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CONCEPTS AND APPLICATIONS OF TRAP CROPPING IN PEST MANAGEMENT

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■ **Abstract** Interest in trap cropping, a traditional tool of pest management, has increased considerably in recent years. In this review we propose a broader definition of trap cropping that encompasses the inherent characteristics of the trap crop plants themselves as well as the strategies associated with their deployment. Inherent characteristics of a trap crop may include not only natural differential attractiveness for oviposition and feeding, but also other attributes that enable the trap crop plants to serve as a sink for insects or the pathogens they vector. Successful deployment of trap crops within a landscape depends on the inherent characteristics of the trap crop and the higher value crop, the spatial and temporal characteristics of each, the behavior and movement patterns of insect pests, and the agronomic and economic requirements of the production system. Thus, trap cropping is more knowledge-intensive than many other forms of pest management. We review recent references on trap cropping, classify them according to their modalities and level of implementation, and provide a synthesis of the factors that influence the success of trap cropping. Last, we provide a list of recommendations and guidelines that should prove helpful in moving trap cropping forward to its full potential.

INTRODUCTION

The concept of trap cropping fits into the ecological framework of habitat manipulation of an agroecosystem for the purpose of pest management. Many different methods alter the habitat as part of an integrated pest management (IPM) strategy, and such manipulation can occur at the within-crop, within-farm, or landscape level (73). Prior to the introduction of modern synthetic insecticides, trap cropping was a common method of pest control for several cropping systems (27, 126, 129). The recent resurgence of interest in trap cropping as an IPM tool is the result of concerns about potential negative effects of pesticides on human health and the environment, pesticide resistance, and general economic considerations of agricultural production.

Trap crops have been defined as "plant stands grown to attract insects or other organisms like nematodes to protect target crops from pest attack, preventing the pests from reaching the crop or concentrating them in a certain part of the field where they can be economically destroyed" (50). The fundamental tenet of this definition involves differential pest preference between plant species, the plants that function as trap crops and those to be protected. We suggest this definition is limited in theory and practice because differential preference alone is not the key concept utilized in many examples of what is commonly termed trap cropping. One example of the limitation of this definition is that the same species of plant that serves as a trap crop can also be used as the crop to be protected if it is grown in a particular spatial or temporal manner or with a particular added trait. Therefore, we propose a broader definition of trap crops as plant stands that are, per se or via manipulation, deployed to attract, divert, intercept, and/or retain targeted insects or the pathogens they vector in order to reduce damage to the main crop. This broader definition encompasses the inherent characteristics of the trap crops themselves as well as their deployment.

MODALITIES OF TRAP CROPPING

The main modalities of trap cropping can be conveniently classified according to the plant characteristics or how the plants are deployed in space or time. Other modalities, such as biological control–assisted and semiochemically assisted trap cropping, may not easily lend themselves to such dichotomous classifications but can provide important contributions to trap cropping. In some cases, examples of trap cropping may fit one or more of these modalities, and for effective trap cropping a combination of modalities may be required.

Modalities Based on the Trap Crop Plant Characteristics

For trap cropping modalities based on the characteristics of the trap crop plant per se, we define conventional, dead-end, and genetically engineered trap cropping.

CONVENTIONAL TRAP CROPPING We use this term to define the most general practice of trap cropping, in which a trap crop planted next to a higher value crop is naturally more attractive to a pest as either a food source or oviposition site than is the main crop, thus preventing or making less likely the arrival of the pest to the main crop and/or concentrating it in the trap crop where it can be economically destroyed. This modality was the primary focus of the two previous reviews (50, 61). Examples of such practices have been used in traditional agriculture in developing countries as well as in large-scale farming operations in industrialized countries.

One of the most widely cited examples of successful conventional trap cropping, which served as a major contributor to the development of IPM in the central valley of California in the 1960s, is the use of alfalfa as a trap crop for lygus bugs in cotton (40, 124). This example is remarkable because it is still used today at the commercial level. Other examples of conventional trap cropping in commercial operation include the use of highly attractive varieties of squash to manage squash bugs and cucumber beetles in several cucurbitaceous crops (90).

DEAD-END TRAP CROPPING This term was coined to describe plants that are highly attractive to insects but on which they or their offspring cannot survive (115). Dead-end trap crops serve as a sink for pests, preventing their movement from the trap crop to the main crop later in the season (13). Yellow rocket, *Barbarea vulgaris* var. *arcuata*, works as a dead-end trap crop for the diamondback moth, *Plutella xylostella* (12–14, 56, 76, 115). Sunn hemp, *Crotalaria juncea*, has also been suggested as a dead-end trap crop for the bean pod borer, *Maruca testulalis* (59). High ovipositional preference for host plants on which larvae do not survive has been reported in additional cases, especially among Lepidoptera (127, 128).

As suggested above, the definition of trap cropping should not be limited to differential attractiveness between plant types. Besides the use of highly attractive hosts naturally unsuitable for target pest development, plants can also be rendered dead-end trap crops by treating them with conventional insecticides or by genetic engineering. Dead-end trap crops should be located where they can intercept insect pests (e.g., field borders) and reduce pest damage in the main crop.

GENETICALLY ENGINEERED TRAP CROPPING This modality of trap cropping may not be considered unique in and of itself because it can produce plant characteristics that fit other modalities we describe. However, because of its present importance and growing potential, we believe it bears special consideration. There are already examples of genetic engineering (i.e., the deliberate manipulation of genes through the use of biotechnology) in trap cropping, and its importance in the development and improvement of trap crops is likely to increase in the future. For example, potatoes that have been genetically engineered to express proteins from *Bacillus thuringiensis* (Bt) have been used as trap crops to manage Colorado potato beetle (*Leptinotarsa decemlineata*) populations. If Bt potatoes are planted early in the season to attract immigrating Colorado potato beetle, they can act as an early-season, dead-end trap crop (51) and prevent colonization of the interior of the field that is planted to non-Bt potatoes. Collards, *Brassica oleracea* var. *acephala*, expressing the Cry1Ac protein from Bt have the potential to be used either for direct control or as a dead-end trap crop for Lepidoptera (23). Bt collards may have some advantages over other proposed dead-end trap crops, such as the weed *B. vulgaris* (14, 115), because Bt collards may be approved for human consumption in the future and thereby serve not only as a trap crop but also as a marketable crop. Such use would expand the traditional view of a trap crop.

Trap cropping based on genetically engineered plants can also be effective in controlling insect-vectored pathogens. In these cases, it is the virus, not the insect, that is trapped. For instance, when a virus-laden insect probes a noninfected transgenic plant, the virus is rapidly removed from the aphid's stylet. This type of trap crop also fits within the definition of barrier crops, which can be an effective crop management strategy for the control of nonpersistently transmitted aphid-borne viruses under specific circumstances (35). The use of genetically engineered plants, however, offers additional possibilities because the same plant species can be used as a barrier crop and the protected crop. This is illustrated by the papaya ringspot virus (PRSV) (43), which is transmitted by many aphid species in a nonpersistent manner, making it difficult to control with insecticides. In Hawaii PRSV-resistant papaya are grown commercially and have been deregulated for U.S. consumers, but they have not been approved by Hawaii's traditional high-value export market, i.e., Japan. However, some growers in Hawaii are using borders of PRSV-resistant papaya as a trap crop to reduce the movement of PRSV into the interior of the field where nongenetically engineered papaya are grown (44). This successful tactic allows production of both conventional and genetically engineered papaya.

Modalities Based on the Deployment of the Trap Crop

Trap cropping should be viewed in the larger context of landscape ecology (71). Within any agroecosystem there is a changing mosaic of habitats that vary through time in their attractiveness and suitability to insect pests and/or their natural enemies (64). From the standpoint of trap cropping, the most relevant parameters of the landscape structure are those that refer to the spatial pattern of vegetation patches, including their distribution, size, shape, configuration, number, and type. Insects and their host plants interact and become influenced by size, fragmentation, and connectivity of host patches (133). The main modalities of trap cropping that can be distinguished on the basis of their deployment include perimeter, sequential, multiple, and push-pull trap cropping.

PERIMETER TRAP CROPPING Perimeter trap cropping can be defined as the use of a trap crop planted around the border of the main crop (20). The use of field margin manipulation for insect control is becoming common in IPM programs and is similar in practice to the early use of traditional trap cropping using borders of more attractive plants. For example, borders of early-planted potatoes have been used as a trap crop for Colorado potato beetle, which moves to potato fields from overwintering sites next to the crop, becoming concentrated in the outer rows, where it can be treated with insecticides, cultural practices, or even propane flamers (52, 54, 140). The potato trap crop could also be made of Bt potatoes (51). Similar success has been reportedly achieved in commercial fields with perimeter trap cropping for control of pepper maggot, *Zonosemata electa*, in bell peppers by using a trap crop of hot cherry peppers (20). Results from studies with the papaya fruit fly, *Toxotrypana curvicauda*, indicated that damage decreased as distance from the native vegetation (the source of flies) increased (7). The authors suggest using a perimeter of papaya trees planted 10 m around the main papaya grooves as a trap crop to reduce fly damage. However, perimeter trap cropping does not always provide the best spatial design for trap cropping (72, 96).

SEQUENTIAL TRAP CROPPING This modality involves trap crops that are planted earlier and/or later than the main crop to enhance the attractiveness of the trap crop to the targeted insect pest. An example of this is the use of an early-season trap crop of potatoes to manage Colorado potato beetles, which we described also as a perimeter trap cropping example (52). Another example of sequential trap cropping is the use of Indian mustard as a trap crop for diamondback moth, which requires planting mustard two or three times through the cabbage season because Indian mustard has a shorter crop cycle than cabbage and other cole crops (92, 122). Field studies have also shown that dusky wireworms, *Agriotes obscurus*, could be managed in strawberry fields by planting wheat as a trap crop one week before planting strawberries (137).

MULTIPLE TRAP CROPPING Multiple trap cropping involves planting several plant species simultaneously as trap crops with the purpose of either managing several insect pests at the same time or enhancing the control of one insect pest by combining plants whose growth stages enhance attractiveness to the pest at different times. All the multiple trap cropping cases that we found in the literature belong to the latter category. For example, a mixture of Chinese cabbage, marigolds, rapes, and sunflower has been successfully used as a trap crop for the pollen beetle, *Melighetes aeneus*, in cauliflower fields in Finland (49). Other cases of multiple trap cropping are the use of a mixture of castor, millet, and soybean to control groundnut leafminer, *Aproarema medicella* (87) in India, and the use of corn and potato plants combined as a trap crop to control wireworms in sweet potato fields (113).

PUSH-PULL TRAP CROPPING The push-pull (69, 99) or "stimulo-deterrent diversion" (83) strategy is based on a combination of a trap crop (pull component) with a repellent intercrop (push component). The trap crop attracts the insect pest and, combined with the repellent intercrop, diverts the insect pest away from the main crop. A push-pull strategy based on using either Napier or Sudan grass as a trap crop planted around the main crop, and either desmodium or molasses grass planted within the field as a repellent intercrop, has greatly increased the effectiveness of trap cropping for stem borers in several countries in Africa (69). Stem borers are the most important biotic constraint to corn production in Africa, and the push-pull strategy has allowed small farmers to control them while managing various parasitic weed species in the genus *Striga* (67). In addition, the use of molasses grass as a repellent intercrop enhances stem borer parasitoid abundance, thereby improving stem borer control (68). The push-pull strategy could also be combined with Bt corn to reduce the potential evolution of Bt resistance in stem borers (4).

Additional Trap Cropping Modalities

BIOLOGICAL CONTROL-ASSISTED TRAP CROPPING Our definition of trap cropping focuses on the interactions between the plant and the pest rather than on the natural enemies of the insect pest. We chose this delineation to preserve the distinction between habitat manipulation for enhanced biological control and the various examples of what we suggest constitute trap cropping (see Reference 73 for information on the use of companion plants to enhance populations of natural enemies). However, in addition to diverting insect pests away from the main crop, trap crops can also reduce insect pest populations by enhancing populations of natural enemies within the field. For example, a sorghum trap crop used to manage cotton bollworm, *Helicoverpa armigera*, also increases rates of parasitism by *Trichogramma chilonis* (139). The increase in parasitism of stem borers by *Cotesia* spp. when using molasses grasses as an intercrop further enhances the effectiveness of push-pull trap cropping (67).

SEMIOCHEMICALLY ASSISTED TRAP CROPPING The principles underlying the effects of trap cropping on insect behavior are similar to those behind semiochemicals and other behavior-based methods for pest management (39). In conventional trap cropping, attraction to the plant may be due to semiochemicals naturally produced by the trap crop. Semiochemically assisted trap crops are either trap crops whose attractiveness is enhanced by the application of semiochemicals or regular crops that can act as trap crops after the application of semiochemicals. One of the most successful examples of this trap crop modality is the use of pheromone-baited trees that attract bark beetles to facilitate their control (18, 19). Pheromone-baited fly traps hung on perimeter trees acting as trap crops have also been suggested for fruit fly management in papaya orchards (7). The use of semiochemical toxic baits may also enhance the effectiveness of trap crops (91, 138). Within the modality of semiochemically assisted trap cropping one may wonder whether pheromones used to attract insects fit within even a broad definition of trap cropping, as it is insect-to-insect communication (pheromone) rather than plant-to-insect communication (kairomone) that is occurring. We suggest this distinction may not be valid considering that there has been some progress toward developing plants that produce insect pheromones (88). Having plants express semiochemicals, rather than applying them to the plants in some other fashion, would overcome some of the reasons for low adoption of semiochemically assisted trap cropping, e.g., frequent application of costly semiochemicals.

APPLICATIONS OF TRAP CROPPING IN INSECT PEST MANAGEMENT

Attempts to use trap cropping in insect pest management have been common in entomological research. Table 1 summarizes recent and relevant references on trap cropping and is organized by insect order and species, location of testing, crop, and modality of trap crop used. It also includes the level of implementation of the trap crop and our interpretation of whether it was successful. Success in preliminary laboratory, greenhouse, screenhouse, or field studies may not necessarily result in a successful use at the commercial level, where additional variables and different environmental conditions may affect insect behavior. Adoption of trap cropping is also dependent on the potential economic return to the grower in a particular situation. In those cases in which we classify a particular trap cropping system as successfully used in commercial fields, we could not find reliable data on the actual area in which it is grown.

INCREASING THE EFFECTIVENESS OF TRAP CROPS

In general, combining biological and/or insecticidal control to supplement the effects of the trap crop can increase the effectiveness of a trap crop. In addition to the inherent characteristics of a particular plant used as a trap crop, insect preference can be altered in time and space to enhance further the effectiveness of a trap crop. Plant breeding can be used to develop trap crop cultivars with enhanced attractiveness to the insect pest and/or low larval survival, such as glossy wax traits (33), or attractiveness to natural enemies (75, 95). Enhancing the effectiveness of the trap crop is vital to minimize the land sacrificed to production when using trap cropping (14). General guidelines for trap cropping recommend that about 10% of the total crop area be planted with the trap crop (50), although the percentage of trap crop needed for each particular system has to be determined for each case. For example, to reduce diamondback moth populations, between 5 and 13% of the crop area should be reserved for the trap crop (14, 122).

Cultural control methods can also be used to increase the effectiveness of trap crops. Host utilization by most insect herbivores, particularly specialists, is consistent with the resource concentration hypothesis in that they are more likely to find and remain in hosts that are concentrated (107). For example, diamondback moth adults were more attracted to large groups of collard plants than to small groups (79), as well as to larger plants and higher planting densities (12). Water stress can also increase the attractiveness to certain insect pests in some plants (110, 116) but not others (12, 118), indicating that some trap cropping systems could benefit by controlling water stress. The spatial arrangement of the trap crop is also important and is discussed in more detail below.

FACTORS DETERMINING THE SUCCESS OF TRAP CROPPING SYSTEMS

From a commercial standpoint, we consider that currently there are only 10 cases of successful applications of trap cropping in agricultural and forest systems (Table 1). From a biological point of view, the potential success of a trap cropping system depends on the interaction of the characteristics of the trap crop and its deployment with the ecology and behavior of the targeted insect pest. However, the characteristics of the trap crop and insect alone are not sufficient to predict whether a trap crop will be successful. Ultimately, the combination of insect and trap crop characteristics and practical considerations determines the success of a trap cropping system.

TABLE 1 Recent and most relevant attempts to use trap cropping in insect pest management

Insect pest species	Country	Crop	Trap crop (modality)^{a}	Reference(s) (Level of implementation)^{b}
Order Coleoptera: beetles and weevils				
Acalymma vittatum (F.)	United States	Cucurbitaceae	Cucurbitaceae (C, S)	(48) (F)
Striped cucumber beetle		Cucumber	Squash (C)	(100) (F)
		Cucurbitaceae	Squash (C, S, SA)	(90, 91, 125) (F, S)
Agriotes obscurus (L.)	Canada	Strawberry	Wheat and other grains (M, S, SA)	(137, 138) (F)
Dusky wireworm				
Anthonomus grandis grandis Boheman	United States	Cotton	Cotton (SA)	(63) (U)
Boll weevil				
Ceutorhynchus assimilis (Paykull)	United States	Oilseed rape	Oilseed rape (S)	(22) (E, U)
Cabbage seedpod weevil				
Conoderus spp.	United States	Sweetpotato	Corn and wheat (M, S)	(113) (F)
Wireworm				
Dendroctonus ponderosae Hopkins	Canada	Coniferae	Coniferae logs and trees (SA)	(18, 19) (S)
Dryocoetes confusus Swaine	United States			
Dendroctonus rufipennis Kirby				
Bark beetles				
Diabrotica undecimpunctata howardi Barber	United States	Peanuts	Squash (S)	(16) (F)
Southern corn rootworm		Cucurbitaceae	Cucurbitaceae (C, S)	(48) (F)
Leptinotarsa decemlineata (Say)	United States	Potato	Potato (S, SA)	(52, 53, 80, 81, 140) (P, F)
Colorado potato beetle	Canada	Tomato	Potato (S)	(54) (F)
Melighetes aeneus F.	Finland	Cauliflower	Chinese cabbage, marigolds, rapes, and sunflower (M)	(49) (S)
Pollen beetle				

Phyllotreta cruciferae Goeze	United States	Cruciferous crops	Yellow rocket (C)	(108) (F)
Phyllotreta stiolata (F.)		Broccoli	Wild mustard (C)	(5, 70) (F)
Phyllotreta nemorum L.		Collard		
Flea beetles	Denmark		Yellow rocket (D, C)	(2, 26) (P)
Order Diptera: flies and leafminers				
Anastrepha obliqua (Macquart)	Mexico	Mango	Plum (C)	(6) (F)
Toxotrypana curvicauda Gerstaecker		Papaya	Papaya (C, SA)	(7) (F)
Fruit fly				
Bactrocera cucurbitae Coquillet	United States	Tomato and Cucurbitacea	Corn (C)	(32) (F)
Melon fly				
Atherigona soccata Rondani	United States	Peppers	Peppers (different variety) (C, P)	(20) (F)
Zonosemata electa (Say)				
Pepper maggot				
Delia radicum (L.)	France	Several crucifers	Chinese cabbage (C)	(109) (P)
Cabbage maggot			Turnip (C)	(109) (P)
Order Hemiptera: bugs				
Anasa tristis (De Geer)	United States	Watermelon Cucurbitaceae	Squash (C, S, SA)	(30, 90, 91, 125) (S)
Squash bug				
Creontiades dilutus (Stål)	Australia	Cotton	Alfalfa (C)	(82) (P, F)
Green mirid				
Lygus hesperus Knight	United States	Strawberry	Daisy and yarrow (C)	(144) (U)
Lygus bug	United States	Cotton	Alfalfa (C)	(40, 124) (S)
Lygus lineolaris (Palisot de Beauvois)	United States	Peach	Canola (C)	(38) (F)

(*Continued*)

TABLE 1 (*Continued*)

Insect pest species	Country	Crop	Trap crop (modality)^a	Reference(s) (Level of implementation)^b
Tarnished plant bug		Cotton	Fleabane (C)	(37) (F)
Lygus rugulipennis Poppius	Sweden	Lettuce	Alfalfa, clover, melilot, mugwort, and vetch (C)	(102) (S)
European tarnished plant bug	United Kingdom	Strawberry	Scented mayweed and alfalfa (C)	(31) (U)
Euschistus heros (F.)	Brazil	Broccoli	Mustard and rape (S)	(77) (F)
Nezara viridula (L.)		Soybean	Soybean (S, B)	(25) (F, C)
Piezodorus guildinii (Westwood)	Nigeria	Soybean	Soybean and cowpea (S)	(57) (F)
Stink bug complex	New Zealand	Corn	Mustard (C, P)	(103) (F)
Murgantia histrionica (Hahn) Harlequin bug	United States	Broccoli	Mustard and rape (S)	(77) (F)
Order Homoptera: aphids, leafhoppers, planthoppers, and whiteflies				
Acyrthosiphon pisum (Harris)	United States	Potato	Potato, sorghum, soybean, and wheat (C)	(29, 101) (F)
Aphids helianthi (Monell)				
Aphis gossypii Glover	Malaysia	Chilli	Brinjal (C)	(55) (F)
Aphids	United States	Papaya	Papaya (G)	(36, 43) (S)
Bemisia tabaci (Gennadius)	Lebanon	Tomato	Cucumber (C)	(3, 9) (F)
Bemisia argentifolii Bellows & Perring	United States	Bean	Eggplant and squash (C)	(119, 120) (F)
Whiteflies		Cotton	Sharpleaf groundcherry (C)	(34) (F)
		Tomato	Squash (C)	(111, 112) (P, F)
Empoasca fabae (Harris) Potato leafhopper	United States	Broccoli	Mustard (S)	(70) (F)
Potato leafhopper	United States	Alfalfa	Alfalfa (uncut) (C)	(141) (F)
Macrosteles quadrilineatus Forbes Aster leafhopper	United States	Lettuce	Lettuce (S)	(145, 146) (P, F)

Order Lepidoptera: butterflies and moths				
Acrolepiopsis assectella (Zeller)	Sweden	Leek, Chives	Chives (C)	(10) (U)
Leek moth			Chives (S)	(10) (P, F)
Aproarema modicella (Deventer)	India	Groundnut	Castor, millet, soybean (M)	(87) (F)
Groundnut leafminer				
Busseola fusca (Fuller)	Eritrea	Maize, millet, and wheat	Sudan grass (C)	(46) (P, F)
Chilo partellus (Swinhoe)				
Stem borers	South Africa	Maize	Napier grass (C)	(136) (F)
			Sweet sorghum (C)	(104) (U)
	Kenya	Maize, sorghum	Napier and Sudan grass (B, PP)	(41, 42, 65, 66, 68, 69) (S)
Crocidolomia pavonana (F.)	Indonesia, United States	Cabbage	Chinese cabbage and Indian mustard (S)	(121) (P)
Cabbage cluster caterpillar	Guam	Cabbage	Chinese cabbage, Indian mustard, and radish (C)	(117) (F)
Chrysoteuchia topiaria (Zeller)	United States	Cranberry	Foxtail and red top (C)	(106) (F)
Cranberry girdler				
Helicoverpa zea (Boddie)	United States	Tobacco	Corn (B)	(98) (F)
Corn earworm		Cotton	Sorghum (C, B)	(132) (F)
Heliothis armigera (Hübner)		Pepper	Lupin (C)	(1) (F)
Cotton bollworm, fruit borer	Australia	Cotton	Chickpea and pigeon pea (C) (only 1% of total crop)	(114) (U)
			Field pea (C)	(45) (F)
	Ethiopia	Beans	Maize (C)	(1) (F)
	India	Tomato	Marygold (C, B), sorghum (C, B)	(123, 139) (F)
		Cotton	Beans, maize, okra, sunflower, pigeon pea (C)	(123) (U)

(*Continued*)

TABLE 1 (*Continued*)

Insect pest species	Country	Crop	Trap crop (modality)[a]	Reference(s) (Level of implementation)[b]
Heliothis virescens (F.)	United States	Tobacco	Tobacco (C, B)	(130, 131) (F)
Tobacco budworm			Nicotiana kawakamii (C)	(60) (F)
Hellula undalis (F.)	Guam	Cabbage	Chinese cabbage, Indian mustard, and radish (C)	(117) (F)
Cabbage webworm				
Maruca testalis (Geyer)	Nigeria	Cowpea	*Crotalaria juncea* (C)	(58, 59) (P)
Cowpea pod borer				
Ostrinia nubilalis (Hübner)	United States	Millet	Millet (different variety) (C, S)	(8) (F)
European corn borer		Non-Bt and Bt corn mixture	Bt Corn (G, S)	(94) (F)
Spodoptera litura (F.)	India	Groundnut	Castor and sunflower (C)	(142) (S)
Cutworm	Guam	Cabbage	Chinese cabbage, Indian mustard, and radish (C)	(117) (U)
Plutella xylostella (L.)	Canada	Rapeseed	Rape (glossy) (C)	(135) (P)
Diamondback moth		Canola	Canola (glossy) (C)	(62) (P)
	Guam	Cabbage	Indian mustard (C)	(117) (U)
	India	Cabbage	Indian mustard (S)	(92, 122) (F, S)
	South Africa	Cabbage	Indian mustard (C)	(24) (P, F)
	Sweden	Cabbage	Indian mustard (C)	(10) (P, F)

	United States	Cabbage	Indian mustard (C)	(17, 78) (U) (13) (P)
			Wild mustard (C)	(28) (F)
			Yellow rocket (D, P)	(12, 13, 56, 76, 115) (P); (14) (F)
			Collards (C, B, G)	(13, 23, 33) (P); (84–86) (F); (115) (U)
Order Orthoptera: crickets, grasshoppers, and locusts				
Valanga nigricornis (Burmeister) Shorthorned grasshopper	Malaysia	Rubber	Tropical kudzu (C)	(11) (P)
Zonocerus variegates (L.) Shorthorned grasshopper	Nigeria	Various crops	Eggplant (C)	(89) (BO)
Order Thysanoptera: thrips				
Frankliniella occidentalis (Pergande)	Canada	Nectarine	Sagebrush and other wildflowers (C, S)	(93) (U)
	United States	Lettuce	Crownbeard and other wildflowers (C)	(143) (F)

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[a] Modalities include conventional (C), multiple (M), biological control–assisted (E), dead-end (D), genetically modified (G), sequential, early, and/or late planting (S), semiochemically assisted (SA), push-pull (PP), and perimeter (P) trap cropping.

[b] Levels of implementation include unsuccessful, no potential shown in preliminary studies in the field and/or the laboratory (U); behavioral observation (BO); good potential shown in preliminary studies in the laboratory, greenhouse, and/or screenhouse (P); good potential shown in preliminary studies in the field (F); and successfully used by growers in commercial fields (S).

The most important insect characteristics that determine whether an insect may be subject to management by trap crops are the insect stage targeted by the trap crop and the insect's ability to direct its movement, its migratory behavior (mobility and mode of colonization), and its host-finding behavior (pre-alighting versus post-alighting). The insect stage to be controlled by the trap crop is of critical importance in designing an effective trap crop strategy. For example, adult female Lepidoptera select plants for oviposition but it is the larvae, which typically have limited mobility, that are the damaging stage (105). On the other hand, it is the mobile adult crucifer flea beetle, *Phyllotreta* spp., that selects host plants and causes injury. To select a successful trap crop in the first case requires knowledge of the ovipositional preference; in the second case knowledge of adult feeding preference is required. The ability of insects to direct their movements as a result of the presence of the trap crop should also be considered in the deployment of trap crops (97). In simulation models, Potting et al. (97) concluded that small insects with limited ability to detect hosts and move to them would be unsuitable for trap cropping, citing studies conducted with the hop aphid, *Phorodon humuli* (74), and the whitefly, *Bemisia argentifolii* (120), as evidence. Colonization patterns of these insects are largely due to passive, random, high-altitude aerial dispersal. However, trap crops taller than the main crop and planted in the borders could act as barrier crops (35). On the other hand, larger insects in the orders Coleoptera and Lepidoptera generally have an enhanced capacity for directional flight that makes them more amenable for trap cropping (97). For example, some trap crops elicit aggregation and partial inhibition of flight (arrestment) in diamondback moth, reducing its movement and colonization of the main crop (14). The spatial arrangement of the trap crop should be reflective of the patterns of field colonization by the insect. For insects that move into the field (e.g., Colorado potato beetle) rather than emerge from the field (e.g., Southern corn rootworm) after overwintering, a high perimeter-to-area ratio may increase the chances of a perimeter trap crop intercepting the insect pest (47). Regarding host-finding behavior, the strength of arrestment seems to be the most important parameter influencing the effectiveness of a trap crop in insects with post-alighting host-recognition behavior (21, 97). However, in insects that use olfactory or visual cues to find plants, the actual aggregation in the trap crop was a combination of attraction and arrestment.

In general, the attractiveness of the trap crop and the proportion of trap crops in the field are important factors in the arrestment of the insect and in the success of a trap cropping system (15). Low proportions of trap crop in a field may not be sufficient to reduce insect pest populations significantly, even if the trap crop is highly attractive and results in insect arrestment (14, 114). Fields with a low perimeter-to-area ratio are also less likely to result in effective trap cropping than are those fields with a layout resulting in a high perimeter-to-area ratio (47). Ultimately, the development of a successful trap cropping system requires the combination and fit between trap crop and its deployment and the characteristics of the targeted insect pest. Understanding the interaction between these factors has been advanced greatly by the combination of specific trap cropping systems with general modeling studies (15, 47, 97, 145). For example, the residency index, a measure of the time an organism spends between entering and leaving a unit area (134), is an important factor in the success of a trap crop managing an insect pest (47). A highly attractive trap crop is necessary to increase the residency index of an insect in an environment (47).

Among the 10 successful cases of trap cropping at a commercial level, the orders of the targeted insect pests involved three cases of Coleoptera, three cases of Hemiptera, three cases of Lepidoptera, and one case of Homoptera. The cases of Coleoptera, Hemiptera, and Lepidoptera involved insects that directed their movement and tended to aggregate on a highly attractive trap crop. Although lacking the characteristics to make it amenable for trap cropping (i.e., dispersal by passive movement and inability to redirect flight), the successful case of control of a virus carried by a homopteran pest (aphids) was possible because of the combination of a perimeter trap crop acting as a barrier crop (intercepting aphids moving passively into the field) and genetically engineered papaya plants acting as a sink for the virus carried by the aphids.

GENERAL LIMITATIONS OF TRAP CROPPING

The reasons why only a limited number of cases of trap crops (Table 1) are implemented at the commercial level vary with the crop system and the insect pest. In many cases, crops are attacked by a complex of insect pests and because trap crops tend to be relatively species specific makes them less practical compared with other alternative IPM strategies, e.g., the use of broad-spectrum insecticides that can control a complex of insect pests. Furthermore, the cost of insecticide control is often low compared with the cost of setting aside land for trap cropping, especially in the case of vegetables and other high-value crops. Agronomic and logistical considerations associated with implementing trap crops, such as different planting dates and fertilizer requirements of the trap crop and main crop, are also likely to limit the practical use of trap cropping. Most importantly, pest management practices need to show consistent results, and, as shown in Table 1, the success of some trap cropping systems, such as in the case of diamondback moth, has been highly variable, increasing the risk of economic loss to the grower. Trap cropping is also knowledge-intensive and demands information on the temporal and spatial attractiveness of potential trap crops to maximize their effectiveness. In some situations trap cropping may even require cooperation between growers because pests move freely between property boundaries. There might be cases in which trap crops may inadvertently put the main crop at risk if they harbor certain insects and pathogens that could be harmful to the main crop, although we did not find any reference for this situation in the literature. Finally, because in most situations trap cropping does not entail a "product" that can be sold, such as an insecticide, there are limitations in research funding. However, research on trap cropping may be attractive to other funding sources, such as those that intend to find alternatives to conventional insecticides.

CONCLUSIONS AND RECOMMENDATIONS

In situations in which trap cropping has been successfully implemented, it has provided sustainable and long-term management solutions to control difficult pests. Successes have occurred in both developed (e.g., lygus bugs on cotton) and developing countries (e.g., use of push-pull trap cropping to control stem borers in corn). With the advent of biotechnology, new opportunities for trap cropping have arisen, as illustrated by the examples of Bt potatoes and PRSV-resistant papaya. Some examples of more traditional trap cropping methods, such as the use of mustard to control stink bugs in corn (103) and the use of certain varieties of pepper to control pepper maggot (20), will likely be implemented at a commercial level. To develop trap cropping to its full potential, however, requires a multifaceted approach involving research and extension. In the past two decades there has been an increased research effort on trap cropping, as evidenced by more than 150 scientific publications since the two most recent reviews (50, 61) on trap cropping. There has also been at least one entomological symposium devoted entirely to trap cropping (http://esa.confex.com/esa/2003/techprogram/session_1315.htm). Funding may continue to be a limiting factor for research in trap cropping, but new opportunities are becoming available, including programs devoted to pest management alternatives and organic agriculture.

Organic growers and those farmers interested in biologically based pest management programs have especially shown increased interest in trap cropping, as have nongovernmental organizations and other educational organizations working in developing countries where access to effective insecticides is limited. In our opinion, trap cropping will be greatly enhanced if farmers, scientists, and extension educators expand their concepts of trap cropping to include the diverse modalities we highlight in this chapter.

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