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Review

# Biological control of arthropod pests using banker plant systems: Past progress and future directions

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ABSTRACT

The goal of banker plant systems is to sustain a reproducing population of natural enemies within a crop that will provide long-term pest suppression. The most common banker plant system consists of cereal plants infested with *Rhopalosiphum padi* L. as a host for the parasitoid *Aphidius colemani* L. *Aphidius colemani* continually reproduce and emerge from the banker plants to suppress aphid pests such as *Aphis gossypii* Glover and *Myzus persicae* Sulzer. Banker plant systems have been investigated to support 19 natural enemy species targeting 11 pest species. Research has been conducted in the greenhouse and field on ornamental and food crops. Despite this there is little consensus of an optimal banker plant system for even the most frequently targeted pests. Optimizing banker plant systems requires future research on how banker plants, crop species, and alternative hosts interact to affect natural enemy preference, dispersal, and abundance. In addition, research on the logistics of creating, maintaining, and implementing banker plant systems is essential. An advantage of banker plant systems over augmentative biological control is preventative control without repeated, expensive releases of natural enemies. Further, banker plants conserve a particular natural enemy or potentially the 'right diversity' of natural enemies with specific alternative resources. This may be an advantage compared to conserving natural enemy diversity per se with other conservation biological control tactics. Demonstrated grower interest in banker plant systems provides an opportunity for researchers to improve biological control efficacy, economics, and implementation to reduce pesticide use and its associated risks.



## 1. Introduction

Interest in biological control has increased over recent decades for many reasons (van Lenteren and Woets, 1988; Bailey et al., 2009). First, a greater appreciation for environmental stewardship among regulators, growers, and the public has promoted development of more sustainable farming practices (Kogan, 1998). Second, a number of arthropod pests have developed resistance to one or more pesticides leaving growers to search for alternative management strategies (McCaffery, 1998). Finally, consumers increasingly demand products that are grown in a sustainable manner and are free of insecticide residue (Dabbert et al., 2004). Despite this, growers have been slow to adopt biological control as part of their pest management program. For example, biological control is practiced in just 5% of the estimated 741,290 acres of greenhouses worldwide (van Lenteren, 1995). The primary factors affecting adoption of biological control are efficacy, predictability, and cost (Parrella et al., 1992; Van Driesche and Heinz, 2004).

Banker plant or open-rearing systems combine aspects of augmentative and conservation biological control in an attempt to mitigate these factors. Banker plant systems typically consist of a non-crop plant that is deliberately infested with a non-pest herbivore (e.g. Hansen, 1983; Bennison and Corless, 1993; Van Driesche et al., 2008; but see Stacy, 1977; Pickett et al., 2004). The non-pest herbivore serves as an alternative host for a parasitoid or predator of the target crop pest. As a form of conservation biological control, banker plant systems provide alternative food or hosts for natural enemies so they can survive and reproduce for long periods even when no pests are present (e.g. Stacey, 1977; Hansen, 1983; Bennison, 1992). However, as in augmentative biological control, a specific natural enemy is established on the banker plants to target a specific pest (e.g. Stacey, 1977; Hansen, 1983; Bennison, 1992). By increasing survival and reproduction of natural enemies within the cropping system, banker plant systems are intended to provide preventative, long-term suppression of arthropod pests.

Banker plant systems have received relatively little attention from researchers compared to augmentative or conservation biological control despite their potential to improve biological control efficacy and adoption. For example a topic search for "conservation biological control" or "augmentative biological control" in Web of Science retrieves 175 and 119 papers, respectively. In contrast, a topic search for "'banker plant' or 'open rearing system'" retrieves just 15 papers. Other papers exist but are found in conference

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proceedings or other less accessible sources. The difficulty in accessing these papers makes a review of the topic especially pertinent. This will increase awareness of banker plant systems and provide access to knowledge that would be limited without the library resources available at large academic institutions.

In this paper, I review existing research on banker plant systems with a view toward improving the efficacy and implementation of banker plant systems in the future. To this end I organized this paper into the following sections. First, I describe banker plant systems and provide a review of past research. Second, I identify key factors that affect the efficacy and practicality of banker plant systems and which are in need of future research. Third, I discuss approaches to improve research and adoption of banker plant systems. Finally, I present potential advantages of banker plant systems compared to augmentative and conservation biological control. By presenting past research and a path for future progress I hope to increase the rigor and scope of research on this promising biological control tactic.

## 2. Materials and methods

ISI Web of Knowledge, Agricola, and Biological and Agricultural Index databases were searched using the terms "banker plant" or "open-rearing system" which primarily located papers in peer-reviewed journals. The literature cited in these papers was used to identify articles in the gray literature such as conference proceedings and bulletins. Two types of papers were included in the review. Papers that implemented banker plant systems in greenhouses or field cropping systems (Table 1) and papers that investigated some aspect of natural enemy life history or behavior with the stated goal of improving banker plant systems (Table 2). Papers were included even if they did not meet the standards of scientific rigor used by other review papers (e.g. Collier and Van Steenwyk, 2004; Wade et al., 2008). Thus, papers without statistically sound experimental designs were included to shed light on the breadth of agricultural systems, pests, and natural enemies for which banker plant systems have been investigated. To present this breadth of research, multiple studies within a paper are listed separately in Table 1.

## 3. Results and discussion

A total of 29 studies in 21 publications were found that implemented banker plants in greenhouse or outdoor cropping systems (Table 1). Another 30 studies in 13 publications addressed natural enemy behavior or life history with the goal of improving banker plant systems (Table 2). As some publications contained both types of studies a total of 31 publications were included (Tables 1 and 2). Of the 31 publications 14 (45%) were published in one of 10 different peer-reviewed journals. Of the remaining publications 8 (26%) were published in bulletins of the International Organization for Biological Control (IOBC) and 9 (29%) were published as conference proceedings, dissertations, or book chapters. Twenty three (74%) of the 31 papers reviewed had scientists from European institutions as first author compared to 4 (13%) from North America, 3 (10%) from Asia, and 1 (3%) from South America. This likely reflects the emphasis placed on biological control in Europe compared to other parts of the world (van Lenteren and Woets, 1988).

### 3.1. Description of banker plant systems and review of past research

Banker plant systems consist of a plant that directly or indirectly provides resources, such as food, prey, or hosts, to natural enemies that are deliberately released within a cropping system. The goal of banker plant systems is to sustain a reproducing population of those natural enemies within a crop to provide season long control of a particular pest. Stacey (1977) published the first paper describing a banker plant system. This system was designed to suppress whitefly, *Trialeurodes vaporariorum* Westwood (Hemiptera: Aleyrodidae), populations in greenhouse tomatoes by supporting populations of *Encarsia formosa* Gahan (Hymenoptera: Aphelinidae). Stacey (1977) attempted to find a compromise between the two augmentative release methods considered most reliable at the time. These were the 'pest in first' method in which growers deliberately infest their crop with whitefly in order to support parasitoids and the 'multiple release' method in which parasitoids are released repeatedly throughout the season (van Lenteren and Woets, 1988). Stacey (1977) grew tomato plants in a greenhouse separate from the tomato crop, infested them with whitefly, and then allowed *E. formosa* to colonize the whitefly nymphs. These plants were placed in a production greenhouse at a density of 1 banker plant per 350–625 crop plants. This early experiment demonstrated that *E. formosa* populations could be sustained for over 8 weeks on banker plants. However, whiteflies eventually moved onto crop plants.

To avoid introducing pests into crop plants, research began to focus on using non-crop banker plants infested with non-pest alternative prey or hosts. Aphids were the target pest in 25 (86%) of the studies that implemented banker plant systems perhaps due to the availability of alternative hosts (Table 1). A typical banker plant system targeting aphids uses a cereal such as wheat or barley to support populations of bird cherry–oat aphids, *Rhopalosiphum padi* L. (Hemiptera: Aphididae). *Rhopalosiphum padi* feeds only on grasses (Poaceae) and so is not a threat to most greenhouse vegetable or ornamental crops. *Rhopalosiphum padi* serves as an alternative host for the parasitoid *Aphidius colemani* that also parasitizes pests such as *Aphis gossypii* Glover (Hemiptera: Aphididae). *Aphis gossypii* is one of the most frequent and damaging pest of greenhouse vegetable and flower production in the world and was investigated in 76% of studies targeting aphids though often in combination with other species such as *Myzus persicae* Sulzer (Hemiptera: Aphididae) (Blumel, 2004; Van Driesche et al., 2008). Several studies have tested a banker plant system consisting of cereal plants, *R. padi*, and *A. colemani* to target *A. gossypii* and found that parasitism is generally greater and aphid populations are lower in greenhouses with banker plants compared to those without banker plants (Mulder et al., 1999; Conte et al., 2000a; Goh et al., 2001).

Jacobson and Croft (1998) tested wheat, rye, and corn as banker plants to support *R. padi* and *A. colemani*. In a comprehensive series of experiments, they compared three densities of banker plants (1 banker plant/50, 75, or 150 $m^2$) to the multiple release, or 'trickle', method of sustaining *A. colemani* populations in the greenhouse. Both release methods maintained aphid densities well below those in greenhouses with no parasitoids. However, in each experiment the method that offered superior control of aphids was dependent on banker plant density, release rate, and season. Further, control was not always below thresholds acceptable to growers (Jacobson and Croft, 1998). Similar variability was found in recent banker plant research in which *A. colemani* was supported by *R. padi* on barley (Van Driesche et al., 2008). In small research greenhouses *A. colemani* suppressed population growth of *A. gossypii* on daisy and *M. persicae* on pansy compared to populations in the absence of banker plants (Van Driesche et al., 2008). However, banker plants with *A. colemani* did not suppress *A. gossypii* population growth on pansy or *M. persicae* on daisy. Further, adequate suppression of *M. persicae* on pansy (only combination tested) was not achieved in commercial greenhouses (Van Driesche et al., 2008).

In the majority (92%) of studies implementing banker plant systems aphids were targeted with parasitoids, particularly

**Table 1**
Research and demonstration projects that have implemented banker plant systems in greenhouse and outdoor ornamental and food crops. References that included more than one study are listed multiple times.

| Target pests | Natural enemies | Banker plant | Alternative host | Crop | Trophic level data[a] | Reference |
|---|---|---|---|---|---|---|
| *A. gossypii* | *A. colemani, A. aphidimyza* | Barley | *S. graminum* | Melon | 3, 2 | 1 |
| *A. gossypii* | *A. colemani* | Wheat | *R. padi* | Melon | 2 | 2 |
| *A. gossypii* | *A. colemani* | Wild grasses | *R. padi* | Melon | 2 | 2 |
| *A. gossypii* | *L. testaceipes, A. colemani* | Wild grasses | *R. padi* | Cucumber | 2 | 3 |
| *A. gossypii* | *A. colemani* | Barley | *R. padi* | Watermelon | 2 | 4 |
| *A. gossypii* | *A. colemani* | Barley | *R. padi* | Cucumber | 2 | 4 |
| *A. gossypii* | *A. colemani* | Maize, rye grass, wheat | *R. padi* | Cucumber | 2 | 5 |
| *A. gossypii* | *A. colemani* | Maize | *R. padi* | Cucumber | 2 | 5 |
| *A. gossypii* | *A. colemani* | Maize | *R. padi* | Cucumber | 2 | 5 |
| *A. gossypii* | *A. colemani* | Maize | *R. padi* | Cucumber | 2 | 5 |
| *A. gossypii* | *A. matricarae, A. aphidimyza, C. carnea* | Wheat | *R. padi* | Cucumber | 3, 2, e | 6 |
| *A. gossypii* | *A. colemani, A. aphidimyza* | Wheat, Barley | *R. padi* | Cucumber | 3, 2 | 7 |
| *A. gossypii* | *A. colemani* | Millet | *R. padi* | Melon | 3, 2 | 8 |
| *A. gossypii* | *A. colemani* | Millet | *R. padi* | Cucumber | 3, 2 | 9 |
| *M. persicae* | *A. aphidimyza* | Broad beans | *M. viciae* | Pepper | 3, 2 | 10 |
| *M. persicae* | *E. cerasicola* | Paprika | *M. persicae* | Paprika | 3, 2, 1 | 11 |
| *M. persicae* | *A. abdomnialis* | Oats | *S. avenae, M. dirhodum, R. padi* | Pepper | 3, 2 | 12 |
| *A. gossypii* | *L. testaceipes* | Sorghum | *S. graminum* | Pepper | 3, 2 | 13 |
| *B. brassicae* | *D. rapae* | Cabbage, turnip | *B. brassicae, M. persicae, M. euphorbiae* | Cauliflower | 3, 2 | 14 |
| *M. euphorbiae, M. persicae* | *A. abdomnialis* | Potato | *M. euphorbiae* | Roses | 2 | 15 |
| *A. gossypii, M. persicae* | *A. colemani* | Barley | *R. padi* | Red pepper | 2 | 4 |
| *A. gossypii, M. persicae* | *A. colemani* | Barley | *R. padi* | Pansies, daisies | 2 | 16 |
| *A. gossypii, M. persicae* | *A. colemani* | Barley | *R. padi* | Pansies, daisies | 2 | 16 |
| *A. gossypii, A. solani, M. euphobiae* | *A. colemani, A. ervi, L. testaceipes, A. aphidimyza* | Not reported | *R. padi* | Cucumber | 3, 2 | 17 |
| *A. gossypii, T. urticae, T. vaporariorum* | *A. colemani, P. persimilis, E. formosa* | Barley | *R. padi* | Watermelon | 3, 2 | 18 |
| *B. tabaci* | *E. hayati* | Cantaloupe | *B. tabaci* | Cantaloupe | 3, 2 | 19 |
| *B. tabaci* | *E. hayati* | Cantaloupe | *B. tabaci* | Cantaloupe | 3, 2 | 19 |
| *T. vaporariorum* | *E. formosa* | Tomato | *T. vaporariorum* | Tomato | 3, 2 | 20 |
| *T. vaporariorum* | *D. hesperus* | Mullen | *Mullen* | Tomato | 3, 2, e | 21 |

1, Kim and Kim (2004); 2, Conte et al. (2000a); 3, Conte et al. (2000b); 4, Goh et al. (2001); 5, Jacobson and Croft (1998); 6, Bennison (1992); 7, Bennison and Corless (1993); 8, Schoen and Martin (1997); 9, Schoen (2000); 10, Hansen (1983); 11, Hofsvang and Hågvar (1979); 12, Kuo-Sell (1989); 13, Rodrigues et al. (2001); 14, Freuler et al. (2003); 15, Blumel and Hausdorf (1996); 16, Van Driesche et al. (2008); 17, Bünger et al. (1997); 18, Goh (1999); 19, Pickett et al. (2004); 20, Stacey (1977); 21, Lambert et al. (2005).

[a] This refers to the trophic level on which data was collected based on the conceptual model developed by Gurr et al. (2000). 3 indicates data was collected on natural enemy abundance/behavior; 2 indicates data was collected on changes in pest abundance, predation, or parasitism; 1 indicates data was collected on changes in plant quality or yield; e indicates an attempt to assess the economic cost or value associated with banker plants.

*A. colemani* L. (Hymenoptera: Braconidae) (Table 1). However, predators have also been used alone or in conjunction with parasitoids to manage *A. gossypii* or other aphids (Table 1). A unique approach is the use of the specialist predator *Aphidoletes aphidimyza* Rondani (Diptera: Cecidomyiidae) in combination with or instead of parasitoids (Hansen, 1983; Bennison, 1992; Bennison and Corless, 1993; Bünger et al., 1997; Kim and Kim, 2004). This gall midge has predacious larvae which consume aphids after paralyzing them by injecting them with toxin (Harris, 1973). Adults lay eggs near aphids and have an exceptional ability to locate even small aphid colonies (Mansour, 1975). Developing banker plant systems to support this predator is complicated by its need to pupate in soil rather than pupating on plants within aphid mummies as parasitoids do. This was addressed by providing capillary matting as a substrate for pupation by Bennison (1992) but not by other researchers (Hansen, 1983; Bünger et al., 1997; Kim and Kim, 2004). The practicality and efficacy of *A. aphidimyza* banker plant systems requires further refinement and demonstration. Research to date has often included augmentative releases of *A. aphidimyza* in addition to banker plant populations (Kim and Kim, 2004) or in addition to parasitoid banker plant systems (Bennison and Corless, 1993; but see Hansen, 1983) rather than self-sustaining populations on banker plants.

Banker plant systems have been tested that target pests other than aphids. Banker plants targeting whiteflies were investigated in 5 (17%) studies (Stacey, 1977; Goolsby and Ciomperlik, 1999; Pickett et al., 2004; Lambert et al., 2005). Lack of alternative hosts that are not crop pests has hampered the development of banker plants targeting whitefly. Thus, as in original experiments by Stacey (1977), *Bemisia tabaci* Gennadius (Hemiptera: Aleyrodidae) or *T. vaporariorum* are both pest and alternative host for *Eretmocerus hayati* Zolnerowich and Rose (Hymenoptera: Aphelinidae) or *E. formosa*, respectively (Goolsby and Ciomperlik, 1999; Pickett et al., 2004). Perhaps inspired by this problem Lambert et al. (2005) investigated using mullen *Verbascum thapsus* L. (Scrophulariaceae) to provide plant food for the omnivorous predator *Dicyphus hesperus* Knight (Hemiptera: Miridae). Arnó et al. (2000) took a similar approach and found that, *Nicotiana* spp. (Solanaceae) could be used to both attract and maintain populations of the omnivorous predator *Macrolophus caliginosus* Wagner (Hemiptera: Miridae) for whitefly control in greenhouse tomatoes. A concern with this system is that, as omnivores, these mirid bugs can damage tomato leaves and fruit (Alomar and Albajes, 1996; Albajes and Gabarra, 2003). However, development of banker plant systems that require only plants to provide pollen or other resources may simplify implementation and maintenance.

**Table 2**
Research projects that have investigated natural history, behavior, or ecology of natural enemies, alternative foods, or pests with the stated goal of improving banker plant systems for use in greenhouse and outdoor agricultural systems.

| Target pests | Natural enemies | Banker plant | Alternative host | Crop | Objective (number of experiments) | Reference |
|---|---|---|---|---|---|---|
| *A. gossypii* | *A. colemani* | Barley | *R. padi* | Watermelon | Evaluate parasitoid oviposition preference and development in relation to aphid size and temperature (4) | 1 |
| *A. gossypii* | *E. cerasicola* | Swede | *M. persicae* | Cucumber | Determine the effect of parasitoid larval host on female parasitoid choice (2) | 2 |
| *M. persicae* | *E. balteatus* | Barley | *R. maidis* | Pepper | Determine if banker plants attract retain syrphid flies in greenhouses (1) | 3 |
| *M. persicae* | *A. aphidimyza* | None | *S. avenae*, *M. dirhodum*, *R. padi* | Pepper | Evaluate the nutritive value of four aphid species for *A. aphidimyza* (2) | 4 |
| *M. persicae* | *L. testaceipes*, *A. colemani* | Wheat | *S. graminum* | Beans | Evaluate reproduction of each parasitoid on both aphid species (1) | 5 |
| *M. persicae* | *A. aphidimyza* | None | *M. dirhodum* | None | Evaluate nutritive value of two aphid species for *A. aphidimyza* (3) | 6 |
| *A. gossypii*, *M. persicae* | *A. colemani* | None | None | None | Evaluate survival of *A. colemani* exposed to two insecticides to be used in combination with banker plants (1) | 12 |
| *B. argentifolii* | *E. hayati* | Cantaloupe | *B. argentifolii* | Cantaloupe | Develop method for producing cantaloupe banker plants, evaluate parasitoid emergence from banker plants in field, and the effect of imidacloprid on whitefly and parasitoid development (4) | 7 |
| Unnamed whitefly | *M. caliginosus* | Tobacco | Tobacco | Tomato | Determine if tobacco plants attract predators into greenhouse and provide overwintering habitat (2) | 8 |
| *F. occidentalis* | *A. degenerans* | Castor beans | Pollen | Pepper | Investigate mite movement from banker plants to crop plants (1) | 9 |
| *F. occidentalis* | *A. degenerans* | Castor beans | Pollen | Pepper | Investigate mite dispersal from banker plants and how diets of pollen and prey affect mite fecundity (3) | 10 |
| *T. urticae* | *N. fallacis* | Arborvitae | *O. ilicis*, *O. ununguis* | None | Investigate dispersal of predatory mites from banker plants in nurseries (3) | 11 |
| *Liriomyza spp.* | *Dacnusa sibirica*, *Opius pallipes*, *Diglyphus isaea* | *Ranunculus asiatica* | *Phytomyza caulinaris* | Tomato, lettuce | Evaluate the suitability of Ranunculus spp. for an alternative host of three parasitoids targeting leaf miner pests (3) | 13 |

1, Goh et al. (2001); 2, Hågvar and Hofsvang (1994); 3, Pineda and Marcos-García (2008); 4, Kuo-Sell (1989); 5, Starý (1993); 6, Kuo-Sell (1987); 7, Goolsby and Ciomperlik (1999); 8, Arnó et al. (2000); 9, Ramakers and Voet (1996); 10, Ramakers and Voet (1995); 11, Pratt and Croft (2000); 12, Van Driesche et al. (2008); 13, van der Linden (1992).

Plant provided resources have also been investigated to create banker plant systems to support predatory mites (Ramakers and Voet, 1995, 1996). In the only banker plant studies targeting thrips, castor bean *Ricinus communis* L. (Euphorbiaceae) plants were used to support populations of the predatory mite *Amblyseius degenerans* Berlese (Acari: Phytoseiidae) (Ramakers and Voet, 1995, 1996). Castor bean pollen increased *A. degenerans* reproduction as well as prey and was superior to pollen from other plant species (Ramakers and Voet, 1995). After 4 months each banker plant supported 11,500 mites [100-fold increase] although dispersal throughout greenhouse crops of sweet pepper and cucumber was relatively slow (Ramakers and Voet, 1995, 1996). A similar system targeting thrips uses 'Black Pearl' ornamental peppers as a pollen source to support *Orius insidiosus* Say (Hemiptera: Anthocoridae). This system has been described in industry publications (e.g. Wainwright-Evans, 2009), suggesting interest among growers, but no scientific research has been published investigating its efficacy.

Only two banker plant systems have been investigated for use in outdoor growing systems. Pratt and Croft (2000) investigated dispersal of predatory Phytoseiid mites from arborvitae (*Thuja occidentalis* 'Pyramidalis) banker plants in a nursery setting. Pickett et al. (2004) conducted a rigorous set of experiments to determine if a banker plant system consisting of cantaloupe seedlings infested with *B. tabaci*, and *Eretmocerus* spp. (Hymeoptera: Aphelinidae) parasitoids could suppress *B. tabaci* in cantaloupe fields. Initial work developed the banker plant system by testing the preference of *B. tabaci* and *E. hayati* for different cantaloupe varieties (Goolsby and Ciomperlik, 1999). The variety selected was least preferred by *B. tabaci* but produced the most parasitoids indicating either a preference for oviposition in that variety or increased survival of parasitoid larvae (Goolsby and Ciomperlik, 1999). Field experiments demonstrated good parasitoid survival under commercial growing conditions with a production rate of approximately 100 parasitoids per plant and nearly 30,000 and 69,000 per acre in two different years of the study (Goolsby and Ciomperlik, 1999). In 2 years of replicated field experiments at commercial farms suppression of *B. tabaci*, as measured by percent parasitism, was greater in fields with banker plants than those where *E. hayati* was hand released and fields with no-parasitoid augmentation (Pickett et al., 2004).

### 3.2. Factors that affect the efficacy and practicality of banker plant systems

Banker plant systems consist of three basic components: host plant, alternative host or prey, and natural enemies. In the following sections, I identify specific aspects of each component that affect the efficacy and practicality of banker plant systems. In each section, I discuss existing research that could benefit the development of banker plant systems. Some research discussed may not have been intended to support the development of banker plant systems but demonstrates useful experimental approaches to optimizing each component of banker plant systems.

#### 3.2.1. Banker plant species

Many different banker plant species have been tested in studies implementing banker plant systems. However, plant species have not been systematically evaluated for their effect on the growth of alternative hosts and natural enemies. Plants of low quality for herbivores due to low nutrition or high defenses – can reduce herbivore development and reproduction (Price et al., 1980). This reduces the number of hosts available for parasitoids (or prey for other natural enemies) and restricts their ability to reproduce. Further, the development time, longevity, and death rate of parasitoids can be affected by the plant on which their host is feeding (Price et al., 1980; Turlings and Benrey, 1998; Caron et al., 2008; Inbar and Gerling, 2008). Commercially available banker plant systems can be barley infested with *R. padi* (IPM Laboratories, Inc.) or winter wheat infested with *Sitobion avenae* (Koppert Biological Systems) that can be infested with parasitoid wasps or syrphid flies. However, research indicating that barley or wheat plants support development and reproduction of parasitoids, such as *A. colemani*, better than other similar plants is lacking. Therefore, efficacy and implementation of banker plant systems will benefit from research that determines how plant species affects natural enemy behavior and population growth.

It is important that banker plants can be grown quickly and inexpensively. Plants also need to be compatible with horticultural requirements, such as light and temperature, of the crop with which they are grown. Plants must also remain healthy under severe feeding by aphids or other herbivores (Kim and Kim, 2004). Bennison (1992) found that wheat would often succumb to mildew or disease and need to be replaced. Likewise, Jacobson and Croft (1998) found corn would sustain feeding by *R. padi* for 4 months where as ryegrass and wheat needed to be replaced more frequently. Plant cultivars that are resistant to disease may also improve the health and longevity of banker plants.

### *3.2.2. Alternative prey or host species*

Similar to plant species, banker plant experiments and demonstrations have used many different alternative prey species to support natural enemies. Alternative host or prey characteristics influence natural enemy development time, birth rate, death rate, and sex ratio. Development of parasitoids can differ between herbivore species on the same plant species (Hoddle et al., 1998; Ode et al., 2005). Similarly, parasitoid development can be affected by host size or instar (Hoddle et al., 1998; Chau and Mackauer, 2001; Henry et al., 2005). For example, survival to emergence of *A. colemani* is lower and offspring sex ratio is more male biased in *R. padi* – an alternative host in banker plants systems – than in *A. gossypii*, *M. persicae*, and *Schizaphis graminum*. Aphid species also have different nutritive value for predators such as *A. aphidimyza* wherein, adult weight and egg production are less when fed *M. persicae* compared to three other aphid species (Kuo-Sell, 1987, 1989).

Alternative hosts can also affect natural enemy feeding and oviposition preference. Strong preference for alternative hosts on banker plants could reduce parasitoid efficacy in the crop. Ode et al. (2005) found that *R. padi*, which is commonly used as an alternative host in banker plant systems, was least preferred for oviposition by *A. colemani* compared to three greenhouse pests targeted by banker plant systems: *A. gossypii*, *M. persicae*, and *S. graminum*. This is a positive finding because it suggests that *A. colemani* will utilize the alternative host when pests are absent but parasitize pests when they are present. Similar lines of research describe how host or prey type affects attack rate and abundance of other natural enemies such as the whitefly parasitoid *E. formosa* (Hoddle et al., 1998).

Providing plant based resources such as pollen and leaves instead of alternative prey or hosts could be a useful approach to developing banker plant systems. This approach reduces the complexity of banker plant systems and seems particularly appropriate for predatory mites (McMurtry and Croft, 1997). Castor bean pollen supported reproduction by the predator *A. degenerans* as well as prey (Ramakers and Voet, 1995). Pollen increases reproduction by *Amblyseius hibisci* Chant (Acari: Phytoseiidae) resulting in greater biological control of the pest tetranychid mites (McMurtry and Scriven, 1966a,b). Similarly, mullen plants increase the longevity and birth rate of *D. hesperus* increasing its abundance in tomato greenhouses (Sanchez et al., 2003). However, *D. hesperus* remains on mullen for longer periods of time than peppers and will also feed on the leaves and fruit of tomatoes and other plant species (McGregor et al., 2000; Van Laerhoven et al., 2006). Thus, although plant–omnivore associations show potential for banker plant systems, omnivores present many challenges to biological control (Coll and Guershon, 2002).

### *3.2.3. Natural enemy species*

As discussed so far, the abundance and attack rate of natural enemies is intimately linked to herbivores and plants. Factors, such as diet breadth, dispersal ability, and intrinsic rate of increase, differ between natural enemy species and could also determine the efficacy of one natural enemy species over another (van Steenis, 1992). Literature on many ecological issues, that affect biological control such as diet breadth (Symondson et al., 2002; Coll and Guershon, 2002), intraguild predation (Rosenheim et al., 1995), and natural enemy diversity (Straub et al., 2008), has been reviewed recently and are beyond the scope of this review. I will discuss these issues only as they are likely to affect the development and implementation of banker plant systems.

The abundance of natural enemies in a habitat is affected by births, deaths, immigration, and emigration. In greenhouse production systems immigration and emigration are restricted to varying degrees because they are enclosed buildings (van Lenteren and Woets, 1988; Avilla et al., 2004). Therefore, births and deaths are the primary factors affecting the abundance of natural enemies in greenhouses. On the same host, parasitoid species differ in factors affecting their intrinsic rate of increase ($r$). For example, with *A. gossypii* as a host, *A. colemani* and *Aphelinus varipes* Förster (Hymenoptera: Aphelinidae) differ in fecundity, oviposition rate, development time, survival, sex ratio of adults, and $r$ (van Steenis, 1992; Chau and Heinz, 2004; Yano, 2006). Therefore, the abundance of *A. colemani* ($r = 0.44$ at 25 °C) would increase faster than *A. varipes* ($r = 0.29$ at 25 °C) and the population would be more female biased (Yano, 2006). However, $r$ may be a poor indicator of natural enemy efficacy because the ability to suppress pest populations is dependent on attack rate per natural enemy not simply birth rate or abundance (Holt and Lawton, 1994; Yano, 2006).

Attack rate of a natural enemy depends, in part, on their ability to locate and travel to a pest. Aphid specialists such as *Aphidius* spp. and *A. aphidimyza* increase the efficacy of biological control by using olfactory cues to locate aphids and their host plants (Du et al., 1996; Choi et al., 2004). In addition, natural enemies that fly tend to disperse more efficiently than natural enemies that walk (Heinz, 1998; Osborne et al., 2004). For example, the parasitoid *A. colemani* disperses greater distances than larvae of *Chrysoperla rufilabris* Burmeister (Neuroptera: Chrysopidae) after 10 h in a greenhouse (Heinz, 1998). As a consequence *A. colemani* located 97% of aphid infested plants whereas *C. rufilabris* located 50% fewer (Heinz, 1998). Similarly, predatory mites disperse less efficiently than parasitoids and flying predators such as *A. aphidimyza* (Ramakers and Voet, 1995, 1996; Pratt and Croft, 2000; van Schelt and Mulder, 2000). Natural enemy dispersal is a more important factor in banker plant systems than in augmentative biological control where the grower may disperse natural enemies throughout the crop by hand.

The value of "generalist" compared to "specialist" natural enemies in biological control has been debated for many years (Coll and Guershon, 2002; Symondson et al., 2002). In most cases, banker plant systems require a natural enemy to be generalist to the extent that they utilize the pest and the alternative host or prey. Using aphids as an example, there are three options of natural enemies. First is a parasitoid, such as *A. colemani*, that is an aphid specialist. Second, is *A. aphidimyza* which is a predator that specializes on aphids. Third, is a generalist predator such as *Orius* spp. (Hemiptera: Anthocoridae) or *Chrysoperla* spp. There are few data comparing the efficacy of these different natural enemy options. However, parasitoids that specialize on a particular host must kill that host in order to feed and reproduce. This obligatory link between reproduction and host killing ensures that parasitoids will kill banker plant alternative hosts or pest hosts rather than each other or non-target arthropods.

A few studies have incorporated more than one natural enemy into banker plant systems (Bennison, 1992; Bennison and Corless, 1993; Bünger et al., 1997; Goh, 1999; van Schelt and Mulder, 2000; Kim and Kim, 2004). Multiple natural enemy species can be used in biological control to increase suppression of a single pest species (Avilla et al., 2004; Chau and Heinz, 2004) and to target multiple pest species (Jacobson, 2004; Murphy and Broadbent, 2004). Multiple natural enemy species can improve biological control if they target different life stages of a pest species or occur in different parts of a habitat (Sih et al., 1998; Straub et al., 2008). However, antagonistic interactions between natural enemy species, such as intraguild predation, can reduce biological control (Rosenheim et al., 1995; Sih et al., 1998; Straub et al., 2008).

Multiple natural enemies to target a single pest species can be incorporated in banker plant systems by using two aphid specialists such as *A. colemani* and *A. aphidimyza* that would share the same banker plants (Bennison, 1992; Bennison and Corless, 1993; Conte et al., 2000b; Kim and Kim, 2004). Some authors have reported success of this method although evidence is based on small unreplicated experiments and was not compared to single natural enemy systems (Bennison, 1992; Bennison and Corless, 1993; Conte et al., 2000b; Kim and Kim, 2004). Combining a generalist natural enemy, such as lady beetles, with a specialist parasitoid can result in complementary control (Snyder et al., 2004) or intraguild predation of parasitoid mummies, depletion of alternative hosts by lady beetles, and reduced control (Rosenheim et al., 1995). It is possible that multiple banker plant species could be used to maintain multiple natural enemy species, but this has not been investigated. If multiple plant, prey, or natural enemies are investigated, examination of food-web structure could be a valuable tool to understand interactions most important for pest suppression under different circumstances (Tylianakis et al., 2007).

Timing of natural enemy release is important in augmentative biological control (Daane and Yokota, 1997; Yano, 2006; Lopes et al., 2009) and the same is true of banker plant systems (Kim and Kim, 2004; Crowder, 2007). Efficacy is maximized by introducing the natural enemies and banker plants before pests are on the crop (Kim and Kim, 2004; Yano, 2006; Lopes et al., 2009). This allows natural enemy abundance to increase on alternative hosts so they can quickly find and kill small populations of pests. This emphasizes the preventative rather than curative pest management goal of implementing banker plant systems.

### *3.3. Approaches to improve research and adoption of banker plant systems*

Information available to make recommendations on banker plant systems is limited because a small number of papers have been published in journals and proceedings that can be difficult to access. In addition, many reports on banker plant systems function as demonstrations rather than experiments that test a hypothesis because they lack statistically valid methods such as replication of experimental units and treatments that serve as experimental controls. For example, 10 of the 29 studies (34%) that implemented banker plant systems (Table 1) were conducted with banker plants as the only treatment (Stacey, 1977; Hansen, 1983; Bünger et al., 1997; Schoen and Martin, 1997; Conte et al., 2000a,b; Schoen, 2000; Rodrigues et al., 2001; Freuler et al., 2003; Lambert et al., 2005). Others have banker plants as a treatment in one greenhouse and a second treatment – no pest management, chemical control, or augmentative releases – in a second greenhouse (Kuo-sell, 1989; Goh, 1999; Goh et al., 2001; Kim and Kim, 2004). In this situation, pseudo-replication is a common pitfall wherein plants within a greenhouse are treated as experimental units to measure pest populations.

Experiments need to compare banker plant systems to a proper experimental control with no natural enemies or other management tactics and to currently recommended management tactics (Collier and Van Steenwyk, 2004). Therefore, an experiment should include chemical control or augmentative biological control as a treatment to demonstrate if banker plant systems provide pest suppression that is as good or better than what growers are already using (e.g. Kehrli and Wyss, 2001; Vasquez et al., 2006).

Conceptual models to improve and evaluate biological control research have been established by Wade et al. (2008) and Gurr et al. (2000) in which experiments are placed on a hierarchy indicating the level of 'success' that has been achieved and thus relevancy to growers. At the low end of these hierarchies are experiments demonstrating changes in natural enemy abundance or behavior (Gurr et al., 2000; Wade et al., 2008). Experiments demonstrating changes in pest abundance, yield, and profit rank increasingly higher because these results get closer to the ultimate goals of reducing insecticide use and improving profit (Gurr et al., 2000; Wade et al., 2008). Therefore, response variables should include measurements of pest density and some measure of yield in food crops or plant damage and aesthetic quality in ornamental crops. Pest density and yield variables need to be evaluated relative to thresholds established by growers or regulators rather than statistically significant differences between treatments (Kehrli and Wyss, 2001; Collier and Van Steenwyk, 2004). This information will allow the economic costs and benefits of banker plant systems to be evaluated.

### *3.4. Potential advantages of banker plant systems*

Augmentative and conservation biological control are practiced to varying degrees in greenhouse and field cropping systems (van Lenteren, 2000; Landis et al., 2000). A drawback of augmentative biological control is that natural enemies have to be purchased and released repeatedly or in large numbers to manage pests effectively which is generally more expensive than applying pesticides (Collier and Van Steenwyk, 2004; Van Driesche and Heinz, 2004; Vasquez et al., 2006). In a recent review, Collier and Van Steenwyk (2004) identify ecological factors that limit the efficacy of augmentative biological control in outdoor cropping systems. These factors were ranked by the number of times authors cited them as affecting the outcome of a study. The most commonly cited factor was "unfavorable environmental conditions" at the time of release (Kehrli and Wyss, 2001; Collier and Van Steenwyk, 2004). In banker plant systems, natural enemies develop and emerge continuously thus reducing the impact of unfavorable conditions on a single day (Pickett et al., 2004). The second most cited factor was "enemy dispersal" or emigration from the crop (Norton and Welter, 1996; Collier and Van Steenwyk, 2004). Factors that contribute to dispersal or disappearance of natural enemies include lack of prey and the third most cited factor intraguild predation (Rosenheim et al., 1995; Collier and Van Steenwyk, 2004; Crowder, 2007). Similar factors including "physical environment", "access to necessary food", and "conflicts with other natural enemies" were identified by Van Driesche and Heinz (2004) as affecting natural enemies in greenhouses. Banker plant systems have the potential to mitigate these factors because prey is continuously available and natural enemies that emigrate or are consumed will be replaced by newly emerging natural enemies.

The timing and method of natural enemy release is critical to biological control in greenhouse and outdoor cropping systems (van Lenteren and Woets, 1988; Collier and Van Steenwyk, 2004; Crowder, 2007). Proper timing of a release can be achieved by scouting to detect pests at very low densities when an augmentative release of natural enemies will be most effective (Van Driesche and Heinz, 2004). An alternative tactic, supported by recent theoretical research, is repeated releases of low densities of natural enemies to prevent pest outbreaks (Van Driesche and Heinz, 2004; Yano, 2006; Lopes et al., 2009). By placing banker plants in a greenhouse or field before pests arrive, the crop may be inoculated from pests by natural enemies that reproduce on the banker plants (Pickett et al., 2004; Yano, 2006). In addition, natural enemies are present all season long without having to repurchase and release them, which could be cost prohibitive (Collier and Van Steenwyk, 2004). For example, in corn, *Trichogramma* parasitoids may be released at 22,000 – over 3,000,000/ha at a cost of $4.75–$715.00/ha with no guarantee of success due to negative biotic and abiotic factors (Losey et al., 1995; Prokrym et al., 1992; Collier and Van Steenwyk, 2004). In cantaloupe fields, up to 100,000/acre (247,000/ha) *E. formosa* were released from banker plant systems over a 4-month-period without having to repurchase or release (Goolsby and Ciomperlik, 1999; Pickett et al., 2004). This could make banker plant systems more effective and economical than augmentative biological control.

In conservation biological control, natural enemies are not purchased but are attracted and sustained by providing them with resources and reducing negative cultural practices (Landis et al., 2000). However, although conservation biological control often increases natural enemy abundance, reduced pest abundance or increased yield has rarely been demonstrated (Jonsson et al., 2008). For example, flowering strips and other shelter habitats, as conservation biological control tactics, increase predation, parasitism, or yield in some cases but not others (Pfiffner and Wyss, 2004; Griffiths et al., 2008). In addition to natural enemies, conservation biological control tactics, such as habitat manipulation, attract and sustain a diverse suite of herbivores, detritivores, and plant provided foods (Landis et al., 2000; Frank and Shrewsbury, 2004). Banker plant systems often conserve a single natural enemy species that is selected for its efficacy in controlling target pests with a particular food resource. This could reduce interactions with intraguild predators and alternative foods that weaken biological control in some cases (Rosenheim et al., 1995; Symondson et al., 2002). However, research has also found that maintaining a diverse pool of natural enemies increases pest suppression in agriculture (Loreau et al., 2001; Tscharntke et al., 2005; Straub et al., 2008). Thus there is potential for banker plants to be used in maintaining multiple natural enemies to create the 'right diversity' (Landis et al., 2000 p. 177) to manage a particular pest complex (Bennison, 1992; Bünger et al., 1997; Goh, 1999; Kim and Kim, 2004).

If insecticide applications are required after an augmentative release, natural enemies that were purchased will be killed. Habitat manipulations such as beetle banks provide refuge from pesticide use and a source of natural enemies to replace those that are killed (Landis et al., 2000; Lee et al., 2001). A similar benefit exists with banker plant systems. If pesticide applications are necessary, banker plants can be protected by removing them from the greenhouse. After a safe interval, banker plants can be returned to the greenhouse to begin replacing natural enemies that were killed by pesticides. The option to use insecticides to control other pest species or eruptive populations may instill confidence in growers and increase implementation.

## 4. Conclusions

In a body of research spanning 32 years, researchers have investigated banker plant systems to support 19 natural enemy species targeting 11 pest species (Table 1). Despite this there is little consensus of an optimal banker plant system for even the most frequently targeted pest *A. gossypii*. As such, there is no foundation to make recommendations of specific plant-alternative host-natural enemy combinations that will provide reliable control for growers. Progress in development and implementation of banker plant systems has suffered from a lack of experimental rigor in some cases but primarily from the small amount of research than has been conducted on any particular system.

To improve efficacy and implementation of banker plants systems, basic biological and ecological research needs to be conducted on the plants, pests, alternative hosts, and natural enemies involved in a particular system and how they interact with each other. The effect of banker plants, crop species, pests, and alternative prey on natural enemies' behavior, preference, dispersal, birth rate, and death rate will help establish optimal banker plant systems for different agronomic situations. Research on the logistics of banker plants systems such as banker plant density in a greenhouse, initial density of alternative hosts and natural enemies, and creating and maintaining banker plants will also be essential. This will provide growers and extension personnel the tools necessary to implement banker plant systems. Finally, implementation of agronomic innovations requires on-farm trialing by researchers and growers to demonstrate the cost and benefits of an innovation under realistic circumstances (Pannell et al., 2006; Cullen et al., 2008).

'Success' in biological control can be measured as "...whether crop damage is reduced to the extent that adequate control – usually regarded as maintenance below the economic injury level – is afforded, and whether significant proportions of farmers adopt this approach to pest management" (Gurr et al., 2000 p. 112). This review highlights several potential advantages of banker plant systems that could make them more economical and efficacious than other augmentation or conservation biological control tactics. However, economic advantages such as continuous production and release of natural enemies may be counter-acted by costs associated with banker plant maintenance. Thus, even as research focuses on optimizing banker plant systems the economics of these systems needs to be evaluated. However, banker plant systems have been highlighted frequently in industry publications suggesting that there is interest in this technique and acceptance among growers (e.g. Gill et al., 2007; Wainwright-Evans, 2009). Grower interest provides a window of opportunity for researchers to help optimize the efficacy of these systems so adoption can be increased. If research demonstrates long-term, preventative, and inexpensive control of arthropod pests, banker plant systems have the potential to increase the success and implementation of biological control.

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