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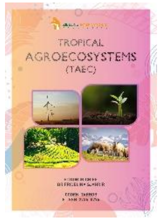

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REVIEW ARTICLE

LANDSCAPE ENGINEERING: HUMAN-MEDIATED ALTERATIONS OF CROP ECOSYSTEMS FOR ECO-FRIENDLY PEST MANAGEMENT

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ABSTRACT

Agricultural pests pose a growing challenge to global food security, exacerbated by climate change, habitat fragmentation, and the overuse of chemical pesticides. Conventional pest management, heavily reliant on synthetic chemicals, has led to pesticide resistance, non-target effects, and biodiversity loss, necessitating ecologically sustainable alternatives. Landscape engineering offers a promising strategy by modifying agricultural habitats to enhance ecosystem services, particularly natural pest regulation. Intercropping, hedgerows, cover crops, and non-crop refuges are examples of habitat diversification techniques that can be included into agricultural landscapes to promote natural enemies, prevent pest invasion, and lessen the need for chemical treatments. Empirical evidence underscores the intricate interplay between landscape composition, pest population dynamics, and natural enemy efficacy, highlighting the role of spatial and temporal habitat heterogeneity in pest suppression. Furthermore, the synergistic integration of landscape engineering with biological control approaches, including conservation, augmentative, and classical biological control, strengthens its potential for sustainable pest management. Addressing knowledge gaps in landscape-scale pest ecology, refining predictive models, and enhancing the adoption of agroecological principles are critical to optimizing these strategies for practical implementation. The transition toward landscape-mediated pest management not only mitigates the environmental costs associated with conventional approaches but also contributes to long-term agricultural resilience, biodiversity conservation, and ecosystem stability.

KEYWORDS

Agricultural landscapes, habitat diversification, food security, sustainable agriculture, ecosystem health.

1. INTRODUCTION

The 1960s saw the development of the integrated pest management (IPM) concept in response to worries about the environmental effects of pesticides. According to a United Nations Human Rights Council report, 200,000 people worldwide perish each year from poisonous pesticide exposure, with low-income nations accounting for 99% of these deaths (Nag and Gite 2020). The idea behind IPM was to shift crop protection practices by offering a substitute for the unilateral intervention with chemicals. This would require a more profound comprehension of insect and crop ecology and the application of multiple complementary tactics. The idea was that pest issues could be predicted using ecological theory as a foundation for altering production methods and inputs. Additionally, ecological design was considered to be able to lessen the susceptibility of agricultural systems to insect outbreaks.

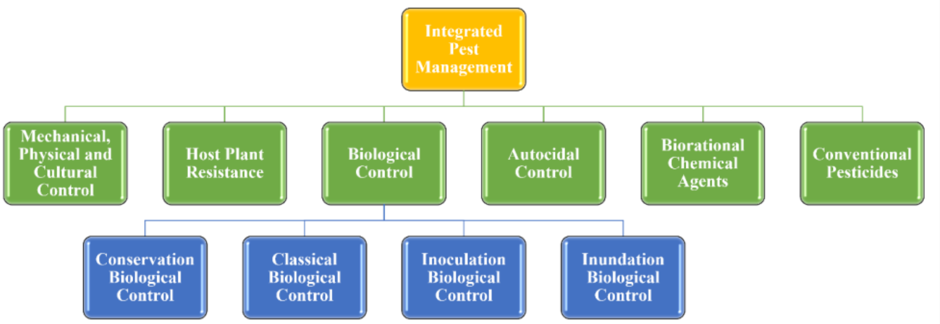

Figure 1: Biocontrol methods in comparison to other integrated pest management strategies

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It state that historically, hunts for "silver bullet" ways to control insect outbreaks have dominated IPM tactics (Lewis et al., 1997). This is the main reason why IPM research has been hesitant to develop a theory that will help farmers go beyond the methods of production that are now in use. The focus has shifted from understanding why agro-ecosystems are vulnerable to understanding how to make them more resilient to pests, with an emphasis on strategies to control pests and minimize crop damage. One strategy to develop the ecosystem management approach in IPM is to understand that the proper balance of soils, crops, nutrients, moisture, sunlight and coexisting organisms is what leads to crop health and sustainable yields. When this equilibrium of ideal growing circumstances is maintained and crop plants maintain their ability to withstand stress and misfortune, the agro-ecosystem is robust and prolific. Agro-ecosystems that are diversified and adaptive can bounce back from occasional shocks after the stress has passed (Altieri and Rosset, 1996).

In agricultural landscapes, ecosystem function and biodiversity are significantly impacted by the loss of habitat variety caused by agricultural intensification since the middle of the 20th century (Benton et al., 2003). This has led to adverse impacts on biodiversity, human and ecosystem health, soil and water quality, and possibly agricultural productivity (Tscharntke et al., 2005; Ray et al., 2012). Agricultural productivity is supported by a healthy ecosystem and the species that inhabit it, providing ecosystem services like crop pollination, insect control, and nutrient cycling. Long-term food security and environmental health depend on our ability to comprehend these ecosystem services and incorporate their management into contemporary, environmentally responsible, and productive crop production systems. Because essential food supplies and overwintering grounds have been removed, the growth of monocultures has resulted in a decline in the number and activity of natural enemies. Numerous experts are worried that as habitat loss accelerates, biological control agents that rely on these habitats to suppress pests are contributing less to the overall reduction of pests, making agro-ecosystems more susceptible to invasion and outbreaks.

Naturally occurring enemies generally do not thrive in monocultures (Andow, 1991). Many of the resources that natural enemies require to feed, reproduce, and flourish are absent from such basic agricultural systems, including other hosts and prey, pollen, nectar, and refuge locations. Farm insects are vulnerable to significant harm from common cultural practices like tillage, weeding, spraying, and harvesting. Invertebrate herbivores thrive in fields that are heavily fertilized, weeded, and irrigated because they perceive monocrops as concentrated sources of food. Monocultures' susceptibility to pest incursions is caused by a variety of causes, viz. –

- Diminished diversity of landscapes: The advent of contemporary agriculture has brought about significant alterations to the diversity of landscapes. Consistent trends toward simplification have included a loss in inter- and intra-specific variation within the planted field, an increase in the density of crop plants, a drop in the age structure and physical quality of the crop population, and the expansion and aggregation of fields.

- Less plant diversity on farms: Numerous ecologists have tested the hypothesis that less plant diversity in agro-ecosystems increases the likelihood of invasive species colonizing, which increases the abundance of herbivorous insects. Numerous investigations have demonstrated that combining specific plant species with the main herbivore's host produces a reasonably consistent outcome: specialized species typically show higher abundance in monoculture as opposed to varied agricultural systems (Andow, 1983).

- Insect pest outbreaks caused by pesticides: Numerous instances of outbreaks of insect pest and/or revival after insecticide applications are documented in the literature (Pimentel, and Perkins, 1980). Pesticides either don't work to control the intended pests or cause other pest issues. The main method that using pesticides might result in the failure of pest management is through the development of resistance in insect pest populations. A variety of insecticides and acaricides have caused more than 500 species of arthropods to develop resistance (Van Driesche, and Bellows, 1996).

- Pest outbreaks caused by fertilizer: proposed that the type of fertilizer applied (chemical vs. organic) could influence a crop's physiological vulnerability to insects (Luna, 1988). The majority of research assessing the response of mites and aphids to nitrogen fertilization found that aphid and mite populations were significantly boosted by increases in nitrogen rates. According to the study, the green peach aphid, Myzus persicae, showed increased fertility and developmental rates in direct proportion to the amount of soluble nitrogen present in the leaf tissue (Van Emden, 1966). It examined fifty years of research on insect attack and crop nutrition and discovered that fewer than fifty studies demonstrated that regular fertilization regimes reduced herbivore damage, while 135 studies demonstrated that N-fertilized crops had higher damage and/or growth of leaf-chewing insects or mites (Scriber, 1984). These findings support the theory that large nitrogen inputs might cause significant amounts of herbivore damage in crops, which has consequences for fertilizer usage patterns in agriculture.

Measures encouraging landscape diversity should be incorporated into crop management techniques in order to lessen the negative effects of landscape simplification. "Ecological engineering" as a concept can serve as a useful tool in this situation.

2. Manipulating Habitats through Ecological Engineering

The practice of symbiotically integrating society's economy with the environment through the integration of technology design and ecological self-design is known as ecological engineering. The phrase "ecological engineering" was coined by Odum, who was the first to use it to refer to the manipulation of the environment by humans employing marginal quantities of additional energy to regulate systems whose primary energy sources remain natural (Odum, 1962). “The design of human society with its natural environment for the benefit of both,”, is a recent definition of ecological engineering according to (Mitsch and Jorgensen, 1989). The application of quantitative methods and ecological theory, together with the idea that humans are a part of nature rather than existing outside of it, are some of the traits of this engineering discipline. Contrary to the more modern term "ecosystem engineering," ecological engineering is a deliberate human endeavor. This is a reference to the way that other animals, instead than intentional designers, construct their environments through their innate nature.

Agro-system biological control can be improved with this new technology by maintaining or increasing plant diversity or by giving natural foes of pests enough of a place to call home. Habitat manipulation is altering the cropping system to enhance or boost a natural enemy's efficacy. These settings provide cover for numerous adult parasitoids and predators, as well as sources of nectar. In addition to offering natural enemies different dietary and shelter options, mixed plantings can improve habitat variety (Mani, 2022).

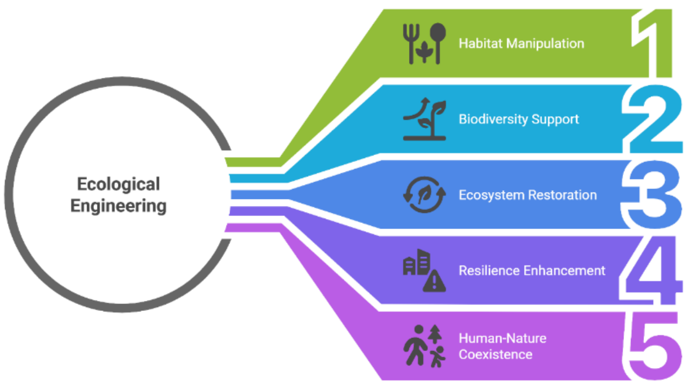

Figure 2: Unveiling the dimensions of Ecological Engineering

A further biological control mechanism for conservation is habitat management. Conservation biological control aims to preserve the natural enemies found in the environment in order to manage agricultural pests efficiently. When we modify the cropping system to enhance or benefit the natural enemies, we are attempting to conserve the natural enemies by manipulating the agricultural region and its surroundings.

The techniques employed for centuries to support generalist predators in agricultural systems are the origin of modern habitat management. The usage of straw shelters, which have been employed by farmers of China for more than two thousand years and are still in use today, to create temporary spider refugia and sites for overwintering during cyclic farming disturbances is an example of an early habitat manipulation approach (Dong and Xu, 1984). In order to combat caterpillar pests, another method was devised in Burma in the 1770s. It involved attaching bamboo canes between citrus trees to allow predatory ants to migrate between the plants (Van-Emden, 1990).

3. Landscape Engineering: A Subset of Habitat Manipulation

The foundation of biological control has traditionally been the local establishment of natural enemy populations, but recent studies have shown that the dynamic interactions between pests and their natural enemies are significantly influenced by the form of the landscape. Case studies using arable crops show how significant pest predators and parasitoids have profited from a significant amount of the landscape's non-crop habitats. Landscape composition affects the diversity and richness of the natural enemy complex because different habitat types may promote different species of natural enemies. Therefore, a mosaic of agricultural landscapes may coexist with a diverse range of natural enemies. Natural enemies frequently make good homes in non-crop habitats, which also operate as source habitats from which less desirable agricultural areas are invaded. In contrast to crop habitats, natural enemies can only function as drains if they exhibit preference for non-crop habitats all year long. The ability of a habitat to function as a source or sink is based on its size and quality relative to its surroundings (Dunning et al., 1992). In this context, higher and more diverse populations of natural enemies, significant colonization of arable fields by natural enemies, a considerable reduction in pest densities, which lowers damage levels, an increase in yield or quality, and a situation where benefits outweigh costs are all factors that increase the farmer's benefit from a diversified landscape.

In recent decades, the importance of the spatial environment for interactions between herbivores, plants, and their enemies has come to light (Ricklefs, 1987; Kareiva, 1990). Due to the high degree of mobility exhibited by many creatures, research have expanded in scope to encompass processes occurring across entire landscapes. They claim that traditional spatial concepts such as island biogeography and metapopulation theory are not widely applied to annual crops (Tscharntke and Brandl, 2004). Reduced agricultural landscapes with a small number of annual crop species predominating typically exhibit impoverished biodiversity (Stoate et al., 2001; Benton et al., 2003). Crop fields in these types of landscapes are not separated from one another; in fact, they could be far from less damaged habitats that could serve as immigration hotspots. At some point in their lives, many animals become dependent on resources that are unavailable to annual crops. If their dispersal ability is less than the distance to these resources, these species may become scarce or disappear in environments where crops predominate (Tscharntke and Brandl, 2004). For instance, fewer parasitoids can establish themselves in agricultural areas due to their limited ability to disperse. Natural herbivore enemies may be freed from natural regulation and do more and more damage to crops when they become locally destitute. An undisturbed soil surface for the overwintering and larval development of a wide variety of insects and spiders, pollen and nectar sources for adults of parasitoid Hymenoptera and Diptera, and perennial plant cover are all resources for biological control agents that are normally unavailable in fields that are ploughed annually (Landis et al., 2000; Gurr et al., 2003; Tscharntke et al., 2005).

"Ingenium," which means "cleverness" in Latin, is where the word engineering originates. Engineering can be defined as an area of study or practice that focuses on development or change in a certain field. "Landscape engineering" refers to the multidisciplinary process of designing and constructing artificial landscapes using engineering and other applied sciences. While it embraces traditional reclamation, it is not the same. Landscape engineering is the practice of altering the crop landscape using a variety of techniques. Investigating the elements influencing dynamics of arthropods at the landscape scale is part of it.

Insect pests and their management by natural enemies are significantly influenced by the features of the landscape. Basically, either directly through the pest's reproduction or spread, or indirectly through upsetting its natural adversaries, the nature of the environment influences the pest's abundance. In addition, the makeup of the landscape influences the diversity and quantity of the natural enemy complex. Increased diversity in the landscape led to a higher and more varied population of natural enemies, which in turn improved insect pest control. In addition to this, it aids in lowering the number of pests, minimizing damage, and raising yield or quality. The occurrence of uncultivated zones within the field's history or in its vicinity is unmistakably recognized as a potential risk for wireworm infestation and subsequent crop damage. As a result, farmers often factor this consideration into their crop rotation management practices (Lefko et al., 1998; Jedlička et al., 2007; Hermann et al., 2013; Kozina et al., 2015; Furlan et al., 2017). A diverse environment may also have an impact on the role of insects as pest controllers and the preservation of biodiversity. The "Push-Pull Strategy" is the fundamental science that underpins landscape engineering.

4. Push-Pull Strategy

The "push-pull" strategy modifies the distribution and abundance of insect pests and/or natural enemies in agro-ecosystems by exploiting a range of triggers to change their behavior (Miller and Cowles, 1990; Khan et al., 1997; Bhattacharyya, 2017). By applying chemical stimuli that dissuade pest insects, the push-pull technique effectively repels or deters them from feeding on the primary crop. In order to lure pests off the main crop and into other regions, like trap crops, where they congregate and are easier to manage, highly alluring stimuli are used simultaneously (Khan et al., 1997). Although the push and pull components of the technique alone might not be sufficient to bring insect populations below economic thresholds, their combination improves the effectiveness of the strategy. Furthermore, this technique can support biological control and insect natural enemies because the push and pull components are frequently non-toxic (Khan and Pickett, 2004). Push-pull methods are not new, but one of the greatest examples was developed recently in Africa to control stem borers on wheat crops (Khan et al., 2001). This technique makes use of both trap crops and intercropping, while also utilizing plants that are suitable for the local environment and may be included into the agricultural system. This method makes use of plant species that both draw insect natural enemies to the fields and repel pests away from the primary crop, all without the use of chemicals or poisons. When African farms used the push-pull strategy, the number of beneficial insects increased overall, but the number of pests decreased (Khan et al., 2001).

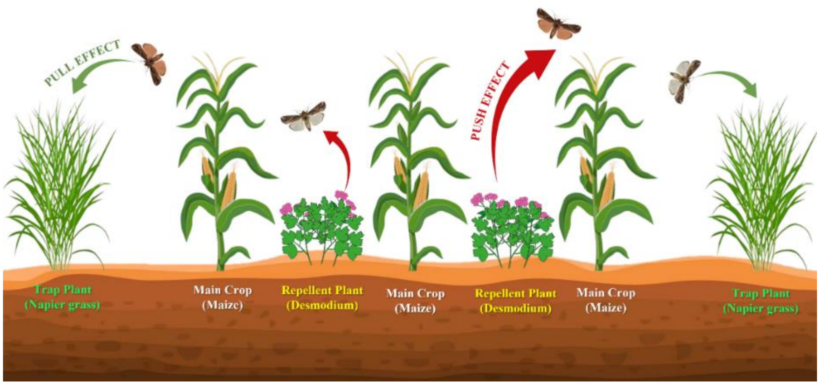

Figure 3: Mechanism of Push-Pull Strategy

5. Different Techniques of Landscape Modification

Increased activity of natural enemies and decreased pest pressure may be favored by diversity in agro-ecosystems. Nonetheless, a number of writers have pointed out that rather than promoting diversity in general, it is more vital to identify and supply the essential components of diversity in order to selectively boost natural enemies. It has been demonstrated, in fact, that some pest issues can be made worse by merely increasing diversity. Understanding the resources required by natural enemies can help lead the process of identifying the essential components of variety, even though it may be a challenging task. Potential strategies include increasing the availability of substitute foods like nectar, pollen, and honeydew; establishing habitat where alternate hosts or prey are present; and establishing a microclimate or shelter where natural enemies can overwinter or seek safety from environmental extremes or pesticides. Furthermore, the temporal accessibility of these resources could be controlled to promote natural enemies' activity in the early part of the season. Lastly, it is important to think about how to arrange these resources spatially to increase natural enemy activity within the crop. Below is a discussion of the numerous mechanisms of landscape alteration.

5.1 Possible Hosts and Prey Alternatives

Crop pest parasitoids and their predators rely on non-crop ecosystems to sustain populations of alternate hosts and prey (Sotherton, 1984; Kozar et al., 1994; Wyss, 1996; Khan et al., 2000; Denys and Tscharntke, 2002). By enhancing the fitness of natural enemies or giving them alternative hosts and prey during times when host and prey density is low in fields, this improves natural pest management. Honeydew is a food source for several parasitoids and other natural enemies (Wäckers et al., 2005). Therefore, the existence of alternate prey that feeds on sap in settings other than cropland may improve agricultural pest management. On the other hand, environments that offer substitute hosts or prey could also serve as home to pest species, leading to an increase in pest populations. The following are the various ways that alternate hosts can be provided:

5.1.1 Cover Cropping

Cover crops, also referred to as "living mulch," are an essential agro-ecological pest management strategy that involves planting annual or perennial herbaceous plants either before or after the primary crop to cover the soil for a season or the entire year (Altieri, 2018; Reeves, 2018; Kahl et al., 2019). Cover crops can increase natural enemies by increasing the complexity of the habitat of the cropping system (Kahl et al., 2019). In agriculture fields, cover crops are planted, sometimes among permanent crops and sometimes in rotation with annual crops. These plants have been widely employed to produce organic matter, lessen soil compaction, add or retain soil nutrients, decrease soil erosion, and help control pests (Bugg et al., 1991; Bugg and Waddington, 1994). Utilizing them improves crop nutrition and soil health in organic and sustainable farming systems. Plants with flowers, such clovers (*Trifolium* spp.) and buckwheat (*Fagopyrum esculentum* Moench), have been encouraged to be grown as cover crops in order to supply insects with nectar sources during the off-season. Flowering cover crops are being used more and more as part of a broader "farmscaping" strategy to prepare fields for a variety of beneficial species during the course of the growing season. Other cover crops that are employed to improve biological control include rye, *Secale cereale* L. (Poaceae), sunhemp, *Crotalaria juncea* L. (Fabaceae), and marigold, *Tagetes patula* L. (Asteraceae).

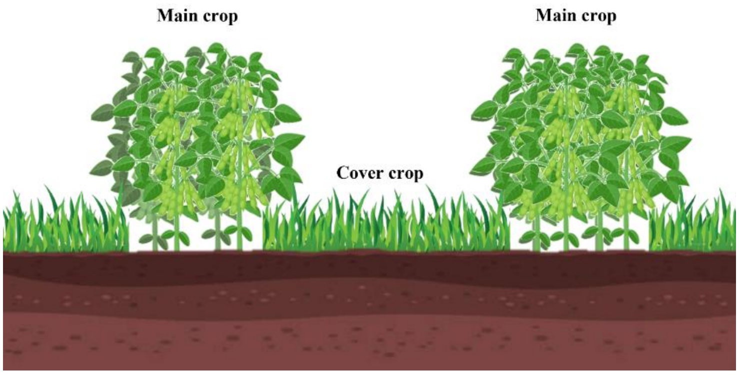

Figure 4: Cover cropping

5.1.2 Intercropping

Monoculture stands as the most demanding in terms of labor and resources among all forms of crop production worldwide. Regrettably, monocultures face heightened susceptibility to pests, diseases, and weeds, thus amplifying a range of biological challenges as this system expands (Mir et al., 2022). Growing two or more crops concurrently during the growing season is known as intercropping. It is a combination of agricultural systems. A wider drop in pest species is observed when intercropping is practiced, as it has a significant impact on the number and richness of natural enemies. Increased yield is the outcome of intercropping's ability to decrease insect pest and boost natural enemies. It was found that, in contrast to pure cropping, intercropping increased and decreased pest in 53% and 18% of the tests, respectively. In order to lessen pest load on the primary crop, intercropping divides herbivore populations between the crop and the intercrop (Root, 1973). Another reason it helps with pest deterrence or repellant is because non-crop visual or chemical signals change insect behavior and may reduce pest damage (González-Chang et al., 2017). By building a physical barrier, preventing pests from moving between plants, or supplying floral supplies for the pests' natural enemies, this type of habitat management also works (Smith and McSorley, 2000).

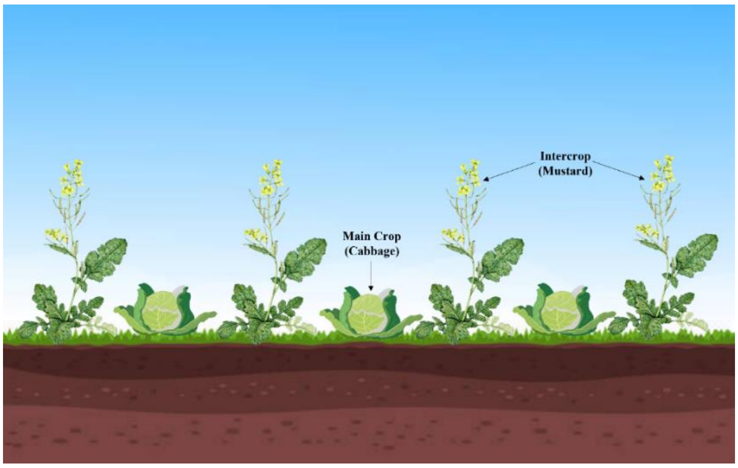

Figure 5: Intercropping for reduced pest incidence

5.1.3 Trap Cropping

In order to reduce the damage that insect pests inflict to the main crop, trap crops are utilized or modified to attract, reroute, intercept, and/or detain them (Hokkanen, 1991; Shelton and Badenes-Pérez, 2006; Sarkar et al., 2018). Trap cropping holds significant promise in attracting and preserving natural enemies within agricultural systems (Panwar et al., 2021). Pests can be controlled once they have gathered in a trap crop by physically destroying the additional vegetation and the pest along with it, or by using pesticides in much more targeted areas (Hokkanen, 1991; Pickett et al., 2014; Reddy, 2017). In their research used few Chinese cabbage cultivars as a promising alternative strategy of pest management against cabbage root fly, *Delia radicum* (Lamy et al., 2020). In addition to finding that the plants draw a lot of natural enemies, suggested that Indian mustard and buckwheat could be used as trap crops for the Diamondback moth, *Plutella xylostella* in cabbage (Sapkota et al., 2022). Trap cropping has historically been used to combat a single pest species, but it can occasionally be effective against multiples.

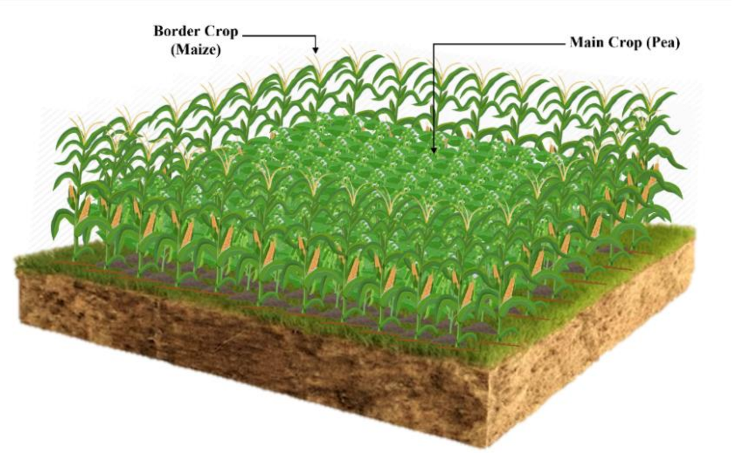

Figure 6: Utilization of border crop in pest management

5.2 Alternative Pollen and Nectar Sources

In agricultural landscapes, manipulating structurally resource-poor habitats by adding flowering plants and grasses can increase beneficial insect populations. This is because optimal vegetation shape and sufficient flower abundance are necessary for various insect populations (Long et al., 1998; Kells et al., 2001; Rebek et al., 2005; Zurbrügg and Frank, 2006; Fountain, 2022). Seminatural environments are also home to pollen and nectar, which are essential for many species (Pickett and Bugg, 1998; Wäckers et al., 2005). A greater diversity of flora, particularly flowering weeds, has been shown to increase the density of parasitoids, syrphid flies, and carabid beetles (Lys et al. 1994) (Médiène et al., 2011; Powell 1986; Patt et al. 1997; Hausammann 1996; Sutherland et al. 2001). Consumption of floral nectar by numerous species may increase the prevalence of parasitism (Powell, 1986). Extra-floral nectar, which is produced by a variety of plants, such as cotton (Gossypium hirsutum) and faba beans (Vicia faba), is an essential source of sustenance for adult parasitoids (Bugg et al., 1989). Flowering plants may improve field margin habitats for beneficial arthropods and pollinating insects (Kati et al., 2021).

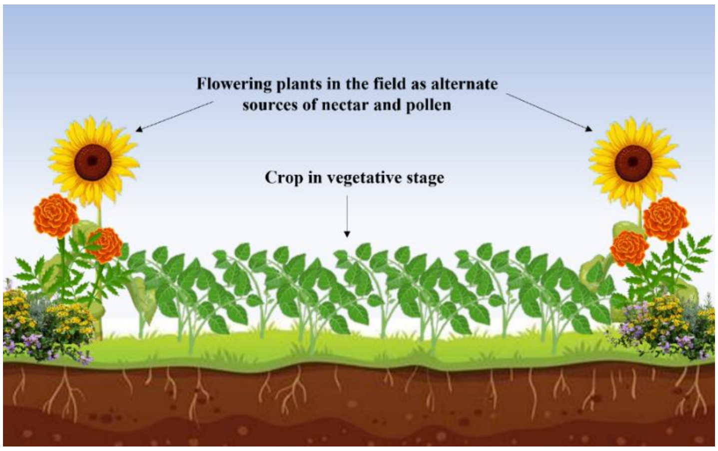

Figure 7: Blooming plants as alternative sources of pollen and nectar

But just putting flowering plants on farms won't deliver the expected boost in biological control, and in some cases, it can even work against you by providing more food for pest insects. The necessity of customizing resource plants for particular natural enemies capable of suppressing pests has come to light more recently, although more research is required to customize this for particular agricultural systems (Jonsson et al., 2008). To illustrate the diversity of plants that parasitoids and predators can consume, one field of study has thoroughly investigated the nutritional value of plant resources (Wäckers et al., 2005). Because wildflower habitats support natural enemy populations, they can improve the provision of pest regulatory services in commercial orange orchards under standard management techniques (Mockford, 2021).

5.2.1 Chocolate Box Ecology

Adjusting habitats to enhance pest control has been referred to by critics as "chocolate-box ecology." It adds floristically diverse plants to try to supply natural enemies with ample pollen, nectar, and nutrient-rich food. However, due to the unpredictability of this habitat manipulation method, researchers are increasingly screening plant species to identify the best species or applying a variety of selection criteria to establish the right botanical composition (Pfiffner and Wyss, 2004). "Chocolate box ecology" refers to the vibrant floral show that results from planting a variety of flowering plants to improve biological control. But if this strategy is applied without understanding the important pests and how plants, pests, and natural enemies interact, it might not work. These methods emphasize that the "right kind" of diversity must be chosen because it is the quality of variety—not the quantity—that matters (Polasezek et al., 1999). Researchers and practitioners are developing a variety of strategies to guarantee that the right kinds of diversity are used for ecological engineering-based pest control (Gurr et al., 2004).

5.3 Areas for Overwintering and Shelter

Insect pests' natural adversaries need protection from environmental dangers; in fact, their survival may be severely hampered by exposure to extremes of temperature, precipitation, or pesticide use. The presence of suitable environments may encourage natural adversaries to forage, relax, overwinter, or build nests. Planting a variety of species together can enhance habitat diversity, offering alternative food sources and shelter to natural enemies (Josephrajkumar et al., 2022). Aggregations of different natural enemies that overwinter and rest are frequently seen in agricultural areas. Different species tend to congregate at different locations, which can include woody and herbaceous plants as well as man-made structures (Beane and Bugg, 1998). In order to give refuge from inclement weather, lacewing houses have even been constructed and tested (McEwen and Sengonca, 2001). These lacewing houses have been effectively used as a way to supplement biological management in crop fields by increasing the number of lacewings in the agroecosystem (McEwen and Sengonca, 2001).

Figure 8: Weed refuge to aid overwintering natural enemies

Because they are more resilient to disturbance than ephemeral annual crop systems, perennial agricultural systems may be more receptive to biological conservation control. Thus, it is possible for perennial crops to sustain natural enemy resident populations year after year. Nevertheless, the practice of harvesting the entire field disrupts the local arthropod fauna in certain perennial crops, such as alfalfa (*Medicago sativa* L.). One of the earliest efforts at habitat management was to provide a refuge for alfalfa bug natural enemies that were spread by cutting. According to the study, there are several ways to create shade in orchards: adding peppermint to the leaf debris, covering apple tree bases with vegetable debris secured with plastic, encircling smaller trees with similar debris, or creating burlap and aluminum refugias for peach trees (Tamaki et al., 1968).

5.4 Agro-forestry

In order to maximize the benefits of biological interactions, agro-forestry is an intensive land-management system that crops, animals, and/or trees together on a landscape scale. While satisfying the needs of agriculture for multiple uses and sustained yield, agro-forestry also strikes a balance with the demands placed on ecosystems to maintain diversity and productivity (Nair, 1993). Although little research has been done on pest interactions within agro-forestry systems, it has been anticipated that agro-forestry will reduce insect outbreaks that are frequently associated with monocultures. Suggested that vineyards accompanied by nearby and integrated trees have been observed to mitigate arthropod pest damage through the augmentation of predatory insect and bat populations, resulting in elevated rates of parasitism and predation (Favor et al., 2024). Microclimatic, nutritional, natural enemies, and other elements can all have diverse effects on pest populations when it comes to different agro-forestry designs, yet these regulatory aspects interact with one another. By providing locations for oviposition and/or overwintering, alternative food sources before pest outbreaks, and habitats with various hosts or prey, more complex landscapes may therefore support a greater number of natural predators and parasitoids (Landis et al., 2000). Although the outcomes may differ, some research has unequivocally demonstrated that the presence of trees in agricultural systems and the complexity of the landscape can have a positive impact on the biological control of particular pests (Perfecto et al., 2004; Bianchi et al., 2008,; Tscharntke et al., 2011; Karp et al., 2013). According to the study, certain tree types also provide a haven for bird predators, which are crucial for controlling pests (Boesing et al., 2017).

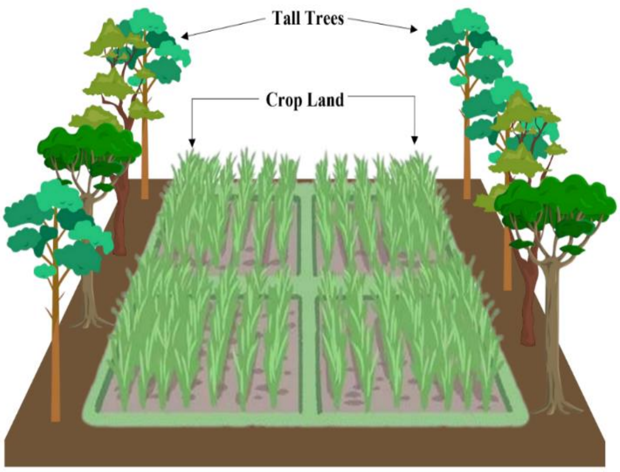

Figure 9: Pest management with agro-forestry where tall trees harbour predacious insects and avians

5.5 Beetle Bank

By building elevated earth banks known as "beetle banks" and planting perennial grasses on them, fields can be equipped with an appropriate overwintering habitat (Wratten, 1992). For oviposition sites, natural enemies could prefer non-crop vegetation. The weed A*calypha ostryaefolia* is native to the area and is preferred by *Coleomegilla maculata* (Coleoptera: Coccinellidae) for egg laying. It found that *C. maculata* was significantly more prevalent in maize plots with an *A. ostryaefolia* border than in plots without one (Cottrell, 1998).

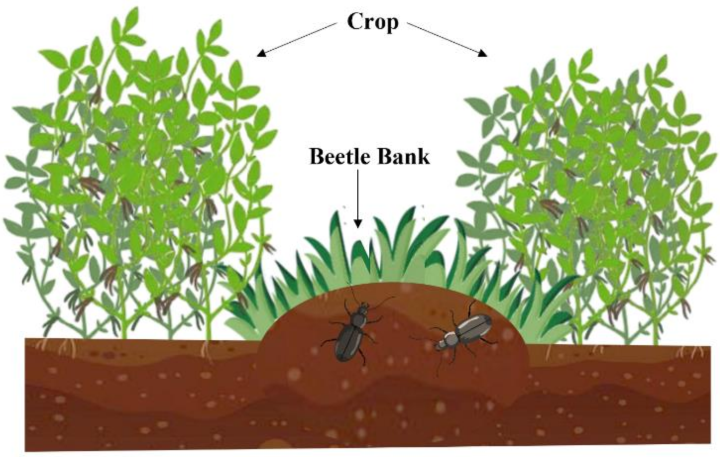

Figure 10: Beetle Bank

5.6 Planting Repellent Species

These can be grown as main crops or border crops, and they keep pests away from the crop mostly by releasing volatile plant compounds that repel them. Tomato borer and mosquitoes are repelled by basil. Garlic wards against carrot fly, spider mites, weevils, beetles, and aphids. Cucumber beetle is deterred by radish. Garlic wards off cabbage moths. Marigolds ward off nematodes, cucumber beetles, and bugs. *Myzus persicae* infestations in commercial greenhouses may be controlled by planting mint, mung beans, celery, and coriander next to ventilation holes (Wang et al., 2021).

6. How Landscape Affects Natural Enemies?

As the subject of landscape ecology has expanded over the past century, so too has research into the impact of landscape-level parameters on biological management of insect pests (Turner et al., 2001). According to the study, new tools and techniques for closely analyzing aerial photography or remotely sensed data of the landscapes surrounding crop fields are now available (Bianchi et al., 2006). These techniques and instruments have produced new information when paired with measurements of pest-natural enemy interactions in agriculture fields.

Reduced landscape structural complexity, increasing habitat fragmentation, and isolation often weaken the biotic interactions that regulate pest populations (Robinson, 1992; Landis et al., 2000; Tscharntke et al., 2007; Rodriguez-Saona et al., 2012). Practically speaking, this means that farms in more varied landscapes can depend more on biological management that occurs spontaneously than farms in environments that are subjected to more extensive management. In more varied landscapes with a range of crop types, natural habitat, permanent wooded land, and an abundance of floral supplies, natural enemies are less likely to disperse and are more likely to have their ecological demands met near to the crop field. High levels of landscape diversity, especially flowering plants, can combine with farm management practices to influence the natural enemy population that helps control pests in agricultural areas. Therefore, found that aphid population growth was slower in organic farms than in conventional farms, and that biological control was higher in fields situated in landscapes with a higher proportion of perennial crops and more field margins (Östman et al., 2001). Suggested that perennial cropland has the potential to enhance semi-natural habitats within Agri-Environment Schemes (AES), offering a balanced approach that fosters both agricultural productivity and biodiversity preservation (Wang et al., 2021).

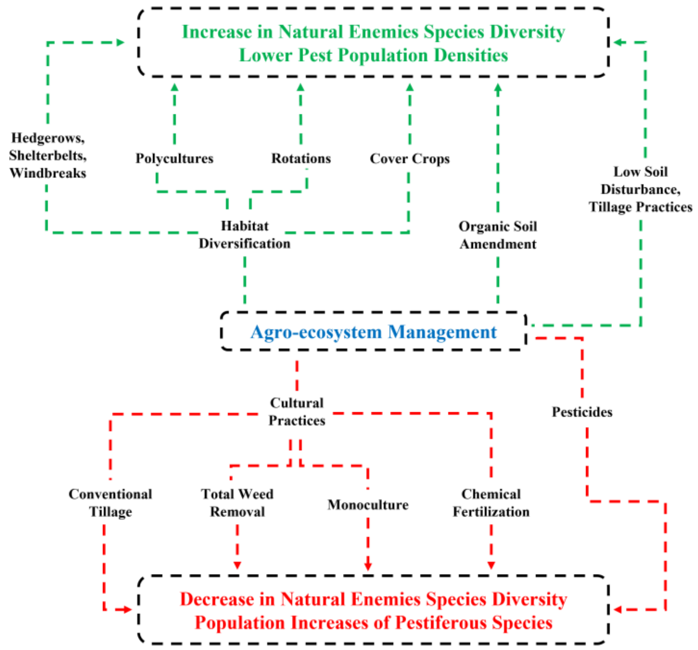

Figure 11: Impact of Landscape Architecture on the Population of Natural Enemies

7. Challenges and Future Scope

Advancing research on tritrophic interactions, cultural practices and traditional farming methods is essential for enhancing natural enemy efficacy in pest management through landscape engineering. These approaches focus on modifying agricultural landscapes to promote natural pest suppression while maintaining ecological balance. Understanding how traditional practices influence pest-predator dynamics can inform the development of conservation strategies that align with ecological processes. Additionally, further research is required to refine technologies that optimize the efficiency of natural enemies and ensure their long-term conservation within agroecosystems. Integrating these strategies into IPM modules will facilitate their implementation across diverse cropping systems. However, the disconnect between researchers and farmers remains a significant barrier, necessitating improved knowledge transfer and collaboration for effective adoption. Furthermore, most studies on habitat manipulation and semiochemicals have been conducted in limited geographic areas, highlighting the need for broader, landscape-scale research to generate comprehensive, scalable data. Expanding such research efforts will strengthen ecologically based pest management strategies, fostering biodiversity conservation while reducing dependence on chemical pesticides and enhancing agricultural sustainability.

8. Conclusion

Landscape engineering offers a transformative approach to sustainable pest management by leveraging habitat modifications to support natural enemy populations and enhance ecological balance. While significant theoretical advancements have been made in understanding population dynamics at the landscape scale, the complexity of diverse cropping systems and management practices remains a challenge. The growing body of research in recent decades highlights a global commitment to refining pest control strategies that align with sustainable agriculture. By integrating landscape engineering with biological control methods, pest management can become more resilient, reducing reliance on chemical inputs while improving long-term effectiveness. Moving forward, expanding large-scale studies, strengthening interdisciplinary collaboration, and bridging the gap between researchers and farmers will be crucial in refining and implementing these strategies. Embracing landscape engineering as a core component of pest management will help shape agricultural systems that are ecologically robust, economically viable, and capable of supporting global food security.

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Authors' Contributions

All authors contributed significantly towards the final make-up of the paper. Conceptualisation (AKM); Data curation (SDR); Visualisation (AKM and SDR); Supervision (AKM); Writing-original draft (SDR); Writing-reviewing and editing (SDR).

Ethical Approval

Research Involving Human Participants And/Or Animals

This article does not contain any studies with human participants or animals performed by any of the authors.

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