **5**: 305–309. doi:10.1071/EA9650305.

Carnegie, A.J., Bi, H.Q., Arnold, S., Li, Y., and Binns, D. 2009. Distribution, host preference and impact of parasitic mistletoes (Loranthaceae) in young eucalypt plantations in New South Wales, Australia. Botany, **87**. This issue.

Daniel, J.T., Templeton, G.E., Smith, R.J., and Fox, W.T. 1973. Biological control of northern jointvetch in rice with endemic fungal disease. Weed Sci. **21**: 303–307.

de Jong, M.D., Scheepens, P.C., and Zadoks, J.C. 1990. Risk analysis for biological control: a Dutch case study in biocontrol of *Prunus serotina* by the fungus *Chondrostereum purpureum*. Plant Dis. **74**: 189–194. doi:10.1094/PD-74-0189.

Deeks, S.J., Shamoun, S.F., and Punja, Z.K. 2001. *In vitro* germination and development of western hemlock dwarf mistletoe. Plant Cell Tissue Organ Cult. **66**: 97–105. doi:10.1023/A:1010663108233.

Falkingham, C. 1997. Those amazing mistletoe plants. Vic. Nat. **114**: 164–165.

Funk, A., Smith, R.B., and Baranyay, J.A. 1973. Canker of dwarf mistletoe swellings on western hemlock caused by *Nectria fuckeliana* var. *macrospora*. Can. J. For. Res. **3**: 71–74. doi:10.1139/x73-010.

Greenham, C.G., and Brown, A.G. 1957. The control of mistletoe by trunk injection. J. Aust. Inst. Agric. Sci. **23**: 308–318.

Greenham, C.G., and Brown, A.G. 1959. Mistletoe control. J. Aust. Inst. Agric. Sci. **25**: 73.

Hawksworth, F. 1983. Mistletoes as forest parasites. *In* The biology of mistletoes. *Edited by* M. Calder and P. Bernhardt. Academic Press, Sydney, Australia. pp. 317–333.

Hawksworth, F.G., and Johnson, D.W. 1989. Biology and management of dwarf mistletoe in lodgepole pine in the Rocky Mountains. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo. USDA For. Serv., Gen. Tech. Rep. RM-169.

Hawksworth, F.G., and Shaw, C.G. 1984. Damage and loss caused by dwarf mistletoe in coniferous forests of western North America. *In* Plant diseases: infection, damage, and loss. *Edited by* R.K.S. Wood and G.J. Ellis. Blackwell, Oxford, UK. pp. 285–297.

Hawksworth, F.G., and Wiens, D. 1996. Dwarf mistletoes: biology, pathology, and systematics. USDA For. Serv.,Washington, D.C. Agriculture Handbook 709.

Herring, M., and Watson, D. 2005. Mistletoe: scourge or saviour of our threatened woodlands? Woodland Wanderings (Grassy Box Woodlands Conservation Management Network Newsletter), **4**: 9–11.

Jurskis, V., Turner, R.J., and Jurskis, D. 2005. Mistletoes increasing in 'undisturbed' forest: a symptom of forest decline caused by unnatural exclusion of fire? Aust. For. **68**: 221–226.

Kelly, P., Reid, N., and Davies, I. 1997. Effects of experimental burning, defoliation and pruning on survival and vegetative resprouting in mistletoes (*Amyema miquelii* and *A. pendula*). Int. J. Plant Sci. **158**: 856–861. doi:10.1086/297500.

Kope, H.H., and Shamoun, S.F. 2000. Mycoflora associates of western hemlock dwarf mistletoe plants and host swellings collected from southern Vancouver Island, British Columbia. Can. Plant Dis. Surv. **80**: 144–147.

Kope, H.H., Shamoun, S.F., and Oleskevich, C. 1997. First report of *Colletotrichum gloeosporioides* on *Arceuthobium tsugense* subsp. *tsugense* in Canada. Plant Dis. **81**: 1095. doi:10.1094/PDIS.1997.81.9.1095B.

Makowski, R.M.D., and Mortensen, K. 1992. The first mycoherbicide in Canada: *Colletotrichum gloeosporioides* f. sp. *malvae* for round-leaved mallow. *In* Proceedings of the 1st International Weed Control Congress, Melbourne, Victoria, Australia. 17–21 February 1992. Vol. 2. *Edited by* E.S. Delfosse and R.R. Scott. DSIR/CSIRO, Melbourne, Australia. pp. 298–300.

McKinnell, F.H., Hopkins, E.R., and Fox, J.E.D. 1991. Forest management in Australia. Surrey Beatty and Sons, Chipping Norton, Sydney, Australia.

Minko, G., and Fagg, P.C. 1989. Control of some mistletoe species on eucalypts by trunk injection with herbicides. Aust. For. **52**: 94–102.

Morris, M.J., Wood, A.R., and Den Breeyen, A.D. 1998. Development and registration of a fungal inoculant to prevent re-growth of cut wattle tree stumps in South Africa, and brief overview of other bioherbicide projects currently in progress. *In* IV International Bioherbicides Workshop — Programme and Abstracts. 6–7 August 1998. *Edited by* D.S. Main and M.N. Burge. University of Strathclyde, Glasgow, Scotland. p. 15.

Muir, J.A. 1967. Occurrence of *Colletotrichum gloeosporioides* on dwarf mistletoe (*Arceuthobium americanum*) in western Canada. Plant Dis. Rep. **51**: 789–799.

Ramsfield, T.D., Shamoun, S.F., and van der Kamp, B.J. 1999. Fungal parasites of lodgepole pine dwarf mistletoe in British Columbia. Can. J. Plant Pathol. **21**: 204.

Ramsfield, T.D., Shamoun, S.F., and van der Kamp, B.J. 2005. Infection of *Arceuthobium americanum* by *Colletotrichum gloeosporioides* and its potential for inundative biological control. For. Pathol. **35**: 332–338.

Reid, N., and Fittler, J. 2008. Results of mistletoe pruning and pollarding trials for Southern New England Landcare and Meat & Livestock Australia. Ecosystem Management, University of New England, Armidale, NSW, Australia.

Reid, N., and Landsberg, J. 2000. Tree decline in agricultural landscapes: what we stand to lose. *In* Temperate eucalypt woodlands in Australia: biology, conservation, management and restoration. *Edited by* R.J. Hobbs and C.J. Yates. Surrey Beatty & Sons, Chipping Norton, NSW, Australia. pp. 127–166.

Reid, N., and Yan, Z. 2000. Mistletoes and other phanerogams parasitic on eucalypts. *In* Diseases and pathogens of eucalypts. *Edited by* P.J. Keane, G.A. Kile, F.D. Podger, and B.N. Brown. CSIRO, Collingwood, Victoria, Australia. pp. 353–383.

Reid, N., Fittler, J., Kar, A., Storey, A., and Cook, T. 2008. Effect of spray applications of several herbicides on the mortality of box mistletoe (*Amyema miquelii*) and host saplings (*Eucalyptus blakelyi* and *E. melliodora*). Ecosystem Management, University of New England, Armidale, NSW, Australia.

Ridings, W.H. 1986. Biological control of strangler vine in citrus: a researcher's view. Weed Sci. **34**(Suppl. 1): 31–32.

Rietman, L.M., Shamoun, S.F., and van der Kamp, B.J. 2004. Assessment of *Neonectria neomacrospora* as a potential biological control agent for hemlock dwarf mistletoe. M.Sc. thesis, Department of Forest Sciences, The University of British Columbia, Vancouver, B.C.

Rietman, L.M., Shamoun, S.F., and van der Kamp, B.J. 2005. Assessment of *Neonectria neomacrospora* (anamorph *Cylindrocarpon cylindroides*) as an inundative biocontrol agent against hemlock dwarf mistletoe. Can. J. Plant Pathol. **27**: 603–609.

Robbins, K., Johnson, D.W., Hawksworth, F.G., and Nicholls, T.H. 1989. Aerial application of ethephon is ineffective in controlling lodgepole pine dwarf mistletoe. West. J. Appl. For. **4**: 27–28.

Scharpf, R.F. 1987. Resistance of Jeffrey pine to dwarf mistletoe. *In* Parasitic flowering plants. *Edited by* H.C. Weber and W. Forstreuter. Phillips Universität, Marburg, Germany. pp. 745–753.

Scharpf, R.F., Smith, R.S., and Vogler, D. 1987. Pruning dwarf mistletoe brooms reduces stress on Jeffrey pines, Cleveland National Forest, California. Pacific Southwest Forest and Range Experiment Station, Berkeley, Calif. USDA, For. Serv., Res. Paper PSW–186.

Scharpf, R.F., Smith, R.S., and Vogler, D. 1988. Management of western dwarf mistletoe in Ponderosa and Jeffrey pines in forest recreation areas. Pacific Southwest Forest and Range Experiment Station, Berkeley, Calif. USDA, For. Serv., Gen. Tech. Rep. PSW–103.

Shamoun, S.F. 1998. Development of biological control strategy for management of dwarf mistletoes. *In* Proceedings of the 45th Western International Forest Disease Work Conference. 15–19 September 1997. *Compiled by* R. Sturrock. Pacific Forestry Centre, Prince George, BC, Victoria, B.C., Canadian Forest Service. pp. 36–42.

Shamoun, S.F. 2000. Application of biological control to vegetation management in forestry. *In* Proceedings of the X International Symposium on Biological Control of Weeds. 4–14 July 1999. *Edited by* N.R. Spencer. Montana State University, Bozeman, Ma. pp. 87–96.

Shamoun, S.F. 2006. Implementation of weed biocontrol in forest vegetation management for conifer production. *In* Handbook of sustainable weed management. *Edited by* H.P. Singh, D.R. Batish, and R.K. Kohli. The Haworth Press, Inc., Binghamton, New York. pp. 475–506.

Shamoun, S.F., and DeWald, L.E. 2002. Management strategies for dwarf mistletoes: biological, chemical and genetic approaches. *In* Mistletoes of North American conifers. *Technical coordinators* B.W. Geils, J.C. Tovar, and B. Moody. Rocky Mountain Research Station, USDA, For. Serv., Gen. Tech. Rep. RMRS-GTR-98. pp 75–82.

Shamoun, S.F., Ramsfield, T.D., and van der Kamp, B.J. 2003. Biological control approach for management of dwarf mistletoes. N. Z. J. For. Sci. **33**: 373–384.

Sumampong, G., Shamoun, S.F., and Punja, Z.K. 2008. Occurrence of *Phoma argillacea* on *Rubus spectabilis* in British Columbia and an evaluation of its potential as a forest weed biological control agent. Can. J. Plant Pathol. **30**: 74–84.

TeBeest, D.O., and Templeton, G.E. 1985. Mycoherbicides: progress in the biological control of weeds. Plant Dis. **69**: 6–10.

Vogelgsang, S., and Shamoun, S.F. 2004. Evaluation of an inoculum production and delivery technique for *Valdensinia heterodoxa*, a potential biological control agent for salal. Biocontrol Sci. Technol. **14**: 747–756. doi:10.1080/09583150410001720725.

Wall, R.E. 1994. Biological control of red alder using stem treatments with the fungus *Chondrostereum purpureum*. Can. J. For. Res. **24**: 1527–1530. doi:10.1139/x94-199.

Watson, D.M. 2001. Mistletoe—a keystone resource in forests and woodlands worldwide. Annu. Rev. Ecol. Syst. **32**: 219–249. doi:10.1146/annurev.ecolsys.32.081501.114024.

Wicker, E.F., and Shaw, C.G. 1968. Fungal parasites of dwarf mistletoes. Mycologia, **60**: 372–383. doi:10.2307/3757167.

Zhao, S., and Shamoun, S.F. 2005. Effects of potato dextrose broth and gelatin on germination and efficacy of *Phoma exigua*, a potential biocontrol agent for salal (*Gaultheria shallon*). Can. J. Plant Pathol. **27**: 234–244.