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Pine weevil *Pissodes nemorensis:* threat to South African pine plantations and options for control

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Pissodes nemorensis Germar (Coleoptera: Curculionidae) is native to North America, where it causes significant damage to young trees of various _Pinus_ species. In North America, it can be associated with the pitch canker pathogen, _Fusarium circinatum_, that kills young trees and causes cankers on established trees. _Pissodes nemorensis_ was first detected in South Africa in 1942 and has since been responsible for significant damage to local pine plantations. In South Africa, _P. nemorensis_ is present throughout all pine-growing areas, and is often associated with trees that are stressed by factors such as hail damage and poor species–site matching. It also causes primary damage, by killing growing shoots of pines, resulting in forking or branching of tree leaders. With the recent appearance of the pitch canker fungus in South African nurseries, there is much concern that _P. nemorensis_ will become associated with this pathogen here. The management of _P. nemorensis_ is essential to avoid losses to South African pines, but has received little attention. We review the available information on the biology, phenology, host preference, and damage potential of _P. nemorensis_. Other economically important species of _Pissodes_ are considered where relevant. We also refer to our observations of the pest in the field and laboratory in South Africa, and present the options for the management of _P. nemorensis_ under South African conditions and priorities for future research.

Introduction

Intensively managed pine plantations form part of a major industry in South Africa and cover approximately 1.4 million hectares of land.[1] Species of pine grown include *Pinus radiata*, *P. patula*, *P. elliottii* and *P. taeda*, as well as hybrids of these species. *Pissodes nemorensis* Germar (Coleoptera: Curculionidae) is one of several pests of pine plantations in North America. This insect, also known as the deodar weevil, was first reported on pines in South Africa in 1942 (G.D. Tribe, ARC-Plant Protection Research Institute, unpubl. report). Since its introduction, *P. nemorensis* has continued to cause substantial damage to pine plantations and is widely distributed in all pine-growing regions of the country. Our recent surveys (unpubl.) have revealed that the weevil is causing more damage in plantations than was previously thought.

There are several unanswered questions regarding the introduction and spread of *Pissodes nemorensis* in South Africa. There is extensive movement of wood products such as wooden boxes and crates between the countries of the northern hemisphere and South Africa. This makes the enforcing of quarantine at entry points into the country extremely difficult. As a result, it is possible that there could have been repeated introductions of *P. nemorensis* and of related species. Furthermore, it is not clear whether the current wide distribution of *P. nemorensis* in South Africa is the result of the extensive movement of wood and beetles between different provinces or due to multiple introductions through different entry points.

Identification of *Pissodes*

The morphological features of *Pissodes* species are so similar that much difficulty has been experienced in identifying species, when based only on these characters. This has been a severe handicap to studies of species distribution, population dynamics and forest management.[2] As a result, there has been a shift towards using molecular techniques to better understand species composition and population structure of *Pissodes*.

In recent years, mitochondrial DNA (mtDNA), by virtue of its simple structure, maternal inheritance and relatively rapid evolutionary rates, has become widely used to study the population structure, taxonomy, and phylogeny of animal species.[3-5] Langor and Sperling investigated the variation in mtDNA among members of the *Pissodes strobi* species complex in

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Table 1. Economically important species of *Pissodes*, their distribution and host range.

Species	Area of occurrence	Hosts	References
P. strobi Peck	Canada	*Picea* spp.; *Pinus* spp.	34
P. nemorensis Germar	Canada, U.S.A., South Africa	*Pinus* spp., *Picea* spp., *Cedrus* spp.	25
P. schwartzi Hopkins	Canada, U.S.A.	*Pinus* spp.	35
P. fiskei Hopkins	Canada, U.S.A.	*Picea* spp.	36
P. piceae Hopkins	Poland, USSR	*Abies alba*	37
P. validirostris C.R. Sahlberg	Sweden, France, Turkey, U.S.S.R., China	*Pinus* spp.	38
P. notatus Fabricius	Sweden, Portugal, Spain, France, Italy, Yugoslavia, Greece, Turkey, Israel, Algeria	*Pinus* spp.	39
P. terminalis Hopping	Canada, U.S.A.	*Pinus banksiana, P. contorta*	40
P. hercyniae Hopkins	Sweden, Finland, Germany, Czechoslovakia	*Pinus* spp., *Picea* spp.	26, 41
P. zitacuarence Sleeper	Mexico	*Pinus ayachaute, P. leiophylla, P. lawsonii*	11, 42
P. cibriani O'Brien	Mexico	*Pinus patula*	11, 42
P. webbi Hopkins	U.S.A.	*Pinus* spp.	17
P. radiatae Hopkins	U.S.A.	*Pinus* spp.	17
P. murraynae Hopkins	U.S.A.	*Pinus murrayana*	17
P. burkei Hopkins	U.S.A.	*Abies lasiocarpa*	17
P. similis Hopkins	Canada	*Abies* spp.	17

western Canada, which includes the white pine weevil, *P. strobi* (Peck), the lodgepole terminal weevil, *P. terminalis* Hopping, the deodar weevil, *P. nemorensis* Germar, and *P. schwarzi* Hopkins.[6,7] They concluded that interspecific sequence divergences for Pissodes are much higher than those reported for most other closely related, non-parthenogenetic insect species.[3,8,9] Examination of mtDNA, therefore, provides a reliable means for identifying species of *Pissodes*.

Distribution and host range

The genus *Pissodes* includes 55–60 species worldwide, some of which are undescribed, including 21 species from North and Central America, and 15 Palaearctic species, with southern range extensions into the montane regions of Asia and Central America (Table 1).[10,12–15] New species of *Pissodes* continue to be described. Recently, Langor *et al.* described two new species (*P. punctatus* and *P. yunnanensis*) from southwestern China. *Pissodes nemorensis* is native to North America, occurring together with other species of *Pissodes* such as *P. strobi* and *P. terminalis*. In South Africa, this insect occurs in all pine-growing provinces.[16]

Species of *Pissodes* feed on and breed in the cambium and phloem of conifers (Pinaceae), except *P. validirostris*, which attacks seed cones.[10,11,17] Most species feed on *Pinus*, although other Pineaceae such as *Picea*, *Abies*, *Larix* and *Pseudotsuga* are also attacked.[17] In its native habitat, *P. nemorensis* attacks deodar (*Cedrus deodara*) and Atlas cedar (*Cedrus atlantica*), cedar of Lebanon (*Cedrus lebani*), and various southern pines.

In South Africa, *P. nemorensis* causes more damage in the Eastern Cape and Western Cape than in other provinces. The reason for this difference is not known. *Pissodes nemorensis* feeds on all commercially grown pine species in South Africa, but some species appear to be more susceptible to attack than others. The insect is more frequently encountered on *P. radiata* and *P. patula* than on *P. elliottii*. The host preference of *P. nemorensis* has, however, not been studied experimentally, and clearly deserves more attention.

Pest status and damage

Many species of *Pissodes* are secondary pests, that attack weakened or recently killed trees, and thus usually have no significant economic impact.[17] However, *P. strobi* causes growth loss and stem deformities on *Pinus* and *Picea* throughout North America.[18,19] A few other species around the world occasionally also reach outbreak levels and cause significant damage.[16]

All 21 species of *Pissodes* in North America infest the bark and outer wood of coniferous trees.[11,17] The species that are pests of *Pinus* and *Picea* commonly attack young trees, mostly killing terminal leaders, which results in growth loss and crooking or branching of the trunk.[20,21] After being attacked, trees may take one to several years to resume growth, depending on growing conditions. Fast-growing trees, on good sites, are able to develop a new leader in a year. In the process of recovery, branches from the uppermost whorl below the damaged terminal compete for dominance and trees remain with multiple leaders for one or two years. Most commonly, only one leader will succeed, though forks sometimes develop in trees. Depending on the number of internodes destroyed and the growth characteristics of the tree, permanent stem defects can develop at the point of injury.[19]

In North America, adults and larvae of *P. nemorensis* can kill terminal and lateral branches, as well as girdle the stems of small trees. During autumn, weevil larvae feed on the inner bark of leaders, lateral branches, and stems of small trees. Infestations usually remain unnoticed until the following January, when infested branches begin to turn brown. Small trees may be girdled and killed.[22]

In South Africa, *P. nemorensis* is mainly associated with trees that are under stress or with stumps, hence it is largely considered a secondary pest. In some cases, it has been recorded as being associated with lower stem parts and the root collar.[23] Our surveys in 2002 and 2003 (unpubl.) revealed a high incidence of *P. nemorensis* in young pine stands that had been damaged by hail. Also, large populations of *P. nemorensis* have been observed on logs that had been lying on the ground for a long time. In some provinces of South Africa, particularly in the Western Cape, damage by *P. nemorensis* is primary. Damage levels are generally minimal in healthy stands, however, and are not comparable to levels reported for North American plantations, where young stands can suffer up to 40% of leaders dead in one season.[19]

The recent outbreaks of the Sirex wood wasp (*Sirex noctilio* Fabricius) appear to have increased the populations of *P. nemorensis*. *Sirex noctilio* was first recorded near Cape Town in 1994[24] and has recently spread up the coast towards the port city of Durban (B. Hurley, Forestry and Agricultural Biotechnology

Institute, Pretoria, unpubl. report). Large areas of trees have been damaged by *Sirex* and these dying trees provide attractive breeding material for *P. nemorensis.* It is also possible that the weevils have contributed to tree mortality, although this has not been determined with certainty.

Interaction with pathogens

A few species of *Pissodes* are known to interact with pathogens. *Pissodes nemorensis* has been reported as a vector and wounding agent of the pitch canker fungus, *Fusarium circinatum* Nirenberg and O'Donnell, that causes pitch canker in North America.[22,25] In South Africa, Zwolinski *et al.* found a close association between the incidence of *P. nemorensis* and the fungus *Diplodia pinea* (Desm.) Kickx, causing die-back on *P. radiata* and resulting in extensive losses.[26] In France, the spruce weevil, *P. piceae,* has been reported to be a vector of the wood-staining fungal pathogens, *Ophiostoma canum* (Münch) H. & P. Sydow and *O. ips* (Rumbold) Nannfeldt.[27,28]

The fact that *P. nemorensis* can act as a vector of pathogens such as *F. circinatum* is a major concern for South African forestry. The pitch canker fungus was recorded for the first time in South Africa relatively recently.[29,30] Here, the disease has not been found on established trees, but causes devastating losses in nurseries. It was first detected in a single nursery in Mpumalanga and spread to virtually all pine-growing nurseries within ten years. Two of the three most important species of pines, namely, *P. patula* and *P. radiata* (representing 80% of pines grown in South Africa)[1] are highly susceptible to this pathogen.[30] *Pinus elliottii,* which is the second most widely planted species after *P. patula,* is moderately susceptible.[30] *Pinus radiata* is also highly susceptible to attack by *P. nemorensis* and, in the Western and Eastern Cape, up to 40% of the young pine leaders can be destroyed annually.[31] This wounding alone would provide suitable sites for infection by *F. circinatum.* Assuming that the insect were to carry the fungus, much greater damage would most likely occur, since the rate of infection of trees would be higher as a result of the insect carrying the fungus from infected to healthy trees.

Biology

Pissodes species undergo complete metamorphosis (Fig. 1 a, b). The eggs are pearly white, oblong, and equally rounded at both ends. The larvae are yellowish-white, cylindrical and legless grubs with a reddish brown head. Pupation takes place in chambers excavated in the xylem and covered with wood fibres. The pupae, about the same size as the adults, are shiny white at first, darkening while maturing, with well-developed wings and legs. Adult weevils are rusty red to grey-brown, have long snouts and cylindrical and posteriorly tapered bodies about 6 mm long. They have ridged and roughened wings with patches of lighter brown or grey scales.[11,17,32]

In their native range in the northern hemisphere, most species of *Pissodes* emerge in autumn (from late August to October). After emergence, adults feed for a while, disperse, and when temperatures drop and the photoperiod shortens, they hibernate in the duff. Early in spring (late March, April), adults fly or crawl to terminal leaders of host trees and begin feeding and mating. Oviposition starts soon afterwards. Larval stages are found in early summer (early June to early July) and by midsummer pupation occurs. Depending on local climatic conditions, there are variations of this life cycle. In colder conditions, such as the north coast of Canada, or at higher elevations in the British Columbia interior and Rocky Mountains, a proportion of the population may overwinter as pupae, as teneral adults and possibly as mature larvae.[2,32,33]

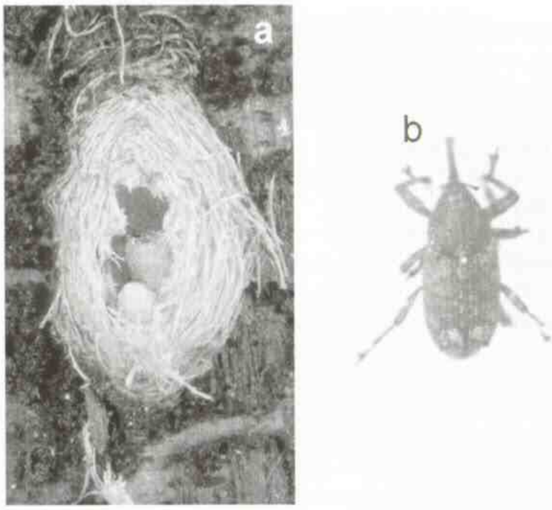

Fig. 1. Larval (**a**) and adult (**b**) stages of *Pissodes nemorensis* in South Africa. Adults reach a size of 6–8 mm.

After emergence during April and May in North America, *P. nemorensis* adults feed briefly on the inner bark of nearby trees, sometimes girdling stems and twigs, before dispersing for the summer. Adults feed occasionally during the summer. Feeding activity increases just prior to and during the autumn reproductive period. Females lay from one to four eggs in feeding punctures. The newly hatched larvae bore into the inner bark, where they construct winding galleries, which may girdle the stem. Pupation occurs during March and April. There is one generation per year.[22]

In South Africa, larval stages are found mainly during the summer months (December to February), and pupae in March and April. Adults emerge in winter (June to August) and start feeding soon after emergence. Oviposition begins a few weeks after emergence, which continues through to November. There is only one generation per year, but slight overlapping of generations is evident with, for example, larval, pupal and adult stages found in early winter (pers. obs.).

Control

Silvicultural control

Management of *Pissodes* populations by stand manipulation has long been recognized as a viable control method.[43] The objective is to modify the stand microclimate to make it unsuitable for successful weevil attack or survival. It has been demonstrated that lower rates of weevil damage occurred in spruce under a broadleaf overstorey than in the open.[44–46] Dense stands and shaded habitats are unfavourable for weevil development.[18] The low temperatures prevailing in dense, shaded stands restrict feeding and oviposition. Experiments conducted at the University of British Columbia showed that weevils move around very little in shaded pine stands, as shade has a negative effect on the weevil's visual response to attractive pine leaders.[45,47]

Sanitation of plantations, by removing fallen branches, especially clearing of slash, reduces pest populations and consequently diminshes their impact on trees. Bellocq and Smith[48] found an inverse relationship between weevil mortality and the depth of the litter on the forest floor. For these reasons, sanitation and the curtailment of sawlog storage around clear-felled and replanted compartments has been prescribed for the management of all pine-infesting cambiophagous insects in South Africa, including *P. nemorensis.*[49–51] Other silvicultural management practices in South Africa that are already in place, such as species–site matching, also play significant roles in reducing pine weevil damage. This is because species planted on inappropriate sites are more likely to be stressed, and thus more attractive to *P. nemorensis*.

Host resistance

Host resistance has shown great promise for *Pissodes* management in the northern hemisphere. In eastern North America several studies have demonstrated variation in susceptibility or resistance to *P. strobi* in eastern white pine (*Pinus strobus*). Different species and populations of some *Pinus* species, as well as their hybrids, show considerable genetic variation in susceptibility to *Pissodes*.[52] A principal mechanism of resistance is by producing resins. Boucher *et al.* found a significant negative correlation between tree resin, canal density and adult weevil mass.[53] They observed that trees characterized by a low density of resin canals, such as white pine, favour the development of heavier adult weevils. This suggests that a high density of resin canals constrains larval feeding, which results in lower adult weevil mass.

Pines planted in South Africa are exotic and genetic diversity is limited, compared to regions where these trees are native. However, there is considerable variation in terms of disease and pest resistance among the locally grown pine species. *Pinus elliottii* is generally more resistant to many of the known pests and diseases in South Africa.[30,49,50,54] It is also more resinous than the other pine species, and damage due to *P. nemorensis* is likely to be less than that on, for example, *P. patula*. Furthermore, *P. elliottii* is moderately resistant to infection by the pitch canker fungus and this is cause for some optimism.

Pissodes nemorensis has been found to be widely distributed and to attack all of the commercially grown pine species in South Africa. However, it is more prevalent in the Cape, where the dominant pine species is *P. radiata*. Whether higher levels of damage are due to differences in species planted or the environment or a combination of these factors is yet to be established. To be able to select for a significant level of genetic resistance to *P. nemorensis*, it may be necessary to introduce *Pissodes*-resistant *Pinus* species from centres of diversity of these trees and to incorporate them into existing tree-breeding programmes. This option is obviously long term.

Biological control

Few parasitoids and predators attack *Pissodes* in Europe and North America.[55,56] *Allodorus crassigaster* (Hymenoptera: Braconidae) has shown some potential for limiting the population of *P. strobi*. It is an egg–larval parasite, and has been found to parasitize a number of *Pissodes* species besides *P. strobi*. This parasitoid is native to North America, where it is distributed throughout the range of *Pissodes* secies.[57]

Allodorus crassigaster has some useful attributes that could be exploited for biological control. It appears to have good searching ability. Its fecundity is high and one female can parasitize many hundreds of *Pissodes* eggs. Its host range is restricted to *Pissodes* species. These attributes are not shared by any of the other parasitoids found to attack *Pissodes*. The other parasitoids prey on insects besides *Pissodes*, thus potentially interfering with the effect of any release on the target population.[57] Research on *A. crassigaster* is continuing in Canada, but it has not yet been released in the field. This parasite is the prime candidate for evaluation in quarantine in South Africa for biological control of *P. nemorensis*.

In South Africa, *P. nemorensis* has not yet reached outbreak levels, despite its detection over 60 years ago.[51] This could be due to control by natural enemies that restrict population build-up to outbreak levels. This subject clearly deserves study. Recently, two groups of insect parasitoid were found, by researchers of the Forestry and Agricultural Biotechnology Institute at the University of Pretoria, to kill *P. nemorensis* in the field. The one group belongs to the order Diptera, family Stratiomyidae, genus *Gobertina*. The second group belongs to the order Hymenoptera, family Pteromalidae and genus *Pycnetron*. *Gobertina* species have not been reported as having associations with *Pissodes* in the past, but *Pycnetron* species have been reported as parasitizing *P. nemorensis* in the Phillipines (G.L. Prinsloo, ARC-Plant Protection Research Institute, pers. comm.). Both parasites were found emerging from the pupal chambers, suggesting that they colonize larvae or pupae. Further studies are being conducted on these natural control agents for their potential against *P. nemorensis*.

Chemical control

Insecticides can be an effective pest management tool. However, the use of conventional contact insecticides in forest plantations is restricted to small (<10 ha), high-value plantations, such as seed orchards, and genetic tests. Insecticides could also be used in plantations where silvicultural, genetic and biological methods are impractical or provide inadequate levels of control.[19] However, plantation certification by bodies such as the Forestry Stewardship Council will most probably preclude the use of chemical control in South African plantations.

In Canada, pyrethroid insecticides, particularly permethrin and methoxychlor, resulted in acceptable control of *P. strobi*.[58] Synthetic pyrethroids are a group of insecticides that are less toxic to humans than organophosphates. They are also generally less persistent environmental pollutants than organochlorines, but are very destructive to the biological control and natural control of pests. Experimental systemic insecticide injections of trees have achieved three years of control in Canada.[59] Because only individual trees are injected, any harmful effects of pesticides on non-target organisms are minimized. Work is continuing in Canada to develop systemic insecticide injection formulations of longer duration and higher efficacy. This method of selective chemical insecticide deployment could form part of an integrated pest management system, although the intensive nature of plantation forestry might preclude this approach.[34]

The use of insect growth regulators (IGRs) is another option for weevil control. These chemicals disrupt moulting and have a sterilizing effect.[60] Dimilin has been found to be effective in reducing damage due to *P. strobi* attack in Canada.[61] IGRs strongly disrupt natural control and biocontrol of a range of forestry pests, by killing the beneficial insect more effectively than the pests. Given that many potential pests in South African forestry are indigenous insects, normally held under good natural control, IGRs should be avoided. Furthermore, IGRs are biologically potent at minute concentrations, and their drift onto crops and natural ecosystems many kilometres away kills aquatic arthropods in streams, interfering with their ecology.

The chemical control of *P. nemorensis* has not been implemented in South Africa. This is mainly because the damage levels on pines have not been quantified, and the use of insecticides would be uneconomical and ecologically disruptive. Nevertheless, Kirsten *et al.* reported that *P. nemorensis* is an important pest of *P. radiata* in the Cape, and that knapsack sprays of pyrethroid insecticides on young *P. radiata* have shown promise.[54] It is desirable to extend such tests to include all the commercially grown pine species and several pyrethroid insecticides. This will make it possible to establish a database of insecticide options for possible use in specific, restricted situations.[62]

Integrated pest management

Integrated pest management (IPM) is a widely accepted approach to the control of forestry pests. It involves a formulated combination of separate but compatible control options. The integrated measures aim to reduce pest damage to economically acceptable levels. The adoption of such methods to control high status pests will be important for the sustainability of commercial plantations in the future in South Africa.

Effective IPM requires accurate estimates of the potential damage that has to be curtailed, so that the necessary management steps can be prescribed. In forestry, the importance of an infestation depends on the extent to which the management objectives will be affected. Expected damage to a plantation must be calculated and projected to the time of harvest. A particular management policy will be beneficial only if its addition to an IPM programme is cost-effective and significantly increases the possibilities of attaining the management target.[34,63]

Future prospects

Pissodes nemorensis is clearly causing significant damage to South African pine plantations. To reduce its impact, it will be necessary to gain an increased understanding of the pest. One of the areas that requires careful study is the taxonomy of *Pissodes* in South Africa. Although the *Pissodes* species that infests South African pines is believed to be *P. nemorensis*, this identification was based on samples collected when the insect was first detected in plantations in the southern Cape. Currently, it is not clear whether it is the same species that occurs throughout South Africa or whether there have also been introductions of other, morphologically similar species. The taxonomy of these populations needs to be confirmed, based on samples collected from all areas of occurrence in the country, using morphological identification and DNA-based techniques.

One area of investigation that demands urgent attention is the possible interaction between *P. nemorensis* and the pitch canker fungus. *Pissodes nemorensis* is known to be associated with this pathogen in its native range. Since both the weevil and the fungus occur in South Africa, there is clearly a need to understand the dynamics of the local interaction between these organisms. The current lack of understanding of this interaction, as well as other aspects of the biology and control of *P. nemorensis* leaves the South African forestry industry in a vulnerable position. Concerns about *Pissodes* acting as vector of pitch canker also raise questions about the wisdom of selecting *P. validirostris*, rather than other cone-feeding insects, as a potential agent for biological control of the weed *Pinus pinaster* in South Africa.

An effective pest management strategy will be based on a thorough understanding of the biology and population dynamics of the pest. The biology and phenology of *P. nemorensis* in South Africa is different from that in its area of origin. For example, most species of *Pissodes*, including *P. nemorensis*, are known to overwinter as adults in North America,[19,43] but adult activity is at its peak in the winter months in South Africa (pers. obs.). Furthermore, variation in the phenology of *P. nemorensis* is evident in the different provinces of South Africa. For example, in the Western Cape, adult stages emerge from cocoons only in winter months, whereas in Limpopo and Mpumalanga adults have been seen to emerge in March. Thus, more information is needed on the similarities and differences in the biology and population characteristics of the pest, in the different pine-growing regions of South Africa.

The future management of *P. nemorensis* needs to include various control options that can be applied under South African forestry conditions. Silvicultural control measures can be combined with existing tree-growing practices. Host resistance can offer a longer-term means of pest management. Selected insecticides should be tested for their efficacy against the weevil, for possible use in times of outbreaks and in seed orchards or other small areas of high-value trees. Biocontrol agents to combat *P. nemorensis* should be actively sought. Preliminary studies have shown that some parasitoids that attack *P. nemorensis* are already present in South Africa. Research is under way to determine the life stages of the weevil infested by these parasites and to understand their biology, phenology, host specificity and efficacy. If the results of these studies prove promising, a next step could be to develop techniques for mass-rearing of the parasites for release in the field. Priority should be given to introducing a potent natural enemy such as *A. crassigaster*, from North America, to suppress *P. nemorensis* permanently in South Africa by means of cost-effective, environmentally benign, classical biological control.

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The Working for Water Programme: scientific challenges in the field of invasive alien plant management

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