

# Habitat manipulation to mitigate the impacts of invasive arthropod pests

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**Abstract** Exotic invaders are some of the most serious insect pests of agricultural crops around the globe. Increasingly, the structure of landscape and habitat is recognized as having a major influence on both insect pests and their natural enemies. Habitat manipulation that aims at conserving natural enemies can potentially contribute to safer and more effective control of invasive pests. In this paper, we review habitat management experiments, published during the last 10 years, which have aimed to improve biological control of invasive pests. We then discuss during what conditions habitat management to conserve natural enemies is likely to be effective and how the likelihood of success of such methods can be

improved. We finally suggest an ecologically driven research agenda for habitat management programmes.

**Keywords** Conservation biological control · Ecosystem services · Habitat management · Pest management

## Introduction

Exotic invaders are some of the most serious arthropod pests in agricultural landscapes. In the USA, for example, introduced arthropod pests have been estimated to cause losses worth around \$20 billion each year (Pimentel et al. 2005). For many of these invasive pests, chemical pesticides are still the dominant form of control, contributing to additional costs in the form of degraded environmental and human health (Mack et al. 2000; Paoletti and Pimentel 2000). Classical biological control, i.e. the intentional introduction of exotic natural enemies, has had some spectacular successes in controlling invasive pests (Zeddies et al. 2001; Menzler-Hokkanen 2006), but only about 10% of all introductions have contributed to management of the targeted arthropod pests (Greathead and Greathead 1992; Gurr and Wratten 2000). It has been suggested that low availability of key resources for natural enemies, such as alternative food and overwintering sites, in many agroecosystems is one reason limiting biological control effectiveness (Gurr and Wratten 1999).

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Support for this hypothesis comes from various studies showing that density and diversity of natural enemies tend to be higher in landscapes with a high proportion of non-crop vegetation (see Bianchi et al. 2006 for a review). Habitat management can be used to provide natural enemies with resources that can be limiting in agroecosystems (Barbosa 1998; Pickett and Bugg 1998; Landis et al. 2000; Gurr et al. 2004; Jonsson et al. 2008). This approach can lead to improved biological control, but it often requires in-depth knowledge of the natural enemies and the most appropriate, selective resources to deploy. In this paper we discuss how habitat management can be used to conserve natural enemies of invasive pests. We first give a general introduction to habitat management and review how successful this approach has been to improve biological control of invasive pests to date. We then discuss under what circumstances different types of habitat management are likely to be effective, and how the likelihood of success can be improved. Based on this, we finally propose an ecologically driven research agenda to inform development of habitat management programmes for invasive pests.

### Habitat management and biological control

The potential for pest management through habitat manipulation has long been recognised. Elton (1958) and Pimentel (1961) suggested that outbreaks of pest insects are less likely in diverse crop situations than in monocultures. Root (1973) found that pest populations were lower in polycultures of collard (kale) and meadow vegetation compared to collard monocultures. He identified two potential mechanisms behind such patterns: the ‘resource concentration’ hypothesis where specialist herbivores are less likely to find and remain on host plants within a polyculture and the ‘enemies’ hypothesis where natural enemies are more effective in diverse crop environments (Root 1973). We concentrate this review on effects relating to the ‘enemies’ hypothesis.

The ‘enemies’ hypothesis implies that habitat management can be used to conserve and enhance natural enemies (Pickett and Bugg 1998; Landis et al. 2000). This type of conservation biological control can provide natural enemies with a favourable microclimate, shelter, hibernation sites and alternative

food sources, such as nectar, pollen and alternative prey (Landis et al. 2000). One of the most well-known habitat management techniques to conserve natural enemies is the provision of beetle banks. These are usually grass covered earth banks located in the middle of a field (Thomas et al. 1991, 1992). These banks can provide overwintering sites for ground living predatory beetles in the families Carabidae and Staphylinidae and for spiders and this can increase their density (Thomas et al. 1991, 1992) and diversity (MacLeod et al. 2004). Predation has been found to increase close to beetle banks (Collins et al. 2002), but this effect is not universal (Prasad and Snyder 2006). Other ecological advantages of the banks are that relatively rare European farmland bird and mammal species nest on, and hunt along them (Thomas et al. 2001).

Another well-known type of habitat management to conserve natural enemies is the sowing of flower strips to provide nectar and pollen as food sources for natural enemies (Piffner and Wyss 2004; Gurr et al. 2005; Heimpel and Jervis 2005). One example where this approach has been successful is in the control of the light-brown apple moth (*Epiphyas postvittana* (Walker)), an invasive leafroller (Lepidoptera: Tortricidae) in New Zealand. This species, which originated from Australia (Danthanarayana 1975), is considered one of the most important pests on grapes, apples and other horticultural crops in New Zealand, especially on the South Island (Scott 1984). Availability of flowering buckwheat (*Fagopyrum esculentum* Moench) (Scarratt 2005) and alyssum (*Lobularia maritima* (L.)) (Berndt and Wratten 2005) can increase fecundity and longevity and increase the proportion of female offspring of *Dolichogenidea tasmanica* Cameron, a key parasitoid of the leafrollers. Parasitism rates and leafroller densities have been shown to increase and decrease, respectively, in vineyards close to buckwheat and alyssum (Scarratt 2005; Irvin et al. 2006), although increased parasitism rates and/or decreased pest densities has not been achieved in all trials (Berndt et al. 2002; Berndt et al. 2006). Recent unpublished data indicate that leafroller densities can in some cases be reduced to below the economic threshold when flowering buckwheat is available. Provision of buckwheat has now been adopted as a measure to control leafrollers in vineyards in all major wine regions of New Zealand (Fig. 1).



**Fig. 1** Buckwheat, *Fagopyrum esculentum*, in a New Zealand vineyard to enhance biological control of leafrollers

#### ‘Success’ of habitat management trials

Several reviews have been published on the ‘success rate’ of habitat management trials. Andow (1991) found that polyculture led to decreased insect pest densities in 52% of studies compared with 15% of such studies where pest densities were higher in polycultures. Many of these studies did not distinguish between the ‘resource concentration’ and the ‘enemies’ hypothesis, but based on indirect evidence it was suggested that positive processes related to the former are more common (Andow 1991). Thus, although we here concentrate on effects mediated by natural enemies, it must be acknowledged that effects relating to the ‘resource concentration’ hypothesis can be significant.

Gurr et al. (2000) reviewed studies of habitat management for conservation biological control published during the 1990s and found that 19/22 studies reported positive effects on natural enemy populations while 15/22 showed lower pest densities. Of these, only 4/8 showed positive effects on the yield or quality of the crop. More recently, Heimpel and Jervis (2005) reviewed evidence that floral nectar improves biological control by parasitoids. In 7/20 of the reviewed studies, parasitism rates increased with floral nectar sources available, but in only one study was a concomitant decrease in pest density recorded.

We conducted a similar analysis of habitat management experiments published between 1998 and 2007 aimed at improving biological control of invasive pests. We considered only peer-reviewed journal articles presenting results from open field trials where

the effect of habitat manipulation on invasive pests was studied either through assessment of parasitism or predation rates and/or of pest population densities. Studies that did not estimate these rates were considered only if the effects on both natural enemy and pest densities were measured. We found 15 studies fulfilling these criteria (Table 1). Fourteen of the 15 papers reported at least some positive effects of habitat manipulation on either population densities of natural enemies or on predation or parasitism rates, whereas one study found that habitat manipulation decreased predation rates. The latter occurred probably because *Harmonia axyridis* Pallas (Coleoptera: Coccinellidae), a key predator of the rosy apple aphid, *Dysaphis plantaginea* (Passerini), was feeding on extrafloral nectaries on peach trees instead of the pest (Spellman et al. 2006; Brown and Mathews 2007). In 4/7 studies, pest densities decreased following habitat manipulation and in one the pest population increased close to the flower strips that were provided, probably because the pest itself was attracted to and feeding from the flowers (Baggen and Gurr 1998; Baggen et al. 1999). In one of the studies that found a negative effect of habitat management on pest populations the effect on predation rate was also negative (Brown and Mathews 2007). It was suggested that the mechanism behind decreasing pest populations in this case was related to the resource concentration hypothesis (Root 1973) rather than through improved biological control. Three of the 15 studies considered effects on either crop damage or yield, but none of these studies reported beneficial effects. Baggen and Gurr (1998) reported increased pest damage close to certain floral subsidies probably because the pest was exploiting those floral resources, whereas Schmidt et al. (2007) found that alfalfa grown as a cover crop decreased crop yield in soybean most likely because the alfalfa competed with the crop. The latter was the only study that considered economic consequences of habitat management and it concluded that it was not cost effective (Schmidt et al. 2007).

#### When is habitat management likely to be successful?

Here we discuss factors that are likely to affect the outcome of habitat management experiments, and that can help explain the mixed effectiveness of such

**Table 1** Analysis of habitat manipulation studies to conserve natural enemies of invasive pests published between 1998 and 2007

Study	Enemy population	Predation/ parasitism rate	Pest population	Pest damage	Crop yield	Economic assessment	Source
EFN bearing peach trees in apple	NA	–	+	NA	NA	NA	Brown and Mathews (2007)
Alfalfa as a cover crop in soybean	+	NA	+	NA	–	–	Schmidt et al. (2007)
Floral subsidies in vines	NA	+	0	NA	NA	NA	Berndt et al. (2006)
Floral subsidies in apple	NA	+	+	0	NA	NA	Irvin et al. (2006)
Beetle banks in mixed vegetables	+	0	NA	NA	NA	NA	Prasad and Snyder (2006)
Floral subsidies in ornamental plants	NA	0/+	0/+	NA	NA	NA	Rebek et al. (2006)
Floral subsidies in broccoli	NA	+	NA	NA	NA	NA	Lavandero et al. (2005)
Floral subsidies in cabbage	NA	0/+	0	NA	NA	NA	Lee and Heimpel (2005)
Floral subsidies in turf grass	NA	+	NA	NA	NA	NA	Rogers and Potter (2004)
Floral subsidies in wheat	NA	+	NA	NA	NA	NA	Tylianakis et al. (2004)
Floral subsidies in vines	+	0	NA	NA	NA	NA	Berndt et al. (2002)
Floral subsidies in turf grass	0/+	0	NA	NA	NA	NA	Braman et al. (2002)
'Refuge' crop strips in alfalfa	0	+	NA	NA	NA	NA	Hossain et al. (2002)
Floral subsidies in potato	NA	+	–	–	NA	NA	Baggen and Gurr (1998)
Floral subsidies in vines	+	+	NA	NA	NA	NA	Stephens et al. (1998)

A '+' denotes a beneficial effect from a pest management point of view, '–' a deleterious effect, '0' a non-significant effect and 'NA' that it was not studied. Thus, for example, a '+' in the respective columns refers to an increase in enemy populations, predation/ parasitism rates, crop yield and economic profit, and a decrease in pest populations and pest damage

trials to date. Success of habitat management is likely to depend both on the composition of the local food web and the extent to which suitable and limiting resources are provided that target the right natural enemies.

#### Selecting target species

A first prerequisite for habitat management to improve biological control is that potentially effective natural enemies are available in the food web of the targeted herbivore. Invasive species may frequently lack specialist natural enemies and this may require introductions of the latter through classical biological control programmes. Although habitat manipulation was initially developed to support

native natural enemies, this approach can be useful for conserving introduced natural enemies as well (Gurr and Wratten 1999).

A continuing discussion relates to whether one or multiple natural enemies are needed for effective biological control. In many cases success of classical biological control programmes has been attributed to single species, even if multiple species have been introduced (Denoth et al. 2002). However, experiments explicitly studying the relationship between natural enemy diversity and biological control suggest that this relationship is highly idiosyncratic (Straub et al. 2008). One way that increasing natural enemy diversity may positively affect biological control is through the 'sampling' effect. This implies that with increasing diversity in a natural enemy

community it is more likely that particularly effective species are present. Thus, the ‘sampling’ effect is not an effect of diversity per se but relies on species’ identity and properties. Several studies have shown that species identity is an important factor in prey suppression (Schmitz and Suttle 2001; Chalcraft and Reserits 2003; Straub and Snyder 2006). Cardinale et al. (2006) argued that the ‘sampling’ effect is often a main driver of diversity—ecosystem function relationships. If the only benefit from increasing natural enemy diversity for biological control is that the most effective natural enemy is more likely to be present, then it may be most efficient to identify that species by experiment and then target it in habitat management measures (Snyder et al. 2006).

Several studies have found a positive relationship between natural enemy diversity per se and biological control (Aquilino et al. 2005; Snyder et al. 2006; Straub and Snyder 2008). Such effects can occur when the feeding niches of different natural enemy species complement each other. Two mechanisms that can lead to niche complementarity are resource partitioning and facilitation. Resource partitioning occurs, for example, when different natural enemy species forage on different parts of a plant (Straub and Snyder 2008), when they attack different life stages of the pest (Wilby and Thomas 2002) or feed on different pest species (Finke and Snyder 2008). Facilitation implies that the presence of one natural enemy species facilitates feeding by another species. Losey and Denno (1998) studied consumption of pea aphids, *Acyrtosiphon pisum* Harris, by one foliage living and one ground living predator and found that aphid consumption was the highest when both predator species were present. In the presence of the foliage living predator aphids dropped off the plant and became accessible for predation by the ground living predator. If niche complementarity is important in a natural enemy community, it may be most effective to target functionally complementary species of natural enemies in habitat management measures. This can be done, for example, by supplying a combination of resources that benefit ground living and foliage living natural enemies. Frank and Shrewsbury (2004) combined beetle banks and flower strips to support ground living and foliage living natural enemies and found a positive effect on predation rates of turf grass pests on golf course fairways. However, this study did not compare the combined

effect of flower strips and beetle banks with the effect of these two measures separately, so it could not be concluded whether combining the two measures created a stronger effect on biological control.

In some cases increasing natural enemy diversity may have a negative effect on biological control because of intra-guild predation or inter-specific interference (Rosenheim et al. 1993; Finke and Denno 2004, 2005; Costamagna et al. 2008). Prasad and Snyder (2006) evaluated the effect of beetle banks in vegetable crops in NW USA and SW Canada. It was found that beetle banks provided through the winter increased the density of predatory beetles in the field during the following crop season, but predation rate of sentinel fly eggs in the crop was unaffected. Further experimentation suggested that intra-guild predation by a large predatory beetle was partly responsible for this lack of effect on predation rate. Thus, if intra-guild predation is strong, habitat management may not improve biological control, although it conserves individual natural enemies. However, habitat manipulation may in some cases decrease the intensity of intra-guild predation. Finke and Denno (2006) showed that by adding structural diversity in the form of thatch to a salt marsh food web, intra-guild predation decreased and predation on a plant hopper herbivore increased. The mechanism was that thatch provided a refuge from intra-guild predation for a predatory mirid bug. The potential for habitat management to decrease negative interactions among natural enemies in crop systems has not been studied.

The local species pool of natural enemies in the crop is partly dependent on the composition of the landscape surrounding the field. Fields located in complex landscapes with a low proportion of annual crops and a high diversity of other vegetation types tend to have a higher diversity of natural enemies than do fields in simpler landscapes dominated by agriculture (Öberg et al. 2007; Schmidt et al. 2008; Gardiner et al. 2009a). Landscape structure may particularly affect beta diversity, i.e. the difference in species composition among sites (Tscharrntke et al. 2008). A high beta diversity may be important as an insurance against fluctuating environmental conditions (insurance hypothesis; Yachi and Loreau 1999; Tscharrntke et al. 2008). If different natural enemy species are effective during different environmental conditions, seemingly redundant species may become important in reducing pest populations in certain situations. The

effect of the insurance hypothesis on biological control has not been rigorously tested, however (Tscharntke et al. 2008).

### Selecting resources to provide

To be successful, habitat management should provide natural enemies with suitable resources that are limiting for these species and that do not invoke unwanted side effects. A convenient way of screening large numbers of food plants is to study visitation rates of natural enemies in the field (Fiedler and Landis 2007a, b). This method can give information about attractiveness of food plants, which is an important factor to consider when selecting which plant species to provide for biological control (Kean et al. 2003; Bianchi and Wäckers 2008). However, flower attractiveness is not strictly related to other floral attributes such as nectar accessibility (Wäckers 2004), so additional experiments are needed to fully evaluate the suitability of flowering plants for natural enemies. Laboratory studies can be used to assess the suitability of food plants by studying how they affect various natural enemy traits including longevity and fecundity (Baggen and Gurr 1998; Tylianakis et al. 2004; Robinson et al. 2008), sex-ratio (Berndt and Wratten 2005) and dispersal ability (Wanner et al. 2006) that are all likely to influence natural enemy efficacy. However, laboratory trials are not enough to predict how resource provision will affect natural enemies in the field. Unequivocal evidence that resources such as nectar and shelter are limiting for natural enemies in agroecosystems is rare. However, Lee and Heimpel (2008) showed that nectar feeding on floral resource subsidies by the parasitoid *Dia-degma insulare* (Cresson) in the field can lead to increased gut content of sugars and improved longevity and fecundity. This study thus provided unique evidence that parasitoids can be sugar limited in the field and that provision of floral resource subsidies can help remedy this.

The extent to which certain resources are limiting for natural enemies will depend on what is available within the crop (extrafloral nectaries, honeydew, flowering weeds, alternative prey etc.), but also on the composition of the landscape surrounding the field. Thies and Tscharntke (1999) found higher parasitism rates on rape pollen beetles close to the field edge compared to in the centre in structurally

simple landscapes dominated by agriculture but no such effect was found in complex landscapes. It has also been shown that conversion to organic farming has the largest effect on spider density in wheat fields in simple landscapes (Schmidt et al. 2005). Both these studies suggest that resource availability in the surrounding landscape is likely to influence the effectiveness of local schemes to conserve natural enemies.

### Avoiding negative side effects

The provision of resources through habitat management can in some cases decrease natural enemy attack rates on the pest although the resource is suitable for the targeted natural enemy. For predators that are true omnivores, i.e. they feed on prey and plant-provided resources in one life stage, decreased predation rates may occur because the predator becomes satiated through feeding on plant resources. Provision of nectar and pollen can decrease the predation rate by ladybeetles (Spellman et al. 2006; Brown and Mathews 2007), predatory mites (Wei and Walde 1997) and brown lacewings (Robinson et al. 2008). In a similar way, presence of alternative prey for generalist predators may in some cases decrease predation rates on the target pest (Prasad and Snyder 2006). The impact of plant resources and alternative prey on true omnivores and generalist predators, respectively is likely to depend on how different resources are distributed in time and space (van Rijn and Sabelis 2005). For such natural enemies, availability of alternative food resources may improve biological control primarily when the target pest is scarce (Polis and Strong 1996; Eubanks and Styrsky 2005; Jonsson et al. 2009).

Unwanted side effects of habitat manipulation may also occur if the resources provided benefit the pest itself (Baggen et al. 1999; Begum et al. 2006; Lavandero et al. 2006) or antagonists of natural enemies of the pest (Araj et al. 2008, 2009). Jonsson et al. (2009) studied the effect of flowering buckwheat on four trophic levels, including alfalfa, pea aphids (*A. pisum*), the omnivorous lacewing *Micromus tasmaniae* Walker and the lacewing parasitoid *Anacharis zealandica* Ashmead. *M. tasmaniae* is a true omnivore that feeds on floral nectar and aphids in its adult life stage whereas *A. zealandica* is a life-history omnivore that feeds only on sugar-rich resources such as nectar as an adult and parasitizes lacewings as larvae.

Laboratory trials showed that fecundity and longevity of *M. tasmaniae* is positively affected by floral availability mainly when aphid availability is low (Robinson et al. 2008; Jonsson et al. 2009). In a field cage experiment, provision of flowering buckwheat decreased lacewing densities when aphid availability was high, probably because buckwheat primarily benefits the lacewing parasitoid during such conditions (Jonsson et al. 2009). One way to decrease the risk for this type of unwanted side effects is to search for food plants that selectively benefit natural enemies of the pest but not the pest itself or key antagonists (Baggen et al. 1999; Begum et al. 2006; Lavandero et al. 2006; Araj et al. 2008).

#### Towards informed landscape management

Habitat management experiments have to date mostly been conducted at a local semi-field or field scale. However, natural enemy fecundity (Bommarco 1998), density (Schmidt et al. 2005) and species diversity (Öberg et al. 2007; Schmidt et al. 2008) as well as parasitism (Thies and Tscharrntke 1999; Thies et al. 2005; Bianchi et al. 2008) and predation rates (Gardiner et al. 2009a) of pests are often strongly influenced by landscape composition, suggesting that it is important to consider large-scale dynamics for habitat management (Bianchi et al. 2006; Tscharrntke et al. 2008). Landscape management might be especially important if effective biological control depends on a high diversity of natural enemies (Tscharrntke et al. 2008). Local management may increase the density of a few common species whereas species richness often depends more on landscape composition (Roschewitz et al. 2005; Schmidt et al. 2005; Schmidt et al. 2008). The spatial scale to consider for management should ideally depend on the dispersal abilities of the targeted natural enemies. Marked natural enemies have been recaptured at distances around 100 m away from the refuges where they were marked (Corbett and Rosenheim 1996; Schellhorn et al. 2008) but many natural enemies are likely to move much longer distances. Corbett and Rosenheim (1996) found that between 55 and 100% of *Anagrus* parasitoids colonising vines in spring had overwintered outside the vineyards, probably in riparian habitats that were located 200 m–10 km away. Several studies correlating landscape composition with parasitism rates of pests have found the strongest effect of landscape structure at

around 1 km diameter around the crop (Thies et al. 2003, 2005; Bianchi et al. 2008), suggesting that dispersal over such distances is common for many parasitoids. Some predators readily move over larger distances; the density of ballooning spiders, for example, correlates strongly with landscape composition at 3 km diameter around the crop (Schmidt et al. 2008). However, the landscape features of importance for natural enemies depend on the biology of individual species. The availability of certain habitat types such as meadows (Kruess and Tscharrntke 1994), forests (Bianchi et al. 2008) and riparian habitats (Corbett and Rosenheim 1996) have all been identified as important for certain natural enemies. Some of these species may also benefit from a high availability of particular crops in the landscape. Gardiner et al. (2009b) found that the ladybeetle *Hippodamia convergens* Guérin-Mèneville was more common in landscapes with a high proportion of corn and soybean crops in mid-western USA.

Achieving landscape management will generally require coordinated adoption of habitat management techniques by a group of farmers in an area. Although large-scale adoption of such methods is still very rare globally (Cullen et al. 2008; Griffiths et al. 2008), notable exceptions do exist. Partnerships where farmer groups together trial and adopt agroecological methods at a large scale have recently emerged in different parts of the world, including California, New Zealand and The Netherlands (Warner 2007; Cullen et al. 2008). These partnerships often aim at improving multiple ecosystem services, such as soil retention, weed suppression and biological control by deploying non-crop plants (Cullen et al. 2008) and this is probably one important reason for their success (Fiedler et al. 2008). The ‘Greening Waipara’ project in the Waipara Valley, in New Zealand, is one such initiative, where to date 46 properties, mostly wineries, work together with researchers at Lincoln University and Landcare Research, New Zealand in an effort to restore native biodiversity to a region currently dominated by intensive agriculture and exotic vegetation (Fiedler et al. 2008; Tompkins 2009; Fig. 2). This project began when studies showed that biological control of the light-brown apple moth can be improved if the non-native plant species buckwheat, alyssum and phacelia (*Phacelia tanacetifolia* Benth.) are drilled between the rows of vines. This led to attempts to find native plants that can have a similar effect (Tompkins



**Fig. 2** Planting of native plant species in a vineyard in the Waipara valley, New Zealand

2009) and a focus on how native plants can provide ecosystem services other than biological control and contribute to conservation (Fiedler et al. 2008). Current research projects at Lincoln University explore how the landscape management conducted within the ‘Greening Waipara’ project affects populations of a range of vineyard pests including grass grubs *Costelytra zealandica* (White), the New Zealand flower thrips, *Thrips obscuratus* (Crawford) and leafrollers and their natural enemies.

## Conclusions and prospects

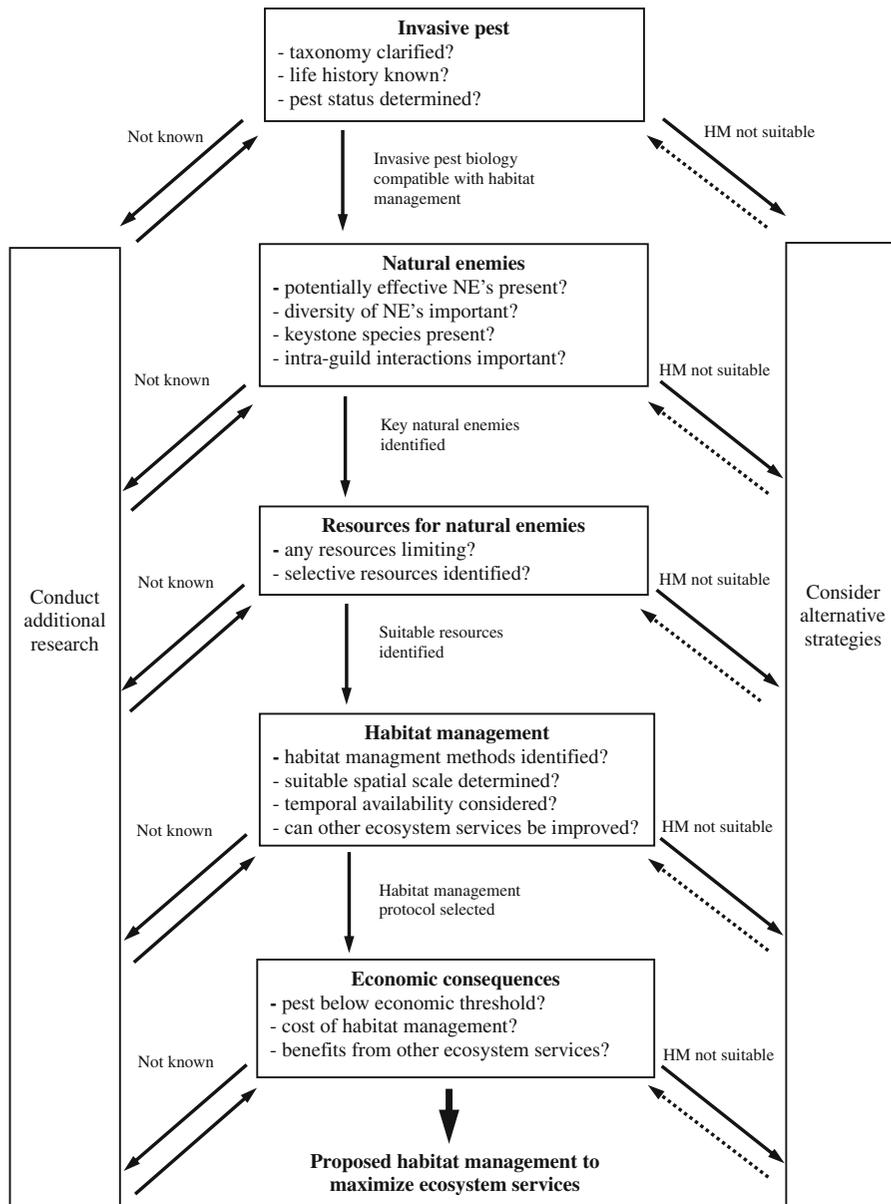
Habitat manipulation experiments have repeatedly demonstrated positive effects on natural enemy populations and/or on parasitism and predation rates but effects on invasive pest populations have been more varied. Few studies have considered effects on crop damage, yield or quality and assessments of the economic consequences of habitat management for growers are extremely rare (Cullen et al. 2008). We strongly recommend that such effects are studied more often in the future. Careful ecological economic research conducted at sufficiently large number of sites is needed for development of general management principles for control of invasive species (Leung et al. 2005). This requires integration of ecology and economics to determine optimal responses to invasive species (Shogren and Tschirhart 2005; Ranjan et al. 2008) and consideration of the complexity and

uncertainty involved with estimating the costs and benefits of invasive species (Leung et al. 2005).

Our review suggests an ecologically driven research agenda to inform development of habitat management programmes for invasive arthropods (Fig. 3). As soon as a target invasive is identified there are a number of key pieces of information that need to be collected. These include clarification of the invader’s taxonomic status and elucidation of its life history in the new range. Typically there will also be studies conducted to determine its current and potential future pest status. As part of these initial investigations it is critical to determine if a community of existing natural enemies is utilizing this new resource. In many cases, any such community will likely be dominated by generalist natural enemies. If no potentially effective natural enemies are found, it would either suggest that the species may be a candidate for importation (i.e. classical) biological control. Alternatively, aspects of the invaders life history or pest status may suggest it is unlikely to be amenable to biological control of any sort, and alternative or complementary management strategies should be pursued.

If potentially effective natural enemies are found to exist, next steps include determining existing natural enemy guilds and food web structure. These may be compared to those in the invader’s native range for clues as to critical missing species, guilds or food web linkages. Intra-guild interactions can be very important in determining the success of any biocontrol effort and need to be examined, as well as determining if keystone species exist in the system (Griffiths et al. 2008; Straub et al. 2008). Again, depending on the results of such studies, importation programmes or alternative strategies may be initiated.

Once key natural enemies are identified, it is necessary to determine if single or multiple species are likely to be most effective and if these species are potentially limited by a lack of critical resources or by particular species interactions. If resource limitation occurs, can selective resources be identified, as well as when, at what spatial scale should they be provided? For practical reasons, many of these studies may be conducted at small spatial scales, i.e. within field cages or small plot experiments. However, for habitat management approaches to be successful it is critical that research rapidly advances to determine the actual effective spatial scales of pest



**Fig. 3** Flow diagram showing a generalized research strategy for developing habitat management approaches for invasive arthropods. Key research questions are identified by *question marks* (?). Before proceeding to the next step the key questions need to be addressed. To do this additional research might be

needed. At each step it can be decided that habitat manipulation is not likely to be successful and alternative strategies need to be considered. ‘HM’ is abbreviation for Habitat Management and ‘NE’ stands for Natural Enemies

enemy interactions and if landscape-scale dynamics are important (Griffiths et al. 2008; Tscharrntke et al. 2008).

Based on these evaluations it should be possible to propose candidate habitat management practices to enhance control of the target invader. Increasingly,

any such modifications of agricultural landscapes will need to take into consideration other ecosystem services, such as pollination (Tuell et al. 2008; Isaacs et al. 2009) that could be maintained or enhanced by the same practices. Fiedler et al. (2008) suggest that habitat management programmes are uniquely

positioned to maximize many of the supporting, provisioning, regulating and even cultural services that society expects from its working landscapes. Finally, all of these considerations need to factor into an evaluation of the economic consequences for the growers. Increasingly, it is clear that to achieve such an optimization of ecosystem services, new incentive structures will need to be put in place that fairly value the full range of ecosystem services that working landscapes provide society (Swinton et al. 2006; Sandhu et al. 2008).

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