

Prospects for ecological engineering for planthoppers and other arthropod pests in rice

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Though traditional pest management methods such as companion planting, trap cropping, and other forms of polyculture have a long history, it is only in recent years that researchers have attempted to underpin such practices with ecologically driven research. “Ecological engineering” for pest management has emerged from conservation biological control and habitat manipulation and is characterized by being based more comprehensively on ecological theory and by being developed via rigorous experimentation. The process of development typically aims to identify and provide the most functional components of biodiversity, rather than simply increasing diversity in an untargeted fashion. This directed approach to understanding and using agricultural biodiversity is important because there are a number of pitfalls in the simplistic assumption that enhanced biodiversity will suppress pests in a risk-free fashion. Results from a range of studies are presented to show the benefits of the adoption of ecological engineering practices that suppress pests directly or indirectly (i.e., via enhanced natural enemy activity). Strategies are suggested that allow ecological engineering approaches to be integrated with mainstream agriculture. As an example, this chapter considers prospects for the management of tropical rice pests, especially brown planthopper (*Nilaparvata lugens*). Pest management in this system currently relies heavily on host-plant resistance and synthetic insecticide applications. There is potential for the management of rice pests, including brown planthopper, to be enhanced through the use of ecological engineering to reduce dependence on pesticides and slow the breakdown of host-plant resistance traits.

Agriculture is under pressure to reduce reliance on chemicals and focus on more sustainable methods of production (Brown and Glenn 1999, Tsakiris et al 2004). In recent decades, integrated pest management (IPM) has shown great potential for reducing the dependence of crop protection on chemical control methods (Pretty et al 1998, Atanassov et al 2002). IPM reflects the idea that pest management requires a coordinated approach, integrating diverse tactics, including cultural, biological, and chemical control (Dent 1991). The maintenance of pest damage below injurious (economically damaging) levels while minimizing hazards to humans and the

environment is another key component of IPM (Prokopy 1994). Even with the implementation of IPM in many crop systems, modern agroecosystems are often inhospitable to natural enemies because of decreasing landscape heterogeneity, frequent disturbance, agrochemical inputs, decreasing genetic diversity, and increasingly homogeneous vegetation (Letourneau 1998).

Despite the homogeneity of agroecosystems, there is wide acknowledgment that biodiversity in agricultural landscapes can potentially enhance a range of ecosystem services such as breakdown and cycling of nutrients, pollination of crop plants, buffering watercourses from runoff, protection from erosion, and biological control of crop pests. Indeed, Costanza et al (1997) estimate the total value of the ecosystem services provided by biodiversity worldwide to be on the order of US\$ 2.6×10^9 . The value of biological control of crop pests alone was estimated at \$100 billion worldwide per annum. Yet, despite the action of biological control, insect pests still destroy an estimated 15% of world food production and lead to annual applications of approximately 3 million tons of pesticides (Pimentel 2004).

Biological control is the activity of predators, parasites, and pathogens in maintaining a pest's population density at a lower average than would occur in the absence of such agents (De Bach 1964). Biological control may involve the inundative release of large numbers of agents in response to escalating pest densities or the inoculative release of exotic agents. Both of these approaches, however, have significant disadvantages. Arthropod agents are labor-intensive to produce and are often prohibitively expensive for all but the most high-value and intensively grown crops. The inundative releases of biological control agents can be economically viable in the case of microbial agents such as *Bacillus thuringiensis* bacterium or *Metarrhizium anisopliae* fungus that can be cultured in vitro. The inoculative release of exotic agents, otherwise known as classical biological control, carries a risk of introducing species that will have severe nontarget effects (Howarth 2000, Twyford 1991). Less well known is the fact that though classical biological control has enjoyed spectacular successes such as the vedalia beetle (*Rodolia cardinalis*) for cottony cushion scale (*Icerya purchasi*) control in California citrus groves (Caltagirone and Doutt 1989), around 90% of arthropod releases for arthropod pest control fail to bring the target species under effective control (Gurr et al 2000).

The aforementioned problems associated with inundative and inoculative biological control have led to growing interest over the last decade in conservation biological control. This approach aims to use cultural practices to enhance the impact of endemic and naturalized or introduced agents and avoid killing existing natural enemies through pesticide use. Pests can also be suppressed directly (i.e., not via natural enemy enhancement) via vegetation structure exerting "resource concentration" effects (Root 1973). Theoretical predictions and empirical data generally support the notion that herbivore abundance tends to be lower in diverse systems relative to simplified systems (Andow 1991, Murphy et al 1998). This fits neatly with the popular perception that diversity leads to stability and productivity (Tilman et al 2005) but, unfortunately, simply increasing the diversity of an agroecosystem is no guarantee of reduced pest damage. The effects of diversifying agricultural landscapes on both

insect pests and their natural enemies are highly variable (Ferro and McNeil 1998). The effect of any particular crop-crop or weed-crop assemblage on species richness, species composition, reproduction, survival, and efficacy of natural enemies is difficult to predict (Letourneau 1998, Barbosa and Wratten 1998). The outcomes can depend on the pest–natural enemy complexes being studied, including dispersal capabilities of the pest and enemies, habitat requirements, and resources necessary for survival and reproduction (Ferro and McNeil 1998). For example, manipulating the composition of ground cover within a crop and the vegetation adjacent to it might enhance biological control of a specific arthropod pest. It may, however, also result in effects that are counterproductive to the overall goal of integrated crop production (Prokopy 1994, Barbosa and Wratten 1998) by exacerbating other pest species, encouraging a crop disease, or introducing a weed species. The resources that diverse vegetation provides may also have a negative effect by enhancing predators or parasitoids of pests' natural enemies, an effect observed in a New Zealand orchard to which buckwheat was added (Stephens et al 1998). It is also possible that enhancing a community of natural enemies may result in intraguild interference, that is, natural enemies of pests interfering with each other. Such effects can result in reduced crop growth via a cascading effect down trophic levels (Snyder and Wise 2001). As a response to such problems and a pathway to better-targeted diversification of agricultural systems, this chapter explores “ecological engineering” for pest management (Gurr et al 2004) and, in particular, its potential in tropical rice pest management.

Ecological engineering

The term “ecological engineering” was first used by Odum (1962) to refer to the “environmental manipulation by man using small amounts of supplementary energy to control systems in which the main energy drives are still coming from natural sources.” The concept of ecological engineering has continued to develop. The central theme of Mitsch and Jørgensen (2003) is the provision of “guidance and methodologies for systematic, intelligent design of ecological systems for the benefit of humans and nature.” Characteristics of approaches that are consistent with ecological engineering as defined by its early proponents are (1) low dependence on external and synthetic inputs, (2) a reliance on natural processes, (3) based on ecological principles, and (4) scope for refinement by ecological experimentation.

The first explicit and systematic application of the broad ecological engineering concept to pest management (Gurr et al 2004) saw the cultural practices used to enhance biological control (i.e., habitat manipulation) as compatible with the ecological engineering philosophy. These methods include (1) trap crops to divert pests from crops, (2) various forms of polycultures to reduce pest immigration or residency, and (3) provision of resources to natural enemies.

The provision of nonhost or nonprey food is one of the most commonly exploited mechanisms of conservation biological control (Gurr et al 1998). For many parasitoids, the provision of sugars is important in maximizing longevity, searching ability, and fecundity (Jervis et al 2004, Shearer and Atanassov 2004). However, because of

the serious potential risks of diversity exacerbating pest damage as described above, there is a need to select carefully the ways in which resources are targeted at desired beneficial species.

Work on nectar quality and flower architecture offers scope to target benefits to specific natural enemy species (Patt et al 1997, Wackers 2004). "Selective" food plants have the potential to increase parasitoid activity without positively affecting pest species (Baggen et al 1999, Gurr et al 1998, Landis et al 2000). Mechanisms by which food plant selectivity works include temporal coincidence between nectar availability and insect foraging, differential attractiveness and morphometric compatibility between the inflorescence and the insect (Baggen et al 1999, Gurr et al 1998), as well as flower color (Begum et al 2004). Prospects for finding flower species that meet the needs of natural enemies, while denying benefit to pests, appear good because of the rapid recent advances in our understanding of selectivity mechanisms. Recent work on the landscape-scale response of pests and natural enemies even suggests that selectivity could be achieved by manipulating the composition of landscape elements (Bianchi et al 2006).

Cover crops of various types can attract natural enemy species by providing plant foods, moderating the microclimate, and supporting nonpest herbivores that serve as alternative host/prey. If not managed carefully, however, cover crops can also behave as weeds by competing with the crop for water and nutrients (Bugg and Waddington 1994, Meyer et al 1992, Nyczepir et al 1998). They can also increase the cost of production or decrease yields (Brown and Glenn 1999) as they require extra maintenance, water, and/or fertilizer beyond that required for the crop (Horn 2000). Noncrop plants can also favor at least some pest species, a risk that was identified in very early work on the potential for habitat manipulation in rice (Lim and Heong 1977).

In order to reduce the potential negative consequences of randomly increasing plant diversity, ecological engineering for pest suppression is characterized by a series of methodical steps aimed at identifying and providing appropriate forms of vegetational heterogeneity in the farm landscape. It would be rare, however, for all of the steps to be completed before some aspect of habitat manipulation is trialed in the field. These steps are

1. The identification of the principal pest species against which additional or augmented suppression is most urgent through field surveys, discussions with growers, and/or use of the literature.
2. A literature review and field surveys to distill available information on the ecology of the selected pest species, and secondary pest species. This includes the identification of endemic or naturalized natural enemies that exist in the region and whether an approach based on plant-herbivore interactions such as resource concentration effects of trap cropping is required. This work is likely to be done in combination with step one.

Table 1. Characteristics of plants to be considered during selection of species for ecological engineering (after Gurr et al 1998).

Hazards
Weed status of plant being considered
Act as an alternative host for a pathogen of the crop
Poison livestock
Potential for contamination of the crop
Economic factors
Dual crop status
Cost and availability of seed
Does not compete with the crop and reduce yields
Biological factors
Pollen production (total/temporal pattern)
Nectar production (total/temporal pattern)
Competitive ability (with weeds and the crop)
Agronomic compatibility with the crop
Flowering periods that do not coincide with the crop and divert pollinating insects
Information that they are able to provide important resources for natural enemies (e.g., food or shelter)
Agronomic tractability (e.g., ability to survive with little maintenance)

3. Preliminary modeling of the pest and natural enemy population dynamics to explore aspects such as the magnitude of pest suppression required for economic control in relation to the spatial and temporal dynamics of the pest and natural enemy populations.
4. Close consultation with growers and agronomists to determine the types of ecological engineering (e.g., field margin borders, within-crop strips, interplanting, ground covers, landscape heterogeneity) that could be accommodated without undue disruption to normal farm practices.
5. The identification of candidate plant species to be used in habitat manipulation through literature reviews, and discussions with growers and agronomists.
6. Risk assessment of candidate plant species (e.g., possible weed, toxic to livestock, or likely to contaminate produce). Such risks can be analyzed in a quantitative fashion using the graded weighted checklist approach of Gurr et al (1998), which assists in determining the suitability of each plant species for vegetation diversification by considering the properties of candidate plants (Table 1). In this system, each criterion is assigned a weighting, based on its relative importance in the particular farming system being examined. Plants (or other habitat manipulation options) are then rated against each criterion, such that a score for each strategy is obtained and the likely suitability determined.
7. The identification of the most efficacious of the candidate treatments using laboratory or glasshouse experiments. Laboratory bioassays are most commonly used to measure the extent of benefit to a small number of natural

enemy species. The earlier modeling (step 3) may, like that of Kean et al (2003), have identified the life-history parameters of the natural enemy that, if enhanced, will have maximum impact on the pest population. These parameters may include search rate, prey conversion efficiency, and consumption rate although, most commonly, fecundity and longevity are used because of the relative ease with which these can be measured. Examples of this include longevity and fecundity of the parasitoids *Copidosoma koehleri* (Baggen and Gurr 1998) and *Trichogramma carverae* (Begum et al 2003). Importantly, equivalent bioassays with the pest should be used in order to prevent the selection of plant species that provide benefit to adults or larvae. The work by Baggen and Gurr (1998) identified borage (*Borago officinalis*) and phacelia (*Phacelia tanacetifolia*) as “selective” food plants that prevented access to nectar by the potato moth (*Phthorimaea operculella*) but benefited strongly its parasitoid, *C. koehleri*. This concept was extended in work with the lightbrown apple moth, *Epiphyas postvittana* (Begum et al 2006), where foliage of candidate plant species was checked for suitability to support larval development as well as the nectar being checked as a food source for adults.

8. Field experimentation is required to develop practical guidelines for farmers on habitat manipulation methods to improve integrated pest management programs. Field studies enable researchers to investigate the spatial and temporal extent of effects on natural enemies and pests in the natural environment, where factors such as neighboring crops, climate, and photoperiod may influence plant-pest-natural enemy interactions. This would include assessing the impacts of those species (e.g., secondary pests and pathogens) not included in earlier laboratory experiments. Parasitoids of predators and hyperparasitoids (the fourth trophic level) may also be enhanced by supplementary resources such as nectar. Therefore, adverse effects of these on the third trophic level (e.g., Stephens et al 1998) need to be ruled out—or at least shown to be minor in relation to the overall enhancement of the third trophic level.
9. Finally, guidelines need to be extended to growers. An example of an ecological engineering project that culminated in the successful extension to growers is the use of raised earth banks sown to the perennial grasses—usually cocksfoot (*Dactylis glomerata*). Such “beetle banks” are now widely established in European cereal fields (MacLeod et al 2004). Adoption of this technology was encouraged by color extension materials produced with support from a major pesticide company and by being featured on national television.

Prospects for ecological engineering of rice pests

Having introduced the potential risks associated with the incautious use of diversity to suppress pests, and the way in which ecological engineering can reduce these in a generic manner, the rest of this chapter explores the potential for this approach in tropical rice.

A number of authors have commented on the fact that because of reduced amounts of disturbance, perennial, semi-permanent systems such as orchards have great potential for habitat manipulation and biological control (Brown 1999, Landis et al 2000). Indeed, habitat manipulation methods have been used successfully to enhance biological control in a number of orchard/vineyard crops worldwide, including grapes (Murphy et al 1998), apples (Brown and Glenn 1999, Brown and Schmitt 2001), pecans (Tedders 1983), citrus (Liang and Huang 1994), and, to a lesser extent, cherry and peach (Bugg and Waddington 1994). Given this background, rice—an annual species with high disturbance between cropping phases—appears to be a crop in which there may be relatively poor scope for ecological engineering to be developed. As elucidated below, however, this is not necessarily the case.

Tropical rice and biological control

Way and Heong (1994) identify several factors and conditions that favor biological control of pests in tropical rice:

1. Stable water supply.
2. Moderate host-plant resistance and the capacity of rice plants for compensatory growth after pest attack.
3. A short fallow period giving relatively stable arthropod populations.
4. Proximity to noncrop vegetation on rice bunds (levees).
5. Withholding early-season insecticide applications.

Although some of these factors are relatively intrinsic to the system, others are conditions that are strongly dependent on farmers adopting appropriate management tactics. For example, there had been significant debate over the value of an earlier recommendation that farmers in a given region adopt synchronous planting after a fallow period (Loevinsohn 1994). This strategy is supported in general terms because most serious rice pests have a narrow diet range (Way and Heong 1994) so would be suppressed by a fallow period without available host plants. Despite the logic of this, asynchronous rice plantings are now more widely accepted not to lead to pest buildup provided that insecticide use is moderated, allowing natural enemies to build up (Way and Heong 1994, Ives and Settle 1997). The presence of rice crops for much of the year and over large areas makes this system quasi-perennial in nature, thus approaching in terms of stability the woody perennial systems referred to above in which conservation biological control efforts have enjoyed success. This effect has contributed to a broader trend whereby rice farmers have shifted from a field-by-field approach to rice pest management toward an area-wide management approach that may extend over large regions (Matteson 2000).

The fact that broad-spectrum insecticide can have very strong *adverse* consequences for pest management is clearly evident in data for *Nilaparvata lugens* (Kenmore et al 1984). Numbers of natural enemies were greater and numbers of *N. lugens* far lower in unsprayed rice. This clearly illustrates the significance of one of the most basic conservation biological control tactics: to avoid pesticide-induced natural enemy mortality. This is further supported by the fact that *N. lugens* is an induced pest, one that was insignificant before the Green Revolution and the accompanying intensification of insecticide use (Heong and Schoenly 1998). Though cases of effects of pesticides on arthropod natural enemies are common, fewer studies focus on impacts upon other taxa of biological control agents. Work by Choo et al (1998) in which imidacloprid was shown to be one of the least harmful of several pesticides on the entomopathogenic nematode, *Agamermis unka*, illustrates the need to consider nonarthropod taxa when selecting insecticide regimes that are most compatible with biological control.

The value of population modeling was stressed in general terms in the earlier introduction to ecological engineering and some valuable work has been done for rice arthropods. Drechsler and Settele (2001) suggest that simplistic generalizations about natural enemy activity being enhanced by asynchronous planting of rice need to be treated with caution. Following an ecological engineering approach whereby habitat manipulation is informed by a knowledge of key aspects of pest and natural enemy biology, the different responses of natural enemies to landscape structure need to be considered as well as the interactions between natural enemy guilds. In tropical rice, a predatory mirid, *Cyrtorhinus lividipennis*, attacks planthopper eggs so is able to persist only in rice crops. Accordingly, when crops are asynchronous, numbers within rice depend on immigration from outside the system. Although this suggests that asynchronous cropping would be the optimal management strategy, favoring biological control of planthoppers, it ignores other natural enemy guilds. Hymenopteran egg parasitoids are particularly important among these but the mirid is not known to differentiate between parasitized and unparasitized eggs. Under the model's assumptions of the parasitoids being superior natural enemies of planthoppers but outcompeted by the mirid, asynchronous cropping conditions that favor the mirid actually increase planthopper numbers because the impact of parasitoids declines. As a result of such complexities, and until future empirical work fills information gaps in pest/natural enemy interactions, the only general conclusion of the modeling by Drechsler and Settele (2001) is that a high proportion of vegetable fields in the landscape reduces pest abundance. These, as well as fruit and timber trees, may serve as sources and sinks for natural enemies. Proximity of such landscape elements is important because, although some natural enemies such as *C. lividipennis* are highly vagile (Riley et al 1987), many others, especially wolf and web-building spiders, colonize rice from adjacent habitats. Noncrop vegetation may also support nonpest insects that serve as alternative hosts to parasitoids that attack planthopper pests. Accordingly, the preservation of such habitats in rice-growing areas may be a useful heuristic message to communicate to farmers.

Cases of antagonistic interactions between natural enemy species such as that mentioned above have helped drive a significant research thrust in agroecology over the last decade, seeking to understand the circumstances under which biological control agents may have additive or even synergistic effects on pest suppression. One particularly relevant study was that of rice pests by Wilby et al (2005). This showed that a complex of three predator species led to an enhancement of predation of the leaf-folder, *Marasima patnalis*, compared with treatments with a single species of predator. No such enhancement was evident for *N. lugens*, suggesting that the greater differences in morphology and behavior of the endopterygote lepidopteran allowed resource-use differentiation between the predator species to a greater extent than was possible for the exopterygote planthopper. Another study of interactions between *N. lugens* predators considered spiders and again illustrated that multiple species of natural enemy may be better than single species provided direct competition for prey was minimal (Sigsgaard 2007). In that work, the small linyphiid, *Atypena formosana*, preyed upon early instars of the planthopper while the larger lycosid, *Pardosa pseudoannulata*, was able to use larger nymphs and adult planthoppers. The presence of both resulted in more even control of pest life stages. That study also suggested that *A. formosana* (as well as the mirid *C. lividipennis*) may serve as intraguild prey of the lycosid.

Collectively, such studies suggest value in not following the typical classical and inundative biological control approach of identifying one or a small number of agents and introducing or releasing only these. A somewhat broader enhancement of several biological control agent species, including generalist predators, may be optimal. Certainly such an approach is more consistent with the “insurance hypothesis” of Yachi and Loreau (1999). This proposes that fluctuations in ecosystem processes such as biological control of pests are buffered more effectively by the presence of multiple (rather than single or few) species. When multiple species are present, apparently redundant species may become important after a disturbance to formerly dominant species. Such “insurance” can be especially important in systems with temporal disturbance that may adversely affect predatory arthropods (Tscharntke et al 2007); at least some species will persist or colonize the crop early and suppress early-season pest outbreaks (Bianchi et al 2006).

The applicability of this to rice is evident from studies in which levels of organic matter were experimentally enhanced (Settle et al 1996). Composted cow manure was added to plots of rice and subsequent arthropod numbers compared with control plots without organic matter supplementation. Results indicated that early-season populations of generalist predators were supported by abundant detritus- and plankton-feeding arthropods, with these alternative prey giving predators a “head start” on later-developing pest populations. A similar study by Jiang and Cheng (2004) investigated the same approach for enhancing biological control of whitebacked planthopper (*Sogatella furcifera*) in China. Composted barnyard manure was added to plots of rice and synthetic fertilizer added to the control plots at rates equivalent to the nutrient present in the manure. Abundance of collembola was enhanced by the manure treatment but effects on pest numbers were less dramatic. Ecologically, this strategy exploits the “detrital shunt” of the food webs (Polis and Strong 1994)

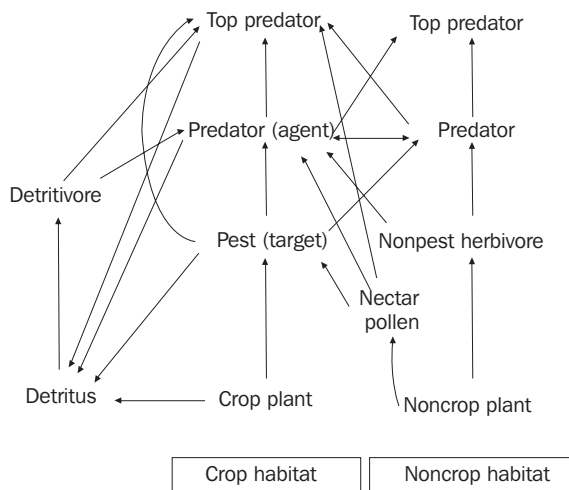


Fig. 1. Schematic representation of an agricultural system food web showing the potential importance of noncrop habitat and detritus. The latter can be augmented by application of organic matter to support predators, allowing populations to develop early in the season before pests arrive.

(Fig. 1) with the allochthonous organic matter constituting a resource subsidy that enhanced numbers of detritivore-feeding prey species. These in turn serve to decouple populations of natural enemies from reliance on pest herbivores. More generally, the role of freshwater aquatic habitats in supporting natural enemies of agricultural pests is not well understood and constitutes a potentially rich line of investigation for ecological engineering in systems such as rice. In tropical rice production, the paddies are connected to or in very close proximity to a network of human-made, natural, and seminatural aquatic habitats through which many invertebrates and prey of invertebrates (e.g., plankton) may readily move. There is significant research interest in the relevance to biological control of the connectivity and permeability of terrestrial vegetation features in farmlands (Tschamtko et al 2008). Extending the spatial analysis and metapopulation approaches from such work to understand and manipulate the aquatic component of agricultural landscapes is an exciting prospect.

Feeding studies on *A. formosana* by Sigsgaard et al (2001) suggest that alternative prey such as collembolan may still be more profoundly important. Spider survival on diets consisting solely of *N. lugens* or of the green leafhopper (*Nephotettix virescens*) led to very poor survival of spiders to the adult stage. In contrast, a mixed diet of either hemipteran with collembolan and drosophila gave faster development time and greater survival. This illustrated that availability of prey such as collembola is essential for the performance of this linyphiid, not simply an early-season, alternative food resource. Making progress in ecological engineering for tropical rice pest management will require an investment of research effort to establish some quite basic knowledge of natural enemy ecology. This is well illustrated by the observation by Way and Heong

(1994) that rice bunds were abundantly colonized by fire ants, *Solenopsis geminata*, but that their role as a natural enemy was unclear. It was not until the study of Way et al (2002) that this ant was shown to be a potentially important predator of *N. lugens*, and other rice pests, including corn rootworm (*Diabrotica adelpha*).

Studies of pest and natural enemy ecology also need to consider the response of each vegetation pattern at a range of spatial scales. Rice bunds are increasingly recognized as near-crop habitats that can support natural enemies. There is, however, a dearth of information on the optimal plant species to establish or encourage on these potentially critical features. An ecological engineering-based approach that experimentally tested the merits of various grass and broadleaf plant species could lead to a powerful strategy for enhancing biological control. Parasitoids, for example, could be enhanced by the presence of nectar-producing species as well as by moderated microclimate and possibly the presence of alternative hosts (Xiaoping et al 1996). Grasses allowed to flower may provide protein-rich pollen for predators as well as structural habitat analogous to that provided by “beetle banks” in temperate cereal production systems (Thomas et al 1991).

At a larger spatial scale, the significance of nonrice landscape elements such as vegetable crops identified through modeling by Drechsler and Settele (2001) provides valuable pointers for ecological engineering research. Crop species choice, timing of sowing and harvesting, spatial pattern, and proximity to rice all offer some scope for exploration. The use of mark-recapture and geographic information system-based studies can identify the temporal and spatial patterns of cropping that are most conducive to rice pest suppression via trap crop, decoy crop, push-pull, resource concentration, and natural enemy-mediated effects.

Woody perennial vegetation, whether cultivated for fruits and nuts or seminatural (possibly protected areas for biodiversity conservation), can provide a highly complex habitat, especially when understorey vegetation is present to provide multiple strata. Landscape elements of such types can support complexes of beneficial and pest arthropods, with diverse trophic relationships (Bugg and Waddington 1994, Altieri and Schmidt 1985).

Though food sprays have been shown to have utility in attracting natural enemies into target crops (Wade et al 2008), the costs are likely to be prohibitive for many tropical rice growers. An alternative approach for manipulating natural enemy movement based on chemical ecology may be viable in the future. It is now well established that plants under attack by arthropod herbivores produce volatile chemicals that attract natural enemies (Bruce and Pickett 2007). Some such herbivore-induced plant volatiles (HIPVs) have been identified, synthesized, and used in slow-release dispensers or as sprays. Under field conditions, methyl-salicylate, *cis*-3-hexen-1-ol, (*Z*)-3-hexenyl acetate, and benzaldehyde have resulted in elevated catches of biological control agents (James 2005). Remarkably, application to plants of a single HIPV, or of jasmonic acid, which is involved in related metabolic pathways, can also induce the production of a natural blend of HIPVs (Lou et al 2005). Such findings suggest that applying synthetic HIPVs to crops can, both directly and indirectly, attract the predators and parasites that could protect crops from pest damage.

Prospects for such an approach to work in rice appear strong. Work on the role of ethylene signaling in rice showed that this hormone is involved in induced defenses against arthropod herbivores (Lu et al 2006). Plants attacked by *N. lugens* produced ethylene 2 to 24 hours after infestation along with HIPVs, and *Anagrus nilaparvatae*, a parasitoid of *N. lugens*, was attracted to emitting plants. The same authors also considered it likely that *N. lugens* activates other—most notably the salicylate—signaling pathways. In other work, exogenous applications of jasmonic acid to rice plants have led to dramatically elevated levels of several volatiles, including aliphatic aldehydes, alcohols, monoterpenes, sesquiterpenes, methyl salicylate, and *n*-heptadecane (Lou et al 2005). The potential for such chemical ecology to be developed into a practical pest management strategy is evident from a doubling of parasitism of *N. lugens* eggs by *A. nilaparvatae* on rice plants that were surrounded by rice plants to which jasmonic acid had been applied compared with control plants. It is likely that other parasitoids, as well as rice pest predators, make use of such plant-provided chemical cues. The same cues may also affect pest behavior, making treated plants less attractive to planthoppers (Karban and Chen 2007).

An ecological engineering approach based on applying selected HIPV elicitors to rice to promote their sink status for natural enemy populations could be especially powerful if linked with manipulation of the nearby vegetation to make it a more effective source habitat for predators and parasitoids.

Conclusions

In conclusion, the ecological engineering approach to pest management is still young but it provides a strategic methodical framework for researchers wishing to apply ecological knowledge and experimentation to pest suppression in the field. Ecological engineering has the potential to complement IPM programs currently being used in many agricultural systems, including tropical rice, by improving the efficacy of natural enemies and reducing reliance on pesticides.

This review has covered the literature pertinent to the nine steps defined for an ecological engineering research program. In terms of the first three steps—that relate to amassing a solid foundation of knowledge on the major pests and their natural enemies and modeling the interactions between them—the economic significance of rice and the long history of research on rice pest management mean that there is a very significant body of work on the species involved but much more could be done to explore the interactions. Modeling as well as experimentation are required. In terms of step 4—liaison with growers and others involved in the industry to establish which types of habitat manipulation may be acceptable—there is a need to canvass the merits of those techniques that the available literature suggests could have utility.

These include

- Further rationalization of pesticide inputs such that timing, type, and spatial pattern of applications are based on rigorous, threshold-driven decision frameworks rather than overestimates of the seriousness of pest damage (Heong et al 1998), peer pressure (Heong and Escalada 1999), inappropriate marketing, and policy settings.
- Possible use of HIPV elicitors (and possibly food sprays) to encourage natural enemy movement into rice at appropriate times.
- Manipulating the detrital shunt of the rice pest food web by adding organic matter to rice paddies early in the season.
- Configuring rice paddies optimally with respect to the wider network of aquatic habitats such as ditches, streams, wetlands, etc., so as to maximize the availability of alternative prey items for natural enemies of rice pests, especially for the early stages of the rice crop.
- Managing the vegetation of bunds to encourage natural enemies such as parasitoids and ants.
- Managing the wider scale pattern of vegetation by preserving and re-establishing perennial woody vegetation.
- Manipulating the spatial and temporal pattern of rice plantings across entire regions.

Not all of these will be deemed acceptable by rice farmers in all production zones but it is encouraging that the available literature suggests potential for several methods that range from highly local strategies that individual growers could implement through to larger scale approaches that could be encouraged on a regional scale.

Those methods that are considered suitable in a given region could be pursued via steps 5–8 of the ecological engineering framework. These would involve experimentation to determine aspects such as which plant species should be preserved or sown into bunds to maximize their role as natural enemy sources and which HIPVs most effectively turn rice into sinks for natural enemy populations. Similarly, experimentation could indicate the efficacy of various forms of available organic matter as a means of providing early-season prey for the natural enemies of rice pests. Geographic information systems accompanied by field surveys could help authorities devise landscape configurations that best impeded rice pest colonization of rice crops while facilitating the early arrival and buildup of natural enemies. Careful studies at these varying spatial scales are required in order to avoid the possible adverse effects of diversity reviewed in the opening sections of this chapter.

Ultimately, step 9, experimentation in such areas, needs to be distilled into simple heuristics or “rules of thumb” that can be readily understood and implemented by farmers. The fact that pests such as *N. lugens* continue to cause severe losses in rice means that implementing an ecological engineering approach is important in order to lessen the dependence on insecticides and slow the breakdown of host-plant resistance traits.

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Notes

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