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The Banker Plant Method in Biological Control

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In the banker plant method, long-lasting rearing units for beneficials are created in the crop by distributing plants infested with herbivores or carrying other food items, such as pollen. The method has been widely investigated over many years and used to aid establishment, development and dispersal of beneficial organisms employed in biological control. In this review, we refine the definition of the banker plant method based on previous concepts and studies and offer the term "banker plant system" to describe the unit that is purposefully added to or established in a crop for

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control of pests in greenhouses or open field. The three basic elements of a banker plant system (banker plant, food source, beneficials) are discussed and illustrated with examples, and the diversity of banker plant systems (classified by target pest) used or investigated is documented. The benefits of using banker plant systems, such as low cost, increased freshness of beneficials, possibility for preventive control and for integration within IPM frameworks, make the method an interesting plant protection option with potential to enhance adoption of biological control in pest management programs.

Keywords banker plant, open-rearing, herbivores, beneficials, greenhouse crops, field crops, arthropod pests, biological control, pest management

I. INTRODUCTION

A. Historic Development of Biological Control in Greenhouses

The first consistent successful use of biological control of pests in greenhouses was recorded in 1927 (Speyer, 1927), however, development of biological control was interrupted with the arrival of new synthetic pesticides in the 1940s (Hussey, 1985). Biological control was subsequently revived in the 1960s and 1970s to deal with newly developed pesticide-resistant pests and further encouraged by the first successful implementations against spider mites and whiteflies (Bravenboer and Dosse, 1962; Parr, 1968; Hussey, 1985). Worldwide greenhouse area currently under biological control is estimated to be around 38,500 ha (van Lenteren, 2007).

In the early history of biological control, the strategy was to release beneficials early in the cropping cycle once pests were observed. Only a few releases were practiced to keep costs at levels acceptable to growers. This inoculative approach had its limitations, an important one being that releases needed to be made at the beginning of pest infestation when pest density was still low. Consequently, failure in establishment of the beneficials was a risk. Over the years, various methods have been developed and implemented in attempts to improve the establishment of beneficial populations (e.g., Gould *et al.*, 1975; Parr *et al.*, 1976). In recent years, biological control, especially with specialist natural enemies, has frequently been based on inundative strategies with repeated releases throughout most of or the whole cropping cycle, thus relying mainly on the immediate effect of released beneficials rather than on progeny production. This approach is especially important in high value crops such as ornamentals.

B. Aiding Beneficial Establishment

Beneficial establishment can be aided through the "pest-in-first" strategy where the grower deliberately initiates a small infestation of pests in the crop thereby creating a more stable foundation for establishment and build-up of the subsequently released beneficials. Although demonstrated as efficient (Markkula and Tiittanen, 1976; Waite, 2001) and although employed by some growers (Bolckmans and Tetteroo, 2002), this strategy has never been widely adopted simply because growers, naturally, are reluctant to purposefully introduce pests into their crops (Parr *et al.*, 1976) and generally consider the strategy risky (Starý, 1993).

Leaving a pest residue for enhancing establishment of predators has been suggested in several studies as a strategy analogous to the "pest-in-first" strategy (Luckmann and Metcalf, 1975; Gonzalez and Wilson, 1982; Messelink *et al.*, 2008). However, more elegant methods that do not involve introduction or maintenance of the target pest in the crop are available. Thus, beneficials may be assisted in their survival and establishment if food or prey items are supplied. Supplemental food, typically a non-pest prey species used for rearing of the beneficial in question, can be provided directly in the product or may be applied post-release directly to the crop, e.g., lepidopteran eggs, to assist establishment of polyphagous mirid bugs (Lenfant *et al.* 2000). Application of artificial food in the form of liquid food sprays, typically composed of carbohydrates and perhaps including protein-rich ingredients, also has great potential, but is still in development (Wade *et al.*, 2008).

Another method to assist establishment of beneficials is by application of rearing units, exemplified with the "slow-release" systems developed and implemented on a large scale for several species of predatory mites (Sampson, 1998; Biobest 2009; Koppert, 2009d) whereby producers deliver mites in small sachets containing prey mites as a base for reproduction. The mites reproduce continuously in the sachets over several weeks and progeny subsequently disperse into the crop.

An alternative way of creating long-lasting rearing units for beneficials in the crop is distribution of plants (usually non-crop plants) infested with herbivores (usually different from the target pest) or carrying other food items. The beneficials are sustained by and usually also reproduce on the alternative food and subsequently disperse to crop plants to target the crop-harboring pests. This method is normally termed the "banker plant (method)."

It might be useful to distinguish between, on the one hand, systems of plants and alternative food merely serving to sustain the beneficials, i.e., supporting development of the beneficial from one stage to another, typically from larval instars to adult; and on the other hand, systems of plants and alternative food, on which the beneficials are able to reproduce. However, relevant details on these aspects are frequently lacking in the literature and distinctions between these two systems often are not possible. In this review we have consequently chosen to let the term "banker plant method" include both types of systems. In the following we therefore use the term "rearing" synonymously with "sustaining and/or rearing."

C. The Banker Plant Method

The banker plant method is sometimes referred to as use of "artificial foci" (Starý, 1970), "open rearing systems" (Bennison, 1992) or "open rearing units" (Bennison and Corless, 1993;

TABLE 1
Plant-based pest control strategies

Concepts	Characteristics	Orientation	Source
Banker plant systems	Plants used to rear/sustain natural enemies	Pest oriented	this review
Trap crops	Plants used to attract, divert, intercept, and/or retain targeted pests	Pest oriented	(e.g., Shelton and Badenes-Perez, 2006)
Push-Pull	Behavioural manipulation of pests by making crop-plants unattractive / unsuitable (push) combined with luring pests toward attractive non-crop sources (pull) where they are subsequently removed (sometimes through biological control)	Pest oriented	(e.g., Cook *et al.*, 2007)
Vegetation management	Restoration of natural control in agroecosystems by designing and constructing vegetational architectures, e.g.,flower strips	Crop oriented	(e.g., Altieri and Letourneau, 1982)
Habitat management	A subset of conservation biological control methods; alternation of habitats to improve performance / survival of natural enemies	Crop / landscape oriented	(e.g., Landis *et al.,* 2000)

Schoen, 2000; Gotte and Sell, 2002), or employment of an "alternative host and parasitoid association in first" strategy (Starý 1993), but more commonly "banker plants," "banker plant systems" or related terms are used indiscriminately. In this article we use the term "banker plant system" to mean a rearing and release system consisting of three basic elements (Pratt and Croft, 2000a) (banker plant, alternative food, beneficials) purposefully added to or established in a crop for control of pests in greenhouses or open field. The term "banker plant" in itself we use to describe the plant component of the banker plant system; "alternative food" is the prey or host, or other alternative food substances added to or produced by the banker plant; and "beneficial" is the predator, parasitoid or insect pathogenic organism released on the banker plant. Application of the "banker plant method" thus means to make use of a banker plant system to aid the development and dispersal of beneficials for biological control (Pratt and Croft, 2000a).

In general, the term "banker plant" is broader than the term "banker plant system," since banker plants can be employed without deliberate releases of beneficials but as an aid to boost natural populations of predators and parasitoids in an agroecosystem. As an example, Bribosia *et al.* (2005) used Rowan trees [*Sorbus aucuparia* L. (Rosaceae)] as banker plants to harbor released rowan aphids [*Dysaphis sorbi* Kaltenbach (Homoptera: Aphididae)]. Rowan aphids then served as an alternative host for the naturally occurring parasitoid *Ephedrus persicae* Froggatt (Hymenoptera: Braconidae) to enhance biological control of the rosy apple aphid *D. plantaginea* (Passerini) (Homoptera: Aphididae) in apple orchards. Several other methods bear close resemblance to the banker plant method and are termed as such by some authors, e.g., addition of flower strips in field crops (Freuler *et al.*, 2001; Freuler *et al.*, 2003), and use of companion plants to attract and maintain predators (Lopez and Shepard, 2007a, b; Mizell and Knox, 2009). Other related methods are the use of trap crops to attract pests away from the crop itself (Shelton and Badenes-Perez, 2006; Buitenhuis *et al.,* 2007; Lee *et al.,* 2008) and the exploitation of hedgerows and similar habitats as a reservoir and/or overwintering site for beneficials. These methods are somewhat overlapping and are summarized in Table 1.

Some pubications have included limited reviews of banker plant systems (van Lenteren, 1988; Maisonneuve, 2002; Enkegaard, 2006). Recently, Frank (2010) completed a more comprehensive examination of the subject. The review by Frank (2010) identified published literature by searching various databases using the terms "banker plant" or "open-rearing system." The review provided an explanation of what is needed to increase the rigor and scientific basis supporting utilization of specific banker plant systems. However, it was somewhat limited in scope and coverage and did not discuss a significant amount of relevant literature. As such, there are still a number of gaps that need to be addressed, which is one objective of this review. For example, related strategies, such as companion plants, trap plants, habitat management and slow-release systems for predatory mites are noted and briefly discussed. Practical use of banker plants, particularly in the greenhouse environment, and their commercial significance to the biocontrol industry are reviewed, and cost and efficiency of the system are compared to direct inundative releases of natural enemies.

II. DEVELOPMENT OF THE BANKER PLANT METHOD

A. Overview

The earliest investigations of the banker plant method as defined here were made by Starý (1970) who used it for releasing the parasitoid *Diaeretiella rapae* (McIntosh) (Hymenoptera:

Braconidae) from Brassica banker plants infested with cabbage aphids, *Brevicoryne brassicae* (L.) (Homoptera: Aphididae) to control peach-potato aphid (*Myzus persicae* (Sulzer) (Homoptera: Aphididae) in greenhouse crops (Table 2). Later in the 1970s, Parr and Stacey (1976) investigated its usefulness for biological control of whiteflies in tomato with the parasitoid *Encarsia formosa* Gahan (Hymenoptera: Aphelinidae) (Table 3).

The first banker plant systems to be studied in biological control can be considered as refinements of the "pest-in-first" strategy in that the banker plant was the same species as the crop and the food was not an alternative food but the same species as the target pest (Parr and Stacey 1976). Further improvements occurred by changing to non-crop banker plants and/or by replacing the banker plant pest with a true alternative food (e.g., Blümel, 1988, 1989; Kuo-Sell, 1987, 1989). Initially the banker plant method was primarily developed by scientists and advisors who disseminated the know-how to growers. This process continues today, although some banker plant systems are now commercially available (Schoen, 2000) from some beneficial producers (e.g., EWH BioProduction 2010; Koppert, 2009c). Thus, in Ontario, Canada, a number of ornamental growers are in collaboration with scientists and advisors to develop their own banker plant systems in an attempt to enhance the effectiveness of biological control programs. For example, against pests such as western flower thrips an ornamental pepper plant is presently being developed as a banker plant for *Orius* sp. (Hemiptera: Anthocoridae), with the alternative food supply being pollen produced by the pepper (G. Murphy, pers. obs.). As another example, Dutch organic growers recently started to intercrop their sweet pepper plants in early season with cabbage aphid infested cabbage plants, on which the predatory midge *Aphidoletes aphidimyza* Rondani (Diptera: Cecidomyiidae) is released (G. Messelink, pers. obs.). Many different banker plant systems (Tables 2–4) have now been developed, tested and, in some cases, implemented in practice. Many of these systems were not discussed in the literature reviewed by Frank (2010).

B. The Banker Plant

The banker plant harbors alternative food and beneficials. In a few cases, among the investigated systems (6% of systems listed in Tables 2–4), the plant species chosen as banker plant is the same as the crop species (Parr and Stacey, 1976; Stacey, 1977; Goolsby and Ciomperlik, 1999; Pickett *et al.*, 2004; G. Murphy, pers. obs.). While this was originally done as a refinement of the "pest-in-first"-strategy, in more recent cases, the choice was deliberate. This could be based on the expectation that by using the same variety as the crop, unpredicted effects of different varieties or plant species could be avoided (Goolsby and Ciomperlik, 1999; Pickett *et al.*, 2004). Alternatively it could be a result of growers taking immediate advantage of in-house observations on differential attractiveness between varieties; for instance, by moving more susceptible varieties in among less susceptible varieties and using their more attractive qualities as the starting point for a banker plant system (G. Murphy, pers. obs.). In addition, by choosing a banker plant of the same plant species as the crop, need for additional propagation of specific banker plants is avoided and banker plants may be harvested alongside the crop (Stacey, 1977). In fact, Goolsby and Ciomperlik (1999) showed that their cantaloupe banker plants produced a normal yield, thus offsetting the cost of banker plants. Yet another advantage is that plant management usually becomes easier since no special changes need to be made in terms of height management, irrigation requirements, nutrition needs, and awareness of other potential pests and diseases.

These few cases aside, the species of banker plant is usually different from crop plant species (Tables 2–4) as recommended by Starý (1993) who even suggested that banker plant species should not be included in the host plant range of the target pest when developing a banker plant system for use of parasitoids against aphids. Other than the known relationship between the beneficial species intended for use and its various prey and their host ranges, reasons for choosing a specific plant species as banker plant are seldom provided (e.g., Blumel and Hausdorf, 1996; Jacobson and Croft, 1998; van Lenteren, 1995) and no specific rule-of-thumb seems to exist, other than banker plant species should be acceptable for the inoculated beneficials and support their long-term colonization (Pratt & Croft, 2000a). Monocotyledons have frequently been used as banker plants (41% of systems listed in Tables 2–4), primarily reflecting their suitability as a host for aphid species that can serve as alternative prey for parasitoids employed for biocontrol of aphids, the pest group that has been targeted most often in banker plant studies. Among dicotyledons a wide range of plants have been studied as banker plants (Tables 2–4), with tobacco and castor beans used a little more frequently than other plant species.

However, when a choice between several banker plant species is possible, considerations on ease of cultivation (Maisonneuve, 2002), handling and maintenance, as well as susceptibility to plant diseases, should be made. The last of these should be considered in order to reduce the risk that banker plants succumb to infections of diseases such as botrytis (Jacobson and Croft, 1998) but also to minimize risk of cross-infection of the crop (Maisonneuve, 2002) for instance through vectoring of plant virus by the target pest (Schoen, 2003). In addition to this, banker plant species should not, of course, be suitable for infestation by and population build-up of other pest species in the cropping system (Maisonneuve, 2002) although this aspect may be of minor concern in situations where banker plants need to be replenished at frequent intervals.

Another important quality for banker plant species intended for use especially in greenhouses is their adaptability to the greenhouse environment. For example, tolerance to high temperatures (e.g., such as exhibited by millets compared to cereals) may be used as a selection criterion (Schoen, 2000) so that high temperatures do not result in banker plant mortality (Kim and Kim, 2004; van der Linden, 1992). Day length and

TABLE 2
List of banker plant systems against aphids.

Banker Plants	Herbivores / Foods	Beneficials	Target pests	Crops	Source
Bread wheat (*Triticum sativum*)	*Sitobion avenae*	*Aphidius ervi*	aphids	(G)	Bennison, PC
Broad bean (*Vicia faba*)	*Acyrthosiphon pisum*	*Aphidius ervi*	aphids	(G)	Blümel, PC
Milkweed (*Asclepias* sp.) *Nerium oleander*	*Aphis nerii*	Aphids parasitoids	aphids	ornamentals (F)	Osborne, pers. obs.
Wheat or barley	*Rhopalosiphum padi*	*Aphidius colemani* *Aphidoletes aphidimyza*	*Aphis gossypii*	cucumber (G)	Bennison and Corless, 1993
Wheat	*Rhopalosiphum padi*	*Aphidius matricariae* *Aphidoletes aphidimyza* *Chrysopa carnea*	*Aphis gossypii*	cucumber (G)	Bennison, 1992
Wheat	*Rhopalosiphum padi*	*Aphidius matricariae* *Aphidoletes aphidimyza*	*Aphis gossypii*	cucumber (G)	Albert, 1995
Finger millet (*Eleusine coracana*)	*Rhopalosiphum padi*	*Lysiphlebus testaceipes*	*Aphis gossypii*	cucumber (G)	Boll *et al.*, 2001b, 2001a
Unknown	*Rhopalosiphum padi* *Macrosiphum dirhodum*	*Aphidius colemani, A. ervi, Lysiphlebus testaceipes* and *Aphidoletes aphidimyza*	*Aphis gossypii*	cucumber (G)	Bunger, 1997
Rough bluegrass (*Poa trivialis*)	*Rhopalosiphum padi*	*Lysiphlebus testaceipes*	*Aphis gossypii*	melon (G)	Chiarini and Conte, 1999
Italian ryegrass (*Lolium multiflorum*)	*Rhopalosiphum padi*	*Lysiphlebus testaceipes*	*Aphis gossypii*	melon (G)	Chiarini and Conte, 1999
Wheat' Wild Poaceae	*Rhopalosiphum padi*	*Aphidius colemani*	*Aphis gossypii*	cucumber, melon (G)	Conte 1998 Conte *et al.*, 1999, 2000a, 2000b
Barley	*Rhopalosiphum padi*	*Aphidius colemani*	*Aphis gossypii*	watermelon (G)	Goh, 1999
Common barley (*Hordeum vulgare*)	*Rhopalosiphum padi*	*Aphidius colemani*	*Aphis gossypii*	watermelon, sweet pepper (G)	Goh *et al.*, 2001
Common barley (*Hordeum vulgare*)	*Rhopalosiphum padi, R. maidis*	*Aphidius colemani*	*Aphis gossypii*	cucumber (G)	Goh *et al.*, 2001
Maize Wheat Ryegrass	*Rhopalosiphum padi*	*Aphidius colemani*	*Aphis gossypii*	cucumber (G)	Jacobson and Croft, 1998
Barley	*Schizaphis graminum*	*Aphidius colemani*	*Aphis gossypii*	cucumber; oriental melon (G)	Kim and Kim, 2003, 2004
Wheat	*Rhopalosiphum padi*	*Aphidoletes aphidimyza* *Aphidius matricariae*	*Aphis gossypii*	cucumber (G)	Lamparter 1992
Sorghum (*Sorghum bicolour*)	*Schizaphis graminum*	*Lysiphlebus testaceipes*	*Aphis gossypii*	sweet pepper (G)	Rodrigues *et al.*, 2001

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TABLE 2
List of banker plant systems against aphids *(Continued)*.

Banker Plants	Herbivores / Foods	Beneficials	Target pests	Crops	Source
Finger millet (*Eleusine coracana*)	*Rhopalosiphum padi*	*Aphidius colemani*	*Aphis gossypii*	courgette, melon, cucumber (G)	Schoen and Martin, 1997 Schoen, 2000 Martin *et al.*, 1998 Delgado, 1997 Vergniaud, 1997 Fischer and Leger, 1997
Wheat	Aphids	*Aphidius colemani*	*Aphis gossypii*	cucumber (G)	Shiono, 2005 Saito, 2005
Common barley (*Hordeum vulgare*)	*Rhopalosiphum padi*	*Aphidius colemani*	*Aphis gossypii*	cucumber (G)	Blümel, PC
Bread wheat (*Triticum sativum*)	*Schizaphis graminum*	*Aphidius colemani*	*Aphis gossypii*	cucumber (G)	Blümel, PC
Common barley (*Hordeum vulgare*)	*Rhopalosiphum padi*	*Aphidoletes aphidimyza*	*Aphis gossypii*	cucumber (G)	Blümel, PC
Bread wheat (*Triticum sativum*)	*Schizaphis graminum*	*Aphidoletes aphidimyza*	*Aphis gossypii*	cucumber (G)	Blümel, PC
Winter wheat	*Sitobion avenae*	*Aphidius ervi*	*Aulacorthum solani*	sweet pepper (G)	van Schelt, 1999
Winter wheat	*Sitobion avenae*	*Aphelinus abdominalis*	*Aulacorthum solani*	sweet pepper (G)	van Schelt, PC
Common barley (*Hordeum vulgare*)	*Rhopalosiphum padi*	*Aphidoletes aphidimyza*	*Aulacorthum solani* *Brachycaudus helichrysi*	chrysanthemum (G)	Ramakers and Maaswinkel, 2002
Elder (*Sambucus nigra*)	*Aphis sambuci*	Syrphids	*Dysaphis plantaginea*	apple (F)	Bribosia, 2003
Triticale (*Triticosecale rimpaui*)	*Sitobion avenae*	*Aphidius ervi*	Large aphids		Jansson, PC
Potatoes-shoots	*Macrosiphum euphorbiae*	*Aphelinus abdominalis*	*Macrosiphum euphorbiae*	rose (G)	Blumel and Hausdorf, 1996
Rose (*Rosa* sp.)	*Macrosiphum rosae*	*Praon volucre*	*Macrosiphum euphorbiae*	tomato (G)	Maisonneuve, 1990
Finger millet (*Eleusine coracana*)	*Sitobion avenae*	*Aphelinus abdominalis*	*Macrosiphum euphorbiae* *Aulacorthum solani*	tomato (G)	Fischer, 1997
Finger millet (*Eleusine coracana*)	*Sitobion avenae*	*Aphidoletes aphidimyza*	*Macrosiphum euphorbiae* *Aulacorthum solani*	tomato (G)	Fischer, 1997
Finger millet (*Eleusine coracana*)	*Sitobion avenae*	*Episyrphus* sp.	*Macrosiphum euphorbiae* *Aulacorthum solani*	tomato (G)	Fischer, 1997
Finger millet (*Eleusine coracana*)	*Sitobion avenae*	*Aphidius ervi*	*Macrosiphum euphorbiae Myzus persicae*	tomato (G)	Fischer, PC
Finger millet (*Eleusine coracana*)	*Sitobion avenae*	*Praon* sp.	*Macrosiphum euphorbiae*	tomato (G)	Fischer, PC

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TABLE 2
List of banker plant systems against aphids *(Continued)*.

Banker Plants	Herbivores / Foods	Beneficials	Target pests	Crops	Source
Cereals (triticale, oat)	*Metopolophium dirhodum*	*Aphidoletes aphidimyza*	*Macrosiphum euphorbiae Macrosiphum rosae Rhodobium porosum*	rose (G)	Gotte and Sell, 2002
Winter wheat	*Rhopalosiphum padi*	*Aphidius colemani*	*Myzus nicotianae*	sweet pepper (G)	van Schelt, 1999
Broad bean (*Vicia faba*)	*Megoura viciae*	*Aphidoletes aphidimyza*	*Myzus persicae*	sweet pepper (G)	Hansen, 1983 Blümel, PC
Paprika (caged)	*Myzus persicae*	*Ephedrus cerasicola*	*Myzus persicae*	sweet pepper (G)	Hofsvang and Hagvar, 1979
Oat (*Avena sativa*)	*Metopolophium dirhodum*	*Aphidoletes aphidimyza*	*Myzus persicae*	(G)	Kuo-Sell, 1987
Oat (*Avena sativa*)	cereal aphids	*Aphidoletes aphidimyza*	*Myzus persicae*	sweet peppers (G)	Kuo-Sell, 1989
Wheat	*Schizaphis graminum*	*Aphidius colemani Lysiphlebus testaceipes*	*Myzus persicae*	beans (G)	Starý, 1993
Finger millet *Eleusine coracana*	*Sitobion avenae*	*Aphidius ervi*	*Myzus persicae Macrosiphum euphorbiae*	tomato, sweet pepper, eggplant (G)	Fischer, PC
Brassica crops	*Brevicoryne brassicae*	*Diaeretiella rapae*	*Myzus persicae*	various greenhouse plants (G)	Starý 1970
Barley	*Sitobion akebiae*	*Aphidius gifuensis*	*Aulacorthum solani Myzus persicae*	vegetables (G)	Ohta and Honda, 2010

G = Greenhouse; F = Field; PC = personal communication

light intensity can also play a role. Thus for some banker plant species [e.g., *Ranunculus asiaticus* L. (Ranunculaceae)], long day lengths are unfavorable (van der Linden, 1992) while others (e.g.,wheat) may need more light later in the season (van Schelt, 1999).

Before settling on a specific plant species to be used as a banker plant, consideration needs to be given to the growth habits and environmental needs of different species, to minimize the need for banker plant replacement and thus the amount of work involved with operating the system. Thus, Jacobson and Croft (1998) compared three potential plant species for use in a parasitoid banker plant system for aphid biocontrol and found that herbivore-infested maize could maintain quality in greenhouses for 3 months and only once required supplemental additions of the alternative food compared to herbivore-infested wheat or ryegrass, which could only be maintained for 3 to 4 weeks. Likewise, Goolsby and Ciomperlik (1999) compared 10 potential varieties of cantaloupe for use in a parasitoid banker plant system for whitefly biocontrol and found that shortcomings of some varieties (e.g., reduced supportiveness for herbivore reproduction) could be overcome by adjustments of the ratio between the alternative food and the beneficials inoculated on plants. The keeping quality of herbivore-infested banker plants is also important when the banker plant method is intended to be applied in a preventive strategy before an infestation with the target pest has developed. In these cases the banker plant system may need a keeping quality of up to several months (Bennison and Corless, 1993). It should, however, be noted that a limited keeping quality of banker plants in some cases may be advantageous in order to stimulate dispersal of beneficials to the crop (L. Osborne, pers. obs.).

Considerations on the above-mentioned quality aspects are naturally important but it must be kept in mind that the inherent intention of a banker plant system is that inoculated beneficials should be sustained and preferably have a high degree of reproduction and progeny production and, consequently, that the plant species should be as supportive as possible for the proliferation of added alternative prey. In designing the banker plant system, care should therefore be taken to ensure optimum density of the herbivores in relation to health and keeping quality of the banker plant to sustain system durability and optimum production of beneficials (Hansen, 1983; Goolsby and Ciomperlik, 1999; Pratt

TABLE 3
List of banker plant systems against whiteflies.

Banker Plants	Herbivores / Foods	Beneficials	Target pests	Crops	Source
Tobacco (*Nicotiana tabacum*)	*Trialeurodes vaporariorum*	*Encarsia formosa*	whiteflies	potted herbs (G)	Schmidt, 1996
Cantaloupe Watermelon	*Bemisia tabaci*	*Eretmocerus hayati* *Eretmocerus* sp.	*Bemisia tabaci*	cantaloupes, watermelon (F)	Goolsby and Ciomperlik, 1999 Pickett *et al.,* 2004
Papaya (*Carica papaya*)	*Trialeurodes variabilis*	*Encarsia transvena* *Delphastus pusillus* *Paecilomyces fumosoroseus*	*Bemisia tabaci*	tomato, cucumber, sweet pepper (G)	Osborne *et al.*, 1991
Nipplewort (*Lapsana communis*)	*Aleyrodes proletella*	*Encarsia formosa*	*Trialeurodes vaporariorum*	cucumber (G)	van der Linden and van der Staaij, 2001
Tobacco (*Nicotiana tabacum*)	*Trialeurodes vaporariorum*	*Encarsia formosa*	*Trialeurodes vaporariorum*	cucumber, tomato, eggplant (G)	Blumel, 1988, 1989
Mullein (*Verbascum thapsus*)	plant sap, *Ephestia* eggs	*Dicyphus hesperus*	*Trialeurodes vaporariorum*	tomato (G)	Lambert *et al.*, 2005
Borecole (*Borecole oleracea*)	*Aleyrodes proletella*	*Encarsia formosa*	*Trialeurodes vaporariorum*	tomato, cucumber, sweet pepper (G)	Laska and Zelenkova, 1988
Nipplewort (*Lapsana communis*) Greater Celandine (*Chelidonium mjajus*)	*Aleyrodes proletella*	*Encarsia formosa*	*Trialeurodes vaporariorum*	cucumber (G)	van der Linden and van Staij, 2001
Nipplewort (*Lapsana communis*)	*Aleyrodes proletella*	*Macrolophus caliginosus*	*Trialeurodes vaporariorum*	cucumber (G)	van der Linden and van Staij, 2001
Tomato (*Lycopersicon esculentum*)	*Trialeurodes vaporariorum*	*Encarsia formosa*	*Trialeurodes vaporariorum*	tomato (G)	Parr and Stacey, 1976 Stacey, 1977
Tomato (*Lycopersicon esculentum*) or cucumber (*Cucumis savitus*)	*Trialeurodes vaporariorum*	Encarsia formosa	*Trialeurodes vaporariorum*	tomato or cucumber (G)	Xu, 1991
Common mullein (*Verbascum thapsus*)	plant sap	*Dicyphus hesperus*	*Trialeurodes vaporariorum*	tomato (G)	Sanchez *et al.*, 2003
Tree tomato (*Cyphomandra betacea*)	plant sap + Ephestia eggs	*Macrolophus caliginosus*	*Trialeurodes vaporariorum*	tomato, cucumber, sweet pepper (G)	Fischer, PC
Tobacco (*Nicotiana tabacum*)	plant sap, Ephestia eggs	*Macrolophus caliginosus*	*Trialeurodes vaporariorum*	tomato (G)	Fischer, PC
Foxglove (*Digitalis* sp.)	plant sap	*Macrolophus caliginosus*	*Trialeurodes vaporariorum*	tomato (G)	Helyer, PC

(Continued on next page)

TABLE 3
List of banker plant systems against whiteflies *(Continued)*.

Banker Plants	Herbivores / Foods	Beneficials	Target pests	Crops	Source
Sage (*Salvia* sp.)	plant sap	*Macrolophus caliginosus*	*Trialeurodes vaporariorum*	tomato (G)	Helyer, PC
Egg plant (*Solanum melongena*)	*Trialeurodes vaporariorum*	*Encarsia formosa*	*Trialeurodes vaporariorum*	rose (G)	Pijnakker, pers. obs
Egg plant (*Solanum melongena*)	*Trialeurodes vaporariorum*	*Macrolophus caliginosus*	*Trialeurodes vaporariorum*	sweet pepper (G)	Ramakers, pers. obs.
Tobacco (*Nicotania tabacum*)	plant sap	*Macrolophus caliginosus*	*Trialeurodes vaporariorum*	tomato (G)	Schoen, PC
Tomato (*Lycopersicon esculentum*)	*Trialeurodes vaporariorum*	*Encarsia formosa*	*Trialeurodes vaporariorum*	tomato, cucumber (G)	Walker, PC
Tobacco (*Nicotiana tabacum*)	*Ephestia* eggs	*Macrolophus caliginosus*	whiteflies	tomato (G)	Arno *et al.*, 2000
Tobacco (*Nicotiana tabacum*) Tamarillo (*Cyphomandra betacea*)	*Ephestia* eggs	*Macrolophus caliginosus*	whiteflies	ornamentals (G)	Fischer, 2002
Castor bean (*Ricinus communis*)	pollen, extrafloral nectar	*Amblyseius swirskii*	whiteflies	(G)	Hoogerbrugge *et al.*, 2009
Tobacco (*Nicotiana tabacum*)	Unknown	*Macrolophus caliginosus*	whiteflies	tomato (G)	Schoen, 2003
Tobacco (*Nicotiana tabacum*) Tamarillo (*Cyphomandra betacea*)	*Ephestia kuehniella*	*Macrolophus caliginosus*	whiteflies	tomato (G)	Fischer, 2003 Fischer and Terrettaz, 2003
Papaya (*Carica papaya*)	*Trialeurodes variabilis*	*Encarsia transvena*	whiteflies	ornamentals (F)	Osborne, 2005

G = Greenhouse; F = Field; PC = personal communication

and Croft, 2000a). To further sustain the system it is sometimes necessary to replenish with fresh banker plants and/or with the herbivore/alternative food (e.g., van der Linden, 1992; van der Linden and van der Staaij, 2001). However, replenishment should not be so frequent that intended dispersal of beneficials from banker plants to the crop is hampered but, instead, should be designed as a balance between reduced availability of alternative food and dispersal stimulation (e.g., Starý, 1993), addition of supplemental material to maintain the system (Hansen, 1983) and increased dispersal duration (Pratt and Croft, 2000a). As an illustration of the intricacy of designing a banker plant system that is sufficiently supportive for beneficials, but at the same time sufficiently stimulating for dispersal, it can be mentioned that a system of papaya and *Trialeurodes variabilis* (Quaintance) (Homoptera: Aleyrodidae) was so attractive to the beneficial lady beetle *Delphastus pusillus* (LeConte) (Coleoptera: Coccinellidae) that the beetle refrained from dispersing to the targeted tomato crop (L. Osborne, pers. obs).

C. The Alternative Food

A banker plant system can be based on use of alternative food in the form of herbivores or surrogate food, such as pollen (Ramakers and Voet 1995, 1996; van Rijn and Tanigoshi 1999) or unviable lepidopteran eggs (e.g., *Ephestia kuehliniella*) [Arno *et al.* 2000; Fischer 2002, 2003, Fischer and Terrettaz 2003)]. Alternative food can be provided in the form of herbivore prey for both specialised (oligophagous) and generalist (polyphagous) beneficials, or as a surrogate food, such as pollen for the latter. When based on herbivores there are two possibilities: either to use the same herbivore species as the target pest, which obviously possesses some risks; or to use an herbivore species different from the target pest.

The target pest has been chosen as the banker plant herbivore in several cases especially in the early history of investigation of banker plant systems (Hofsvang and Hagvar, 1979; Stacey, 1977; Parr and Stacey, 1976) (Tables 2–4), but also in more recent years (Blumel and Hausdorf, 1996; Goolsby and

TABLE 4
List of banker plant systems against thrips, mites, leafminers, planthoppers.

Banker Plants	Herbivores / Foods	Beneficials	Target pests	Crops	Source
Floss flower (*Ageratum mexicanum*) Common morning glory (*Ipomoea purpurea*)	Pollen	*Amblyseius andersoni*	*Eriophyes macrotrichus*	hornbeam (F)	van der Linden, PC
Floss flower (*Ageratum mexicanum)* Common morning glory (*Ipomoea purpurea*)	Pollen	*Amblyseius cucumeris*	*Eriophyes macrotrichus*	hornbeam (F)	van der Linden, PC
Floss flower (*Ageratum mexicanum)* Common morning glory (*Ipomoea purpurea*)	Pollen	*Euseius finlandicus*	*Eriophyes macrotrichus*	hornbeam (F)	van der Linden, PC
Castor bean (*Ricinus communis*)	pollen, extrafloral nectar	*Amblyseius swirskii*	*Frankliniella occidentalis*	(G)	Messelink *et al.*, 2005
Castor bean (*Ricinus communis*)	pollen, extrafloral nectar	*Iphiseius degenerans*	*Frankliniella occidentalis*	(G)	Ramakers & Voet, 1995, 1996 van Rijn and Tanigoshi, 1999
Sweet pepper (*Capsicum annuum*)	Pollen	*Orius laevigatus*	*Frankliniella occidentalis*	(G)	Bennison, PC
Chrysanthemum (*Chrysanthemum* sp.)	Pollen	*Orius laevigatus*	*Frankliniella occidentalis*	(G)	Bennison, PC
Garland Chrysanthemum (*Chrysanthemum coronarium*)	Pollen	*Orius* sp.	*Frankliniella occidentalis*	cucumber, sweet pepper (G)	Fischer, PC Monnat, 1993
Castor bean (*Ricinus communis*)	pollen, nectar	*Amblyseius degenerans*	*Frankliniella occidentalis*	Alstroemeria (G)	Maisonneuve, PC
Sweet pepper (*Capsicum annuum*)	pollen	*Orius laevigatus*	*Frankliniella occidentalis*	rose (G)	Pijnakker, pers. obs.
Tall buttercup (*Ranunculus acris*)	*Phytomyza caulinaris*	*Dacnusa sibirica* *Diglyphus isaea*	*Liriomyza huidobrensis*	lettuce (G)	Goossens, 1992
Buttercup (*Ranunculus* sp.)	*Phytomyza caulinaris*	*Dacnusa sibirica* *Diglyphus isaea*	*Liriomyza* spp.	lettuce (G)	van der Linden, 1992
Barnyard grass (*Echinochloa utilis*) Rice (*Oriza sativa*)	*Sogatella vibix* / *Nilaparvata lugens*	*Cyrtorhinus lividipennis*	*Nilaparvata lugens*	rice (F)	Matsumura and Urano, 2001
Floss flower (*Ageratum mexicanum*) Common morning glory (*Ipomoea purpurea*) Livingstone daisy (*Mesembryanthemum criniflorum*)	plant sap, pollen	*Amblyseius andersoni*	*Phytoptus canestrinii*	boxwood (F)	van der Linden, PC

(Continued on next page)

TABLE 4
List of banker plant systems against thrips, mites, leafminers, planthoppers *(Continued)*.

Banker Plants	Herbivores / Foods	Beneficials	Target pests	Crops	Source
Castor beans (*Ricinus communis*)	pollen	*Amblyseius degenerans*	spider mites, thrips	sweet pepper, cucumber (G)	Ramakers and Voet, 1995, 1996
Arborvitae (*Thuja occidentalis*)	*Oligonychus ununguis*	*Neoseiulus fallacies*	*Tetranychus. urticae*	(G, F)	Pratt and Croft 2000a, 2000b
Rhododendron (*Rhododendron* sp.)	*Oligonychus illicis*	*Neoseiulus fallacies*	*Tetranychus. urticae*	(G, F)	Pratt and Croft, 2000a, 2000b

G = Greenhouse; F = Field; PC = personal communication

Ciomperlik, 1999; G. Murphy, pers. obs.). In some instances the banker plant system was encaged to prevent infestation of the crop (e.g., Hofsvang and Hagvar, 1979; Hoddle *et al.*, 1998), whereas, in others, risk of crop infestation seemed low as reported by Blümel and Hausdorf (1996) for potato-shoots [*Macrosiphum euphorbiae* (Thomas) (Homoptera: Aphididae) *Aphelinus abdominalis* (Dalman) (Hymenoptera: Aphelinidae)]—system they employed in greenhouse roses.

More frequently, however, alternative food consisting of surrogate food (e.g., pollen) or banker plant specific herbivores have been preferred (e.g., Hansen, 1983; Starý, 1993; Pratt and Croft, 2000a) (Tables 2–4) to eliminate risk of herbivore infestation of the crop (Starý, 1993). In the latter case, the banker plant herbivore interacts indirectly with the target pest via a shared natural enemy. Such indirect prey interactions are very common in nature and have been referred to as "apparent competition" (Holt, 1977) because it looks as if the two species compete for a shared resource, whereas they, in fact, interact via the shared natural enemy. With respect to biological control, some studies have demonstrated that presence of one pest species is enhancing suppression of another pest species (e.g. Karban *et al.*, 1997; Muller and Godfray, 1997; Liu *et al.*, 2006; van Veen *et al.*, 2006; Messelink *et al.*, 2008). These studies might be useful for developing banker plant systems as well.

In selecting the alternative food for a banker plant system, its effect on behavior and biology of the beneficials needs to be considered (van der Linden, 1992). It is necessary to ensure that the alternative food is among the preferred foods (Starý, 1993) as well as being sufficiently suited for beneficial sustainment or reproduction, population build-up and for fitness of resulting progeny (e.g., Ohta and Honda, 2010).

In addition, there are other factors to consider when the choice of alternative food is made, the most important being the risk of an herbivore becoming a pest of the target cropping system or perhaps even of the greater area in which the banker plant system is to be implemented – non-indigenous species should therefore be avoided. The safest choice will be to select a strictly monophagous or oligophagous herbivore (Starý, 1993) of no agricultural significance. Starý (1993) recommended employing a taxonomist for herbivore selection to avoid introducing a potential pest by accident. However, application of such a narrow, and very likely difficult and time-consuming, selection criterion may not be needed if the banker plant system is to be used in a crop that cannot be attacked by the herbivore and if risk of infestation of neighboring cropping systems can be regarded as negligible, for instance due to a mismatch between ecological requirements of the herbivore and prevailing cropping conditions.

In this case, even herbivores that are normally considered as common or even serious pests can be a valid choice (Schoen, 2000; Jacobson and Croft, 1998); a choice that in fact was made for most of the banker plant systems developed for use in greenhouses. For example, the bird cherry-oat aphid, *Rhopalosiphum padi* (Linnaeus) (Homoptera: Aphididae), an important pest of cereals (Lowles, 1995), is used as alternative prey for aphid parasitoids for biological control in greenhouse vegetables (e.g., Neil *et al.*, 1997; Hansen, 2000). Similarly cabbage whitefly, *Aleyrodes proletella* (L.) (Hemiptera: Aleyrodidae), a serious pest of cabbage (Nebreda *et al.*, 2005), could be used as an alternative host for *E. formosa* for biological control of greenhouse whiteflies in greenhouse cucumber (Laska and Zelenkova 1988; van der Linden and van der Staaij, 2001).

D. The Beneficial

Beneficials used in banker plant systems are parasitoids, predators or insect pathogenic organisms capable of parasitizing, preying on or infecting both the target pest and the alternative food. Parasitoids and predators have been the beneficials most frequently chosen for banker plant systems whereas insect pathogenic organisms have been rarely used (Tables 2–4).

Among parasitoids exploited in banker plant systems, species applicable for control of aphids have been most thoroughly investigated. Species encompass *Aphidius colemani* Viereck, *Aphidius ervi* Haliday, *Praon volucre* Haliday, *D. rapae*, *Lysiphlebus testaceipes* Cresson, *Ephedrus cerasicola* Starý (Hymenoptera: Aphidiidae) and *A. abdominalis* (e.g., Starý, 1970; Hofsvang and Hagvar, 1979; Maisonneuve, 1990; Blumel and Hausdorf, 1996; Delgado, 1997; van Schelt, 1999; Boll *et al.*, 2001a, b). Fewer parasitoid species have been investigated in connection with banker plants for control of whiteflies [*Encarsia* sp. (e.g., Xu, 1991; Osborne *et al.*, 1991) and *Eretmocerus* sp. (e.g., van der Linden and van Staij, 2001; Pickett *et al.*, 2004) (Hymenoptera: Aphelinidae)] and of leafminers [*Dacnusa sibirica* Telenga (Hymenoptera: Braconidae) and *Diglyphus isaea* Walker (Hymenoptera: Eulophidae) (e.g., Goossens, 1992)].

Banker plant systems based on parasitoids may become infested with hyperparasitoids attacking beneficial parasitoids and developing at their expense (Sullivan, 1987). Hyperparasitism may, therefore, become a limiting factor for a successful outcome of the control (e.g., Starý, 1970; van Schelt, 1999; G. Murphy, pers. obs.) in some periods of the year (summer, late summer), during which a discontinuation in their use becomes necessary (G. Murphy, pers. obs.).

Predators investigated for use in banker plant systems encompass mirid bugs (Heteroptera: Miridae) [*Dicyphus hesperus* Knight (Lambert *et al.*, 2005), *Macrolophus caliginosus* Wagner (e.g., Arno *et al.*, 2000), *Cyrtorhinus lividipennis* Reuter (Matsumura and Urano, 2001)], pirate bugs (Heteroptera: Anthocoridae) [*Orius* sp. (e.g., Monnat, 1993)], ladybirds (Coleoptera: Coccinellidae) [D. pusillus], predatory mites (Acari: Phytoseiidae) (*Amblyseius* sp., *Iphiseius* sp., *Neoseiulus* sp., *Euseius* sp., *Phytoseiulus persimilis* Athias-Henriot) [e.g., van Rijn and Tanigoshi, 1999; Pratt and Croft, 2000a, van der Lindern, pers. comm.)], and larvae of lacewings (Neuroptera: Chrysopidae) (*Chrysopa carnea* (Stephens) [Bennison, 1992)], of syrphids (Diptera: Syrphidae) (Bribosia, 2003) and of cecidomyids (Diptera: Cecidomyiidae) [*A. aphidimyza* (e.g., Bennison 1992; Albert 1995)] (Tables 2–4).

Mostly generalist predators have been investigated, although a few oligophagous species, for instance, *D. pusillus* (e.g., Osborne *et al.,* 1991), have also been considered. A banker plant system based on a polyphagous predator has the advantage of being able to exert control on several pests. For example, mullein banker plants with *D. hesperus* gave successful control of whiteflies as well as of thrips and furthermore contributed to control of aphids in conjunction with the gallmidge *A. aphidimyza* (Lambert *et al.*, 2005). However, in some cases it may be a drawback to implement banker plant systems harboring polyphagous predators if these are able to act as intraguild predators of other beneficials released in the crop. This consideration is nonetheless also valid for other biological control methods (inundation, inoculation) with possible intraguild predators.

The only insect pathogenic organism that has been investigated in connection with banker plant-based biological control is the fungus *Isaria fumosorosea* Wize (was *Paecilomyces fumosoroseus* (Wize) Brown and Smith) (Deuteromycota: Hyphomycetes) (Osborne *et al.*, 1991). In the system, aimed at control of whiteflies in greenhouses, the fungus was added together with the parasitoid *Encarsia transvena* Timberlake and the ladybird *D. pusillus* to papaya banker plants infested with papaya whiteflies (*T. variabilis*).

In most cases, different pest species in a crop under a biological control scheme must be targeted with several beneficial species and employment of a banker plant system that can sustain more than one beneficial species may therefore be an option. Thus Blümel and Hausdorf (1996) suggested combining the use of several aphid parasitoids and predators within one banker plant system to control different aphid species. Likewise van der Linden and van der Staaij (2001) noted that banker plants could potentially be used as a reservoir of both parasitoids and predators either from the beginning of establishment of the system or by addition at appropriate times of further beneficial species to an existing banker plant system. In fact, a few banker plant systems involving combinations of several species of natural enemies have been investigated (Osborne *et al.*, 1991; Bennison, 1992; Lamparter, 1992; Bennison and Corless, 1993; Albert, 1995; Bunger, 1997; van der Linden and van Staij, 2001). However, if banker plants are used to harbor more than one beneficial species, consideration should be given to possible negative interactions between beneficials (competition, intraguild predation). For example, the function of a banker plant system with *D. sibirica* was disrupted by invasions of another parasitoid, *D. isaea*, which acts as an intraguild predator of the former (van der Linden, 1992). Similarly, problems could arise if banker plants simultaneously harbor the aphid parasitoid, *A. colemani*, and gallmidge, *A. aphidimyza*, since the latter is capable of preying on aphids parasitized by the former (Enkegaard *et al.*, 2005) and presumably also by other parasitoids. Negative interactions that preclude use of the same banker plants as a carrier of several pest-beneficial-systems may also exist not only at the beneficial level but also at the herbivore level. For example, van Schelt (1999) noted negative results achieved using a banker plant system harboring the aphids *R. padi* and *Sitobion avenae* (Fabricius) (Homoptera: Aphididae) as host for the parasitoids *A. colemani* and *A. ervi*, respectively, due to the former aphid species outcompeting the latter. Similarly, the same interaction is likely to preclude use of these two systems separately in the same greenhouse, since the *A. ervi* system is eventually infested by *R. padi*.

E. The Target Pest and Target Crop

Although the range of pests intended to be targeted through use of the banker plant method has gradually increased (Figure 1), the number of pest groups addressed by this method is still somewhat limited (Tables 2–4). The major group of pests targeted is aphids (49% of systems listed in Tables 2–4), followed by whiteflies (31%), thrips and mites (each 8%) and leafminers (2%). The reason behind these differences probably relates to the fact that biological control of aphids and whiteflies in many cases can be achieved with parasitoids that are more easily handled in banker plant systems than predators, whereas biological control of mites and thrips mainly relies on use of predators. Leafminers are frequently targeted with parasitoids and the reason for low numbers of developed or investigated banker plant systems must therefore be sought in other aspects than the nature of the applied beneficial, presumably in

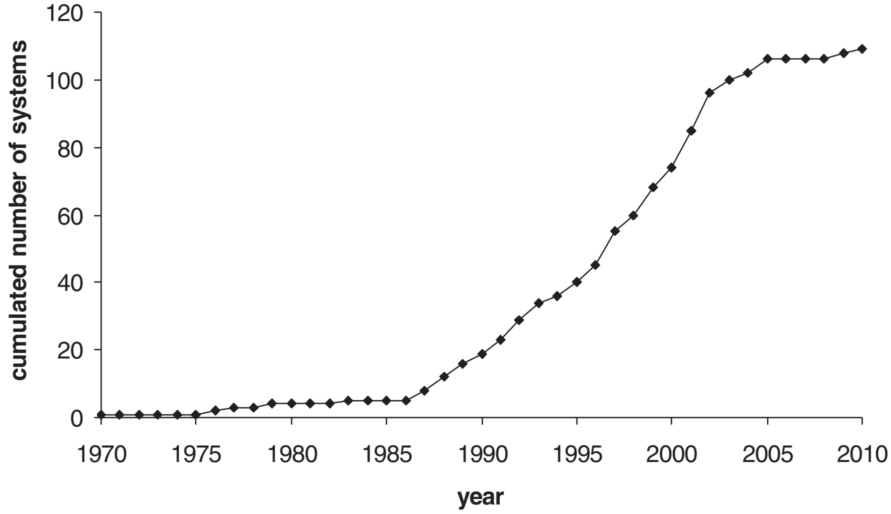

FIG. 1. Cumulative number of reports on development and/or employment of banker plant systems from 1970 to present based on the year of first published report (Tables 2–4). The personal communications listed in Tables 2–4 were gathered in 2002 on systems that may have been investigated or implemented prior to this time. Consequently the personal communications from Tables 2–4 were evenly distributed on the years 1987–2002.

difficulties in finding suitable herbivore leafminers, preferably host specific and at the same time adapted to conditions in which the banker plant system is intended to operate. The vast majority of banker plant systems have been developed for and/or implemented in greenhouse crops (90%), primarily in greenhouse vegetables (88% of greenhouse systems for which the crop type is known), and to a lesser extent in greenhouse ornamentals (12%) (Tables 2–4, Figure 2). Only very few systems (10%) have been developed for implementation in field crops (Tables 2–4, Figure 2). These differences partly reflect the history of inoculative/inundative biological control, which started in greenhouse vegetables, progressed to greenhouse ornamentals (Enkegaard & Brødsgaard, 2005) and still is used only to a limited degree in field crops. They also reflect difficulties posed by different crops/cropping systems to biocontrol in general, and thus also to use of the banker plant method. These difficulties relate to the following: 1) the relative ease of biocontrol in habitat-simplistic crops in closed greenhouse systems with controlled and relatively stable environments as opposed to more habitat-diverse crops grown in open fields under fluctuating environmental conditions; and 2) the lower damage threshold and generally more complicated production process of greenhouse ornamentals compared to vegetables (Enkegaard and Brødsgaard, 2005).

However, use of banker plant systems in field crops may increase in the future. Thus, in the opinion of some authors, the

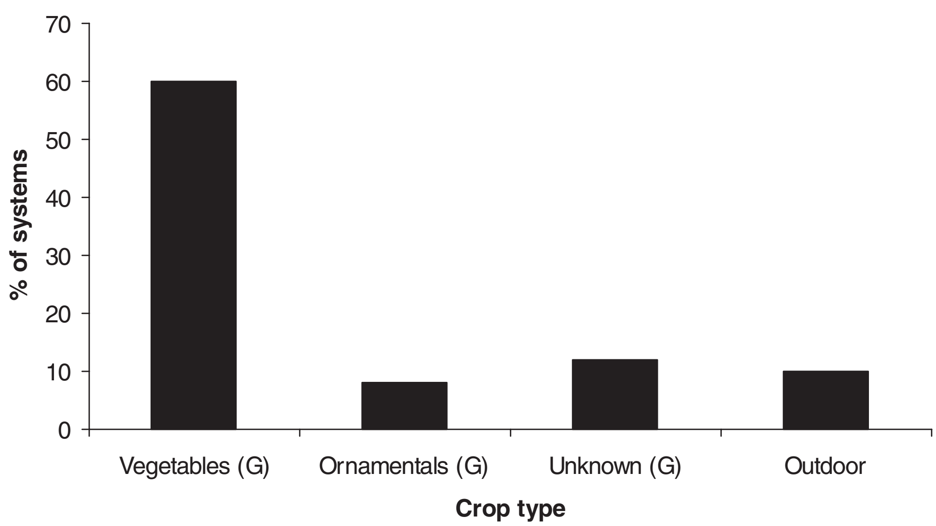

FIG. 2. The percentage of banker plant systems listed in Tables 2–4 developed for and/or implemented in the various categories of crops. G: greenhouse crops

banker plant method could be used to augment many different parasitoid species against a variety of pests and could enable other augmentation programs to extend use of biological control in annual cropping systems (Goolsby and Ciomperlik, 1999). The same authors developed a banker plant system based on target pests and target crop plants for control of *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae) in cantaloupe and spring melon with *Eretmocerus hayati* Zolnerowich and Rose and *Encarsia* sp. (Hymenoptera: Aphelinidae), respectively. The system fit well with the cropping practice and overcame one of the major obstacles for use of this method in field crops: the need for large quantities of banker plants to adequately cover and be evenly spaced over very large fields (Goolsby and Ciomperlik, 1999).

F. Practical Use

In Europe (Schoen, 2000) and in countries such as Canada (G. Murphy, pers. obs.) some banker plant systems have been commercially available for a number of years from several beneficial producers. Within the last few years, however, some producers have discontinued these products. In other areas commercial sale is low or nonexistent (Bueno V., Federal University of Lavras, Brazil, pers. comm., 2008; Hanafi A, Institut Agronomique et Veterinaire Hassan II, Morocco, pers. comm., 2008). In the latter regions, banker plant systems may, however, still be implemented through supportive systems set in place by local universities or research stations that either 1) supply beneficials and herbivore-infested plants to growers who subsequently maintain the systems themselves, or 2) introduce the banker plant concept to growers who then operate their own banker plant systems independently of outside advice or support as has been practiced in the United States and Canada (Glenister C., IPM Laboratories, USA, pers. comm., 2008; G. Murphy, pers. obs.).

The commercial systems are (and were) primarily banker plants (typically wheat or barley infested with cereal aphids) aimed at supporting the action of aphid parasitoids (*A. colemani, A. ervi, A. abdominalis*). However, other systems are also being implemented in practice although not commercially available. These include pollen-producing ornamental pepper plants for support of *Orius insidiosus* (Say) (Hemiptera: Anthocoridae) (BioBest, 2008) for thrips control in ornamentals (R. Valentin, Biobest Canada, pers. comm., 2008; G. Murphy, pers. obs.); whitefly-infested papaya plants for support of whitefly parasitoids, predators and fungi for whitefly control in greenhouse vegetables (L. Osborne, pers. obs.); and grass mite-infested corn plants for support of spider mite predators for use in ornamentals (L. Osborne, pers. obs.).

It has not been possible to obtain accurate estimates of the extent of practical implementation of the banker plant method. However, interest among growers for and uptake of banker plant usage seem to vary between regions. Thus it seems that uptake is lower among U.S. greenhouse growers (estimate of 1–5% of growers use banker plant systems) compared to Canadian growers (estimate: 10–25%) (Glenister C., IPM Laboratories, USA, pers. comm., 2008). This probably reflects a higher interest in use of biological control generally among Canadian growers. Greater use of banker plant systems as a component of biocontrol systems is an extension of this philosophy, with a number of growers collaborating on various non-commercialized banker plant systems with local scientists and/or local biocontrol producers (G. Murphy, pers. obs.). Also in Europe variations appear to exist among countries – thus seemingly very few growers in the UK (less than 5%) seem to implement banker plant systems (Bennison J., ADAS, UK, pers. comm., 2008; Jacobson R., RJC Ltd., UK, pers. comm., 2008), whereas interest seems higher in countries such as Denmark where the estimate is 20% (Jepsen M,. GartneriRådgivningen, Denmark, pers. comm., 2008). In the Netherlands, banker plants for aphid control are estimated to be used on approximately 120 ha (van Schelt J, Koppert, the Netherlands, pers. comm., 2008). In regions where banker plants are not yet implemented, an interest is foreseen by biocontrol researchers (Bueno V., Federal University of Lavras, Brazil, pers. comm., 2008; Hanafi A., Institut Agronomique et Veterinaire Hassan II, Morocco, pers. comm., 2008).

The presently rather low sales figures for banker plant systems reported by European biocontrol companies (Hansen E., EWH BioProduction, Denmark, pers. comm., 2008; Vermeulen J., Biobest, Belgium, pers. comm., 2008) and the decision as far as some companies are concerned to phase out banker plants as commercial products seem at least in part to be a reflection of the fact that growers tend only to buy herbivore infested banker plants, which they subsequently propagate themselves to last throughout the season (GreatRex R., Syngenta Bioline, UK, pers. comm., 2008; Hansen E., EWH BioProduction, Denmark, pers. comm., 2008; Vermeulen J., Biobest, Belgium, pers. comm., 2008).

G. Benefits or Drawbacks

Banker plant systems are considered to be an effective key control strategy within the framework of biological pest management in greenhouses (Gotte and Sell 2002), with the following benefits over regular inundative release of beneficials: 1) reduced expenses for purchasing beneficials, 2) increased efficiency of introduced beneficials (probably in large part a reflection of the freshness of the beneficial compared to beneficials received from transit material), 3) making early releases of beneficials possible, 4) establishing permanent mini rearing units in the crop, and 5) attracting naturally occurring beneficials (Schoen, 2000; Maisonneuve, 2002). In addition, when generalist predators are employed in a banker plant strategy, they may benefit from the mixed diet of different prey (i.e., target prey and alternative prey). Different prey can have complementary nutritional values (Evans *et al.*, 1999), thus increasing the food quality for predators and stimulating their population build-up. Banker plant systems may also be used for introducing natural enemies that are not (as yet) commercially available, such as the predatory mite *Euseius ovalis* (Evans) (Acari: Phytoseiidae) that can be sustained on pollen-producing castor bean plants (Messelink *et al.*, 2009). The latter can be exploited for research purposes or used by growers teaming up with local research stations with non-commercialized beneficial rearings. In addition, Pratt and Croft (2000b) considered plant mobility as an attractive attribute of banker plants and growers can relatively easily evaluate the quality of purchased beneficials by monitoring their establishment on the banker plants. This can result in banker plants acting as a valuable educational resource for growers and greenhouse employees, by providing an easily accessible focal point for observation of biocontrol principles.

Drawbacks may, however, also exist when banker plant systems are employed. For instance, as mentioned above, there is a risk of infestation of some types of systems with hyperparasitoids. Another drawback may be that the target pest species benefits from the presence of a marginal host on banker plants because it acts as a sink source (Heimpel *et al.*, 2003). Presence of an unsuitable or less suitable host results in a distraction effect (Meisner *et al.*, 2007). This might play a role when using the banker plant system with *R. padi* as an alternative host of the parasitoid *A. colemani*, because it results in lesser mortality rates of the target aphid *M. persicae* (Ode *et al.*, 2005). However, the outcome of the sink source mechanism may, in this case, be negligible as the parasitoid has a preference for the target pest. Besides, it will be an advantage to have the alternative host provided to assist establishment of the parasitoid rather than having no alternative hosts at all. An additional disadvantage is that a banker plant system may have a negative effect on the target pest because of satiation effects: there are too many prey for the shared natural enemy and this dilutes the effect on the target pest species (apparent mutualism, Abrams & Matsuda, 1996). This, however, will only be a transient phenomenon occurring when both target pest and alternative prey/hosts are present in high densities. The resulting strong numerical response of the shared natural enemy will soon tackle this problem.

1. *Efficiency*

Not all reports on banker plant systems compare efficiency to that of other release methods and, if done, it is usually in the form of experimental set-ups rather than in real production systems. Efficiency can be viewed strictly in terms of output (e.g. number of beneficials introduced per cost) or in terms of results (effectiveness of control).

Superior efficiency of banker plant systems compared to other release methods has been documented for aphid control in greenhouses using *A. aphidimyza* and *Aphidius matricariae* Haliday (Hymenoptera: Braconidae) (Bennison, 1992) or *A. colemani* (Bennison and Corless, 1993); and by Pickett *et al.* (2004) for control of the whitefly *B. tabaci* with *Eretmocerus* parasitoids in cantaloupe. Blümel and Hausdorf (1996) compared inundative releases of *A. abdominalis* with the banker plant method for control of aphids on rose, with both treatments combined with pesticide application. Although both methods gave sufficient control, the authors indicated that the banker plant system had several advantages over inundative releases, including lower cost and constant presence of parasitoids.

Greater effectiveness of banker plant systems is likely to be related to superior quality of the freshly produced beneficials compared to products that have been in transit for days before arriving in the greenhouse. In addition, banker plant systems greatly increase the potential for successful establishment; under inoculative or inundative biocontrol strategies natural enemies have to search large areas of low-density and generally aggregated occurrence of prey or hosts whereas in a banker plant strategy they are released directly onto sites of ample resources.

2. *Preventive Releases*

An important advantage of banker plant systems is the possibility to establish a preventive presence of beneficials in the crop before the target pests have actually infested it. Thus, Hansen (1983) developed a banker plant system based on seedlings of broad beans infested with Vetch aphids *Megoura viciae* Buckton (Hemiptera: Aphididae) as the herbivore to ensure survival of the aphid gallmidge, *A. aphidimyza*, until the target aphid, *M. persicae*, appeared, thereby off-setting the need for time-consuming scouting of the crop to discover the first infestation. Other authors have similarly noted that parasitoid or predator populations built up on banker plants prior to actual pest infestation of the crop, thus allowing for immediate action of beneficials when the latter eventually occurred (Bennison, 1992; Blümel and Hausdorf, 1996¸ Jacobson and Croft, 1998). Fischer and Terrettaz (2003) used the banker plant method as a preventive release method to overcome the problem that *M. caliginosus* generally establishes too slowly in protected tomato crops to provide adequate control of whiteflies in the spring.

In addition to their function as a method of preventive introductions, banker plant systems may also assist the continued survival of beneficials in the cropping system in times when the target pest has been suppressed to a negligible level (Starý, 1993).

3. *Cost*

The lower cost involved with use of banker plant systems compared to direct releases is stated by many authors as an important benefit. As an example, Bennison (1992) showed that a banker plant system against *A. gossypii*, costing 40 pounds per ha per week, produced 75 *A. matricariae* per m^2 per week, which was 300 times as many as introduced under biocontrol schemes with direct releases. Likewise, Ramakers and Voet (1995) developed a banker plant system for *Amblyseius degenerans* (Berlese) (Acari: Phytoseiidae) based on flowering castor beans for control of western flower thrips [*Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae)] in sweet pepper in greenhouses and stated that the method was cheap, albeit slow, necessitating preventive establishment. Banker plant systems have also been developed in order to be able to make use of beneficials that are otherwise considered too expensive to be used in regular inundative releases as was documented by Lambert *et al.* (2005) for the mirid *D. hesperus* used for whitefly control in tomatoes.

However, other authors indicate that cost of the banker plant method may be similar to cost of traditional releases, as reported by Jacobson and Croft (1998) for aphid control by *A. colemani* based on maize, wheat and ryegrass plants infested with *R. padi* in greenhouse cucumber. Others have found the use of banker plants to be more expensive than direct releases as shown for the mirid *M. caliginosus* in protected tomatoes, although the cost/efficacy ratio supported the banker plant method (Fisher & Terrettaz, 2003).

The cost of purchasing beneficials to initiate and maintain a banker plant system is, however, not the only cost involved, as the system requires considerable labor and skill to produce and to maintain, while multiple releasing requires little labor (Jacobson and Croft, 1998). The amount of labor needed for these activities will probably be dependent upon the banker plant system in question.

H. Suggestions for Development and Use of a Banker Plant System

The following are chronological steps usually associated with development of a banker plant system: 1) a specific pest problem is present in a specific cropping system, 2) a beneficial species is available, which 3) has been found suitable for the present crop conditions and is 4) judged to be potentially efficient, but for which 5) mass releases in numbers and frequencies sufficient to achieve control are either too expensive (e.g., Lambert *et al.*, 2005) or too slow, thus necessitating preventive releases (Hansen, 1983). With regard to the last of these, preventive releases as a direct inundative strategy are practiced in some cases for some beneficial species, e.g., *Amblyseius cucumeris* (Oudemans) (Acari: Phytoseiidae), *A. colemani*, *E. formosa* and *P. persimilis* (Biobest, 2009; Koppert, 2009a, Koppert, 2009b), but this strategy may become expensive, especially when repeated introductions are needed over a prolonged period before the target pest appears in the crop.

The first step in developing a banker plant system for a particular beneficial is to identify a suitable herbivore or other alternative food and a suitable plant species. In this phase it must be decided if these two components of the banker plant system should be similar to the target pest and target crop, or whether the components should differ from these.

From the point of view of reducing risk of possible infestation on the crop with the alternative prey, it would be advantageous to choose the second option. However, from a practical point of view, it might be an advantage to operate with the target pest and/or crop as components of the banker plant system to reduce labor in handling of the system and perhaps even to provide the grower with a possibility to eventually harvest (from) the banker plants (Stacey, 1977; Goolsby and Ciomperlik, 1999). If this option is chosen, potential risks must be clearly understood and appropriate steps taken to mitigate them.

When the banker plant system is composed of a plant and an herbivore different from the targets, considerations must be made to adaptation of the herbivore and plant to prevailing conditions, in which the system will be operating. At the same time it should be verified that the herbivore does not attack the target crop or at least only does so to a limited extent (Blümel and Hausdorf, 1996).

The next step involves evaluations of productivity of the banker plant system (e.g., Goolsby and Ciomperlik, 1999). Although the system augments beneficials and increases parasitisation or predation of target pests, its output of beneficials may still be too low to ensure satisfactory control (e.g., Pickett *et al.*, 2004) and research to clarify the optimal balance between quantity of alternative food on the banker plant and number of beneficials added to the system is likely to be needed in this phase (e.g., Goolsby and Ciomperlik, 1999). Output of beneficials from the banker plant system may be compared to recommended release rates used in biocontrol based on inoculative and inundative strategies (e.g., Bennison, 1992). An output that surpasses these rates is, of course, advantageous, although satisfactory control may be achieved even with lesser yielding banker plant systems, as demonstrated by Hofsvang and Hagvar (1979) for their aphid-controlling system based on *E. cerasicola*. An issue closely related to the productivity of a banker plant system is the need for and frequency of renewal of alternative food and/or the plant itself. A good banker plant system may last for the entire growing season as indicated by Hansen (1983), while others should be replaced at regular intervals (e.g., van Schelt, 1999; van der Linden and van der Staaij, 2001; Koppert, 2009c).

Dispersal of beneficials from the banker plant to the crop is, naturally, essential for efficient functioning of the system and should be evaluated in connection with efficacy assessments (Pratt and Croft 2000a). Mobility and dispersal are desirable characteristics of a beneficial to be applied through a banker plant system, although poorer dispersal can, to some extent, be offset by increasing the number of banker plants established per unit area (Pratt and Croft, 2000a) or by designing the banker plant system as mobile units (Ramakers and Voet, 1995) to be shifted to places in the crop where a beneficial boosting is needed.

The final step in development of a banker plant system is determination of the suitable time of introduction (Kim and Kim, 2004) and compatibility of the system with other measures employed in the crop for control of diseases and additional pests. Timing of introduction may be seen in relation to the infestation level of the target pest. For example, setting up the banker plant system prior to infestation of the crop with the target pest allows the system to establish and start producing before the pest level becomes too high and biocontrol becomes difficult to achieve (Hansen, 1983). Or it may be seen in relation to the time of year since only some periods may provide conditions for optimal function of the banker plant system, as noted by Jacobson and

Croft (1998) who found that their maize-based banker plant system for aphid control was more effective in midsummer than in late spring.

Regarding integration of the use of banker plant systems with other measures, use of pesticides specifically needs to be considered in terms of its potential to cause problems due to negative effects on the alternative food (e.g., Koppert, 2009c) or, of course, on the beneficial itself. Pesticides with the least harmful effect on the system should therefore be selected as proposed by Blümel and Hausdorf (1996) who combined use of a parasitoid-based banker plant with *M. euphorbiae* as alternative food with application of a selective aphicide for control of the same aphid species in greenhouse cut roses, obtaining a reduction in the number of chemical applications by up to 75%. Alternatively, banker plant systems designed as mobile units may be removed from the crop at times of spraying (Pratt and Croft 2000a; Koppert, 2009c). Integration of banker plant systems with other biological control strategies generally seems to cause little problems (e.g., Goh, 1999; Conte *et al.*, 2000a), although situations may arise where other released beneficials invade banker plants and compete with or predate on the banker plant's beneficial.

III. CONCLUSIONS

The banker plant method has been investigated as a tool to aid development, dispersal and establishment of beneficial organisms employed in biological control for more than 35 years. The number of systems developed as well as the number of pests targeted through this method has increased steadily over the years, although the number of systems commercialized over the years has remained relatively low. In spite of this and in spite of the present reluctance of many beneficial producing companies to preserve formerly existing banker plant products on the market, growers in many regions are still keen to implement the method, which in many cases has proved itself applicable, advantageous and effective.

In our opinion the banker plant method has potential to enhance efficacy of beneficials, which would otherwise be applied inoculatively or inundatively. This potential is far from exhausted and further research, combined with grower and advisor driven developments and adjustments of user-friendly and cost-effective systems, will assist the adoption of biological control as an alternative to use of pesticides. Although banker plant systems primarily have been developed for use in protected crops, the possibility to use the method in field crops needs to be further exploited.

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