Chapter 1

Companion Planting and Insect Pest Control

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Additional information is available at the end of the chapter

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1. Introduction

There is growing public concern about pesticides' non-target effects on humans and other organisms, and many pests have evolved resistance to some of the most commonly-used pesticides. Together, these factors have led to increasing interest in non-chemical, ecologically-sound ways to manage pests [1]. One pest-management alternative is the diversification of agricultural fields by establishing "polycultures" that include one or more different crop varieties or species within the same field, to more-closely match the higher species richness typical of natural systems [2, 3]. After all, destructive, explosive herbivore outbreaks typical of agricultural monocultures are rarely seen in highly-diverse unmanaged communities.

There are several reasons that diverse plantings might experience fewer pest problems. First, it can be more difficult for specialized herbivores to "find" their host plant against a background of one or more non-host species [4]. Second, diverse plantings may provide a broader base of resources for natural enemies to exploit, both in terms of non-pest prey species and resources such as pollen and nectar provided by the plant themselves, building natural enemy communities and strengthening their impacts on pests [4]. Both host-hiding and encouragement of natural enemies have the potential to depress pest populations, reducing the need for pesticide applications and increasing crop yields [5, 6]. On the other hand, crop diversification can present management and economic challenges for farmers, making these schemes difficult to implement. For example, each of two or more crops in a field could require quite different management practices (e.g., planting, tillage and harvest all might need to occur at different times for the different crops), and growers must have access to profitable markets for all of the different crops grown together.

"Companion planting" is one specific type of polyculture, under which two plant species are grown together that are known, or believed, to synergistically improve one another's growth

[7]. That is, plants are brought together because they directly mask the specific chemical cues that one another's pests use to find their hosts, or because they hold and retain particularly effective natural enemies of one another's pests. In this chapter we define companion plants as interplantings of one crop (the companion) within another (the protection target), where the companion directly benefits the target through a specific known (or suspected) mechanism [8, 9]. Companion plants can control insect pests either directly, by discouraging pest establishment, and indirectly, by attracting natural enemies that then kill the pest. The ideal companion plant can be harvested, providing a direct economic return to the farmer [2] in addition to the indirect value in protecting the target crop. However, "sacrificial" companion plants which themselves provide no economic return can be useful when their economic benefit in increased yield of the target exceeds the cost of growing the companion [10, 11].

Companion planting has received less attention from researchers than other diversification schemes (such as insectary plants and cover crops), but this strategy is widely utilized by organic growers [8, 9]. Generally, recommendations on effective companion-target pairings come from popular press articles and gardening books, which make claims of the benefits of bringing together as companions aromatic herbs, certain flowers [12], or onions (*Allium* L. spp.) [13]; nearly always, vegetables are the protection target. However, these recommendations most-commonly reflect the gut-feeling experiences of particular farmers that these pairings are effective, rather than empirical data from replicated trials demonstrating that this hunch is correct. Indeed, more-rigorous examinations of companion-planting's effectiveness have yielded decidedly mixed evidence [e.g. 9, 14 and 15]. Here, we first review companion plants that disrupt host-location by the target's key pests, and then those that operate by attracting natural enemies of the protection target's pests. For companions operating through either mechanism, we discuss case-studies where underlying mechanisms have been examined within replicated field trials, highlighting evidence for why each companion-planting scheme succeeded or failed.

2. Companions that disrupt host location by pests

Herbivorous insects use a wide variety of means to differentiate between host and non-host plants. Consequently, host-finding behavior of the target's pests plays a key role in selecting an effective companion plant. Typically, host plant selection by insects is a catenary process involving sequences of behavioral acts influenced by many factors [16]. These can include the use of chemical cues, assessment of host plant size, and varying abilities to navigate and identify hosts among the surrounding vegetation. Therefore, both visual and chemical stimuli play key roles in host plant location and eventual acceptance. At longer distances, host-location often is primarily through the detection and tracking of a chemical plume [17]. At this scale, abiotic factors may play a strong role. For example, an odorous plume can be influenced not just by plant patch size, but also by temperature and wind speed, which can change the plume's spatial distribution and concentration [17]. As the insect draws near to the host plant, visual cues can increase in importance [17]. Visual indications that a suitable host has been located can include the size, shape and color of the plant [18]. Therefore, based on the dual roles of chemical and visual cues in host-location by herbivores, to be effective disruptors of host-location by the target's pests, companion plants would need to: (1) disrupt the ability of the pest to detect or recognize the target's chemical plume; (2) disrupt or obscure the visual profile of the target; or (3) act simultaneously through both chemical and visual disruption of host location.

Furthermore, ecological differences among pest species are likely to impact the effectiveness of companion planting. For example, specialist herbivores appear to be relatively strongly dissuaded from staying in diverse plantings where their host is just one component of the plant community, whereas generalist herbivores sometimes prefer diverse to simple plantings [19, 20]. Presumably this is because diverse plantings provide relatively few acceptable hosts per unit area for a specialist, but (potentially) several different hosts acceptable to a generalist. Likewise, the size/mobility of the pest is likely to be important. Potting et al. (2005) in reference [21] suggested that smaller sized arthropods such as mites, thrips, aphids and whiteflies that can be passively transported by wind currents, have limited host detection ability. Of course, when a pest moves haphazardly through the environment there is no active host-location behavior for a companion plant to disrupt! Apparently because insects that travel passively with wind currents may cause them to bypass trap crops leading to companion plant failure. Conversely, larger sized insects capable of direct flight have good sensory abilities that allow them to perform oriented movement and thus represent good candidates for control by companion planting [21].

2.1. Companions that draw pests away from the protection target

Trap crops are stands of plants grown that attract pest insects away from the target crop [11, 22] (Fig. 1).

Once pests are concentrated in the trap crop the pests can be removed by different means, such as burning or tilling-under the trap crop [11] or by making insecticide applications to the trap. A highly-effective trap crop can bring a relatively large number of pests into a relatively small area, such that pest management within the trap crop requires coverage of less ground than if the entire planting of the protection target had to be treated. Even if left unmanaged through other means, pests feeding within the trap are not damaging the protection target. Because trap crops are more attractive to the pest, they are usually rendered unmarketable due to pest damage. This means that, to be economically-viable, the cost of establishing and maintaining the trap crop must equal or exceed the value of crop-protection within the protection target.

There are many successful examples of trap cropping. For example, in California the need to spray for *Lygus* Hahn in cotton was almost completely eliminated due to the success of alfalfa trap crops [23-25]. In soybeans, Mexican bean beetles can be controlled using a trap crop of snap beans [26]. Similarly, for over 50 years in Belorussia early-planted potato trap crops have been used to protect later plantings of potatoes from Colorado potato beetle attack [27]. Even though many successful examples of trap crops have been reported, several studies have also demonstrated contradictory results with many declaring unsuccessful [28-31] to unreliable control of pests [32]. For example, Luther et al. (1996) in reference [29] explored trap crops of Indian mustard and Tastie cabbage to control diamondback moth and *Pieris rapae* L. in Scorpio

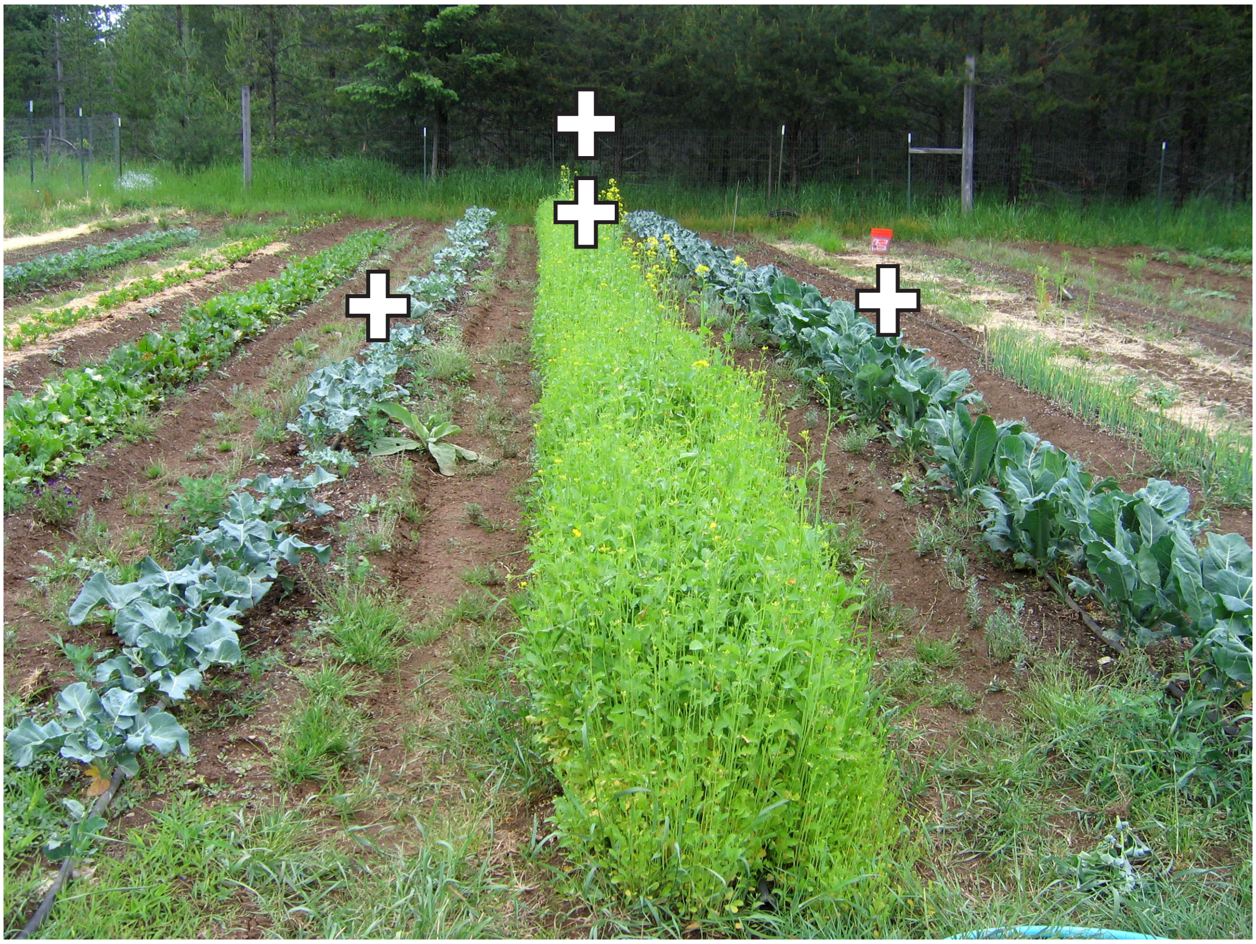

Figure 1. A trap crop of Pacific gold mustard (companion plant) is flanked on both sides by broccoli (target crop). The symbols (+) represent the principal mechanism at work. Here, the trap crop, designated with two (+) signs, are more attractive than the protection target-broccoli. The mustard trap crop is used to attract pest insects away from broccoli.

cabbage and discovered that these trap crops were effective at attracting these pests; however, the distance between the trap crop and the protection target allowed for pests to spillover back into the protection target. In another experiment using Indian mustard as a trap crop, Bender et al. (1999) in reference [30] intercropped Indian mustard with cabbage to control lepidopterous insects and found that Indian mustard did not appear to preferentially attract these insect pests. Overall, the relative effectiveness of the trap crop depends on the spatial dimensions of the trap crop and protection target, the trap crop and protection target species and pest behavior.

The need to control pests in the trap crop can be avoided when "dead-end" traps are deployed. Dead-end trap cropping utilizes specific plants that are highly preferred as ovipositional sites, but incapable of supporting development of pest offspring [33, 34]. For example, the diamond back moth (*Plutella xylostella* L.), a pest of *Brassica* crops, is highly attracted for oviposition to the G-type of yellow rocket (*Barbarea vulagaris* R. Br.), but the larvae are not able to survive on this host plant [35]. This inability to survive has been attributed to a feeding deterrent, monodesmosidic triterpenoid saponin [36] and so larvae cannot complete development.

Similarly, potato plants genetically engineered to express *Bacillus thuringiensis* (Bt) proteins that are deadly to the Colorado potato beetle, and planted early in the season, can act as dead-end traps that kill early-arriving potato beetles [37].

Trap crop effectiveness can be enhanced by incorporating multiple plant species simultaneously. Diverse trap crops include plants with different chemical profiles, physical structures and plant phenologies, therefore, diverse trap crops may provide for a more attractive trap crop. For example, in Finland, mixtures of Chinese cabbage, marigolds, rape and sunflower were used successfully as a diverse trap crop to manage the pollen beetle (*Melighetes aeneus* F.) in cauliflower [38]. Furthermore, Parker (2012) in reference [39] conducted experiments exploring the use of simple and diverse trap crops to control the crucifer flea beetle (*Phyllotreta cruciferae* Goeze) in broccoli (*Brassica oleracea* L. var. *italica*). The trap crops included monocultures and polycultures of two or three species of Pacific gold mustard (*Brassica juncea* L.), pac choi (*Brassica rapa* L. subsp. *pekinensis*) and rape (*Brassica napus* L.). Results indicated that broccoli planted adjacent to diverse trap crops containing all three trap crop species attained the greatest dry weight suggesting that the trap crops species were not particularly effective when planted alone, however, provided substantial plant protection when planted in multi-species polycultures. Thus, diverse trap crops consisting of all three trap crop species (Pacific gold mustard, pac choi and rape) provided the most effective trap crop mixture.

The success of trap crops depends on a number of variables, such as the physical layout of the trap crop (e.g., size, shape, location) and the pests' patterns of movement behavior [40]. For example perimeter trap crops, trap crops sown around the border of the main crop [41], have been used to disrupt Colorado potato beetle (*Leptinotarsa decemlineata* Say) colonization of potato fields from overwintering sites that ring the field [42-44]. However, depending on the pest targeted for control and the cropping system, perimeter trap crops may not be the most effective physical design. For example, a perimeter trap crop may not impede pest movement if the pest descends on a crop from high elevations. In reference [11] Hokkanen (1991) has recommended an area of about 10% of the main crop area be devoted to the trap. A smaller trap crop planting leaves more farm ground available for planting marketable crops.

In general, throughout trap cropping literature, trap crops are most effective when they are attractive over a longer period of time than the target crop, and when trap crops target mobile pests that can easily move among the trap and protection-target plantings [11]. References [11] and [41] reported trap crop success particularly with larger beetles [11] and tephritid flies [41], insects generally capable of direct flight.

2.2. Plants that repel

Plants with aromatic qualities contain volatile oils that may interfere with host plant location, feeding, distribution and mating, resulting in decreased pest abundance [45-47] (Fig. 2).

Moreover, certain plants contain chemical properties which can repel or deter pest insects and many of these products are used to produce botanical insecticides. For example, pyrethrum obtained from dried flower of the pyrethrum daisy (*Tanacetum cinerariaefolium* L.), neem extracted from seeds of the Indian neem (*Azadirachta indica* A. Juss.) and essential oils extracted

Figure 2. Intercroppings of spring onions (companion plant) are implemented to protect broccoli (target crop) from pest attack. Here, spring onions are used as a repellent to push pest insects away from broccoli. The symbols represent their potential attractive (+) and repellent (-) properties.

from herbs such as rosemary, eucalyptus, clove, thyme and mint have been used for pest control [48]. Generally, aromatic herbs and certain plants are recommended for their supposed repellent qualities. For example, herbs such as basil (*Ocimum basilicum* L.) planted with tomatoes have been recorded to repel thrips [49] and tomato hornworms [50]. Plants in the genus *Allium* (onion) have been observed to exhibit repellent properties against a variety of insects and other arthropods including moths [51], cockroaches [52], mites [53] and aphids [54]. These examples represent a wide array of arthropods that respond to repellent odors and demonstrate the potential repellent plant properties can have on pest control.

Furthermore, many studies have reported a wide variety of companion plants to contain repellent properties against pests of *Brassica* crops. *Brassica* species are an economically important crop throughout the world [55], sometimes comprising up to 25% of the land devoted to vegetable crops [56]. These companion plants included sage (*Salvia officinalis* L.), rosemary (*Rosemarinus officinalis* L.), hyssop (*Hyssop officinalis* L.), thyme (*Thymus vulgaris* L.), dill (*Anethum graveolens* L.), southernwood (*Artemisia abrotanum* L.), mint (*Menta* L. spp.), tansy (*Tanacetum vulgare* L.), chamomile (several genera), orange nasturtium (*Tropaeolum Majus* L.)

[57], celery and tomatoes [57, 58]. Similarly, intercropping tomatoes with cabbages has been suggested to repel the diamond back moth [59] and ragweed (*Ambrosia artemisifolia* L.) has been used to repel the crucifer flea beetle (*Phyllotreta cruciferae*) from collards (*Brassica oleracea* L. var. *acephala*) [60], both widespread pests of *Brassica* crops.

Not all studies using repellent companion plants have reported positive results. Early data have suggested no scientific evidence that odors from aromatic plants can repel or deter pest insects [61]. In reference [62] Latheef and Irwin (1979) found no significant differences in the number of eggs, larvae, pupae, or damage by cabbage pests between companion plants; French marigold (*Tagetes patula* L.), garden nasturtium pennyroyal (*Mentha pulegium* L.), peppermint (*Mentha piperita* L.), garden sage, thyme and control treatments. Furthermore, French marigolds (*Tagetes patula* L.) intercropped in carrots did not repel the carrot fly (*Psila rosae* F.) [47]. Even reports of frequently recommended companion herbs did not always improve pest control. For example, there were no differences in diamond back moth oviposition between Brussels sprouts (*B. oleracea*) intercropped with sage (*S. officinalis*) and thyme (*T. vulgaris*) [61]. Sage and thyme represent two common companion plants noted for their pungent odors [9]. Billiald et al. (2005) in reference [63] and Couty et al. (2006) in reference [64] concluded that if these highly aromatic plants were truly repellent, insects would not land on non-host companion plants.

Indeed, other mechanisms other than repellent odors might have a prominent role in plant protection. In reference [61] Dover (1986) noted reduced oviposition by the diamond back moth caused by contact stimuli and not repellent volatiles of sage and thyme. Therefore, sage and thyme were still protecting the target crop; however, this protection was caused by alternative mechanisms other than repellent odors. Similarly, research has demonstrated that aromatic plants such as marigolds (*Tagetes erecta* L.) and mint (*Mentha piperita* L.) did not repel the onion fly (*Delia antiqua* Meigen) or the cabbage root fly (*D. radicum* L.), but instead disrupted their normal chain of host plant selecting behaviors [16, 65, 66].

The response to a repellent plant will vary depending on the behavior of the insect and the plant involved. As a result, a repellent plant that can be effective for one pest might not provide effective control for another [67]. Finally, many experiments to determine plant's repellent capabilities were carried out in laboratory settings and do not necessarily represent field conditions [9].

2.3. Plants that mask

Companion plants may release volatiles that mask host plant odors [59, 60, 68] interfering with host plant location (Fig. 3).

For example, host location by the cabbage root fly (*D. radicum*) was disrupted when host plants were surrounded by a wide variety of plants including weeds and marketable crops [69, 70] such as spurrey (*Spergula arvensis* L.) [71], peas (*Pisum sativum* L.) [72], rye-grass (*Lolium perenne* L.) [72] or clover [73, 74]. However, Finch and Collier (2000) in reference [9] suggested that even though these diverse companion plants contain different chemical profiles, it is unlikely that all would be able to mask host plant odors. Further research has demonstrated

Figure 3. Marigolds (companion plant) are intercropped with broccoli (target crop) to interfere with host plant location. Here, several mechanisms may be involved in protecting broccoli including masking host plant odors or visually camouflaging broccoli making it less apparent. Here, the symbol (+) is shaded to represent a less apparent target crop-broccoli.

that in a wind tunnel, cabbage root fly move toward *Brassica* plants surrounded by clover just as much as *Brassica* plants grown in bare soil indicating that odors from clover did not mask those of the *Brassica* plants [75].

In addition to hiding odors emitted by the protection target, companion plants have also been reported to alter the chemical profile of the protection target. For example, certain companion plants can directly affect adjacent plants by chemicals taken up through its roots [76]. African marigolds (*Tagetes* spp.) produce root exudates which can be absorbed by neighboring plants [77] and may help to explain the reports of African marigold reducing pest numbers [9]. African marigolds also release thiopene, which acts as a repellent to nematodes [78]. Similarly, studies exploring various barley cultivars discovered that airborne exposure of certain combinations of undamaged cultivars caused the receiving plant to become less acceptable to aphids [79-81] and this was also confirmed in field settings [80]. Thus, volatile interactions between odors of host and non-host plants and even single species with different cultivars can affect the behavior of pest insects.

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2.4. Plants that camouflage or physically block

In addition to protecting crops with olfactory cues, companion plants may also physically and visually camouflage or block host plants [9, 14, 15, 20, 47, 60, 82]. The 'appropriate/inappropriate landing' theory proposed that green surfaces surrounding host plants may disrupt host plant finding [9]. The 'appropriate/inappropriate landing' theory was originally inspired from studies exploring the oviposition behavior of cabbage herbivores and found that reduced damage in intercropping systems were attributed to a disruption of oviposition behavior [9]. This can occur when insects land on a companion plant instead of the target crop before or during oviposition [83]. For example, Atsatt and O'Dowd (1976) in reference [84] demonstrated that *Delia radicum* (L.) (cabbage root fly) spent twice as much time on a non-host plant after landing on it compared to a host plant. This demonstrated that companion plants can disrupt and arrest *D. radicum* on inappropriate hosts (companion plants). Consequently, *D. radicum* will start its oviposition process from the beginning which may reduce the total number of eggs layed on the target crop. Studies have found similar post-alighting behavior of *Delia floralis* Fallén (turnip root fly) and the decision to oviposit after landing on host and non-host plants [85, 86].

Companion plants may visually (Fig. 3) or physically (Fig. 4) obstruct host plant location rendering host plants less apparent [87].

For example, host plant location in the crucifer flea beetle (*Phyllotreta cruciferae* Goeze) is disrupted when non-host plant foliage, either visual or hidden, is present [60]. Similarly, Kostal and Finch (1994) in reference [72] and Ryan et al. (1980) in reference [88] both showed that artificial plant replicas made from green card or green paper could disrupt host plant location. Companion plant height is also an important factor in pest suppression. Tall plants can impede pest movement within a cropping system [89]. For example, maize has been used to protect bean plants from pest attack [90] and dill has been used as a vegetative barrier to inhibit pest movement in organic farms (personal observation). Frequently recommended companion plants used as physical barriers include sunflowers, sorghum, sesame and peal-millet [91]. In addition, companion plant barriers may also be used to reduce the spread and transmission of insect vectored viruses [92].

Nevertheless, these mechanisms may not rely solely on physical obstruction [93]. For example, the presence of desiccated clover plants (brown in color), which retained the same architecture as living plants (green in color), but only differed in their appearance from living plants, did not reduce the number of cabbage root fly (*D. radicum*), diamond back moth (*P. xylostella*) and the large white butterfly (*Pieris brassicae* L.) eggs when compared to the target crop on bare ground [93]. However, when live clover surrounded the target crop, the numbers of eggs laid were reduced suggesting that the physical presence of clover alone was not enough to prevent a reduction in oviposition [93]. Therefore, the size, shape, color and chemical profiles of companion plants may interact together reducing pest numbers making it is difficult to tease apart specific mechanisms which may be contributing to pest control.

Figure 4. Dill (companion plant) is used as a physical barrier to protect broccoli (target crop) from pest attack. Here, the height of the dill can impede pest movement.

2.5. Combinations of companion planting techniques

In some systems, different companion planting methods have been combined to work synergistically and improve pest control. For example, in Kenya trap crops have been combined with repellent plants and implemented successfully in a 'push-pull' system [94] to control spotted stem borer (*Chilo partellus* Swinhoe) in maize (*Zea mays* L.) [95, 96]. The repellent plants included a variety of non-host plants such as molasses grass (*Melinis minutiflora* P. Beauv.), silverleaf desmodium (*Desmodium uncinatum* Jacq.) or green leaf desmodium (*Desmodium intortum* Mill.) and the trap crop plantings included Napier grass (*Pennisetum purpurerum* Schumach) or Sudan grass (*Sorghum vulgare sudanense* Hitchc.) [94]. Here, the 'push' (repellent companion plants) drives the pest insect away from the target crop while the 'pull' (trap crop) simultaneously lures the pests toward the trap crop. Kahn and Pickett (2003) in reference [96] have reported thousands of farmers in east Africa to utilize the push-pull strategies to protect maize and sorghum. In addition, Komi et al. (2006) in reference [97] suggested that maize-legumes or maize-cassava intercrops can provide a 'push' for push-pull systems incorporating Jack-bean (*Canavalia ensiformis* L.) as a highly attractive trap crop 'pull'. The goal of the push-pull strategy aims to minimize negative environmental consequences and maximize pest control, sustainability and crop yield [94].

3. Plants that enhance conservation biological control

While the previous theories explored bottom-up forces in which companion plants improved pest control, Root (1973) 'enemies hypothesis' in reference [4] explored top-down mechanisms. He proposed that natural enemy populations are greater in polycultures because diverse habitats provide a greater variety of prey and host species that become available at different times. Furthermore, a greater diversity of prey and host species allows natural enemy populations to stabilize and persists without driving their host populations to extinction [4]. Altogether these theories present processes which may contribute to the lower abundance of pest insects in mixed cropping systems. Not surprisingly, companion plants may provide pest control by one or several of these mechanisms.

Pest populations can be managed by enhancing the performance of locally existing communities of natural enemies [98]. This can be accomplished by incorporating non-crop vegetation, such as flowering plants also known as insectary plants, into a cropping system (Fig. 5).

Figure 5. Flowering companion plants are incorporated into this mixed vegetable farm to enhance the efficacy of natural enemies and improve pest suppression.

Companion plants can provide essential components in conservation biological control by serving as an alternative food source and supplying shelter to natural enemies [99]. Many natural enemies including predators and parasitoids require non-prey food items in order to develop and reproduce [100-102]. For example, adult syrphids whose larvae are voracious predators of aphids, feed on both pollen and nectar [103]. Pollen and nectar are essential resources for natural enemies which satisfy different health requirements. Nectar is a source for carbohydrates and provides energy, while pollen supplies nutrients for egg production [103-106]. In wheat fields in England and in horticultural and pastoral habitats in New Zealand over 95% of gravid female syrphids were found with pollen in their gut [103]. As a result, flowering plants can increase the fecundity and longevity of parasitic hymenoptera [107-109] and predators [110, 111]. In addition to increasing natural enemy fitness, improved nutrition may also enhance foraging behavior [e.g. 112, 113] and increase the female-based sex ratio of parasitoid offsprings [114]. A wide variety of natural enemies utilize non-prey food sources. For example, pollen and nectar have been demonstrated to be highly attractive to variety of predators including syrphids [103, 115, 116], coccinellids [117-119], and lacewings [117].

One method to increase natural enemy density using companion plants includes incorporating certain flowering plants into a cropping system. This is often accomplished by planting flowering strips or border plantings in crop fields. Plants in the family Apiaceae are highly attractive to certain beneficial insect populations and are generally recommended as insectary plants [120]. This can be attributed to their exposed nectaries and the structure of their compound inflorescence which creates a "landing platform" [121, 122]. In addition, natural enemies are attracted to the field by the color and odor of companion plants [123]. Another commonly used insectary plant is *Phacelia tanacetifolia* Benth, which has been employed in borders of crop fields because it produces large amounts of pollen and nectar [124, 125]. For example, White et al. (1995) in reference [116] incorporated plantings of *P. tanacetifolia* near cabbage (*B. oleracea*) to increase syrphid densities to control aphids. Similarly, MacLeod (1992) in reference [126] and Lövei et al. (1993) in reference [127] demonstrated that syrphids are highly attracted to the floral resources provided by coriander and buckwheat. Companion plants may work simultaneously influencing both top-down and bottom-up mechanisms. For example, while some studies have demonstrated dill to improve pest control by containing repellent properties, other studies have indicated that dill may also increase predator populations. Patt et al. (1997) in reference [128] found reduced survivorship and populations of Colorado potato beetle (*L. decemlineata*) when dill was intercropped with eggplant and attributed the lower pest numbers to improved biological control.

Flowering companion plants have been used in different cropping systems to enhance the impact of natural enemies. For example, in organic vineyards, [110, 111] increased natural enemies by supplying access to nectar-producing plants such as alyssum (*Lobularia maritima* L.). Other various herbs have also been used this way in Europe [126, 129, 130] and in New Zealand [115, 127]. Overall, flowering companion plants have been implemented in a variety of crops including cereals, vegetable crops and fruit orchards [99, 131-137] to improve conservation biocontrol. In addition to food resources, companion plants can provide shelter from predators and pesticides as well as favorable microclimates [138, 139] including overwintering sites [140]. Furthermore, companion plants can also influence the spatial distribution of natural enemies in and around crops [141, 142] improving pest control.

Indeed, the advantages of plant-based resources for natural enemies have only recently been recognized by major reviews [99, 143- 146], and the growing empirical evidence has demonstrated their importance in pest suppression. However, the interactions between the companion plant, target pests and their natural enemies are complex. For example, incorporating companion plants may not necessarily improve biological control if the flowering does not coincide with the activity of natural enemies [147], or if natural enemies do not move from the companion plants to the target crop [117, 148]. Moreover, plant structures, such as the corolla, may obstruct feeding by natural enemies [128] and diverse habitats may complicate prey location by predators and parasitoids [143,149, 150]. Just as pest insects may react differently to the same companion plant, predators within the same family can also respond to similar companion plants in different ways. For example, certain syrphids are highly specialized feeders, while others are generalist [151] influencing companion plant selection. However, the possible obstructions to conservation biocontrol can be diminished. One way to improve the effectiveness of companion plants in conservation biocontrol is to select plants that benefit key natural enemies [152]. Again, this highlights the importance of implementing "careful diversification" as a pest management method [144, 153-155]. Overall, incorporating companion plants to enhance biological control holds promise for managing pests in crops.

Companion plants have also been used as banker plants. Banker plants are usually non-crop species that are deliberately infested with a non-pest insect and improves biological control by providing natural enemies with alternative prey [e.g. 156-158, but see 159, 160] even in the absence of pests [e.g. 156, 159, 161]. This allows natural enemy populations to reproduce and persists throughout the season. Banker plants have been used in both conservation and augmentative biological control programs. Many studies have used banker plants consisting of wheat or barley to sustain populations of the bird cherry-oat aphid (*Rhopalosiphum padi* L.) because this aphid feeds only on members of the Poaeceae family and does not pose a threat for vegetable and ornamental production [162]. However, success can be variable. Jacobson and Croft (1998) in reference [163] compared wheat, rye and corn as banker plants in its ability to sustain the bird cherry-oat aphid parasitoid (*Aphidius colemani* Viereck) and found that control was dependent on banker plant density, release rate and season. One successful example was implemented in apple orchards. To control the rosy apple aphid (*Dysaphis plantaginea* Passerini) in apple orchards, Bribosia et al. (2005) in reference [164] used Rowan trees (*Sorbus aucuparia* L.) as banker plants to maintain densities of Rowan aphids (*Dysaphis sorbi* L.) which served as an alternate host for the braconid parasitoid *Ephedrus persicae* Froggatt.

4. Constraints and challenges

Incorporating companion plants into pest management strategies is not without challenges. Farmers often face logistical constraints when incorporating companion plants into their field designs. For example, modern agriculture techniques and equipment are not conducive to growing multiple crops in one field [165]. Furthermore, companion plants may hinder crop yield and reduce economical benefits [166, 167]. Beizhou et al. (2011) in reference [168] reported an outbreak of secondary pests and reduced yield in an orchard setting. Decreased yields can often be attributed to competition for resources by incorporating inappropriate companion plants [169]. In certain cases, vegetational diversification can diminish the impacts of biological control. Generally, greater habitat diversity leads to a greater abundance of prey and host species. For instance, improved diversity can lead to reduced biological control by generalist predators which can be influenced by the greater diversity and abundance of alternative prey [123]. Straub et al. (2008) in reference [152] reviewed findings from natural enemy diversity experiments and found that results can range from negative (reduced control) to positive (improved control) due to effects from intraguild predation and species complementarity.

Therefore, choosing which type of companion plant to incorporate in a diversification scheme is challenging. For example, plant phenology, attractiveness and accessibility of the flowers to natural enemies [128] and pest species will play a key role in plant selection. However, it is possible to minimize the reductions in economic returns within companion planting schemes. It is important to use plants that can provide a satisfactory economic return, if possible, as compared to the target crop planted in monoculture [170]. In conservation biocontrol, to reduce negative impacts from biocontrol antagonists or the targeted pest, Straub et al. (2008) in reference [152] suggested using specific resources that can selectively benefit key natural enemies. Overall, whether companion plants control pests through bottom-up or top-down mechanism, their impact will depend on companion plant selection. This emphasizes the significance of finding the "right type" of diversity that combines species that complement one another in ecologically-relevant ways [67].

Designing companion planting schemes pose several impending issues. For instance, optimal distances between the companion plant and the target crop needs to be determined before specific recommendations can be made. The distance to which an insect is attracted to a source has proven to be variable and is a key area in companion plant success. Evans and Allen-Williams in reference [171] demonstrated that attraction can occur at distances of up to 20 m. Judd and Borden (1989) in reference [172] showed attraction of up to 100 m, however, other researchers have shown distances of only a few centimeters [173-176]. Therefore, adjusting the design depending on the insect's behavior and movement [83], the insect's search mode [177, 178] and diet breadth [20] may necessary for companion plant success. Furthermore, an insect's feeding behavior will affect the success of companion plants in pest management strategies. For example plant structure can affect herbivory. Rape (*B. napus*) can be composed of trichomes that are nonglandular and simple or unbranched [179] and in some cases act as physical barriers that complicate feeding [180].

5. Conclusions

Many examples of companion plant to reduce pest numbers have been demonstrated; fewer diamondback moths were found on Brussels sprouts when intercropped with malting barley, sage or thyme [61]. Similarly, lower numbers of striped flea beetles were observed when Chinese cabbage (*Brassica chinensis* L.) was intercropped with green onions (*Allium fistulosum* L.) [181], while Mutiga et al. (2010) in reference [182] recorded significantly lower numbers of the cabbage aphid (*Brevicoryne brassicae* L.) when spring onion (*Allium cepa* L.) was intercropped with collard (*B. oleracea* var. *acephala*). However, the mechanisms through which companions protect the target are not well understood [183]. Many studies have suggested that chemical properties in the plant can repel insects [94], while others have suggested that companion plants are considered chemically neutral [66]. For example, Finch et al. (2003) in reference [66] demonstrated that commonly grown companion plants used for their repellent properties, marigolds and mint, did not repel the onion fly or the cabbage root fly (*D. radicum*), but rather interrupted their host finding and selecting behaviors [16, 65]. Thus, even though the companion plants did not repel pests, they were still able to disrupt host plant finding through alternative mechanisms. Overall, the effectiveness of companion plants to reduce pest numbers is not being disputed, but rather the mechanisms in which they work.

Caution should be taken before using companion plants in pest management as results can be mixed. For example, experiments conducted by Held et al. (2003) in reference [12] explored several putative companion plants in their ability to deter Japanese beetles (*Popillia japonica* Newman) from damaging roses and concluded that companion plants were unlikely to help. Diversifying cropping schemes is an essential step in the future of pest management. Companion planting represents just one of many areas in which a single farmer can incorporate diversifying schemes to reduce pest densities in an in-field approach. However, relatively subtle factors may determine whether crop-diversification schemes succeed or fail in improving pest suppression and crop response. Therefore, further research is needed on understanding the interactions between plant selection, mechanisms of benefit and patterns in time and crop phenology. Ultimately, cultural control strategies like companion planting can conserve species diversity, reduce pesticide use and enhance pest control.

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