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Understanding Farmscapes and Their Potential for Improving IPM Programs

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ABSTRACT. New pest management programs must strive to achieve sustained, improved crop production and profitable agriculture, while simultaneously conserving natural resources and protecting the environment. Redesigning farms to take advantage of natural biological control can improve the sustainability of integrated pest management programs. A technique common in this approach to pest management is farmscaping, which refers to the arrangement or configuration of plants that promote biological pest management by attracting and sustaining beneficial organisms. Farmscaping is an ecologically based, whole-farm approach to enhancing the efficacy and local abundance of arthropod natural enemies through modification of the environment. However, by adding these resources back to simplified agriculture systems, they provide numerous other ecosystem services such as erosion control, reduced runoff, esthetic benefits, increased revenue, nutrient management, pollination services, soil health, as well as improved pest suppression. Herein, we discuss the strategy of farmscaping, review the theory of how it can improve pest management, and discuss the practicalities and risks involved in incorporating farmscapes into integrated pest management programs.

Key Words: farmscaping, conservation biological control, agroecosystem, IPM, sustainable pest management

As we move into a new era of pest management, programs must use practices aimed at achieving sustained, improved crop production and profitable agriculture, while simultaneously conserving natural resources and protecting the environment. Conservation agriculture emphasizes proactive, multitactic practices in contrast to the "single approach" reactive methods generally used in conventional systems. A technique common in conservation agriculture is farmscaping, which refers to the arrangement or configuration of plants that promote biological pest management by attracting and sustaining beneficial organisms (Bugg and Pickett 1998; Fig. 1). The term farmscaping is more commonly referred to as "conservation biological control or ecological engineering" and has been broadened to incorporate other types of companion plantings such as: 1) living mulches or trap crops; 2) fence rows or borders; 3) island patches within rows or occupying entire rows spaced at regular intervals within the field; or 4) herb or flower cash crops intercropped with vegetable or fruit crops (Gurr et al. 2004; Figs. 2 and 3). However, it is important to note that while some overlap exists among techniques, the primary goals of each are slightly different. For example, trap crops work to attract pest species away from a cash crop, not as a mechanism to attract and conserve natural enemies.

Ideal farmscape plantings provide resources for beneficial insects, suppress weeds, and grow in close proximity to the cash crop without competing for light, water, and nutrients. The configuration of crop plants and companion plants can impact the suite of arthropod pests and natural enemies present in the field (Barbosa 1998, Bugg and Pickett 1998). These practices can have numerous benefits including the potential to enhance activity of arthropod natural enemies and improve biological control, but they might also exacerbate pest populations (Landis et al. 1987, Turnock et al. 1993, Renner 2000, Wäckers et al. 2007, Winkler et al. 2010; Fig. 4). In this article, we review the theory of how farmscaping can improve pest management and discuss the practicalities and potential risks involved in incorporating farmscapes into integrated pest management (IPM) programs.

The Agroecosystem

An agroecosytem can be thought of as a community of living organisms in conjunction with the nonliving components of their environment, interacting as a system that has been modified by humans to produce food, fiber, or other agricultural products (Waltner-Toews 1996). The perturbation of natural processes in simplified systems has a tendency to shift the ecological balance to favor pests (Altieri and Letourneau 1982). Therefore, the primary goal of farmscaping should be to shift the ecological balance back toward a more favorable equilibrium to improve pest control (Norris 1986). It is important to remember that the primary objective in any agroecosystem is crop production, and that these crops are susceptible to but also reliant on the same processes found in natural ecosystems; these processes include trophic interactions, predator–prey dynamics, plant species competition, successional dynamics, and nutrient cycling (Hecht 1987). What differentiates agroecosystems from natural ecosystems is the degree of human input (Gliessman 1990).

When considering biological control within agroecosystems, there are essentially three interacting arthropod communities of interest: plant-feeding pests, natural enemies, and alternative prey. These three communities have close and complex relationships with the vegetation found in these systems. However, the interactions among vegetation, natural enemies, alternative prey, and pests are not thoroughly understood and more research is needed to understand the complexities of these relationships.

Root (1973) formulated two hypotheses that are central to understanding how diversity influences insect populations in agroecosystems. The "enemies hypothesis" states that more natural enemies should be found in diverse plantings because of greater availability of alternative food, shelter, and habitat. The "resource concentration hypothesis" posits that less diverse systems are susceptible to insect pest damage because these large clusters of resources (e.g., monocultures) are easier for pests to locate. Over the past 40 yr, these two hypotheses have led to numerous studies investigating the importance of diversity in agroecosystems by providing nectar and pollen, alternative prey, and microhabitats for shelter and overwintering (van Emden 1965, 1990; Altieri and Whitcomb 1979; Letourneau and Altieri 1983; Norris 1986; Gurr et al. 2012; Landis et al. 2012). A recent meta-analysis by Letourneau et al. (2011) showed overwhelming support for herbivore suppression, natural enemy enhancement, and decreased crop damage in diversified cropping systems. This

Fig. 1. A syrphid fly(top left), coccinellid beetle (top right), and hymenopteran parasitoids (bottom) foraging on flowering buckwheat in a farmscape in Blacksburg, VA.

Fig. 2. Mixed flower farmscapes in vegetable cropping systems.

Fig. 3. Cut flower farmscape in mixed vegetable cropping system.

increase in diversity can be managed within an agroecosystem to help conserve populations of natural enemies.

Numerous studies have shown that habitat diversity in agricultural landscapes has the potential to decrease pest pressure or increase natural control (Bianchi et al. 2006, Gardiner et al. 2009, Power et al. 2009, O'Rourke et al. 2011). The mechanisms behind this are not well understood, and recent research indicates the scale and arrangement may be important (Lee and Heimpel 2005, O'Rourke et al. 2011). In addition, diverse landscapes may make it more difficult for pests to locate hosts, reducing the time and energy available for reproduction (Fahrig and Paloheimo 1988, Schneider 1999, den Belder et al. 2002, O'Rourke et al. 2011). It is likely that reduced pest pressure in more diverse systems results from a combination of factors.

Farmscaping Theory

The idea of farmscaping is centered on the concept of biological control and gained attention in the 1960s. Thirty years later, Pickett and Bugg (1998) assembled a collection of articles that highlighted the research on biological control, focusing on the topic of habitat management. This seminal work became the foundation of farmscaping

Fig. 4. Adult imported cabbageworm butterflies (*P. rapae*) foraging on flowering buckwheat.

theory. The central idea was that natural pest control can be enhanced by providing limited resources to benefit natural enemy communities; such resources include alternative food and hosts, microclimates, and nesting and overwintering habitat (Pickett and Bugg 1998).

Predator–prey populations tend to follow specific oscillating patterns with the peak of the predator's oscillation lagging slightly behind that of prey, unless something interferes with the normal dynamics of the system (Gotelli 2001). Low populations of naturally occurring beneficial insects can be attributed to intensive farming operations including large monocultures, regular cultivation, and use of insecticides (Meehan et al. 2011). These practices lower diversity and, at the same time, maintain a high level of disturbance, limiting resources for insect natural enemies (Rabb et al. 1976, Powell 1986, Dutcher 1993, Landis and Menalled 1998). In addition, these conditions favor rapid recolonization and population growth by pests (Price 1981, Letourneau 1998). Farmscaping is a technique designed to add diversity back to the system and minimize disturbance, leading to increases in natural enemy populations (Landis et al. 2000, Sarthou et al. 2005).

Conservation of natural enemies involves manipulation of the environment to favor natural enemies, either by eliminating adverse factors or providing improved conditions for colonization and survival (DeBach and Rosen 1991, Greathead 1995). Therefore, we must reassess current IPM programs from an ecological perspective, building on the characteristics of the agroecosystem by integrating the ecological principles of natural ecosystems with the human inputs of production agriculture (Hecht 1987, Gliessman 1990, Reijntjes et al. 1992). Maintaining high levels of species diversity is one of the key characteristics of proper functioning of any agroecosystem (Altieri and Letourneau 1982).

Farmscape Considerations and Techniques

Originally, farmscaping was simply thought of as a way of enhancing and conserving beneficial insect communities to improve pest control. Recently, the focus on diversity and ecosystem services has gained attention. The goal is to maximize the benefits from diversifying agricultural landscapes by enhancing biodiversity and ecosystem services such as erosion control, reduced runoff of agrochemicals, esthetic benefits, increased revenue, nutrient management, pollination services, soil health, and pest suppression (Gurr et al. 2003, 2012; Tscharntke et al. 2005; Bianchi et al. 2006; Sandhu et al. 2007; Fiedler et al. 2008; Frank et al. 2008; Isaacs et al. 2009; Smukler et al. 2010). The integration of farmscaping in agriculture will ultimately depend on the desired outcomes. Because the focus of this article is pest management, we will focus our discussion there; however, because it has been estimated that insects provide approximately US$8 billion of ecosystem services in pollination and pest control (Losey and Vaughan 2006), we will briefly highlight how farmscaping can enhance pollinator diversity and pollination services.

Approaches to Farmscaping. There are two basic approaches to farmscaping in relation to pest management: those that work from the bottom up and those that work from the top down. Bottom–up approaches include intercropping, trap crops, companion plantings, and living mulches. These techniques are designed to "mask" or "disguise" the cash crop, or repel pest insects, thereby protecting the crop. These practices may also provide additional ecosystem services by fixing nitrogen, preventing erosion, suppressing weeds, or providing nectar or pollen to beneficial arthropods. Top–down approaches are designed to enhance populations of natural enemies that, in turn, should provide improved pest suppression.

Techniques commonly used to enhance natural enemy populations include insectary plantings, beetle banks, and hedgerows. Hedgerows and insectary plants are designed to provide nectar and pollen for beneficial insects such as pollinators and natural enemies, thereby improving crop pollination and biological pest control in adjacent crops (Griffiths et al. 2008, Hopwood 2008, Morandin et al. 2011). In addition, these practices have been shown to support native bee communities that were otherwise depauperate (Hannon and Sisk 2009, Morandin and Kremin 2013). These practices have tremendous potential to minimize pollinator stress, potentially reducing or slowing the decline of important pollinators without negatively impacting pollination within crops (Morandin and Kremin 2013). Beetle banks are designed to provide shelter and habitat, but also to "mask" the presence of the host crop. Beetle banks are simply grassy ridges in the center of the field that provide proximal overwintering habitat and more rapid colonization by predators (Thomas et al. 1991, Sotherton 1995, Collins et al. 2002, MacLeod et al. 2004).

The basic principle behind all of these practices is to add diversity to a simplified system that provides some limiting resource to beneficial arthropods. This involves planting different crop and noncrop plants such as cover crops and habitat plantings, combined in space and time, to reduce insect pest populations and increase populations of beneficial arthropods. An important consideration when choosing farmscaping plants is the characteristics of the insect–plant interaction in relation to floral use. Nevertheless, most plants are selected for other reasons. A basic principle of conservation biological control is that, after the acquisition of resources, natural enemies will disperse into adjacent cropping systems. The distance over which dispersal takes place will determine the spatial arrangement and overall quantity of resources needed (Wratten et al. 2003). Numerous factors must be considered when selecting plants for farmscaping, and the selection criteria are extremely complex. Recently, however, there has been a tremendous amount of research focused on promoting the use of native plant species for farmscaping (Isaacs et al. 2009, Gurr et al. 2012, Landis et al. 2012).

Farmscaping With Grasses or Shrubs and Trees. When choosing plants for farmscaping, attention is often focused on species that provide nectar (floral and extrafloral, which are nectar glands not associated with the flower) or pollen as complementary food sources for beneficial insects, or on annual species that are easy to establish, grow rapidly, and can be used more flexibly than perennials. Although native, perennial grasses are used as forage habitat, they can also be used to conserve beneficial insects for biological control. Native, perennial grass species provide structure and habitat year round for a variety of generalist predators. Grassy "beetle banks" provide overwintering sites for ground-dwelling species such as carabid and staphylinid beetles. These beetle species develop in soils and are sensitive to cultivation and soil disturbance. Beetle banks serve as a refuge from habitat disruption resulting from agriculture. Evidence suggests that the effects of temperature moderation in refuges containing grassy species that are bunch-like in form is responsible for protecting overwintering populations (Bossenbroek et al. 1977), resulting in more spring breeding adults, higher populations in the banks, and greater diversity of predators (MacLeod et al. 2004).

Farmscaping with native grasses can also harbor arachnids and result in reduced pest species. For example, potatoes planted in small patches (2 by 20 m) interplanted in native big bluestem (*Andropogon gerardii* Vitman) and indiangrass (*Sorghastrum nutans* (L.)) experienced increased mortality of Colorado potato beetle, *Leptinotarsa decemlineata* (Say) because of harvestmen and spiders than monoculture or bare ground control plots (Werling et al. 2012). Grassy species are also desirable in farmscaping as they are low maintenance and tolerant of a variety of sites. In addition, they provide numerous additional ecological functions, including erosion control, carbon sequestration, rapid nutrient cycling, and provide food, shelter, and habitat for other forms of wildlife, such as birds and mammals that also contribute to pest management.

Like grasses, trees are often not thought of from a farmscaping context. However, trees can be reservoirs of important biological control agents that manage key agricultural pests. Trees can provide resources for natural enemies through floral and extrafloral nectaries that provide a complementary food source or serve as a source for herbivores that serve as alternative hosts (Rezende et al. 2014). Trees can create a microenvironment and shelter beneficial insects from wind and rain and help moderate temperature extremes. Management of trees in a cropping system can occur through an agroforestry approach, where trees are cropped alongside cereals, other horticultural crops, and integrated with poultry or livestock. Managing wild trees adjacent to commercial orchards and careful integration of appropriate species can be beneficial in farmscaping for biological control.

In Mexico, several species of tephritid fruit flies are key pests of commercially important fruit trees such as mango (*Mangifera indica* L.) and may be managed effectively by generalist hymenopteran parasitoids. However, mango monocultures are not sufficient to host parasitoids, as they set flowers and fruit during a discrete window of time, leaving parasitoids without resources for the rest of the season. A stable population of parasitoids in this cropping system will depend on "parasitoid multiplier plants" that serve as alternate hosts for fruit fly pests and "parasitoid reservoir plants" that host nonpestiferous fruit flies that can serve as hosts for generalist parasitoids. Management and cultivation of these noncommercially important native tree species in adjacent areas are integral for pest suppression in this system (Aluja et al. 2014) and illustrate how wild, native trees can be an important component in farmscaping for biological control.

Trees can provide extrafloral nectar that serves as a food source for beneficial insects and promotes biological control in managed agroecosystems. Coffee plants in Brazil are shown to benefit from the presence of nearby Inga trees (*Inga subnuda* subsp. *Luschnathiana* (Bentham)) as the Inga trees contain extrafloral nectaries that support parasitoids of the coffee leafminer, *Leucoptera coffeella* (Guérin-Méneville) and coffee berry borer, *Hypothenemus hampei* (Ferrari). In a temperate cropping system, peach trees having extrafloral nectaries were interplanted in an apple orchard in attempts to encourage parasitism of the tufted apple bud moth, *Platynota idaeusalis* (Walker). Although abundance of hymenopteran parasitoids was increased because of attraction to peach trees, there was no increase in parasitism of *P. idaeusalis*. However, the fruit trees experienced less injury from San Jose scale, *Quadraspidiotus perniciosus* (Comstock), and stink bugs (Hemiptera: Pentatomidae) than apple fruit grown in monoculture (Brown et al. 2010), indicating that success in these systems may depend on the relationships being observed.

Although the scope of this review is on biological control provided by arthropods, the contribution of vertebrate predators such as birds and bats to pest management cannot be overlooked, and trees provide nesting habitat and shelter. When birds and bats were excluded from cacao trees in an agroforestry cropping system in Indonesia, the result was an increase in herbivore abundance that resulted in 31% yield loss despite the fact that predatory ants and spiders were released concurrently (Maas et al. 2013). Furthermore, grasses and trees contribute to structural complexity of the habitat, a key indicator of increasing abundance of natural enemies, due to a variety of factors including refuge and alternative resources (Langellotto and Denno 2004). Depending on the key pests and cropping systems studied, trees can be critical to resource provisioning in a farmscaping context.

Famscaping With Native Versus NonNative Plants. It is important to remember that in most cases, plant species differ in their chemical and physical structure and, therefore, are not ecologically equivalent. This is also true when it comes to the benefits of farmscaping. A key example is the concentration, composition, and accessibility of pollen and nectar (Landis et al. 2012). Because plants and insects have a long evolutionary history, it is likely that these characteristics would be more suitable for native natural enemies on native plants. Nevertheless, most plants used in insectary plantings and to some extent hedgerows are nonnatives (Fiedler et al. 2008, Landis et al. 2012).

It is estimated that at least 5,000 species of nonnative plants are now well-established in natural ecosystems throughout North America (Qian and Ricklefs 2006). Most of these species have escaped from the ornamental industry, but there are some notable cases from agriculture such as kudzu. In addition to the potential for plants to escape cultivation, there are numerous other reasons why native plants should be considered for farmscapes. These include local adaptation, increased native plant diversity enhancing other ecosystem services, and decreased costs. While understanding that native plants are likely a better alternative to provide multiple ecosystem services, much more information is needed to determine the best plants for specific situations (Landis et al. 2012).

Most beneficial insects feed on nectar and pollen at some point in their life, so these two characteristics are essential considerations in selecting farmscape plants. Because the accessibility of these resources can vary considerably based on flower and insect morphology, plants must be selected that make these resources accessible to beneficial arthropods (Forehand et al. 2006a,b). Fiedler and Landis (2007) found that floral area, peak bloom, flower height, and decreasing corolla width were the most important characteristic in attracting natural enemies; however, they were also the most important in attracting herbivores as well. Many plants in the carrot family (Apiaceae) make exceptional farmscaping plants because they contain exposed floral nectaries (Tooker and Hanks 2000). In addition, many plants in the legume family (Fabaceae) contain extrafloral nectaries that make nectar resources highly accessible. Plants in the legumes family, in addition to providing food resources, also provide other services such as nitrogen fixation. Buckwheat (Polygonaceae) is a popular cover crop and is also useful in farmscaping, as it is highly nutritious to parasitoid wasp foragers (Nafziger and Fadamiro 2011) and can take up phosphorus (P) under soil conditions that would otherwise limit bioavailability (Zhu et al. 2002). Different plant families provide resources in different ways, and it is important when thinking about farmscaping to try to choose plants that will provide multiple benefits.

Farmscapes in IPM

Insect herbivores find themselves in a precarious position that lies between a diverse community of natural enemies and a chemically well-defended host plant, where competition is fierce and resources few (Lawton and McNeil 1979). In other words, the community of insect herbivores found on any given plant or in a particular habitat is shaped by their ability to deal with plant defenses and still avoid natural enemies. These interactions tend to push insect herbivores to specialize on particular groups of plants. Therefore, specialist herbivores become well adapted to locating preferred host plants. Adding diversity back to these systems can work to reduce pest pressure by "masking" the host plant and by providing resources that will enhance natural enemy communities. Farmscaping can enhance natural enemy populations by providing shelter, nectar, alternative prey, and pollen, and is known by the acronym SNAP (Gurr et al. 2012). Numerous studies have investigated each of these provisioning services and have been summarized in recent reviews (Wäckers et al. 2005, Gurr et al. 2012).

Different types of diversity are intended to target different natural enemy groups. For example, the use of beetle banks specifically targets ground-active predators such as carabid and staphalynid beetles (Thomas et al. 2001, MacLeod et al. 2004). Regardless of the target group, the intended effect is the same. It is expected that target groups will follow a specific hierarchy when using these resources. Wade et al. (2008) outlined these effects as aggregation at the resource, increased fitness, improved searching behavior, increased predation, and ultimately decreased pest abundance. This can potentially eliminate the need for insecticide applications and should lead to increases in yield. While most IPM programs rely on a static threshold that does not take into account natural enemy abundance or function, there is a growing body of literature on adjustable thresholds based on natural enemies (Walker et al. 2010).

Adjustable thresholds have been created in numerous cropping systems, including wheat (Giles et al. 2003), cotton (Naranjo et al. 2002, Conway et al. 2006), soybean (Hallett et al. 2014), and tomato (Hoffmann et al. 1991). These types of dynamic thresholds have the potential to reduce insecticide use by as much as 95% (Walker et al. 2010). The trouble is that diverse natural enemy communities interact in complex ways and different natural enemies contribute to pest suppression in different ways (Hallett et al. 2014). Given these complexities and the fact that thresholds must be kept relatively simple and easy to use to ensure adoption, efficiently developing these types of thresholds will be extremely challenging.

Adult predators and parasitoids are known to visit a number of flowering plants and consume nectar and pollen (Al-Doghairi and Cranshaw 1999, 2004). Studies have shown that available adult food sources can enhance natural enemy longevity and fecundity and may improve natural pest control (White et al. 1995; Hickman and Wratten 1996; Johanowicz and Mitchell 2000; Eubanks and Styrsky 2005; Gurr et al. 2005; Rebek et al. 2005, 2006; Bianchi and Wäckers 2008). Researchers believe that increases in natural enemy abundance will translate to higher levels of pest control; however, this may not always occur (Philips et al. 2014). Farmscaping is often credited for reduced pest pressure, but few studies have thoroughly investigated this claim. While there is no doubt that farmscapes attract natural enemies, how these predators and parasitoids interact and move remains unclear.

By using rubidium as an elemental marker, Long et al. (1998) were able to document that syrphid flies, parasitic wasps, and lacewings were able to move at least 76 m into adjacent field crops after foraging in farmscaped habitat in California. However, more research is needed to document foraging behavior and dispersal of natural enemies from farmscaped habitat to crops in multiple locations. Sunflowers are known to be attractive to beneficial insects, but the benefit to proximal vegetable crops (collards, tomato, okra, and watermelon) was unclear as beneficial insect populations were not as numerous 10 m from the sunflowers (Jones and Gillett 2005). Conversely, Philips et al. (2014) found no difference in parasitism of imported cabbageworm, *Pieris rapae* (L.), 60 m from buckwheat farmscapes in collards.

In addition, the role of omnivorous predators remains largely unknown and warrants further investigation. While several studies have shown that farmscaping attracts numerous predators, the impact that these predators have on pest populations is not known (Forehand et al. 2006a,b; Philips 2013). Moreover, the interactions of these various predator species may be antagonistic or synergistic and may play a major role in the ability of natural enemies to control pests (Prasad and Snyder 2004, Coll 2009). Therefore, there are numerous considerations when implementing farmscaping into IPM programs.

Practicalities, Constraints, and Risks

Design, Establishment, and Maintenance. The idea of farmscaping seems straightforward, but it is a complex process. For farmscaping to work as intended, it is essential to have a thorough understanding of how populations interact. The temporal and spatial arrangement of farmscape plantings must be carefully considered to provide resources that will enhance beneficial insect populations, but not pests. While nectar and pollen use by beneficial insects has been studied intensively, the effect of floral resources on herbivore populations has received very little attention (Latheef and Irwin 1979, Zhao et al. 1992, McEwen and Liber 1995, Baggen and Gurr 1998, Romeis et al. 2005, Wäckers et al. 2007, Winkler et al. 2010). It has been demonstrated that herbivorous and beneficial insects often differ in their ability to exploit floral resources, and that this variation can be used to identify specific sources that are suitable for predators and parasitoids, but not for pests (Baggen et al. 1999, Wäckers 1999, Wäckers et al. 2007, Winkler et al. 2010). Such selectivity can be based on plant characteristics including floral attraction, nectar accessibility, and nutritional suitability, allowing for the identification of plants that meet the needs of beneficial insects while at the same time reducing the risk of pest outbreaks (Wäckers and Van Rijn 2005, Wäckers et al. 2007, Winkler et al. 2010).

Numerous practical reference guides are available and relevant to growers in multiple regions that aid in design, establishment, and maintenance of farmscapes as well as identification of beneficial insects (Altieri and Nicholls 2005, Dufour 2000, Flint and Dreistadt 1998, Holland and Ellis 2008, Kimball and Lamb 2001). Common challenges growers face in adopting farmscaping practices include species selection, weed suppression, timing, and economic considerations such as seed and labor costs. It is recommended that growers start small, experiment with varieties, planting techniques, and placement. Growers should also consider the practicalities of establishing annual or permanent perennial habitat. Many seed distributors are marketing custom seed blends for this purpose that help take the guesswork out of species selection and make it easier to establish habitat (e.g., Good Bug Blend, Peaceful Valley, Grass Valley, CA.). However, seed blends can be expensive, may not be suitable across all regions and sites, and a few species are likely to outcompete and dominate based on seed size and available resources (Geritz et al. 1999, Coomes and Grubb 2003).

Weeds. Weed suppression can be particularly difficult, and management strategies will depend on production system (organic vs. nonorganic) and life cycle (annual vs. perennial). Organic production systems may rely on tillage or solarization as the primary means of weed management in annual systems, while nonorganic growers may use chemical herbicides in combination with other techniques to establish a weed-free seedbed. Perennial habitat may be established with transplants or propagated cuttings and be more expensive and labor-intensive initially, but if properly managed, will not require additional inputs in subsequent years.

Timing. Timing and phenology is important when considering farmscaping. The goal is to have plants flowering early and throughout the growing season so that resources are consistently available to beneficial insects. In addition, it is important to have shelter sites and alternative prey available early to allow beneficial populations to build before target pests arrive. Land resources may be limiting, and farmscaping should not displace crop production. If land resources are limited, farmscaping can be done on land that would not otherwise be productive, such as fence lines, hedgerows, field borders, embankments, slopes, and hillsides. Economic considerations include seed costs and labor and equipment costs for establishment and maintenance. Farmscaping is meant to be low maintenance and is typically rain fed after the first year of establishment, but this depends on the plant species and the climate.

Economics. Limited data are available on economics and cost: benefits of farmscaping. The costs are relatively easy to calculate, but few budget examples are available. One example published by the Yolo County Resource Conservation District, Woodland, CA (Kimball and Lamb 2001), estimated the costs of establishing habitat for beneficial insects in hedgerows. Installation and maintenance costs of establishing grasses and shrubs was US$3,614, including costs of transplants, seeds, herbicide, irrigation, and all labor involved for one 427 by 5 m hedgerow. Costs are expected to be highly variable based on the species and type of plant material used, the scale, and the cultural and management requirements.

One of the major benefits of farmscaping is the supposed savings reaped from eliminating or reducing pesticide sprays owing to suppression by biological control agents, but quantification of this ecosystem service is lacking. One study estimated the value of ecosystem services provided by predatory mesostigmatid mites to suppress the thrips, *Pezothrips kellyanus* (Bagnall), in Australia. It was noted that predatory mites were more abundant when the understory of citrus was planted with dense ground cover of perennial forbs and grasses. The estimated value of natural pest control by mites was estimated at AU$2,640, AU$ 4,610, and AU$ 8,540 per hectare per year at 10, 20, and 40% severity of thrips damage, respectively, resulting in greater economic resilience to price shocks for growers who received biological control by predatory mites (Colloff et al. 2013). Another study showed that alley cropping alfalfa between walnut trees in the midwestern United States reduced damage caused by the alfalfa weevil, *Hypera postica* (Gyllenhal), and added additional cash flow. Reductions in damage were attributed to increased parasitism by *Bathyplectes* spp. (Hymenoptera: Ichneumonidae) wasps and infection by *Zoopththora* spp. pathogenic fungi (Stamps et al. 2009).

Economic analysis of farmscaping is difficult because few studies are able to quantify the reductions in pest populations as a result of habitat manipulation. Although costs can be calculated relatively easily, it is more difficult to quantify the benefits. Furthermore, the benefits to society, such as reduction in environmental pollution and negative effects on applicators because of fewer pesticide applications, may be greater than those to the individual farmer (Griffiths et al. 2008). Ecosystem services provided through farmscaping can be numerous. Besides providing resources for pollinators and beneficial insects, farmscaping can contribute to water quality, erosion control, sediment retention, nutrient cycling, and genetic resources. These nonmarket value services are irreplaceable but can be difficult to calculate and are often not included in simple cost–benefit analyses (Costanza et al. 1997). Cost-share programs such as the Conservation Reserve Program administered through the U.S. Department of Agriculture provide funding and services to help offset the costs associated with conserving and maintaining soil and water resources, including many functions associated with farmscaping. Combined with additional financial incentives and governmental policy programs such as carbon credits, these programs would help improve grower adoption of farmscaping and other sustainable practices.

Scale and Landscape. There is no doubt that farmscaping has the potential to offset insecticide use and maintain pest populations below threshold with minimal inputs and minimal disturbance to the agroecology. However, to date, only a handful of studies have quantitatively measured the impact of farmscaping on pest suppression. Although most research to date has focused on insect populations at a single scale of land use, recently there has been an emphasis on scale, both spatial and temporal, as well as farmscape arrangement.

For example, O'Rourke et al. (2011) found that diverse agricultural landscapes support pest management by directly suppressing pests and by enhancing natural enemy populations and conclude that insect densities and land use interact in very complex ways. In addition, pest suppression is likely to be influenced by landscape diversity, and it has been proposed that local land use matters more where the regional landscapes are less diverse (Tscharntke et al. 2005, 2012; Schmidt et al. 2008; Zaller et al. 2008; Gardiner et al. 2009; O'Rourke et al. 2011). Thus, the ability of a grower to manipulate insect populations by farmscaping may depend on the regional landscape structure; therefore, it is important to examine farm-level diversity in the context of regional landscape diversity. Increasing the spatial scales at which these programs are conducted may lead to better predictions about the effects of diversity on insect populations and pest suppression on a local scale.

Summary and Future Directions

We have come a long way in our understanding of the ecology in farmscaping systems and over the past few decades, our understanding of how plant-provided resources enhance natural enemy activity has greatly increased (Powell 1986, van Emden 1990, Heimpel and Jervis 2005). Nevertheless, insecticide applications remain the predominant strategy used by growers to control pests of vegetable crops. However, in the interest of human and environmental safety, as well as IPM, there is an increasing need for alternative control methods. A thorough understanding of how plant-provided resources and plant diversity influence natural enemy abundance, movement, and pest suppression in adjacent cash crops may provide alternative control methods. Alternative controls should reduce pesticide use, thereby slowing the rate of insecticide resistance and reducing pesticide exposure to the applicator and surrounding environment.

It is also important to remember that while the primary goal of farmscaping is to attract and conserve beneficial insects, farmscapes may serve a number of other purposes as well. Farmscape plantings can be arranged in one or a combination of designs and farm sites. In addition, other practices such as growing herbs and cut flowers can add diversity as well as value to farming operations and enhance pollination and other ecosystem services. Therefore, while there may not be obvious or immediate pest management advantages to farmscaping, additional ecological and economic advantages exist (Fiedler et al. 2008, Frank et al. 2008, Hannon and Sisk 2009, Isaacs et al. 2009, Smukler et al. 2010, Gurr et al. 2012, Morandin and Kremin 2013).

The literature is replete with evidence that farmscaping attracts and conserves beneficial insects. It is also well documented that predators and parasitoids play an important role in regulating many pest populations, even at low numbers. However, comprehensive experiments that evaluate natural enemy conservation as well as determine the true impact of farmscaping on pest suppression are needed. Such studies will be complex and confounded by the fact that generalist predators may be destabilizing these food webs through intraguild predation and omnivory, or they may be playing a more important role in pest suppression than previously thought. Future research should focus on improving our ability to unambiguously evaluate if, in fact, plant-provided resources lead to improved pest suppression. Critical issues include investigating the biology, habitat use, and predation impacts of generalist predators, natural enemy, and pest dispersal from nectar sources, responses of pests to nectar sources, and the impact of plant-provided resources and diversity on intraguild predation and predator–predator interactions. While numerous gaps in our understanding of these systems remain, plant-provided resources and the diversification of agroecosystems may provide growers new biological control options and dynamic thresholds with the potential to reduce insecticide use. With continued efforts and research, the long-term goal of improving IPM program using farmscapes may be feasible (Gurr and Wratten 2000, Wratten et al. 2003, Gurr et al. 2005, Heimpel and Jervis 2005).

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