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Conservation Biological Control and Agroecology: Harnessing Beneficial Insects for Sustainable Crop Production

*Dr. C. Sankar
Department of Veterinary Parasitology, Veterinary College and Research Institute, Udumalpet-642205, Tiruppur, Tamil Nadu, India
*Corresponding Author's email: csankardr@gmail.com

Conservation biological control is an ecological approach that seeks to enhance the activity, abundance and persistence of naturally occurring predators and parasitoids by improving the agricultural environment in which they live. Within agroecology, conservation biological control is closely associated with diversification, habitat management, reduced pesticide hazards, resource provision and landscape-level planning. Beneficial insects can provide important ecosystem services, particularly biological pest suppression and pollination, while their conservation can reduce dependence on external pest-control inputs. Habitat manipulation through flower strips, hedgerows, field margins, cover crops, intercropping, agroforestry and refuge habitats can provide nectar, pollen, alternative prey, shelter and overwintering sites for natural enemies. However, responses are context-dependent and may vary with crop, pest, natural-enemy community, landscape structure and management history. This review discusses the ecological basis of conservation biological control, major beneficial insect groups, agroecological habitat-management strategies, pesticide compatibility, landscape diversification, monitoring and evaluation, integration with integrated pest management, farmer adoption, climate change, challenges and future prospects. Particular emphasis is placed on designing agroecosystems that support functional biodiversity while maintaining crop productivity. Recent evidence and FAO guidance indicate that agroecological diversification can strengthen biodiversity and ecosystem services, but successful implementation requires locally adapted designs, long-term evaluation, farmer participation and enabling institutional conditions.

Introduction

Agricultural ecosystems contain complex communities of insects and other organisms that influence crop productivity. Some insects are herbivorous pests, whereas others act as predators, parasitoids, pollinators, decomposers or components of food webs. Conservation biological control (CBC) focuses on protecting and enhancing naturally occurring natural enemies rather than relying primarily on repeated external releases. The central principle is to modify farming practices and habitats so that beneficial organisms can survive, reproduce and exert stronger pest-regulation services. Agroecology provides a broader framework for this approach. FAO describes agroecology as a holistic and integrated approach that applies ecological and social principles to the design and management of sustainable agrifood systems, seeking to optimize interactions among plants, animals, people and the environment. Its framework emphasizes biodiversity, synergies, resilience, efficiency and context-specific design. The conservation of agricultural biodiversity is directly relevant to biological pest regulation. FAO notes that diverse agricultural landscapes can provide forage and nesting habitat for insects and that perennial vegetation can support pollinators and predators of pest species, contributing to biological control.

Conservation biological control is therefore more than simply avoiding insecticides. It involves intentional ecological design. Farmers can manipulate vegetation, field margins, crop diversity, pesticide selectivity and landscape structure to improve the conditions required by natural enemies. Recent reviews similarly emphasize habitat management, flower strips, hedgerows, intercropping, crop rotation and reduced pesticide exposure as important strategies for conserving beneficial insects.

Concept and Ecological Basis of Conservation Biological Control

Conservation biological control is based on the idea that naturally occurring enemies of crop pests already provide a form of ecosystem service. Predators consume herbivorous insects, while parasitoids develop in or on their hosts and ultimately reduce pest survival. The strength of this natural regulation depends on enemy abundance, species composition, prey availability, habitat quality and the degree of disturbance within the agroecosystem. A key distinction between conservation biological control and augmentative biological control is the source of the natural enemy. Conservation biological control primarily improves conditions for resident natural enemies, whereas augmentative approaches involve deliberate releases of mass-reared organisms. The two approaches can be complementary, but conservation focuses on ecological processes already present in the production landscape. Natural enemies require more than pest prey. Many adult parasitoids and predators require nectar, pollen, honeydew, water, shelter and alternative prey or hosts. Habitat management therefore aims to provide a suitable combination of resources through the crop cycle. The timing, spatial arrangement and quality of these resources can determine whether habitat interventions translate into increased pest suppression.

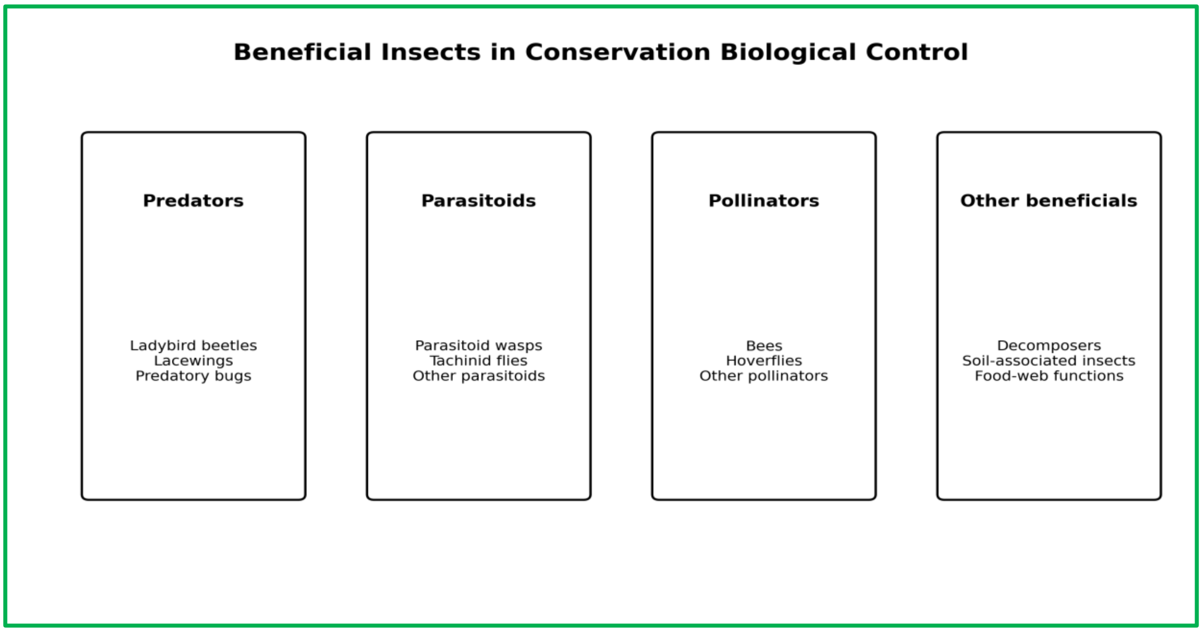

Figure 1. Major groups of beneficial insects and associated ecosystem services relevant to conservation biological control and agroecological crop production.

Major Groups of Beneficial Insects

Predatory insects include ladybird beetles, lacewings, predatory bugs, syrphid larvae and other taxa that consume aphids, whiteflies, thrips, mites, caterpillars and other pests. Their effectiveness depends on prey density, predator searching ability, crop structure and environmental conditions. Parasitoids are especially important in agricultural pest regulation. Many parasitoid wasps and tachinid flies use specific insect hosts for larval development. Adult parasitoids may require nectar or pollen, making flowering resources important in many cropping systems. The relationship between plant diversity and parasitoid abundance is complex because additional vegetation can also provide alternative hosts or shelters for pests.
Pollinators, particularly bees and hoverflies, provide crop pollination services. Some pollinators may also contribute to pest regulation indirectly through food-web interactions or

by serving as indicators of habitat quality. Because pollination and biological control can coexist within agroecosystems, habitat management should consider both services rather than optimizing one at the expense of the other. Other beneficial arthropods and soil-associated organisms contribute to decomposition, nutrient cycling and food-web stability. A broad agroecological perspective therefore considers beneficial insects as components of multifunctional biodiversity rather than viewing them only as biological-control agents.

Habitat Management for Natural Enemies

Habitat management is one of the principal tools of conservation biological control. The objective is to increase the availability of resources that are scarce or absent in intensively managed fields. These resources may include nectar, pollen, alternative prey, shelter, nesting sites and overwintering habitat.

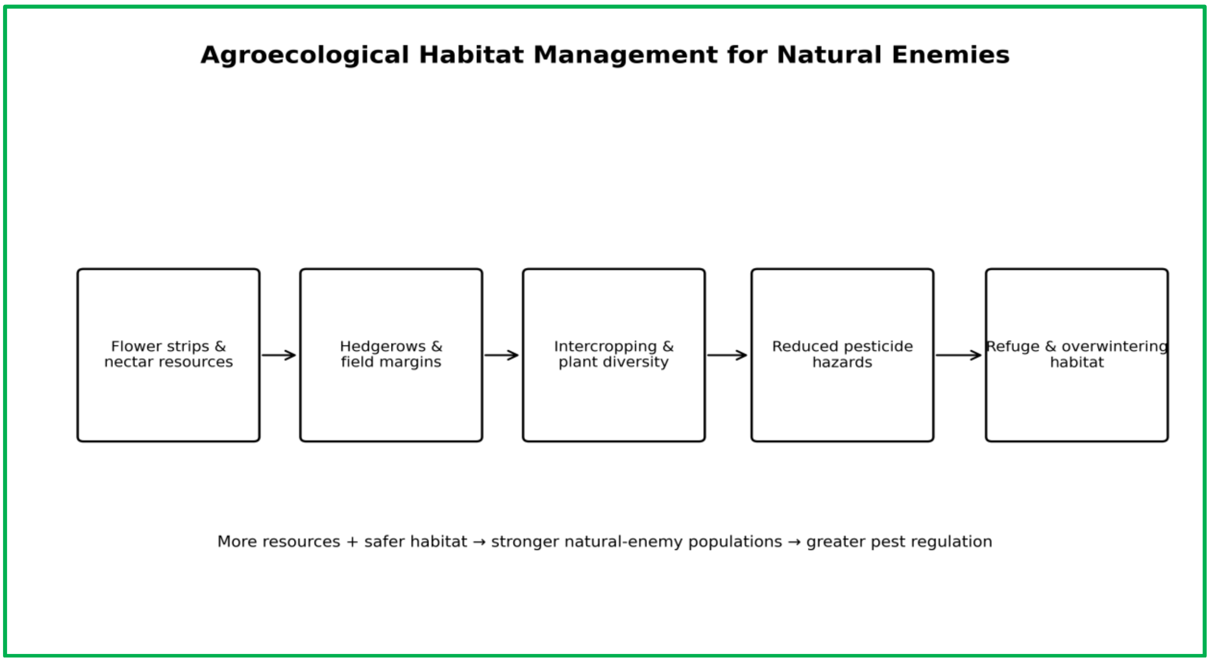

Figure 2. Conceptual pathway linking agroecological habitat management with enhanced resources, refuge and survival of natural enemies.

Flower Strips and Floral Resources

Flower strips can provide nectar and pollen for adult parasitoids, hoverflies, bees and other beneficial insects. Flowering plants can also provide shelter and alter microclimatic conditions. However, plant selection is critical because flowers should provide accessible resources without becoming important hosts for crop pests or pathogens. The temporal continuity of flowering is especially important. A short flowering period may provide resources only during a limited portion of the crop cycle. Multi-species flower mixtures can extend resource availability, although mixtures should be designed for the local climate, soil, crop system and natural-enemy community. Flower strips should not automatically be assumed to increase pest suppression. Their effect depends on whether natural enemies use the resources, whether increased natural-enemy abundance results in higher predation or parasitism, and whether the intervention changes pest abundance. Field-level evaluation should therefore measure both beneficial insects and pest outcomes.

Hedgerows, Field Margins and Perennial Vegetation

Hedgerows and vegetated field margins can provide shelter, alternative food and overwintering sites for beneficial organisms. They can also improve landscape connectivity and create movement pathways between semi-natural habitats and crop fields. FAO identifies perennial vegetation as an important habitat component for pollinators and predators and emphasizes biodiversity as a foundation of ecosystem functioning. The design of margins should consider width, plant composition, flowering period, management frequency and pesticide exposure. Excessive disturbance can destroy habitat, while unmanaged vegetation may sometimes harbour pests or compete with crops. The best design is therefore context-specific and should be adapted to local natural-enemy and pest communities.

Intercropping and Crop Diversification

Intercropping changes the spatial structure of the crop environment and can influence pest host-finding, natural-enemy movement and microclimate. Diverse crop combinations can provide alternative resources and habitats while potentially making it more difficult for specialist pests to locate their host plant. The effects of intercropping are not universal. Plant combinations can sometimes favour pests or create competition for natural enemies. Therefore, crop diversification should be based on ecological compatibility and local evidence. Recent global work on temporally staggered intercropping suggests that diversification can benefit predators and parasitoids and suppress pests, while also emphasizing regional differences in the most effective configurations. Agroforestry and integration of trees with crops can further increase structural diversity. Trees and perennial vegetation may provide refuge and alternative resources for natural enemies, although they can also alter microclimate and pest movement. Site-specific design is essential.

Cover Crops and Ground Habitat

Cover crops can support ground-dwelling predators and contribute to habitat continuity between crop cycles. Vegetative cover may provide shelter, moderate soil temperature and humidity, and support alternative prey. Reduced soil disturbance can also protect soil-associated arthropods. Conservation agriculture principles promoted by FAO include minimum soil disturbance, permanent soil cover and crop diversification, which can enhance biodiversity and biological processes above and below ground. These principles can therefore complement conservation biological control when adapted to the pest and cropping system.

Pesticide Selectivity and Conservation of Natural Enemies

Pesticide exposure is one of the major threats to beneficial insects. Broad-spectrum insecticides can directly kill predators and parasitoids or produce sublethal effects that alter behaviour, reproduction and development. Even when a pesticide provides effective pest suppression, elimination of natural enemies can lead to pest resurgence or secondary pest outbreaks. Conservation biological control therefore requires pesticide-risk reduction. Where chemical intervention is necessary, selection of compounds with lower toxicity to important natural enemies, correct timing, localized application and avoidance of unnecessary treatments can reduce disruption. Pesticide compatibility should be evaluated for the particular natural-enemy species present in the crop. Integrated pest management provides a framework for this approach by combining biological, cultural, physical and chemical tactics. Conservation biological control can strengthen the biological component of IPM, while selective pesticide use can preserve the natural enemies that provide ongoing pest suppression.

Landscape Ecology and Conservation Biological Control

Natural enemies move across field boundaries, and their populations are influenced by landscape composition. Semi-natural habitats, hedgerows, grasslands, woodland patches and riparian vegetation can provide resources that are unavailable within intensively managed crops. Landscape complexity can influence natural-enemy abundance and pest pressure. A large review found that natural enemies were more abundant and pest pressure lower in many complex landscapes than in simplified landscapes, although responses varied among systems and habitat types. Landscape management should therefore extend beyond individual fields. Coordinated planting of flowering resources, conservation of natural vegetation and connectivity among habitats can create a more continuous ecological network. The appropriate spatial scale depends on the mobility of the natural enemy and pest. Agroecology similarly emphasizes territorial and context-specific planning. FAO describes agroecological transitions as processes that require integrated approaches and enabling conditions across ecological, social and economic dimensions.

Monitoring Beneficial Insects and Pest Regulation

Monitoring is essential for determining whether conservation interventions are functioning. Sampling can include sweep nets, visual counts, sticky traps, pitfall traps, suction sampling, beating trays and direct observation. The appropriate method depends on the natural enemy group and crop structure. Monitoring should measure both abundance and function. A larger number of predators does not necessarily mean greater pest suppression if predators are not consuming the target pest. Where feasible, studies should include predation or parasitism rates, pest density, crop damage and yield. Repeated monitoring across seasons is particularly important because natural-enemy populations fluctuate with weather, crop stage and landscape conditions. Short-term increases in beneficial insects may not produce immediate yield effects, whereas long-term habitat changes may improve ecological resilience.

Conservation Biological Control within IPM

Conservation biological control should be embedded within a broader IPM strategy. The first step is monitoring pest and natural-enemy populations. If pest abundance remains below the economic threshold, unnecessary intervention can be avoided. If intervention becomes necessary, biological and cultural methods can be prioritized, followed by selective chemical options where appropriate.

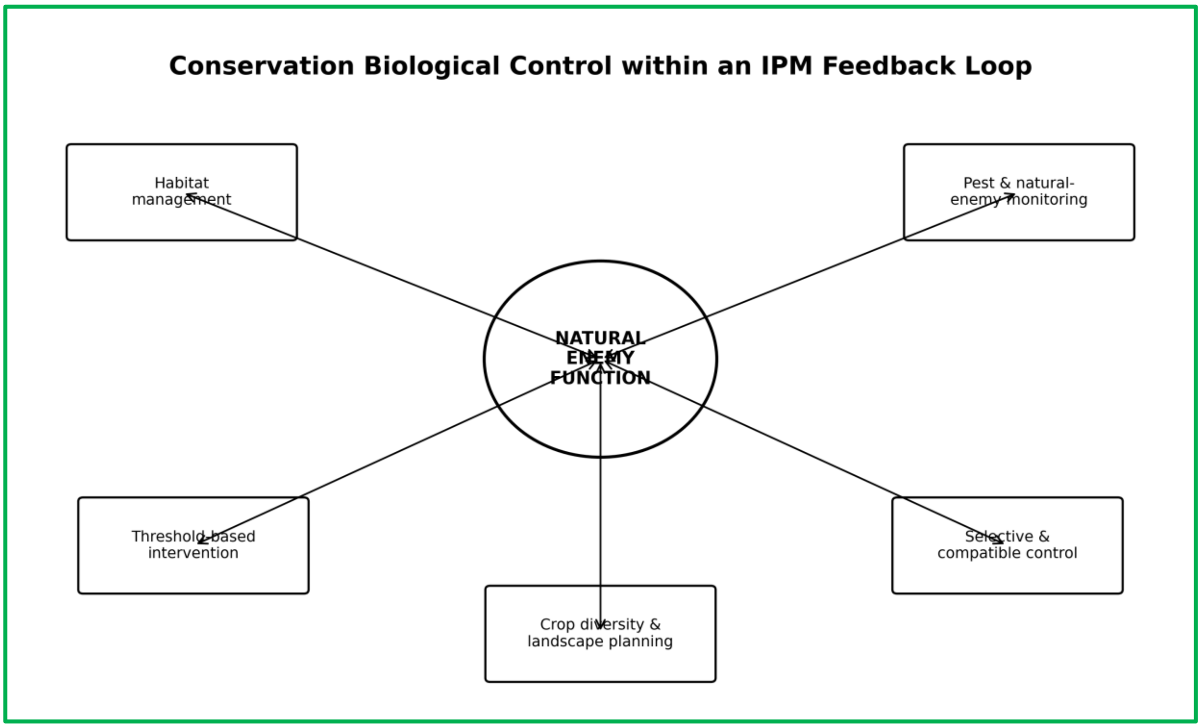

Figure 3. Core components of conservation biological control integrated with monitoring, selective intervention and agroecological landscape management.

Habitat management can be planned before the cropping season by establishing flowering resources, maintaining field margins and reducing disruptive practices. During the crop cycle, scouting can determine whether natural enemies are responding and whether pest populations remain controlled. After intervention, follow-up monitoring can evaluate both pest recovery and natural-enemy survival. This feedback approach is more sustainable than treating biological control as a fixed input. It recognizes that natural-enemy communities respond dynamically to crop management and environmental conditions.

Benefits for Sustainable Crop Production

The primary benefit of conservation biological control is the use of naturally occurring ecosystem services to suppress pests. Effective natural enemies can reduce the frequency or intensity of insecticide applications, thereby lowering pesticide exposure and protecting biodiversity. Agroecological diversification can provide multiple benefits beyond pest control. FAO identifies ecosystem services including pest regulation, pollination, soil health and erosion control as components of sustainable agricultural systems. Beneficial insects can also contribute to production through pollination. A 2024 review of beneficial insects highlighted biological control, pollination and soil-related services and identified habitat management, intercropping, crop rotation and integrated pest and pollinator management as important strategies. Diversified systems may also improve resilience by reducing dependence on a narrow set of external inputs. However, sustainability should be assessed using both ecological and economic indicators because habitat establishment requires land, labour and management resources.

Interactions between Beneficial Insects, Plants and Soil Biodiversity

Above-ground natural enemies interact with plants, herbivores and below-ground organisms. Plant diversity can influence herbivore abundance, natural-enemy behaviour and the availability of floral resources. Soil organic matter and microbial communities can influence plant health and potentially alter interactions among plants and insects. Recent agroecological frameworks emphasize these connections rather than treating pest management as an isolated activity. FAO describes diversified agroecosystems as systems in which mutualistic interactions among plants, insects and soil microbial communities can contribute to plant protection and ecosystem functioning. Understanding these interactions can improve habitat design. For example, plant species selected for floral resources may also affect soil cover, nutrient cycling or crop microclimate. Multi-functional interventions may therefore provide greater sustainability benefits than single-purpose insectary plantings.

Climate Change and Conservation Biological Control

Climate change can modify the distribution, phenology and abundance of both pests and natural enemies. Changes in temperature may alter development rates and the timing of predator-prey or parasitoid-host interactions. Extreme heat, drought and altered rainfall can reduce the availability of floral resources or refuges and may disrupt synchronization between pests and their natural enemies. Agroecology can contribute to resilience by increasing biodiversity and functional redundancy. FAO identifies resilience and adaptation to climate change as important potential benefits of agroecological approaches. Future conservation biological control programmes should therefore select habitat plants and management practices that remain functional under expected climatic conditions. Multi-season monitoring is needed to identify natural enemies that are resilient to environmental variability.

Farmer Adoption and Socioeconomic Considerations

The adoption of conservation biological control depends on more than ecological effectiveness. Farmers must perceive the practice as practical, economically worthwhile and compatible with their production goals. Establishing flower strips or field margins may require land that could otherwise be planted with crops, while changes in pesticide use can require confidence that natural enemies will provide adequate control. Knowledge and extension support are therefore essential. Farmers need information on identifying beneficial insects, interpreting pest and natural-enemy monitoring, selecting habitat plants and using pesticides selectively. Participatory approaches can help adapt interventions to local cropping systems and farmer constraints. FAO emphasizes that agroecology is context-specific and that enabling policies, public investment, institutions and research priorities are important for scaling agroecological transitions. Economic assessments should consider avoided pesticide costs, yield protection, pollination benefits, ecosystem services and long-term resilience. Short-term yield comparisons alone may underestimate the value of conservation practices.

Challenges and Limitations

The response of natural enemies to habitat manipulation is highly context-dependent. A practice that increases parasitoid abundance in one region may have little effect elsewhere because of differences in plant species, pest complexes, climate and landscape structure. Habitat interventions can occasionally produce unintended effects. Additional vegetation may provide refuge or alternative food for pests, or may alter predator-prey interactions in unexpected ways. The ecological consequences should therefore be evaluated rather than assumed. Another challenge is the time required for habitat benefits to develop. Perennial vegetation and landscape restoration may require several seasons before stable natural-enemy communities become established. Long-term studies are needed to distinguish temporary responses from durable changes. Measurement of ecosystem services can also be difficult. Increased biodiversity does not automatically translate into higher yield, and pest suppression may be offset by competition, land-use costs or other management effects. Multi-dimensional evaluation is therefore necessary.

Future Perspectives

Future conservation biological control will increasingly move toward landscape-scale and multifunctional agroecological design. Rather than establishing isolated flower strips, farmers and planners can create networks of habitats that provide resources throughout the year and connect crop fields with semi-natural areas.

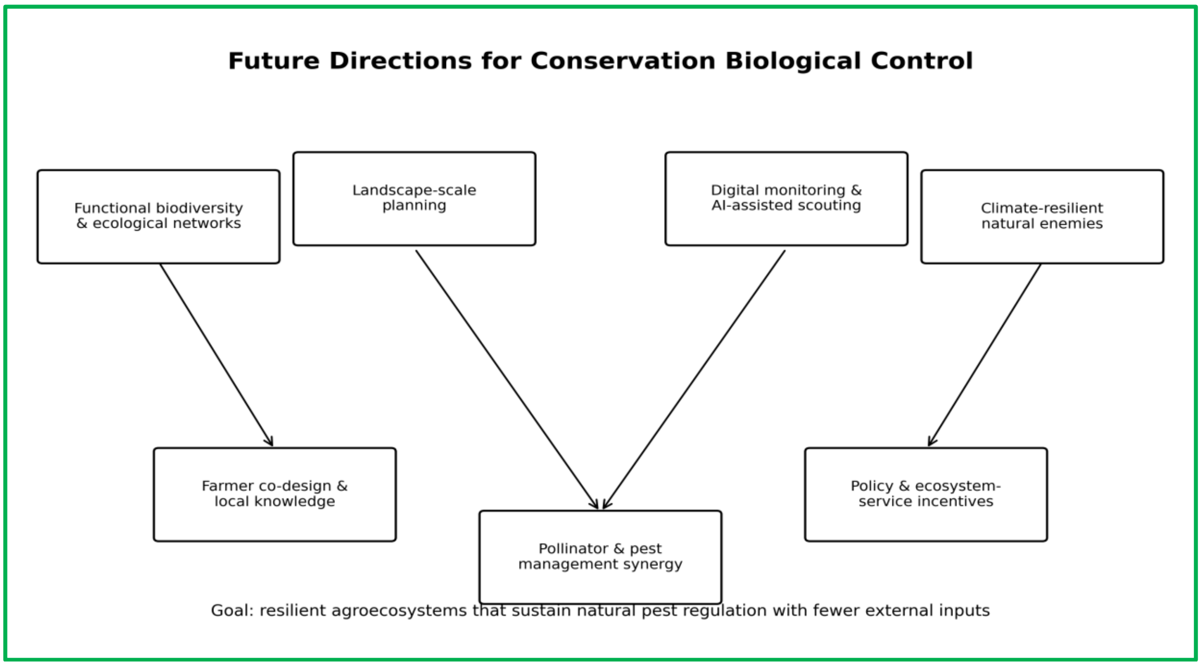

Figure 4. Emerging research and implementation priorities for conservation biological control in agroecological production systems

Digital monitoring can strengthen this approach. Automated insect traps, remote sensing, image recognition and geographic information systems can help quantify beneficial insects and pest hotspots. These technologies can support targeted scouting and provide evidence for adaptive habitat management, although they should complement rather than replace field entomological expertise. Climate-resilient natural-enemy communities and habitat plants will become increasingly important. Research should identify plant combinations that provide resources under heat and water stress while avoiding excessive support for pests. Landscape planning should also consider the movement ranges of key predators and parasitoids. Conservation biological control may also benefit from farmer co-design and local ecological knowledge. Farmers often understand seasonal pest patterns, flowering resources and landscape features that are not fully represented in formal datasets. Combining local knowledge with ecological research can produce more practical and durable interventions. Policy mechanisms that recognize ecosystem services could further encourage adoption.

Incentives for habitat conservation, biodiversity-friendly management and reduced pesticide risk may help overcome the opportunity costs associated with ecological infrastructure.

Conclusion

Conservation biological control provides a practical pathway for harnessing naturally occurring predators and parasitoids as ecosystem-service providers within sustainable crop production. Its foundation is the creation and maintenance of agroecosystems that supply food, shelter, refuge and safe habitat for beneficial organisms while reducing disruptive pesticide exposure. Agroecological practices such as flower strips, hedgerows, field margins, intercropping, crop diversification, cover crops, agroforestry and landscape connectivity can strengthen the ecological conditions required for natural pest regulation. However, the effectiveness of these interventions is context-dependent and should be evaluated using pest abundance, natural-enemy activity, crop damage and yield rather than biodiversity indicators alone. The future of conservation biological control lies in integrating ecological design with monitoring, selective pest management, farmer knowledge and landscape-scale planning. Digital tools, climate-aware habitat selection and ecosystem-service incentives can further strengthen implementation. With locally adapted designs and long-term support, conservation biological control can contribute to reduced pesticide dependence, enhanced biodiversity, improved resilience and sustainable agricultural production.

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