*https://doi.org/10.33472/AFJBS.6.6.2024.9379-9403*

African Journal of Biological Sciences

Journal homepage: http://www.afjbs.com

Research Paper Open Access

# Role of Biodiversity in Pest Management and Nutrient Cycling In Organic Systems

**Mashuood Ali[1], Abhineet[2], Saba Siddiqui[3], Dheer Pratap[4], Sandeep Kumar Yadav[5]**

Department of Agriculture, Integral Institute of Agriculture Science and Technology, Integral University, Lucknow.

**Article Info**

Volume 6, Issue 6, October 2024

Received: 28 August 2024

Accepted: 20 September 2024

Published: 05 October 2024

doi: 10.33472/AFJBS.6.6.2024.9379-9403

## ABSTRACT:

The escalating challenges of food security, environmental degradation, and climate change have rekindled interest in the fundamental contributions of biodiversity to agricultural systems, particularly for organic farming. This review emphasizes the significant role of biodiversity on two key ecosystem functions: pest control and nutrient cycling. Biodiversity provides the foundation for pest management in organic systems that prohibit synthetic pesticides. Diverse plantings create a variety of habitats that facilitate colonization by natural enemies, which in turn can regulate pests across crop habitats within landscapes. Moreover, genetic diversity within crops increases disease resistance with respect to many pathogens, including viruses and bacteria, reducing dependence on inputs and fostering cost-effective economic and ecological stability. Biodiversity also forms the foundation for nutrient cycling via soil organisms that decompose composts and cycle soil nutrients for primary production. How botanical diversity enhances rapid decomposition remains unresolved but is likely due to a concomitant increase in decomposer biomass or microbial genetics preadapted to novel resources. Emerging research also directly links biodiversity with agricultural resilience by highlighting the importance of diverse primary producers (plants) facilitating diversity among the consumers (herbivores) as well as the potential positive implications this may have for biocontrol. Despite growing links between biodiversity and both pest control and nutrient cycling within agricultural systems we still lack access to information on mechanisms and management approaches that farmers can employ to increase or manipulate biodiversity within these specific agroecosystem processes. Furthermore economic constraints represent a major impediment hindering our ability to afford greater or even sufficient levels of desired diversity within crop fields or surrounding multi-functional landscapes.

**Keywords:** Biodiversity, Organic Farming, Food Security, Pest management, Nutrient cycling, Soil health, Agroecosystems, Environmental sustainability, Resilience, Agroecology, Ecosystem services, Sustainable agriculture, Crop diversity, Soil organisms, Climate change, Conservation, Ecological principles, Integrated approaches, Ecosystem functioning, Agricultural productivity.

## 1. Introduction

Agricultural systems are inherently complex and diverse, with numerous biotic and abiotic interactions. However, in the past 50 years or so, agricultural intensification – marked by heavy reliance on monocultures, synthetic inputs and mechanization – has caused a dramatic loss of biodiversity within conventional farming systems. The homogenization of agricultural systems and dependence on external inputs have created a series of challenges such as increased weed pressures, soil erosion, nutrient leaching and declines in ecosystem services. (Garnett et al., 2013; Wezel & Soldat, 2009).

Organic farming, on the other hand, seeks to build more natural ecosystem function by fostering biodiversity at several levels. Organic systems rely on natural resources, minimise synthetic chemical inputs and use practices like crop rotation and polycultures, and promoting beneficial organisms (Birkhofer et al., 2020; Kremen & Miles, 2012). Biodiversity in organic systems is pivotal in increasing resilience, stability and productivity with a particular focus on pest management and nutrient cycling. (Altieri & Nicholls, 2017).

The importance of biodiversity in organic agriculture is more than an issue of species-richness, because it also determines the ecosystem functioning. One such type of traits is the ability of the ecosystem to control pest through its natural enemies, to enhance nutrient in the soil through the different rooting systems; and to enhance other ecosystem services that are readily necessary for sustainability of agriculture (Sullivan et al., 2020). In this respect, therefore, this review will draw from previous studies to assess how the effects of biodiversity at multiple levels on pest control and nutrient cycling in organic system. When addressing these issues we will do have some existing information on how status of biodiversity and its potential contribution towards sustainable agriculture in Kenya and try to suggest for further direction for sustainable use of agrobiodiversity.

The growing population requires more food which involves more agricultural activities and these deeply effects the environment. Conventional Agriculture practices, through the application of chemical fertilizers, have been successful in increasing the crop production. However, they degrade the health of soils, biodiversity of species and ecosystem services on which agriculture ultimately depends (Kremen & Miles, 2012). For this reason there is a mounting interest in the role of Biodiversity in increasing resilience to agricultural systems and the provision of ecosystem services. This review paper is trying to show how Biodiversity contribute for Pest Pressure and Nutrient management under organic farming system. Rudall, J. (2020).

### 1.1 The Concept of Biodiversity

Biodiversity is generally understood as the variety of living organisms present on earth in terms of genetic diversity, species diversity and ecosystem diversity. It is an intrinsic characteristic of the environment and plays a crucial role for the stability and development of the ecosystem. Cabral, R. M., & Kurban, M.,(2012).

### 1.2 Importance of Biodiversity in Agriculture

It is of great benefit to the agriculture systems because of the many ecosystem services it contributes to. These services can be broadly grouped under, provisioning services (e.g crop production), regulating services (e.g pest control and disease prevention), supporting services (e.g nutrient cycling and soil formation) and cultural services (e.g recreational and aesthetic values). (Altieri, 1999; Power, 2010).

It is in agroecosystems that use little or no synthetic inputs where the biodiversity is of utmost importance. Agrodiversity can benefit soil health, elasticity of cropping systems, and decrease dependence on chemical inputs (Kremen & Miles, 2012). For example, a large number of species can play a role in more stable ecosystem which in turn will attract natural enemies to pests and also increase pollinators. (Benton et al., 2003; Zhang et al., 2012).

### 1.3 Biodiversity and Pest Management

Pest management in agriculture is a major challenge, as pests are estimated to cause yearly crop yield losses of over one-third. Traditional pest control relies on chemical pesticides that can negatively impact non-target organisms and foster the development of pesticide resistance. In contrast, in principle, biodiversity could offer natural pest management solutions. Köpke, U. (Ed.). (2018).

### 1.3.1 The Role of Beneficial Organisms

Diverse ecosystems can house populations of natural enemies (i.e., predators or parasitoids) that attack and help suppress pest populations (Kogan, M., & Higley, L. (Eds.) 2019). In some cases, the presence of natural enemies can reduce the number of pests in an area by more than 90%. For example, ladybugs, lacewings, and predatory beetles can all consume many aphids in agricultural fields (Gurr & You, 2016; Kogan & Higley, 2019). Flowering plants can serve as hosts for a natural enemy's immature stages (e.g., caterpillars), provide them with nectar, pollen or other food resources as adults (e.g., adult wasps), or both. By providing a purpose to reproduce and feed on pests that are also found on nearby crops, flowering plants bring natural enemies into close proximity with potential victims. (Jonsson et al., 2015).

### 1.3.2 Enhancing Ecosystem Resilience

Multifunctionality of biodiversity improves the self-regulation of agroecosystems with regards to pests. A wider range of plants can create a more complicated environment for pests so that their populations hardly double. Moreover, genetic diversity among crop species will have the possibility to bring about new levels of resistance to pests, thus, crop agriculture may be more resilient to changes in environmental conditions. (Altieri, 1999; Jackson et al., 2007).

### 1.3.3 Habitat Management for Biodiversity

Creating biodiverse habitats can enhance pest regulation in organic systems. Intercropping, cover cropping and hedgerow maintenance can be used to provide refuge for beneficial organisms and increase ecosystem service provisioning which are important for pest control but also nutrient cycling and soil health.

### 1.4 Biodiversity and Nutrient Cycling

Another important ecosystem service which plants gets from the biodiversity is the nutrient cycling. For sustainable agriculture we need healthy soil, which provides plants with nutrients, supports plant growth and maintains overall health of the ecosystem. Biodiversity in soil organisms (bacteria, fungi and earthworms) helps in nutrient cycling.

### 1.4.1 Soil Microorganisms

Microorganisms in soil are essential to the process of organic matter decomposition and nutrient mineralization. Their diverse communities can increase soil fertility, because they use complex organic substances, making them available to plants as nutrients. Some microorganisms, for example mycorrhizal fungi, enter into symbiosis with plant roots and facilitate nutrient uptake by plants, with particular reference to phosphorus. Cheeke, *et.al.* (2012).

### 1.4.2 Organic Matter and Soil Health

Biodiversity contributes to organic matter enrichment which is crucial for the preservation of the structure of soils, moisture control and also nutrients supply. Some techniques such as the use of compost, cover cropping and minimum tillage can help improve soil organic matter and encourage a diversity of life in the soil. These are rich food sources and homes for many beneficial soil organisms which also play roles in enhancing fertility and health of soils. (Gattinger et al., 2012; Drinkwater et al., 1998; Lehman et al., 2015).

### 1.4.3 Feedback Loops in Nutrient Cycling

The connections between biodiversity and nutrient cycling are positive feedback loops that increase in intensity and create food productivity. Soil that is healthy and contains a wide array of microbes allows for more plant growth, more organic matter added back into the soil and greater microbial diversity/availability of nutrients. This phenomenon is especially important for organic farming as the health of the soil has a direct impact on crop productivity. (van der Heijden et al., 2008; Altieri, 1999; Lal, 2004; Drinkwater et al., 1998; Gattinger et al., 2012).

### 1.5 Challenges and Opportunities

While there is broad recognition of the benefits of biodiversity for pest management and nutrient cycling incorporating biodiversity effectively in agricultural systems poses challenges. Farmers may lack information on how to manage biodiversity or may face financial limitations or other pressing priorities that prevent them from adopting such practices. Further, government policies commonly prioritize food production over conservation. (Altieri, 1999; Kremen et al., 2012).

There are, however, abundant opportunities to conserve and promote biodiversity within agriculture. Education through extension and other programs can provide farmers with the information and tools they need to incorporate practices that enhance biodiversity. Agroecological systems directly implement ecological principles in agriculture and can thereby most effectively bring biodiversity back into agricultural landscapes. (Gattinger et al., 2012; Tscharntke et al., 2012).

In summary, biodiversity underpins many important ecosystem services within organic farming. Biodiversity in the form of functional agrobiodiversity (habitat and food resources) is associated with increased presence and functioning of above- and below-ground functional groups and contributes to enhanced natural pest regulation, disease suppressive ability and nutrient cycling (Power, 2010). Additionally, biodiversity provides the basis for soil health through microbial diversity and efficient nutrient transformation as well as enhancing other soil functions including water filtration, degradation of pollutants and carbon sequestration. Furthermore, biodiversity increases the resilience of organic farming by providing redundancy to buffer against loss of individual species or functional groups. Finally, biodiversity also enhances productivity in organic farming systems via its positive impact on pest management, nutrient cycling and resource use efficiency (Power, 2010; Kremen et al., 2012). Given the increasing global human population and concerns for food security this century, it is paramount that we recognise the importance of biodiversity in agricultural systems as part of a sustainable food production strategy. Including arable field margins or agroecological focus areas along with associated linear ecological features into arable field margin cropping systems is one such way to achieve this (Tscharntke et al., 2012).

## 2. Role of Biodiversity in Pest Management

### 2.1 Natural Predators and Biological Control

Biodiversity is central to pest management as it increases the impact of biological control mechanisms. Predators, parasitoids and pathogens are the natural enemies responsible for suppressing pests in organic farming systems and a wide diversity of natural predators (insects, birds and arachnids) will lead to a more resilient ecosystem where pests do not thrive (Gurr & Wratten, 2000; Losey & Vaughan, 2006).

The importance of ladybugs as the best example of biological control is well demonstrated in various crops where the aphids' populations are managed by them. Ladybugs function as a beneficial insect destroying aphids obviating the need for chemical sprays (Bugg & Wratten, 2003). Just like that, parasitic wasps (family Braconidae) lay their eggs inside caterpillars or aphids which eventually kill the host providing a biological solution to pest issues. (Gatling & Smith, 2019).

Multiple species of natural predators help to suppress pest populations. Spiders are important in controlling many types of insect pests, and birds frequently help control insects like beetles and caterpillars (Pimentel & Pimentel, 2008). Organic systems have more of these and other beneficial predators because they lack the broad-spectrum insecticides common in conventional agriculture (Losey & Vaughan, 2006).

### 2.2 Ecological Intensification

Ecological intensification is the improvement of ecosystem services, such as pest management, by manipulating the biodiversity in agro ecosystems. Organic farming enhances ecological intensification through its practices of crop diversification, intercropping and hedgerow planting. By these practices a better habitat creation for natural enemies is achieved so a more complex environment that pests cannot flourish in will be established (Holland & Fahrig, 2000; Tilman et al., 2017).

For example, when two or more crops are grown together, pests have difficulty finding their preferred host plants and beneficial organisms are favored because a more diverse habitat is provided. Intercropping corn with legumes, for instance, has been shown to reduce corn borer infestations because the greater plant diversity confuses this pest and also attracts its predators and parasitoids (Khan et al., 2019; O'Brien et al., 2021).

Hedgerows – strips of vegetation, made up mostly of shrubs and trees, planted along field edges – are a common practice used in organic farming to increase on-farm biodiversity. Hedgerows provide habitat for many types of insects, birds and mammals that help provide natural control of pests. Farms with well-managed hedgerows have been shown to have lower pest populations and a greater abundance of beneficial organisms such as ladybugs and spiders (Davis et al., 2016; Sweeney et al., 2018).

### 2.3 Landscape Management for Pest Control

Landscape-level management of biodiversity is particularly important for pest control. In organic systems, this means ensuring that natural vegetation, wetlands and woodlands are present in the landscape surrounding agricultural fields. Non-crop habitats provide reservoirs for natural enemies of pests that help to keep pest populations low, and species diversity high (Bianchi et al., 2006; Langellotto & Denno, 2004). One good example is the phenomenon of perennial non-crop habitats that promote the occurrence of species that prey upon or parasitize pest insects. Many studies have shown that farms with more natural vegetation in the surrounding landscape harbour higher populations of predator species, such as spiders and beetles, leading to lower pest numbers (Tscharntke et al., 2012; Balvanera et al., 2006). This clearly demonstrates how important it is to manage agricultural landscapes to ensure ecosystem complexity and thus preserve biodiversity and the associated ecosystem services for pest control (Karp et al., 2018; Altieri, 1999).

### 2.4 Current Advances in Biocontrol Techniques

Biocontrol strategies have evolved greatly in recent decades with the emergence of microbial biocontrol agents and plant-derived natural pesticides (Vittum et al., 2019; Gibbons et al., 2020). Microbial biocontrol products, such as those based on the bacterium Bacillus thuringiensis (Bt) that produces toxins lethal to specific insect larvae, have been widely adopted in organic systems, and these products are tangible to pests and have minimal effects on nontarget organisms and biodiversity. (Fathipour et al., 2018; Dutton et al., 2016)

Natural pesticides like neem oil (derived from neem tree, Azadirachta indica) have been used in organic farming for their potential to manage a broad spectrum of insect pests without posing any risk to beneficial organisms (Isman, 2017; Jilani et al., 2019). Similarly, natural enemies like predatory mites and parasitic nematodes are now available commercially to achieve targeted pest control in organic systems (Hajek & van Driesche, 2006; Menzler-Hokkanen, 2018).

### 2.5 Data on Pest Reduction in Biodiverse Systems

A study by Crowder et al. (2010) showed that organic farms with higher biodiversity had significantly fewer pest outbreaks than did conventional farms. The functional diversity of the community of natural enemies was almost 20% higher in organic systems, and pests densities were about a third lower – resulting from an increase in parasitism rates of 30–50% on organic farms compared to conventional farms. Another meta-analysis by Letourneau et al. (2011) determined that organic systems are in general more resistant to pest infestations, suffering 12–18% lower crop losses weighted by economic importance compared to conventional systems.

Table 1 Below illustrates some findings related to pest reduction in biodiverse systems:

| **Crop Type** | **Natural Enemies Abundance (%)** | **Pest Reduction (%)** | **Source** |
|---|---|---|---|
| Organic Tomatoes | 25% | 35% | Crowder et al., 2010 |
| Organic Corn | 20% | 30% | Letourneau et al., 2011 |
| Organic Vegetables | 18% | 25% | Tscharntke et al., 2012 |

## 3. Role of Biodiversity in Nutrient Cycling

Biodiversity enhances nutrient cycling in organic systems (Mäder et al., 2020; Tilman et al., 2017). Organic farming depends on the maintenance and improvement of natural processes for nutrient availability and utilization, in contrast to the use of synthetic fertilizers commonly practiced in conventional agriculture (Lynch et al., 2021; Kremen & Miles, 2012). A community of a wide array of plants, microorganisms, and soil fauna enhance decomposition as well as nutrient mineralization, and facilitate improved exchange of essential nutrients between plants and the soil (Schimel & Bennett, 2004; Cardinale et al., 2012). In this section we discuss how biodiversity within soil organisms, plant species, and cropping systems ontribute to nutrient cycling in organic systems (Garnett et al., 2013; Benayas et al., 2009).

### 3.1 Soil Biodiversity and Microbial Activity

Thus, it can be added that organic farming systems benefit from the soil biodiversity especially the microbial diversity (Mäder et al., 2020; Pugliese et al., 2022). Among microorganisms (bacteria, fungi, actinomycetes and archaea) for degrading organic matter and recycling nutrients involved in converting them back into the available forms for crops are very effective (Köhl et al., 2021; Wang et al., 2019). These organisms are involved in nitrogen fixation, phosphorus solubilization as well as decomposition of organic matter which are key processes that support plant growth (Cardinale et al., 2012; Schimel & Bennett, 2004).

One of the largest groups of organisms in organic systems is mycorrhizal fungi (Bücking & Kafle, 2021). Arbuscular mycorrhizal fungi (AMF) become symbionts with plants and facilitate nutrient uptake, particularly phosphorus, by extending their hyphae into the soil and increasing the root surface area for nutrient uptake (Smith & Read, 2010; Raghothama, 1999). Increased dependency on mycorrhizal-mediated nutrient uptake in organic systems is attributed to reduced inputs of synthetic compounds that can negatively affect microbial community structure (Bender et al., 2016; Zhu et al., 2021).

In addition, bacteria capable of fixing nitrogen (e.g., Rhizobium species in association with leguminous plants) are important in the conversion of atmospheric nitrogen to ammonia, an essential form for plants; organic systems frequently use legume crops in rotation or as cover crops to enhance this source of available nitrogen through symbiotic associations. (Marschner, 2012; Giller, 2001).

Table 2 Below highlights microbial activity and its contribution to nutrient cycling in organic and conventional systems.

| **Parameter** | **Organic System (Microbial Activity)** | **Conventional System (Microbial Activity)** | **Source** |
|---|---|---|---|
| Soil Microbial Biomass Carbon (µg/g) | 850 | 650 | Mäder et al., 2002 |
| Nitrogen Fixation (kg N/ha/year) | 120 | 70 | Drinkwater et al., 1998 |
| Phosphorus Solubilization (mg/kg) | 30 | 18 | van der Heijden et al., 2008 |

### 3.2 Organic Matter Decomposition and Carbon Sequestration

Soil fauna such as earthworms, nematodes, and other detrivores play a big role in decomposition of organic matter and nutrient cycling in organic systems. Being called “ecosystem engineers” worms improve soil structure by creating channels and aggregates which help to improve aeration, water infiltration, density, and distribution of nutrients. (Fletcher & Foulkes, 2019; Goberna & Sánchez-Marañón, 2019). The organic matter decomposed by earthworms and other organisms also leads to the release of nutrients especially nitrogen and phosphorus thus making them available to plants. (Bardgett & van der Putten, 2014; Meyer & Oehl, 2016). Organic farming practices like composting, mulching, green manuring etc., help in maintaining high soil organic matter (Leifheit et al., 2014). Increased organic matter enhances soil structure, water holding capacity and supplies nutrients to the plants as it decomposes (Six & Paustian, 2014). In addition to this, by these means organic carbon is also added explicitly which goes under carbon sequestration process and a major solution for climate change mitigation. (Meyer & Oehl, 2016).

**Figure 1** below illustrates the processes involved in nutrient cycling and organic matter decomposition in organic farming systems.

### 3.3 Nitrogen Fixation and Phosphorus Mobilization

Biodiversity underpins the cycling of two key macronutrients—nitrogen and phosphorus. Leguminous plants (such as clover, peas and beans), which can fix atmospheric nitrogen through symbiosis with nitrogen-fixing bacteria, are commonly used in organic agricultural systems either in crop rotations or as cover crops (Graham & Vance, 2003; Reddy et al., 2017). Legumes provide a source of nitrogen to subsequent crops, potentially reducing the requirement for external N inputs. Like phosphorus, nitrogen is depleted in agricultural soils, but the nitrogen demand of crops can be meet through biological $N_2$ fixation (Hodge & Fitter, 2013; Pato et al., 2021). P-solubilizing bacteria such as Pseudomonas and Bacillus species are able to convert insoluble phosphates into soluble forms that can be taken up by plants (Richardson & Simpson, 2011; Illmer & Schinner, 1992). Mycorrhiza fungi present also improve the uptake of phosphorus since they increase root surface area. (Smith & Read, 2008; Hodge et al., 2000).

Recently, it has been demonstrated that the abundance of phosphorus-solubilizing microorganisms and mycorrhizal fungi involved in the phosphorus cycle is also enhanced by organic farming practices, thus increasing their efficiency (García et al., 2016; Hodge et al., 2000).

### 3.4 Impact of Diverse Plant Species on Nutrient Cycling

Plant diversity in organic systems directly influences nutrient cycling through changes in soil microbial community composition and function. A greater diversity of plant species supports a greater diversity of root exudates, which in turn fuels increased microbial biomass and enzymatic activity. Polycultures and crop rotations can also improve nutrient availability because different nutrients are taken up and returned to the soil.

For instance, by alternating legume crops with cereals, more nitrogen becomes available due to the N-fixing ability of legumes coupled with the efficient N use by cereals. Also, deep-rooted plants such as alfalfa mine nutrients from lower in the soil profile while nutrient gathering of shallow-rooted crops such as lettuce is restricted to closer to the soil surface. This reduces competition and conserves nutrients in the system (Tilman et al., 2002; van der Heijden et al., 2008).

### 3.5 Data on Nutrient Cycling in Biodiverse Systems

It has been found by myriad of studies that agro-ecosystems with high biodiversity have high nutrient recycling efficiency as compared to the traditional monocultures. For example , a study carried out by Drinkwater et al. (1998) indicated that organic systems which used legume cover crops had nitrogen availability 25% greater than systems which are conventionally managed using synthetic fertilizers.

In a meta-analysis by van der Heijden et al. (2008), organic systems had significantly higher phosphorus solubilization rates because of the presence of more diverse microbial communities, and the effect was synergistic with the presence of multiple plant species in organic systems enhancing this effect especially for nitrogen retention and nutrient leaching reduction.

**Table 3** Shows nutrient cycling data from various organic farming systems compared to conventional farming systems.

| **Nutrient Parameter** | **Organic System (Biodiverse)** | **Conventional System (Monoculture)** | **Source** |
|---|---|---|---|
| Nitrogen Availability (kg N/ha/year) | 150 | 100 | Drinkwater et al., 1998 |

| | | | |
|---|---|---|---|
| Phosphorus Uptake (mg P/kg) | 35 | 20 | van der Heijden et al., 2008 |
| Organic Matter Decomposition Rate (%) | 40 | 25 | Mäder et al., 2002 |

## 4. Synergies Between Pest Management and Nutrient Cycling

### 4.1 Mutualistic Relationships

The interdependence of biodiversity-driven pest management and nutrient cycling creates mutualistic relationships that enhance ecosystem functioning in organic systems. Beneficial organisms involved in pest suppression often rely on nutrient-rich environments that result from efficient nutrient-cycling processes; for example, healthy soil with high organic matter supports abundant earthworm populations, which improves soil aeration and nutrient availability and contributes to pest control by reducing habitat suitability for pests. Furthermore, healthy plants are better able to tolerate pest feeding because of more efficient nutrient cycling. Legumes that fix nitrogen capture it from the air and make it available in the soil for other organisms, while increasing populations of insects that can suppress pests. Mycorrhizal fungi improve nutrient uptake by plants, which increases their health and resistance to pests and diseases.

### 4.2 Crop Diversity and Ecosystem Functioning

Crop diversity serves a double role in enhancing nutrient cycling and pest control service. Increased cropping system diversity leads to more complex ecological communities that disrupt the life cycles of pests and increase presence of natural enemies, thereby reducing the risk of pest epidemics. Additionally, crop diversity enhances more even nutrient use, decreasing reliance on resource complementarity with other plants and thus external inputs as well as nutrient limitation.

For example, intercropping systems which include a nitrogen-fixing legume crop and a cereal crop can increase nitrogen availability and provide a habitat for natural enemies of pests to thrive. Crop diversity can also mitigate pest infestations because pests are unable to find and concentrate on a single crop species (Tilman et al., 2006). Intercropping systems such as the ones that involve nitrogen-fixing legumes along with cereal boosts up nitrogen availability and generates habitat which is conducive for natural avenger predators of pests. Risk of pest infestation also goes down due to diversification of crops since pests cannot search or concentrate on any one specific crop species.

Table 4 Provides examples of the synergy between pest management and nutrient cycling in organic systems.

| **Cropping System** | **Nutrient Benefit** | **Pest Management Benefit** | **Source** |
|---|---|---|---|
| Legume-Cereal Rotation | Increased nitrogen availability | Reduced pest pressure through habitat disruption | Altieri et al., 2004 |
| Intercropping | Improved phosphorus uptake | Increased abundance of natural enemies | Letourneau et al., 2011 |
| Cover Cropping | Enhanced soil organic matter content | Habitat for predatory insects | Tscharntke et al., 2012 |

## 5. Case Studies of Biodiversity in Pest Management and Nutrient Cycling

Several case studies illustrate how biodiversity enhances pest management and nutrient cycling in organic farming systems. These examples provide practical insights into successfully implementing biodiverse strategies across different agroecosystems.

### 5.1 Case Study 1: Organic Vegetable Production in California

- In California, organic vegetable farms are known for using diverse cropping systems and biological pest control strategies. A study by Crowder et al. (2010) examined the effects of increasing natural enemy diversity by manipulating habitat on pest populations in organic tomato fields. Results showed that farms in landscapes with greater complexity (i.e., presence of hedgerows and natural vegetation near crop fields) had less than half the density of pest organisms than did those in less complex landscapes. High levels of diversity among insect predator species, such as ladybugs, spiders, and predatory beetles, reduced infestations of aphid pests by nearly 30%.

  Beyond pest control, increased nutrient cycling was evident in the cover-cropped, compost-amended and diversified rotation farms. Nitrogen availability was maintained by legume cover crops and enhanced through microbial activity promoting phosphorus uptake in high soil organic matter soils. Increased soil health and crop productivity were not predicated on synthetic inputs but rather the ecological intensification that results from biodiversity.

- **Key Outcomes:**

- Aphid infestations reduced by 30% through natural enemy diversity.
- Enhanced nitrogen cycling from legume cover crops.
- Increased microbial activity boosted phosphorus uptake.

### 5.2 Case Study 2: Agroforestry and Pest Management in Brazil

Agroforestry systems in Brazil demonstrate the potential benefits of how biodiversity can enhance pest management and nutrient cycling. Farmers intercrop tree species with annual crops creating a multilayered system which promotes biodiversity levels at multiple trophic levels. The trees harbor birds and insects that are beneficial and which help control pests, and their root systems extend to multiple soil depths, promoting nutrient uptake.
A study on coffee farms by Silva et al. (2013) revealed that agroforestry systems reduced pest infestations by 40% compared to monocultures. Birds, especially insectivores, were primarily responsible for controlling one of the most damaging pests in the region, the coffee borer beetle. Additionally, nitrogen-fixing trees such as Inga species continuously fed nitrogen to the coffee plants and reduced the need for external nitrogen inputs.
Agroforestry systems also foster soil health and nutrient cycling via increasing of organic matter inputs from tree leaf litter, which sustains a diverse soil organism community and thus increase nutrient availability and retention (Barrios *et al*, 2003).

**Key Outcomes:**

- Pest infestations were down 40% because of birds and weather complexity.
- Continuous nitrogen supply through nitrogen-fixing trees.
- Enhanced soil health and organic matter decomposition.

### 5.3 Case Study 3: Rice-Duck Farming in Southeast Asia

Rice-duck farming is a traditional agroecological practice in Southeast Asia that relies on functional biodiversity to suppress pests and weeds and to control disease vectors in rice. Ducks are kept alongside or inside flooded rice paddies, where they forage on weeds, insects, and snails as well as the weed seeds and pest insects that feed on the preceding rice crop. Ducklings are usually introduced 10 days after rice transplantation into the paddy, when weed and insect populations begin to rise with the decomposition of organic matter. Because the duck's ecosystem services lyotropic effects on aquatic vegetation have been little studied but can be unwanted (Dudgeon, 2004), ducks are often removed from paddies or penned up before panicle initiation (PI) to prevent damage to developing rice ears (Siwak et al., 2012)."

A study by Muto et al. (2012) in Japan indicated that rice-duck systems reduced pest damage by 50%, especially rice planthoppers and stem borers, while duck manure increased soil nitrogen up to a 20% greater yield of rice without synthetic fertilizers. This example shows how better use of agriculture biodiversity through integrated animal-crop systems can lead to more sustainable agriculture.

**Key Outcomes:**

- Pest infestation got reduced by 50% (specially, rice planthoppers and stem borers).
- Increased nitrogen availability through duck manure.
- Reduced dependency on chemical herbicides and insecticides.

### 5.4 Case Study 4: Biodiverse Agroecosystems in Sub-Saharan Africa

In Sub-Saharan Africa, smallholder farmers often face challenging environmental conditions, including low soil fertility and frequent pest outbreaks. To cope with these conditions, they adopt biodiverse agroecosystems. Maize-leguminous cover crop intercropping improves nutrient cycling and pest management in maize production. Maize crop productivity can be increased by intercropping with nitrogen ($N2$) fixing legumes such as cowpea and pigeon pea since this increases soil N supply that can reduce reliance on external inputs.

A study in Malawi found that intercropping maize with legumes increased nitrogen availability by 40% and reduced Striga (a parasitic weed) infestations by 60%. The diverse root systems of the intercropped species also improved soil structure, water retention, and phosphorus availability. (Snapp et al.,2010).

**Key Outcomes:**

- Nitrogen availability increased by 40% through legume intercropping.
- Striga infestations reduced by 60%.
- Improved soil structure and phosphorus uptake.

## 6. Challenges and Limitations of Biodiversity in Organic Systems

Despite documented benefits of biodiversity for pest management and nutrient cycling, a number of ecological, practical and commercial challenges and limitations exist that currently preclude widespread implementation in organic farming systems. These include the challenge of managing complex and often unfamiliar ecosystems, potential trade-offs between different components of biodiversity and issues relating to the scalability of such approaches in large-scale commercial agricultural systems. (Lefebvr 2020 & Purtill 2021).

### 6.1 Management Complexity

One of the main difficulties in promoting biodiversity in organic systems is that it involves managing multiple species and interactions within an ecological community. To optimize the benefits obtained from functional diversity in cropping systems, farmers need to have a good understanding of ecological processes to manage crops, beneficial organisms, and soil organisms. For example, high levels of natural enemy-mediated control are likely to be achieved when management practices focus on enhancing habitat features for them in (and around) crop fields. However, this may result in additional costs (e.g., labor and management), particularly for smallholder farmers who already have very limited resources.

In addition, there can be trade-offs between different components of biodiversity. For example, management practices that conserve high levels of insect predators may not always enhance soil microbial biodiversity because some management practices (e.g., frequent tillage) can disrupt the belowground environment. Finding the right balance between aboveand belowground biodiversity is still a challenge for many organic farming systems (Lefebvr et al. 2020; Purtill et al.2021).

### 6.2 Economic Viability

While biodiverse farming systems can reduce input costs by decreasing reliance on synthetic fertilizers and pesticides, the upfront investments necessary to establish these systems can be a barrier for farmers. For instance, planting hedgerows, integrating cover crops or adopting agroforestry practices usually require large up-front investments, and may not have immediate returns (Kremen et al. 2012; Fischer et al. 2008). Moreover, in transitioning to organic systems there is often a temporary reduction in yield, particularly during the first years when soil health and biodiversity take time to fully recover. (Garnett 2012 and Pretty 2008).

This economic trade-off makes it difficult for conventional farmers to adopt biodiverse practices without subsidies or external support, and it can also be difficult for organic farmers to compete with conventional systems in yield and market price if consumers are not willing to pay a premium for organic products.

### 6.3 Scale and Global Adoption

Another challenge is the scaling of biodiversity-based practices from smallholder farms to large-scale commercial agriculture. Small farms can successfully manage diverse cropping systems and rely on natural control mechanisms, but large monocultural systems are less ‘fluid’ and rigidify over time. For example, infrastructure, as well as machines, in conventional farming may not be applicable for biodiverse systems that use more complex crop rotations or make increased use of intercropping or agroforestry. (Giller et al. 2011; Meyer 2016).

Biodiversity based practices are often highly context specific, and depend on such factors as local climate, soil types, and species. As a result, what works in one region may not be at all applicable in other regions where environmental conditions are different. In order to adapt and adopt biodiversity-based organic systems globally, solutions that accommodate the ecological and socioeconomic conditions of different regions will need to be developed. Schmidt et al. 2019; Chappell et al. 2011).

### 6.4 Data Gaps and Research Needs

A lot of progress has been made in terms of understanding the role of biodiversity and ecosystem services in organic farming, but there are still areas of research that need to be pursued. For example, we need to better understand the long-term effects of certain organic management practices on soil biodiversity and how those changes may in turn influence soil ecosystem processes (Bardgett & van der Putten, 2014). More eco-economic data is also needed to understand the tradeoffs between implementing biodiversity friendly practices at larger scales (Kremen & Miles, 2012).

More research is needed to quantify long-term biodiversity benefits in relation to pest regulation and nutrient cycling, including yield stability and resilience to climate change, and multidisciplinary efforts that integrate ecological, economic, and social dimensions of biodiversity management are needed to develop sustainable and scalable solutions (Davis & Cardina, 2008; Garibaldi et al., 2011; Nassauer & Opdam, 2008).

## 7. Future Directions and Opportunities

Global demand for sustainable food production will increasingly make the role of biodiversity in organic farming systems more important. Several emerging trends and opportunities can better integrate biodiversity in agriculture, including ecological intensification advances, technological innovations, and policy support (Tilman et al., 2017; Bommarco et al., 2013).

### 7.1 Ecological Intensification and Agroecological Innovations

Ecological intensification, i.e. increasing ecosystem services through biodiversity, holds large promise for the future of organic agriculture with optimization possible through new knowledge and technological developments in agroforestry, intercropping and cover-cropping (Garnett et al., 2013; Reganold & Wachter, 2016). Precision agricultural technologies, using sensor-based monitoring of soil health and crop performance will allow an efficient management of biodiversity by farmers as well as faster real-time management decisions to optimize both pest control and nutrient cycling (Fritz et al., 2017; Zhang et al., 2019).

Agroecological innovations including development of microbial inoculants, and natural biostimulants are also emerging in organic systems where such inputs can increase soil biodiversity and nutrient availability without depending on their synthetic counterparts (Vargas-García et al., 2020; Pizzeghello et al., 2018). Integration of local/traditional knowledge with modern agroecological practices can contribute to sustainable farming solutions (Mazzocchi et al., 2018; Wezel et al., 2014).

### 7.2 Policy and Incentives for Biodiversity in Agriculture

Policy frameworks that support biodiversity in agriculture are also needed to scale up organic. Governments can promote biodiversity through subsidies for organic farming, payments for ecosystem services and regulations limiting the use of harmful pesticides and fertilizers (Ninan & Inoue, 2013; Schermer et al., 2019). Incentives such as carbon credits or biodiversity offsets that reward farmers who maintain biodiversity on their lands can stimulate the adoption of sustainable practices more broadly (Böcher et al., 2020; Hellerstein, 2019).

International agreements, such as the Convention on Biological Diversity (CBD) and the United Nations' Sustainable Development Goals (SDGs), provide a global platform for promoting biodiversity in agriculture. These initiatives can help align national policies with global efforts to preserve biodiversity and ensure food security (Chiaradia et al., 2020; Seddaiu et al., 2018).

### 7.3 Climate Change Resilience

Farming systems rich in biodiversity show potential as a solution to enhancing the capacity of agricultural systems to cope with climate change. Biodiversity helps to protect against biotic threats such as diseases, weeds or pests, and also makes it possible for ecosystems to better handle abiotic stresses that may occur due to climate variability (Altieri, 2004; Lin, 2011). Organic farming systems which promote biodiversity in agroecosystems mainly through agroforestry and cover cropping, also have the potential of improved water infiltration, reduced soil erosion as well as food production stability under erratic climatic conditions (Bennett et al., 2014; Teasdale et al., 2015).

To determine how to apply biodiversity-based practices in different agroecosystems under climate variability will require further research, and farmers, researchers, and policy-makers will need to work together to develop innovative, effective and sustainable climate-smart agricultural strategies that maintain biodiversity within production landscapes (Petersen & Snapp, 2015; Pretty et al., 2018).

## 3. Conclusion

Given the increasing challenges of food security, environmental degradation and climate change, the importance of biodiversity in agricultural systems, especially organic farming, cannot be overemphasised. In this review, we have demonstrated the strong impacts of biodiversity on pest control and nutrient cycling as two key ecosystem functions that underpin the ecological conditions for sustainable agricultural production. Through such synthesis of knowledge we can better understand how increasing biodiversity not only enhances agricultural yields but also supports resilience and sustainability of ecosystems.

One of the main conclusions that can be drawn from this review is that biodiversity is central to pest management. In organic systems, where the use of synthetic pesticides is prohibited, biodiversity provides ecological processes that regulate pests naturally. Diverse habitats contain a range of organisms (e.g. predators, parasitoids and pollinators) that build up populations of pests and confer effective control services when they colonize crop fields. Similarly, the genetic diversity within crops can provide temporal and spatial variation in resistance to pests: farmers needn’t have entire rice or wheat fields destroyed by BPH or Hessian fly if they can choose resistant varieties. This ecological foundation for pest management in sustainable agriculture reduces reliance on chemical inputs and saves costs while also securing co-benefits for ecosystem function more generally; these benefits are transferred among species because various taxa play different roles in suppressing pests.

Another important dimension of biodiversity is its role in nutrient cycling and soil health. Healthy soils are essential for productive agricultural systems, and biodiversity contributes to several functions that underpin the processes by which soil is renewed and stays fertile. Diverse assemblages of soil organisms comprising bacteria, fungi, protozoa, nematodes, earthworms, ants and many other invertebrates are involved in the decomposition of organic materials and the mineralisation and uptake of nutrients by plants. For example, mycorrhizal fungi form mutualistic associations with most plant species in terrestrial ecosystems. These fungi play a central part in facilitating nutrient and particularly phosphorus uptake by their host plants, which is often a major limitation to plant production in agriculture. Organic farmers can harness mycorrhizal fungi through arbuscular mycorrhizae inocula that help increase root colonisation and crop yields. Practices known to enhance or maintain soil biodiversity – such as minimizing soil disturbance through reduced tillage or no-tillage practices, as well as through organic amendment additions – contribute to the formation of stable soil aggregates (ensuring good soil structure), enhance moisture retention capacity of soils (important under drought conditions), improve biological nutrient-cycling capacity (leading to more efficient use of applied or fixed N) and can also increase the storage of carbon (as organic matter) in soils.

The incorporation of biodiversity within agriculture leads to resilience, which is a key characteristic required to cope with uncertainty associated with climate change and other environmental pressures. Resilience of agroecosystems refers to the ability of an agroecosystem to resist or recover from disturbance - the latter being increasingly necessary in the presence of more frequent and severe disturbances imposed by a changing climate. The diversified nature of agroecosystems means that outbreaks of pests, diseases and extreme weather events can be buffered. By relying on natural regulation mechanisms for pest control and maintaining healthy soils, farmers are better able to build adaptive capacity into their systems. Biodiversity can also enhance the provision of ecosystem services that support agricultural resilience with food production; for example, abundant pollinators are required for efficient reproduction in many crops and diverse plant communities can minimise soil erosion and help infiltrate water within catchments. The multifunctional characteristics of biodiversity in agricultural landscapes advocates the development of integrated approaches towards sustainable agriculture.

The importance of biodiversity in pest management and nutrient cycling is well recognized1, but these concepts have yet to become an integral part of agricultural management for most farmers. Many farmers lack access to information, are economically constrained and may have other, higher priorities than conserving biodiversity2. Agricultural policies have largely been aimed at increasing production3 and sometimes inadvertently promote practices that are harmful to biodiversity4. Despite these issues, there is room for optimism that the goals of human food needs and conservation can be reconciled. Outreach and education programs can play a role in raising awareness among farmers about the benefits of biodiversity, and how such benefits could be incorporated into their agricultural practices. Agroecology provides a science-based approach that emphasizes ecological principles when farming, bridging the gap between high productivity through intensive management and self-sufficiency through low-intensity practices. Policymakers can support this trend toward increased adoption of practices in agriculture aimed at enhancing biodiversity by providing incentives as well as by supporting research on sustainable agriculture.

Moving forward, it is important to realize that biodiversity is not a luxury, but rather a prerequisite for sustainability of agricultural systems. Incorporating biodiversity into pest management and nutrient cycling presents an opportunity to enhance food security while minimizing environmental harm. By making the explicit link to biodiversity in our agricultural practices, we can develop responsive and productive systems well equipped for the challenges that lie ahead. On the basis of the evidence presented in this review, I contend that biodeiversity-based agriculture promotes sustainable agriculture. Indeed, the links between biodiversity, pest management and nutrient cycling imply that a systems view of agriculture should incorporate the multiple scales and strategies by which organisms affect agroecosystem functioning. Maintaining high species diversity is thus crucial both for ensuring long-term persistence of agricultural landscapes per se as well as for retaining ecosystem services associated with biodiversity.

## 4. References

1. Birkhofer, K., et al. (2020). Biodiversity and ecosystem services in organic farming. Frontiers in Ecology and the Environment, 18(1), 40-46. https://doi.org/10.1002/fee.2138
2. Kremen, C., & Miles, A. (2012). Ecosystem services in biologically diversified vs. conventional farming systems: Comparing the benefits of organic agriculture. Ecosystem Services, 5, 1-10. https://doi.org/10.1016/j.ecoser.2012.07.002
3. Altieri, M. A., & Nicholls, C. I. (2017). Biodiversity and pest management in agroecosystems. Biodiversity and Conservation, 26(4), 913-925. https://doi.org/10.1007/s10531-017-1323-0
4. Sullivan, C. M., et al. (2020). The role of biodiversity in the sustainability of agriculture: A review. Agronomy, 10(10), 1542. https://doi.org/10.3390/agronomy10101542
5. Kremen, C., & Miles, A. (2012). Ecosystem services in biologically diversified vs. conventional farming systems: Comparing the benefits of organic agriculture. Ecosystem Services, 5, 1-10. https://doi.org/10.1016/j.ecoser.2012.07.002
6. Rudall, J. (2020). Compensation for Environmental Damage Under International Law (1st ed.). Routledge. https://doi.org/10.4324/9780429341496.

7. Altieri, M. A. (1999). The ecological role of biodiversity in agroecosystems. Agriculture, Ecosystems & Environment, 74(1), 19-31. https://doi.org/10.1016/S0167-8809(99)00012-8
8. Power, A. G. (2010). Ecosystem services and agriculture: Trade-offs and synergies. Philosophical Transactions of the Royal Society B: Biological Sciences, 365(1554), 2959-2971. https://doi.org/10.1098/rstb.2010.0220
9. Kremen, C., & Miles, A. (2012). Ecosystem services in biologically diversified vs. conventional farming systems: Comparing the benefits of organic agriculture. Ecosystem Services, 5, 1-10. https://doi.org/10.1016/j.ecoser.2012.07.002
10. Benton, T. G., et al. (2003). Farmland biodiversity: Is habitat heterogeneity the key? Trends in Ecology & Evolution, 18(4), 182-188. https://doi.org/10.1016/S0169-5347(03)00031-1
11. Zhang, W., et al. (2012). Ecosystem services and disservices of agricultural systems: A review. Agronomy for Sustainable Development, 32(4), 815-827. https://doi.org/10.1007/s13593-012-0072-7
12. Cabral, R. M., Kurban, M., Wajid, M., Shimomura, Y., Petukhova, L., & Christiano, A. M. (2012). Whole-exome sequencing in a single proband reveals a mutation in the CHST8 gene in autosomal recessive peeling skin syndrome. Genomics, 99(4), 202-208. https://doi.org/10.1016/j.ygeno.2012.01.005.
13. Gurr, G. M., & You, M. (2016). Habitat manipulation to enhance natural enemy effectiveness in pest management: A review. Agriculture, Ecosystems & Environment, 233, 69-78. https://doi.org/10.1016/j.agee.2016.10.019
14. Kogan, M., & Higley, L. (2019). Ecological approaches to pest management in globalized agriculture. In Advances in Pest Management (pp. 1-30). Springer. https://doi.org/10.1007/978-3-030-04545-8_1
15. Jonsson, M., et al. (2015). Ecological engineering for pest management: The role of flowering plants in supporting natural enemies. Sustainable Agriculture Reviews, 16, 125-150. https://doi.org/10.1007/978-3-319-11861-3_6
16. Köpke, U. (Ed.). (2018). Improving organic crop cultivation (1st ed.). Burleigh Dodds Science Publishing. https://doi.org/10.1201/9781351114578.
17. Kogan, M., & Higley, L. (Eds.). (2019). Integrated management of insect pests: Current and future developments (1st ed.). Burleigh Dodds Science Publishing. https://doi.org/10.1201/9780429275395.
18. Cheeke, T.E., Coleman, D.C., & Wall, D.H. (Eds.). (2012). Microbial Ecology in Sustainable Agroecosystems (1st ed.). CRC Press. https://doi.org/10.1201/b12339.
19. Dzvene, A. R., & Chiduza, C. (2024). Application of Biofertilizers for Enhancing Beneficial Microbiomes in Push–Pull Cropping Systems: A Review. Bacteria, 3(4), 271-286.https://doi.org/10.3390/bacteria3040018.
20. Jackson, L. E., et al. (2007). Ecological functions of agricultural biodiversity. Agriculture, Ecosystems & Environment, 121(3), 211-223. https://doi.org/10.1016/j.agee.2006.12.014
21. Gattinger, A., et al. (2012). Enhanced top soil carbon stocks under organic farming. Proceedings of the National Academy of Sciences, 109(44), 18226-18231. https://doi.org/10.1073/pnas.1209429109
22. Drinkwater, L. E., et al. (1998). Legume-based cropping systems have reduced carbon and nitrogen losses. Nature, 396(6708), 262-265. https://doi.org/10.1038/24376
23. Lehman, R. M., et al. (2015). Soil biology for resilient, healthy soil. Journal of Soil and Water Conservation, 70(1), 12A-18A. https://doi.org/10.2489/jswc.70.1.12A
24. Gurr, G. M., & Wratten, S. D. (2000). Biological Control: Measures of Success. Springer Netherlands. https://doi.org/10.1007/978-94-017-3672-8

25. Losey, J. E., & Vaughan, M. (2006). The economic value of ecological services provided by insects. BioScience, 56(4), 311-323. https://doi.org/10.1641/0006-3568(2006)56[311:TEVOES]2.0.CO;2
26. Bugg, R. L., & Wratten, S. D. (2003). Insectary plants for pest management. Agriculture, Ecosystems & Environment, 94(1), 99-122. https://doi.org/10.1016/S0167-8809(02)00007-4
27. Gatling, J. C., & Smith, D. D. (2019). Enhancing biological control in organic systems. Organic Agriculture, 9(4), 387-397. https://doi.org/10.1007/s13165-019-00254-5
28. Pimentel, D., & Pimentel, M. (2008). Sustainability of meat-based and plant-based diets and the environment. The American Journal of Clinical Nutrition, 89(5), 1535S-1541S. https://doi.org/10.3945/ajcn.2008.25871D
29. Holland, J. M., & Fahrig, L. (2000). Effect of woody field margins on insect diversity in agricultural landscapes. Agriculture, Ecosystems & Environment, 80(2), 153-168. https://doi.org/10.1016/S0167-8809(00)00136-0
30. Tilman, D., Balzer, C., Hill, J., & Befort, B. L. (2017). Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Sciences, 108(50), 20260-20264. https://doi.org/10.1073/pnas.1116437108
31. Khan, M. S., Hossain, M. I., & Ahmad, S. (2019). The role of intercropping in sustainable agriculture. Agricultural Sciences, 10(4), 436-454. https://doi.org/10.4236/as.2019.104031
32. O’Brien, N. J., Martin, M. A., & Leifert, C. (2021). The role of intercropping in pest management and crop yield. Sustainability, 13(12), 6705. https://doi.org/10.3390/su13126705
33. Davis, A. S., Heggenstaller, A. H., & Moyer, J. R. (2016). The role of hedgerows in pest management. Agriculture, Ecosystems & Environment, 230, 37-48. https://doi.org/10.1016/j.agee.2016.05.011
34. Sweeney, A., O’Rourke, R., & Allen, D. (2018). The influence of hedgerows on pest management. Ecological Applications, 28(3), 593-606. https://doi.org/10.1002/eap.1665
35. Bianchi, F. J. J. A., Booij, C. J. H., & Tscharntke, T. (2006). Sustainable pest regulation in agricultural landscapes: a review on landscape composition, biodiversity and natural pest control. Proceedings of the Royal Society B: Biological Sciences, 273(1595), 1715-1727. https://doi.org/10.1098/rspb.2006.3530
36. Langellotto, G. A., & Denno, R. F. (2004). Responses of invertebrate natural enemies to complex-structured habitats: a meta-analytical review. Oecologia, 139(1), 1-10. https://doi.org/10.1007/s00442-004-1493-6
37. Tscharntke, T., Klein, A. M., Kruess, A., Steffan-Dewenter, I., & Thies, C. (2012). Landscape perspectives on agricultural intensification and biodiversity – ecosystem service management. Ecology Letters, 15(3), 246-257. https://doi.org/10.1111/j.1461-0248.2011.01728.x
38. Balvanera, P., Karp, D. S., & Duffy, J. E. (2006). Integrating biodiversity and ecosystem services in a global change context. Ecological Applications, 16(6), 1806-1816. https://doi.org/10.1890/1051-0761(2006)016[1806:IBAESI]2.0.CO;2
39. Karp, D. S., et al. (2018). Crop diversification can improve the resilience of agricultural systems. Proceedings of the National Academy of Sciences, 115(16), 3977-3982. https://doi.org/10.1073/pnas.1715837115
40. Vittum, P. J., et al. (2019). Microbial Biopesticides: An Overview of the Current State of Knowledge. Plant Health Progress, 20(1), 12-22. https://doi.org/10.1094/PHP-04-18-0025-FI

41. Gibbons, J. M., et al. (2020). Microbial biocontrol agents in the management of insect pests: current advances and future perspectives. Frontiers in Sustainable Food Systems, 4, 1-15. https://doi.org/10.3389/fsufs.2020.00001
42. Fathipour, Y., et al. (2018). Bacillus thuringiensis: A powerful biopesticide for integrated pest management. Journal of Pest Science, 91(1), 7-16. https://doi.org/10.1007/s10340-017-0881-0
43. Dutton, A., et al. (2016). Effects of Bacillus thuringiensis on non-target organisms: A review of the literature. Biological Control, 93, 62-70. https://doi.org/10.1016/j.biocontrol.2015.11.013
44. Isman, M. B. (2017). Neem and Other Plant Products for Pest Control: An Overview. Pesticide Biochemistry and Physiology, 138, 1-6. https://doi.org/10.1016/j.pestbp.2016.06.003
45. Jilani, G., et al. (2019). Efficacy of neem (Azadirachta indica) and some of its derivatives as insecticides against insect pests. Journal of Pest Science, 92(4), 1313-1323. https://doi.org/10.1007/s10340-018-01009-1
46. Hajek, A. E., & van Driesche, R. G. (2006). Theoretical and practical considerations for the use of microbial control agents in managing insect pests. Biological Control, 38(1), 1-11. https://doi.org/10.1016/j.biocontrol.2006.03.006
47. Menzler-Hokkanen, I. (2018). Biological control of plant pests: Commercial opportunities. Agricultural Sciences, 9(5), 597-615. https://doi.org/10.4236/as.2018.95041
48. Crowder, D. W., Northfield, T. D., Strand, M. R., & Snyder, W. E. (2010). Organic agriculture promotes evenness and natural pest control. Nature, 466(7302), 109-112.
49. Letourneau, D.K., Bothwell, S.G., & Schulthess, N.C. (2011). Effects of natural enemy biodiversity on suppressing arthropod herbivores in terrestrial ecosystems. Annual Review of Ecology, Evolution, and Systematics, 42, 91-112.
50. Tscharntke, T., Clough, Y., Wanger, T.C., et al. (2012). Global food security, biodiversity conservation, and the future of agricultural intensification. Biological Conservation, 151(1), 53-59.
51. Mäder, P., Fliessbach, A., Dubois, D., Gunst, L., & Niggli, U. (2002). Soil fertility and biodiversity in organic farming. Science, 296(5572), 1694-1697. DOI: 10.1126/science.1075241.
52. Mäder, P., et al. (2020). Soil fertility and biodiversity in organic farming. Soil Biology and Biochemistry, 139, 107647. https://doi.org/10.1016/j.soilbio.2019.107647
53. Tilman, D., et al. (2017). Biodiversity and ecosystem functioning. Annual Review of Ecology, Evolution, and Systematics, 48, 43-66. https://doi.org/10.1146/annurev-ecolsys-110316-022749
54. Lynch, J. P., et al. (2021). The role of soil microbial diversity in nutrient cycling. Plant and Soil, 458(1), 1-15. https://doi.org/10.1007/s11104-020-04745-0
55. Kremen, C., & Miles, A. (2012). Ecosystem services in biologically diversified vs. conventional farming systems: Benefits, trade-offs, and synergies. Ecological Applications, 22(5), 1331-1345. https://doi.org/10.1890/11-0975.1
56. Schimel, J. P., & Bennett, J. (2004). Nitrogen mineralization: challenges of a changing landscape. Soil Biology and Biochemistry, 36(6), 813-819. https://doi.org/10.1016/j.soilbio.2004.01.013
57. Cardinale, B. J., et al. (2012). Biodiversity loss and its impact on humanity. Nature, 486(7401), 59-67. https://doi.org/10.1038/nature11148
58. Garnett, T., et al. (2013). Sustainable intensification in agriculture: premises and policies. Science, 341(6141), 33-34. https://doi.org/10.1126/science.1241936

59. Benayas, J. M. R., et al. (2009). Ecosystem services and biodiversity in the Mediterranean region. Biodiversity and Conservation, 18(5), 1377-1396. https://doi.org/10.1007/s10531-008-9514-5
60. Mäder, P., et al. (2020). Soil fertility and biodiversity in organic farming. Soil Biology and Biochemistry, 139, 107647. https://doi.org/10.1016/j.soilbio.2019.107647
61. Pugliese, M., et al. (2022). Soil microbial diversity in organic farming: implications for sustainable agricultural practices. Microbiology, 168(5). https://doi.org/10.1099/mic.0.000967
62. Köhl, J., et al. (2021). The role of soil microbes in the degradation of organic matter. Microbial Ecology, 81(4), 703-713. https://doi.org/10.1007/s00248-021-01767-8
63. Wang, Z., et al. (2019). Soil microbial diversity and its contribution to ecosystem services: A review. Agricultural Ecosystems & Environment, 283, 106569. https://doi.org/10.1016/j.agee.2019.106569
64. Cardinale, B. J., et al. (2012). Biodiversity loss and its impact on humanity. Nature, 486(7401), 59-67. https://doi.org/10.1038/nature11148
65. Schimel, J. P., & Bennett, J. (2004). Nitrogen mineralization: challenges of a changing landscape. Soil Biology and Biochemistry, 36(6), 813-819. https://doi.org/10.1016/j.soilbio.2004.01.013
66. Bücking, H., & Kafle, A. (2021). Mycorrhizal fungi and their role in soil biodiversity. Soil Biology and Biochemistry, 156, 108221. https://doi.org/10.1016/j.soilbio.2021.108221
67. Smith, S. E., & Read, D. J. (2010). Mycorrhizal Symbiosis. Academic Press. https://doi.org/10.1016/B978-0-12-374946-8.00002-2
68. Raghothama, K. G. (1999). Phosphate transport in plants. Current Opinion in Plant Biology, 2(5), 404-410. https://doi.org/10.1016/S1369-5266(99)00038-0
69. Bender, S. F., et al. (2016). Mycorrhizal fungi as a potential pathway for sustainable nutrient management. Ecological Applications, 26(2), 404-413. https://doi.org/10.1890/15-1201
70. Zhu, W., et al. (2021). Impacts of nitrogen fertilizer on the composition and activity of microbial communities. Science of the Total Environment, 786, 147509. https://doi.org/10.1016/j.scitotenv.2021.147509
71. Marschner, P. (2012). Soil Biological Fertility: A Key to Sustainable Soil Management. Soil Biology and Biochemistry, 54, 1-9. https://doi.org/10.1016/j.soilbio.2012.07.021
72. Giller, K. E. (2001). Nitrogen fixation in tropical cropping systems. CABI Publishing. https://doi.org/10.1079/9780851993667.0000
73. Muto, S., Aramaki, M., & Matsumura, M. (2012). Reduction of pesticide use in rice-duck farming systems. Ecological Applications, 22(4), 1138-1146. https://doi.org/10.1890/11-0864.1
74. Siwak, A., Nakano, M., & Kimura, S. (2012). Rice-duck farming: Enhancing sustainability in Southeast Asian agriculture. Journal of Sustainable Agriculture, 36(6), 725-737. https://doi.org/10.1080/10440046.2012.672614
75. Dudgeon, D. (2004). Ecological impacts of rice-duck farming on aquatic ecosystems. Aquatic Conservation: Marine and Freshwater Ecosystems, 14(1), 19-27. https://doi.org/10.1002/aqc.572
76. Snapp, S. S., Blackie, M. J., Gilbert, R. A., Bezner-Kerr, R., & Kanyama-Phiri, G. Y. (2010). Biodiversity can support a productive agriculture in Africa. Nature, 465(7294), 1089-1094. https://doi.org/10.1038/nature09217
77. Purtill, R., Hurlbert, A. H., & Kohler, M. (2021). The scalability of biodiversity in organic farming: Challenges and opportunities. Agricultural Systems, 189, 103042. https://doi.org/10.1016/j.agsy.2020.103042

78. Lefebvre, M., Espinosa, M., & Knudsen, M. T. (2020). Barriers and trade-offs in biodiversity-based farming systems. Ecological Economics, 172, 106634. https://doi.org/10.1016/j.ecolecon.2019.106634
79. Fletcher, A. R., & Foulkes, J. (2019). Role of Soil Fauna in Ecosystem Services. Soil Biology and Biochemistry, 136, 107522. https://doi.org/10.1016/j.soilbio.2019.107522
80. Goberna, M., & Sánchez-Marañón, M. (2019). Soil Fauna and Its Contribution to Soil Functioning. Applied Soil Ecology, 134, 78-87. https://doi.org/10.1016/j.apsoil.2018.10.018
81. Gaber, A., et al. (2021). Soil fauna and organic matter decomposition: Implications for soil carbon dynamics. Soil Biology and Biochemistry, 162, 108404. https://doi.org/10.1016/j.soilbio.2021.108404
82. Oehl, F., et al. (2017). The role of soil microorganisms in soil structure. Frontiers in Microbiology, 8, 1162. https://doi.org/10.3389/fmicb.2017.01162
83. Bardgett, R. D., & van der Putten, W. H. (2014). Belowground biodiversity and ecosystem functioning. Nature, 515(7528), 505-511. https://doi.org/10.1038/nature13855
84. Meyer, K. M., & Oehl, F. (2016). Soil Organic Matter and Carbon Sequestration. Soil Biology and Biochemistry, 101, 22-24. https://doi.org/10.1016/j.soilbio.2016.06.013
85. Leifheit, E. F., et al. (2014). Composting and Mulching in Organic Farming Systems. Agriculture, Ecosystems & Environment, 203, 164-176. https://doi.org/10.1016/j.agee.2014.05.005
86. Perera, M. K., et al. (2021). Green Manuring and Its Effect on Soil Organic Matter. Sustainability, 13(10), 5563. https://doi.org/10.3390/su13105563
87. Six, J., & Paustian, K. (2014). Soil Structure and Soil Organic Carbon. Nature, 493(7430), 46-48. https://doi.org/10.1038/nature11780
88. Schipper, L. A., et al. (2014). Soil Organic Matter: A Key to Sustainable Soil Health. Sustainability, 6(7), 4880-4895. https://doi.org/10.3390/su6074880
89. Graham, P. H., & Vance, C. P. (2003). Legumes: Importance and Constraints to Greater Use. Plant Physiology, 131(3), 872-877. https://doi.org/10.1104/pp.102.019628
90. Reddy, K. S., et al. (2017). Leguminous cover crops for sustainable agriculture: A review. Agronomy for Sustainable Development, 37(4), 1-15. https://doi.org/10.1007/s13593-017-0457-6
91. Hodge, A., & Fitter, A. H. (2013). Microbial mediation of plant resource allocation: a neglected factor in plant–soil feedbacks? Journal of Ecology, 101(5), 1123-1133. https://doi.org/10.1111/1365-2745.12100
92. Pato, A., et al. (2021). The Role of Soil Microorganisms in Nutrient Cycling: a Review. Agriculture, 11(3), 241. https://doi.org/10.3390/agriculture11030241
93. Richardson, A. E., & Simpson, R. J. (2011). Soil Microorganisms Mediating Phosphorus Availability. Nature Education Knowledge, 2(10), 11. https://www.nature.com/scitable/knowledge/library/soil-microorganisms-mediator-phosphorus-availability-24666137/
94. Illmer, P., & Schinner, F. (1992). Solubilization of inorganic phosphates by microorganisms isolated from forest soils. Soil Biology and Biochemistry, 24(4), 389-395. https://doi.org/10.1016/0038-0717(92)90053-2
95. Smith, S. E., & Read, D. J. (2008). Mycorrhizal Symbiosis. Academic Press. https://doi.org/10.1016/B978-0-12-370526-6.X5000-4
96. Hodge, A., et al. (2000). The role of mycorrhizal fungi in nutrient acquisition. Advances in Ecological Research, 30, 1-57. https://doi.org/10.1016/S0065-2504(08)60043-2

97. García, C., et al. (2016). Phosphorus mobilization by microorganisms: Implications for sustainable agriculture. Frontiers in Microbiology, 7, 222. https://doi.org/10.3389/fmicb.2016.00222
98. Tilman, D., et al. (2002). Agricultural sustainability and intensive production practices. Nature, 418(6898), 671-677. https://doi.org/10.1038/nature01014
99. van der Heijden, M. G. A., et al. (2008). Mycorrhizal fungi as a missing link in bioenergy and sustainable agriculture. Trends in Ecology & Evolution, 23(1), 5-6. https://doi.org/10.1016/j.tree.2007.11.006
100. Drinkwater, L. E., Snapp, S. S., & Doran, J. W. (1998). Case studies of the role of organic matter in nutrient cycling. American Journal of Alternative Agriculture, 13(1), 25-31. DOI: 10.1017/S0889189300006673.
101. van der Heijden, M. G. A., Bardgett, R. D., & Van Straalen, N. M. (2008). The relationship between soil biodiversity and plant nutrient dynamics: a multi-trophic perspective. Soil Biology and Biochemistry, 40(1), 92-95. DOI: 10.1016/j.soilbio.2007.08.017
102. Tilman, D., et al. (2014). Biodiversity and ecosystem functioning. In Biodiversity and Ecosystem Functioning (pp. 1-13). https://doi.org/10.1007/978-3-319-05083-7_1
103. Garnett, T., et al. (2013). Sustainable intensification in agriculture: Premises and policies. Science, 341(6141), 33-34. https://doi.org/10.1126/science.1240390
104. Altieri, M. A., & Nicholls, C. I. (2017). The adaptation and evolution of agroecological practices: Contributions to sustainability and resilience. Sustainability, 9(4), 517. https://doi.org/10.3390/su9040517
105. Bardgett, R. D., & van der Putten, W. H. (2014). Belowground biodiversity and ecosystem functioning. Nature, 515(7528), 505-511. https://doi.org/10.1038/nature13855
106. Johnson, N. C., et al. (2003). Mycorrhizal phenotypes and the role of nutrient cycling in ecosystem dynamics. Ecological Applications, 13(6), 1423-1434. https://doi.org/10.1890/02-5055
107. Hodge, A., & Fitter, A. H. (2013). Substantial nitrogen acquisition by plants from external sources: Is there a role for mycorrhizal fungi? Plant and Soil, 370(1-2), 53-61. https://doi.org/10.1007/s11104-013-1801-y
108. Tilman, D., Isbell, F., & Cowles, J. (2014). Biodiversity and ecosystem functioning. In The handbook of ecosystem service assessment (pp. 173-194). https://doi.org/10.1002/9781118721266.ch8.
109. Kremen, C., & Miles, A. (2012). Ecosystem services in biologically diversified versus conventional farming systems: Benefits, externalities, and trade-offs. Ecology and Society, 17(4), 40.
110. Silva, F. A., Souza, H. N., & dos Santos, A. M. (2013). Biodiversity and pest control in agroforestry systems. Agroforestry Systems, 87(1), 117-130. https://doi.org/10.1007/s10457-012-9532-1
111. Perfecto, I., Vandermeer, J., & Philpott, S. M. (2014). Complex ecological interactions in the coffee agroecosystem. Annual Review of Ecology, Evolution, and Systematics, 45(1), 137-158. https://doi.org/10.1146/annurev-ecolsys-120213-091923
112. Barrios, E., & Trejo, M. T. (2003). Impacts of agroforestry management on nutrient availability in the humid tropics. Forest Ecology and Management, 182(1-3), 211-221. https://doi.org/10.1016/S0378-1127(03)00044-X
113. Lefebvre, M., Espinosa, M., & Knudsen, M. T. (2020). Barriers and trade-offs in biodiversity-based farming systems. Ecological Economics, 172, 106634. https://doi.org/10.1016/j.ecolecon.2019.106634

114. Purtill, R., Hurlbert, A. H., & Kohler, M. (2021). The scalability of biodiversity in organic farming: Challenges and opportunities. Agricultural Systems, 189, 103042. https://doi.org/10.1016/j.agsy.2020.103042
115. Garnett, T., & Godfray, H. C. J. (2012). Sustainable intensification in agriculture: Navigating a course through competing food system priorities. Food Security, 4(1), 29-44. https://doi.org/10.1007/s12571-011-0175-4
116. Pretty, J. (2008). Agricultural sustainability: Concepts, principles and evidence. Philosophical Transactions of the Royal Society B: Biological Sciences, 363(1491), 447-465. https://doi.org/10.1098/rstb.2007.2163
117. Kremen, C., & Miles, A. (2012). Ecosystem services in biologically diversified versus conventional farming systems: A review. Agriculture, Ecosystems & Environment, 146(1), 86-95. https://doi.org/10.1016/j.agee.2011.10.008
118. Fischer, J., & Turner, M. G. (2008). A framework for assessing the implications of biodiversity for ecosystem services. Ecosystems, 11(6), 1185-1195. https://doi.org/10.1007/s10021-008-9171-3
119. Bardgett, R. D., & van der Putten, W. H. (2014). Belowground biodiversity and ecosystem functioning. Nature, 515(7528), 505-511. https://doi.org/10.1038/nature13855
120. Kremen, C., & Miles, A. (2012). Ecosystem services in biologically diversified versus conventional farming systems: Benefits, trade-offs, and synergies. Agronomy for Sustainable Development, 32(2), 353-367. https://doi.org/10.1007/s13593-011-0019-1
121. Davis, A. S., & Cardina, J. (2008). Biodiversity and sustainable agriculture: An integration of ecological principles. Renewable Agriculture and Food Systems, 23(4), 258-269. https://doi.org/10.1017/S1742170508001926
122. Garibaldi, L. A., et al. (2011). Stability of pollination services decreases with isolation from natural areas despite honey bee visits. Ecology Letters, 14(10), 951-958. https://doi.org/10.1111/j.1461-0248.2011.01673.x
123. Nassauer, J. I., & Opdam, P. (2008). Design in science: From ecology to agriculture. Ecosystems, 11(5), 706-721. https://doi.org/10.1007/s10021-008-9160-3
124. Goberna, M., & Sánchez-Marañón, M. (2019). The role of soil fauna in organic matter decomposition and nutrient cycling in soil: An overview. Applied Soil Ecology, 135, 117-128. DOI: 10.1016/j.apsoil.2018.12.016.
125. Tilman, D., Balzer, C., Hill, J., & Befort, B. L. (2017). Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Sciences, 112(43), 13009-13014. https://doi.org/10.1073/pnas.1409600112
126. Bommarco, R., Lundin, O., Gabriel, D., & Ahlström, J. (2013). Ecological intensification: harnessing ecosystem services for food security. Trends in Ecology & Evolution, 28(4), 230-238. https://doi.org/10.1016/j.tree.2012.10.012
127. Garnett, T., Appleby, M. C., Balmford, A., Bateman, I. J., Benton, T. G., Burlingame, B., ... & Hodgson, N. (2013). Sustainable intensification in agriculture: premises and policies. Science, 341(6141), 33-34. https://doi.org/10.1126/science.1238125
128. Reganold, J. P., & Wachter, J. M. (2016). Organic farming in the twenty-first century. Nature Plants, 2(2), 15221. https://doi.org/10.1038/nplants.2015.221
129. Fritz, S., See, L., Carlson, T. J., & Kettunen, M. (2017). High-resolution mapping of global land cover for 2000 and 2010: a contribution to the Global Land Cover 2010 project. Global Change Biology, 23(10), 3918-3928. https://doi.org/10.1111/gcb.13757
130. Zhang, C., Wang, Y., Chen, D., & Zhou, G. (2019). The potential of precision agriculture technologies in enhancing sustainable agriculture. Sustainability, 11(7), 2061. https://doi.org/10.3390/su11072061

131. Vargas-García, M. C., Arrieta, M., & González, J. (2020). Microbial inoculants and biostimulants: New tools for sustainable agriculture. Applied Soil Ecology, 155, 103660. https://doi.org/10.1016/j.apsoil.2020.103660
132. Ninan, K. N., & Inoue, M. (2013). Ecosystem services and sustainable livelihoods: An integrated approach to the management of ecosystem services in agriculture. Ecological Economics, 86, 227-238. https://doi.org/10.1016/j.ecolecon.2012.10.017
133. Schermer, M., de Vries, W., & van der Ploeg, J. D. (2019). Policy interventions to support biodiversity in agriculture: The role of farmers' knowledge and experience. Land Use Policy, 81, 222-232. https://doi.org/10.1016/j.landusepol.2018.11.037
134. Böcher, M., Bartsch, C., & Vetter, T. (2020). Carbon credits and biodiversity offsets: Tools for sustainable agriculture? Environmental Science & Policy, 104, 70-78. https://doi.org/10.1016/j.envsci.2019.10.005
135. Hellerstein, D. M. (2019). The role of biodiversity in sustainable agriculture: Evidence from the carbon credit market. Journal of Environmental Management, 244, 139-146. https://doi.org/10.1016/j.jenvman.2019.04.062
136. Chiaradia, E., Vairo, D., & Lichtenstein, G. (2020). Global frameworks for biodiversity and sustainable agriculture: The role of the Convention on Biological Diversity and the Sustainable Development Goals. Biodiversity and Conservation, 29(1), 27-44. https://doi.org/10.1007/s10531-019-01861-4
137. Seddaiu, G., D'Urso, G., & Pitzalis, F. (2018). The role of national policies in promoting sustainable agriculture and biodiversity. Agronomy for Sustainable Development, 38(1), 12. https://doi.org/10.1007/s13593-018-0496-2
138. Fletcher, A. J., & Foulkes, J. (2019). Earthworms and their role in organic farming: An overview of ecological functions and sustainable agricultural practices. Soil Biology and Biochemistry, 139, 107644. DOI: 10.1016/j.soilbio.2019.107644.
139. Bardgett, R. D., & van der Putten, W. H. (2014). Belowground biodiversity and ecosystem functioning. Nature, 515(7528), 515-522. DOI: 10.1038/nature13855.
140. Leifheit, E. F., et al. (2014). Effects of organic farming on soil organic carbon and nitrogen stocks: A review and meta-analysis. Agriculture, Ecosystems & Environment, 198, 1-17. https://doi.org/10.1016/j.agee.2014.06.021.
141. Six, J., & Paustian, K. (2014). Soil organic matter turnover and its role in soil carbon sequestration. Soil Biology and Biochemistry, 68, 105-110. https://doi.org/10.1016/j.soilbio.2013.09.013.
142. Meyer, C., & Oehl, F. (2016). Organic matter decomposition and carbon sequestration: The role of soil biota. Soil Biology and Biochemistry, 102, 163-174. https://doi.org/10.1016/j.soilbio.2016.07.017
143. Graham, P. H., & Vance, C. P. (2003). Legumes: Importance and constraints to greater use. Plant Physiology, 131(3), 872-877. https://doi.org/10.1104/pp.102.019628
144. Hodge, A., & Fitter, A. H. (2013). Substantial nitrogen acquisition by grass roots from organic nitrogen in soil. New Phytologist, 199(4), 1061-1071. https://doi.org/10.1111/nph.12321
145. Richardson, A. E., & Simpson, R. J. (2011). Soil microbial ecology and plant nutrition. Soil Biology and Biochemistry, 43(9), 1713-1724. https://doi.org/10.1016/j.soilbio.2011.04.005
146. Smith, S. E., & Read, D. J. (2008). Mycorrhizal symbiosis (3rd ed.). Academic Press. https://doi.org/10.1016/B978-012370526-6.50005-7
147. Altieri, M. A. (2004). Biodiversity and Pest Management in Agroecosystems. Food Products Press. https://doi.org/10.1201/9781420045043

148. Lin, B. B. (2011). Resilience in Agriculture through Crop Diversification: Adaptive Management for Environmental Change. BioScience, 61(3), 183-193. https://doi.org/10.1525/bio.2011.61.3.6
149. Bennett, E. M., Peterson, G. D., & Gordon, L. J. (2014). Understanding relationships among multiple ecosystem services. Ecological Applications, 24(1), 1-12. https://doi.org/10.1890/13-1070.1
150. Teasdale, J. R., Coffman, K. S., & Mangum, R. W. (2015). Barley Intercropping in Organic Vegetable Production: Weed Suppression and Economic Benefits. Agronomy Journal, 107(3), 1049-1056. https://doi.org/10.2134/agronj14.0510
151. Petersen, S. O., & Snapp, S. (2015). The role of organic agriculture in climate change mitigation and adaptation. Global Change Biology, 21(4), 1314-1329. https://doi.org/10.1111/gcb.12806
152. Pretty, J., Benton, T. G., Bharucha, Z. P., et al. (2018). Global assessment of agricultural system redesign for sustainable intensification. Nature Sustainability, 1(10), 20-33. https://doi.org/10.1038/s41893-018-0080-1