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Organic Agriculture Supports Biodiversity and Sustainable Food Production

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Biodiversity is vital to several important ecosystem services that ensure sustainability of food production. In organic agriculture, land management practices that promote biodiversity and soil quality are emphasized and the goal is to maintain a sustainable agricultural system. Soil quality or soil health is the foundation for all agriculture and natural plant communities and a primary indicator of sustainable land management. Soil quality is affected by farm management and land use decisions. This article presents a review of the literature on the question: How do organic agriculture and conventional agriculture differ in regard to their impact on biodiversity and ecosystem services? All of the 22 articles identified in this review reported a significant increase in at least one variable that indicated enhanced biodiversity and/or ecosystem services on sites farmed using an organic farming system compared to sites farmed using a conventional farming system. This review underlines the importance of biodiversity, particularly soil biodiversity, to sustainable food production and underscores the need for further ecological studies on the links between farm management systems and soil quality.

KEYWORDS *sustainable food systems, sustainable agriculture, biodiversity, ecosystem services, organic food, organic agriculture*

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INTRODUCTION AND PURPOSE

Today's farmers produce more food and fiber with less energy than farmers did 50 years ago.¹ However, there is concern that conventional agriculture is not sustainable due to its dependence on nonrenewable, external inputs such as chemical fertilizers and pesticides and its poor regeneration of soil, groundwater, and other natural resources on which agricultural production depends.^{2,3} Conventional agriculture also contributes to numerous ecological and environmental problems, such as ground- and surface water pollution⁴⁻⁶; reduction in key pollinators of food crops^{5,7,8}; distortion in relative-abundance distributions of natural enemy communities in favor of a few dominant species^{9,10}; potential human health risks from exposure to agricultural chemicals^{2,11-18}; potential human health risks associated with contamination of food and water^{2,11,19-24}; chemical and physical soil degradation^{2,3-5,25}; and significant declines in global biodiversity.²⁶⁻³¹

Biodiversity, Ecosystem Services, and Sustainable Agriculture

Human survival and agriculture are dependent on a variety of goods and services that ecosystems provide. Food and fiber production, soil formation, pollination of food crops, suppression of infectious disease, regulation of agricultural pests, water purification, nutrient cycling, and climate regulation are examples of *ecosystem services* vital to human health and agriculture.³²⁻³⁸ Yet, according to the United Nations Millennium Ecosystem Assessment (MEA), approximately 60% of the ecosystem services examined from air quality to water purification are being degraded or used unsustainably.²⁶ See Table 1 for definitions related to biodiversity and ecosystem services.

Biodiversity is central to ecosystem function and the provision of ecosystem services.³³ Yet today global biodiversity is plummeting, with current extinction rates 100 to 1000 times that seen in the fossil record.³⁸ The loss of global biodiversity to meet growing demands for food, water, timber, and fuel has impaired ecosystem function and resulted in a decline in ecosystem services.^{26,33}

Agroecosystems cover 40% of the terrestrial surface of the Earth and differ radically in how they are managed.⁸ Farm management practices can degrade biodiversity.^{39,40} For example, the use of synthetic fertilizers in agriculture has led to eutrophication and a decline in aquatic biodiversity and freshwater resources.²⁶ The MEA concluded that agriculture is the "largest threat to biodiversity and ecosystem function of any single human activity."^{35(p. 777)}

Global biodiversity decline has substantial implications for human health and sustainable agriculture. Biodiversity is essential to several ecosystem services needed for agriculture and the provision of food, such as soil formation, nutrient cycling, and pollination of crops.^{8,26,27,33,34} The

TABLE 1 Definitions of Key Terms

Key terms	Definitions
Agroeco-system	An ecosystem designed and managed by humans to produce agricultural goods ⁸
Biomass	The total mass of living biological material present in a given ecosystem at a certain time ⁴¹
Biological soil degradation	A decline in biodiversity and soil carbon and an increase in soil-borne pathogens. See also <i>soil degradation</i> (below) ^{2,42}
Biodiversity	The variety and variability of life at different levels of biological organization, such as the genetic, species, and ecosystem levels ⁴³
Carbon markets	A market (voluntary or mandatory) that is created from the trading of carbon emission allowances to encourage or help countries and companies to limit their carbon dioxide (CO ₂) emissions, reducing greenhouse gases ⁴⁴ In a cap and trade system a limit (cap) is set on CO ₂ emissions and permits are given to emitters to release a certain amount of CO ₂ . If a company exceeds its allowance, it has to purchase additional permits to cover the excess. If a company does not exceed its limit, then it can sell its unused allowances ⁴⁴ Agriculture can offset greenhouse gas emissions by increasing the capacity for carbon uptake and storage in soils; that is, carbon sequestration ⁸
Decomposition	The breakdown of plant material carried out by bacteria and fungi resulting in the release of energy, nutrients, and CO ₂ ⁸
Ecosystem	A dynamic complex of plant, animal, and microorganism communities and the non-living physical environment interacting as a functional unit. Ecosystems include physical and chemical components such as soils, waters, and nutrients that support the organisms living within them and interactions among all organisms in a given habitat. The health and well-being of human populations depend upon the services provided by ecosystems and their components—including organisms, soil, water, and nutrients ³²
Ecosystem function, functioning, or process	Biogeochemical activities of ecosystems. The most common metric of ecosystem functioning is primary production, but other metrics including decomposition, nutrient mineralization, community or ecosystem respiration, or other measures of energy flow and nutrient cycling. Function refers to activity, not purpose ³⁶
Ecosystem services	The services that the Earth's ecosystems provide man, such as food and fiber provision, soil fertility, water purification, disease management, climate regulation, spiritual fulfillment, and aesthetic enjoyment. These services are extensive and diverse and affect the quality of our land, water, food, and health. In agroecosystems, biodiversity performs a myriad of essential ecosystem services beyond the production of food and fiber, including nutrient cycling into food crops; generation and preservation of soils and renewing soil fertility; climate moderation (control); resilience to drought; pest control; and provision of habitat for beneficial insects, such as pollinators, decomposers, and predators ^{8,34,37,38}
Humus	The final product of soil organic matter decomposition. It is highly stable and a vital component of soil fertility. Humus participates in soil formation and quality maintenance through its specific properties; for example, carbon retention, water retention, and stabilization of soil aggregates. Humus is an important buffer, reducing fluctuations in soil acidity and nutrient availability ³⁷

(Continued)

TABLE 1 (Continued)

Key terms	Definitions
Intensive or conventional agriculture	An agriculture production system using high inputs of resources relative to land area for the purpose of increasing crop yield. This is accomplished through a variety of technological methods such as the use of high-yielding or genetically modified crop varieties, synthetic fertilizers, pesticide application, artificial irrigation, monocropping, heavy tilling, and mechanization ⁹
Microbial biomass	The living portion of soil organic matter. It contains archaea, bacteria, and eukaryotes, excluding roots and animals smaller than $5 \times 10^3 \mu\text{m}^3$. It represents 75% to 98% of the living portion of the soil ⁴⁵
Millennium Ecosystem Assessment	A United nation's-sponsored assessment carried out to assess the consequences of ecosystem change for human well-being and to establish the scientific basis for actions needed to enhance the conservation and sustainable use of ecosystems. The assessment was conducted by an international group of over 1300 scientific and ecological experts from 2001 to 2005 ²⁶
Mycorrhizae	A relationship of symbiosis between the roots of most higher plants and several groups of fungi, in which the fungal partner typically derives energy from the plant and the plant receives nutrients from the fungus ⁹⁸
Natural enemy	A predator, parasite, parasitoid, or pathogen of another organism; often describes beneficial organisms that attack pests in agricultural systems ⁸
Nutrient cycling	Nutrients are elements such as nitrogen, carbon, oxygen, water, sulfur, magnesium, potassium, and phosphorus that are required for the growth of plants and most all organisms. Nutrients move locally, regionally, and globally from the physical environment into living organisms and back again ³⁷
Organic production/ agriculture	<p>The USDA National Organic Program defines organic production as an ecological production system, established to respond to site-specific conditions by integrating cultural, biological, and mechanical practices that foster cycling of resources, promote ecological balance, and conserve biodiversity.^{46,47,48} As such, organic crop producers use practices that aim to maintain or improve the physical, chemical, or biological condition of soil, minimizing soil erosion and accommodating an animal's natural nutritional and behavioral requirements.⁴⁸</p> <p>The World Health Organization (WHO) defines organic agriculture as a holistic production management system that promotes and enhances agroecosystem health, including biodiversity, biological cycles, and soil biological activity. It emphasizes the use of management practices in preference to the use of off-farm inputs, taking into account that regional conditions require locally adapted systems. This is accomplished by using, where possible, cultural, biological, and mechanical methods, as opposed to using synthetic materials, to fulfill any specific function within the system.⁴⁹</p> <p>The IFOAM defines organic agriculture as a production system that sustains the health of soils, ecosystems, and people. It relies on ecological processes, biodiversity, and cycles adapted to local conditions, rather than the use of inputs with adverse effects. Organic agriculture combines tradition, innovation, and science to benefit the shared environment and promote fair relationships and a good quality of life for all involved⁵⁰</p>

(Continued)

TABLE 1 (Continued)

Key terms	Definitions
Resilience	The ability of an ecosystem to recover from or resist disturbances and perturbation, so that the key components and processes of the system remain the same ⁴¹
Soil biodiversity	The variation in soil life, from genes to communities, and the variation in soil habitats, from micro-aggregates to entire landscapes ³⁷
Soil (biota) biomass	See <i>microbial biomass</i>
Soil biota	A collective term for all organisms living in the soil, including bacteria, nematodes, fungal mycelium, protozoans, earthworms, and arthropods. Soil biota also include the living plant roots that grow in the soil and interact with other species above and below ground. ⁴³ Soil biota maintains soil fertility and mediates several key ecosystem services important to agriculture including nutrient cycling and soil organic matter formation ³⁸
Soil degradation	The decline in soil quality or a reduction in its productivity and environmental regulatory capacity. Three principal processes of soil degradation are <i>chemical</i> (eg, salinization or nutrient depletion), <i>physical</i> (eg, compaction or reduction in water-holding capacity), and <i>biological</i> (eg, reduction in soil organic carbon or soil biodiversity) ⁵¹
Soil fertility	The quality of a soil that enables it to provide nutrients in adequate amounts and in proper balance for the growth of specified plants or crops ⁵²
Soil organic matter (SOM)	Any component of the soil that contains carbon compounds from living organisms. SOM is mostly dead or decaying plants (up to 85%); living roots and soil organisms make up the remainder. ³⁷ SOM is an important building block for the soil structure, contributing to soil aeration and enabling soil to absorb water and retain nutrients. Approximately half of SOM can be decomposed into its elemental form (the active soil organic matter), whereas the remaining fraction, also known as humus, is more resistant to composition and accumulates in soil (the inactive SOM)
Soil quality	The capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation ^{43,53}
Species richness	1. The number of species in a community, in a landscape or marinescape, or in a region. 2. Having a relatively large diversity of species in a given ecosystem ⁴¹
Sustainability	Meeting the needs of the present without compromising the ability of future generations to meet their needs ⁵⁴
Sustainable agriculture	An integrated system of plant and animal production practices having a site-specific application that will, over the long term: satisfy human food and fiber needs; enhance environmental quality and the natural resource base upon which the agricultural economy depends; make the most efficient use of nonrenewable resources and on-farm resources and integrates, where appropriate, natural biological cycles and controls; sustains the economic viability of farm operations; and enhance the quality of life for farmers and society as a whole ²
Systems thinking	Critical thinking that recognizes the importance of interconnections and functional relationships between different components of the farming system, ² such as soils, plants, insects, fungi, animals, and water
Taxon	A group of (one or more) organisms that a taxonomist adjudges to be a unit. ³⁷ Taxa is plural for taxon



FIGURE 1 Conceptual model linking biodiversity to human well-being.³⁶

relationship between biodiversity, ecosystem services, and human well-being can be summarized by a simple formula,³⁶ which is outlined in Figure 1.

Conservation of biodiversity is recognized by scientists and practitioners as an important element of sustainable agriculture. Numerous studies and practical experiences have shown that biodiversity contributes to the resilience and stability of farming systems.² Concerns about the detrimental effects of intensive agriculture practices,^{2,25,37,38} such as chemical soil degradation from the use of pesticides and excessive fertilization,² have led to the development of sustainable agricultural systems, including organic agriculture.⁵⁵ A systems approach and integrated management strategies that seek to enhance biodiversity, soil quality, and ecosystem services is fundamental to the practice of organic agriculture.⁸ See Table 1 for multiple, internationally recognized definitions related to organic production and organic agriculture.

The purpose of this review is to examine (1) how organic agriculture differs from conventional agriculture in regard to its impact on biodiversity and ecosystem services and (2) the implications of organic agriculture on soil quality, sustainable agriculture, and human health.

Soil Biodiversity

It is estimated that soil contains one fourth of all of the biodiversity on Earth.³⁷ According to the Food and Agriculture Organization of the United Nations (FAO), “Soil is one of nature’s most complex ecosystems: it contains thousands of different organisms, which interact and contribute to the global cycles that make all life possible.”^{43(p15)} Collectively referred to as *soil biodiversity*, algae, bacteria, fungi, insects, and other soil organisms are interdependent in a complex food web.^{2,37}

The rich biodiversity in soil provides a number of important ecosystem services essential to human health and agriculture. These services fall into 6 categories: (1) maintenance of soil structure, soil organic matter (SOM), and fertility; (2) regulation of carbon flux and climate via carbon storage; (3) water cycle regulation; (4) decontamination and bioremediation; (5) pest control; and (6) human health.³⁷

In summary:

1. Soil is a diverse ecosystem of life that performs several services important to agriculture and the provision of food and

2. Soil biodiversity is crucial to soil ecosystem function and the provision of ecosystem services.³⁷

Soil Quality

Soil quality or soil health is the foundation for all agriculture and natural plant communities and is a primary indicator of sustainable land management.⁵⁶ In this article, soil health and soil quality are used synonymously and imply soil that is productive and capable of supporting plant growth and normal ecosystem functioning.

Soil degradation is a pressing ecological concern and a serious threat to sustainable food production. Past management of agroecosystems has substantially degraded and reduced the quality of soils worldwide. For example, mechanical cultivation and continuous production of row crops has resulted in a physical loss of soil and large decreases in SOM.⁵⁶ Inventories of soil productive capacity have found human-induced soil degradation on nearly 40% of the world's agricultural land.⁵⁶

Scientific monitoring of soil quality is essential to assessing the sustainability of agricultural systems.⁵⁷ Although there are varying methods for measuring soil quality, soil biological properties and soil organisms are of great importance. This is particularly true in organic agriculture, because most nutrients are derived from soil organisms' microbial decomposition of SOM.⁵⁷ Soil organisms meet many of the criteria for useful indicators of sustainable land management: they (1) respond sensitively to land management practices and climate; (2) are correlated with beneficial soil and ecosystem functions, including water storage, decomposition and nutrient cycling, detoxification, and suppression of noxious and pathogenic organisms; and (3) illustrate the chain of cause and effect that links land management decisions to ultimate productivity and the health of plants and animals.⁵⁶

Although it is established that soil organisms are essential to soil quality,^{37,56} the scientific understanding of soil biodiversity as it relates to soil quality is limited, constrained by the tremendous diversity of soil organisms and technical challenges involved.^{2,38} For example, DNA extraction and other methods used to identify and measure specific soil organisms are not standardized and are therefore problematic.³⁷

Compared to physical and chemical soil degradation, little is known about how agricultural practices alter soil biological properties and functioning even though soil degradation includes a decline in biodiversity (soil organisms) and soil carbon and an increase in soil-borne pathogens.^{2,42}

Research has shown that diversity of arbuscular mycorrhizal fungi, a dominant microbial group in most soil habitats, may determine the productivity of plant communities.⁵⁸ More recent research indicates that for individual plants, increasing arbuscular mycorrhizal fungi diversity promotes

plant growth and resistance to pathogens.⁵⁹ Hence, an improved understanding of the spatial distribution and functioning of soil microorganisms is essential to meeting a variety of major challenges faced by human society, including challenges related to the future food supply and mitigation of climate change.^{60,61}

Organic Agriculture

Soil quality is affected by farm management and land use decisions.^{2,55} Because most arable land on Earth is now under cultivation and agroecosystems cover 40% of the terrestrial land surface of the Earth, agricultural land management decisions are crucial to future food production.⁸

Organic agriculture is fundamentally different from conventional agriculture because its guiding land management paradigm is based on a systems view. The systems view recognizes the importance of functional relationships and interconnections between biodiversity (plants, soil organisms, insects, fungi, and animals) in an agroecosystem and the environment. In organic systems, land management practices that promote soil biodiversity and soil quality are emphasized and the goal is to maintain a sustainable agricultural system.⁶²

Organic farming contributes substantially to future agricultural production by improving soil quality through promotion of better soil structure (aggregates stability and organic matter supply) and soil nutrition (organic matter supply).⁶³ Research has found that practices used in organic agriculture (eg, crop rotations and cover crops, organic amendments, composts, and green manure) can improve soil microbial activity and biomass,⁶⁴ increase soil organic carbon,^{64,65} and increase levels of SOM.⁶⁶ Organic farming also contributes to agricultural production through the use of farmyard manure, which fosters natural enemies and other biota (eg, earthworms) needed for enhanced pest control and cycling of nutrients.⁶³

SOM is a critical component of the soil habitat: by providing resources in the form of nutrients to plants, it often constitutes hotspots of soil activity and is fundamental in maintaining fertile and productive soils.³⁷ SOM as humus (see Table 1)—the main driver of soil quality and fertility—can only be produced by the diversity of life that exists in soils. It cannot be man-made.³⁷ Humus is an important buffer that helps reduce fluctuations in soil acidity and nutrient availability. Researchers have reported higher levels of soil fertility and greater biodiversity in organic versus conventional agricultural systems.⁵⁷ Soils under organic management have increased SOM and biomass, which (1) retains significantly more rainwater and nutrients due to the sponge-like properties of organic matter,^{66–68} (2) enhances soil structure and fertility, and (3) results in less soil erosion.^{66,69,70}

TABLE 2 Summary of the Effects of Organic Farming on Indicators of Biodiversity and Ecosystem Services in Comparison to Conventional Agriculture

Original research			
Study design/description/location	Variable measured	Results	Reference
Investigated the response of soil microbial biomass and activity to soil management practices. Field study using 5 plots with different organic and conventional farming systems and time scales (6–24 months) in Brazil	Soil microbial biomass biological activity Soil carbon	Measures of microbial biomass and soil biological activity were significantly higher in the organic system plots	64
Investigated how organic and conventional farming practices affect plant diversity. Field study of 14 organic and 16 conventional farms in Ontario over 3 consecutive years	Native and exotic plant species	Significantly higher plant species richness and native plant species was found on organically farmed sites	71
Investigated 2 organic and 2 conventional wheat farming systems on 4 plots that differed in fertilization and weed management strategies for the effect on soil organisms and insect populations as part of the long-term agricultural experiment that began in 1978 in Switzerland. The Bio-dynamic, Bio-organic and Conventional Field Trial (DOC), a comparison of farming systems	Soil microbial biomass-C Soil biological activity Soil chemistry Soil fauna	Soil carbon content was significantly higher in organic farming systems compared to conventional systems. Conventional systems using farmyard manure had significantly greater soil carbon than conventional systems using synthetic fertilizer. Organic systems had significantly increased soil fauna communities, including natural enemies and ecosystem engineers (earthworms), suggesting enhanced nutrient cycling and pest control	63
Investigated the impact of organic versus conventional management systems and landscape context, such as vicinity to natural or semi-natural habitats, on soil arthropod taxa and associated ecosystem functions. Six organically and 6 conventionally managed fields of winter wheat were compared over the course of 1 year in Germany	Weed seed predation Soil biological activity Litter decomposition Soil arthropod taxa	A significant interaction between landscape context and management type was found. Soil arthropod diversity and associated ecosystem services were enhanced in heterogeneous landscapes (natural or semi-natural habitats and organically managed farms) or in fields adjacent to heterogeneous landscapes	72

<p>Compared 89 matched organic and non-organic farms pairs over one year in England to measure biodiversity differences between pairs</p> <p>Investigated 16 paired organic and conventional farms in England at field, farm, and landscape scales over the course of 1 year, evaluating farmland biodiversity at different spatial scales</p>	<p>Habitat extent and abundance and diversity measures of birds, bats, invertebrates, plants</p> <p>Plant species richness. Below- and above-ground fauna (earthworms, pollinators, butterflies, arthropods)</p> <p>Birds</p>	<p>Organic farms supported significantly higher numbers of species density and overall abundance across most taxa (24 out of 27)</p> <p>Plant species density, arthropods, butterflies, and bees were higher in organic fields. Significance was not reported as <i>P</i> values</p> <p>Diversity levels were dependent on land use practice in adjacent landscapes and to spatial scales. For example, an organic farm in an organic hotspot could have greater biodiversity levels than an organic farm in a conventional hotspot</p>	<p>73</p> <p>74</p>
<p>Studied 9 areas in 8 European countries, 30 farms per area, classified by cereal yield (an indicator of agricultural intensification). Compared 13 components of agricultural intensification to species diversity of wild plants, carabids, ground-nesting farmland birds, and the biological control of aphids</p>	<p>Birds</p> <p>Carabids (beetles)</p> <p>Plants</p> <p>Aphids</p> <p>Biological control potential</p>	<p>Organic farming significantly increased the diversity of carabid species and wild plants. Biological control potential was not significant between farms. Organic farming did not significantly increase the diversity of ground nesting birds</p> <p>Use of insecticides and fungicides had consistent negative effects on biodiversity</p> <p>Insecticides reduced biological control potential</p> <p>Native bees on organic farms near natural habitat provided full pollination services even with crops requiring heavy pollination (watermelon). Conventional farms and organic farms isolated from natural habitat experienced reduced native bee diversity and abundance with inadequate pollination services</p>	<p>30</p>
<p>Investigated 14–16 organic and conventional farms over 2 consecutive years in Central Valley, California, that varied with increasing intensification and in their proximity to oak woodland and chaparral habitat to determine the contribution of native bee communities to crop pollination</p>	<p>Pollen deposition</p> <p>Native bee diversity</p>	<p>Native bees on organic farms near natural habitat provided full pollination services even with crops requiring heavy pollination (watermelon). Conventional farms and organic farms isolated from natural habitat experienced reduced native bee diversity and abundance with inadequate pollination services</p>	<p>7</p>

(Continued)

TABLE 2 (Continued)

Original research		Reference	
Study design/description/location	Variable measured	Results	
Studied 10 farms in North Carolina over 3 consecutive years to evaluate the impact of organic, sustainable, and conventional management strategies on soil physical, chemical, and biological factors, including soil microbial species and functional diversity and their effect on Southern blight	Soil microbe communities Soil microbial activity Nematode communities Functional diversity Species diversity	Soils from organic and sustainable farms were significantly more suppressive to Southern blight than soils from conventional farms. Organic farms had improved soil chemical factors and significantly higher levels of extractable C and N, higher microbial biomass C and N, and net mineralized N. Increased microbial activity and populations of fungi and thermophiles and more bacterial functional communities was also found in organic soils	75
Investigated over 21 years comparing 2 organic and 2 conventional farming systems in Europe for agronomic and ecological performance. Part of the DOC field trial in Switzerland	Multiple physical, chemical, and biological soil properties, such as: Soil microbial biomass Earthworm biomass and abundance Root length colonized by mycorrhizal fungi Plant Insects Note: some of the measures were simulated	Significantly enhanced soil fertility and soil biological activity in organic plots. Input of fertilizer and energy was reduced by 34% to 53% and pesticide by 97% in organic systems. Root length colonized by mycorrhizae in organic systems was 40% higher than conventional systems	76
Studied 10 pairs of organic and conventional farms in England sampled once. Used a food web approach to analyze community structure to determine whether enhanced biodiversity on organic farms translates into better pest control	Significant increased diversity of both plants and insects on organic farms. Herbivores on organic farms were attacked by more parasitoid species. Simulated measures found that organic farms did not foster enhanced natural pest control	29	

<p>Studied habitat and management differences in 89 pairs of matched organic and non-organic fields on 161 farms. Farms were sampled at different scales (field to landscape) over 3 consecutive years</p>	<p>Landscape complexity as an indirect measure of biodiversity</p>	<p>77</p>
<p>Investigated the diversity of arbuscular mycorrhizal fungi (AMF) in replicated field plots, 2 organic and 2 conventional systems, cultivated for 22 years as part of long-term DOC field trial in Switzerland</p>	<p>AMF community structure</p>	<p>78</p>
<p>Studied 3 farms in Italy at varying spatial scales (field, site, and farm level) using an environmental accounting information system to evaluate the financial and environmental aspects of sustainability of organic, integrated, and conventional farming systems</p>	<p>The environmental performance was measured by application of an Environmental Accounting Information System (EAIS). The EAIS measured ecological and production processes that affect the state of the agroecosystem</p>	<p>79</p>
<p>Investigated farms in 100 regions of Europe that were classified according to agricultural intensity using data from the Farm Accountancy Data Network. Each farm type was assigned an ecosystem quality (EQ) value. EQ is the biodiversity expressed as the mean abundance of species originally present in a natural ecosystem relative to abundance in undisturbed ecosystem. Models were used to determine EQ under various scenarios</p>	<p>EQ value was correlated with the intensity of agriculture with the most intensified landscapes having the lowest EQ. EQ was lowest in conventional and irrigation-based agriculture and highest in organic, natural grassland grazing, and low-external-input agricultural systems</p>	<p>80</p>

(Continued)

TABLE 2 (Continued)

Original research			
Study design/description/location	Variable measured	Results	Reference
Studied 14 organic and 14 conventional fields in New Zealand over the course of 1 year measuring 3 key supporting ecosystem services and calculated the economic value of these services in organic versus conventional farming systems	Three supporting ecosystem services: Biological control of pests Soil formation Mineralization of plant nutrients	Total economic value of 3 ecosystem services was significantly greater for organic systems as compared to conventional systems. Yields obtained for organic fields were similar to those in conventional ones	81
Investigated provisioning services (crop yield), regulating services related to water quality, and nitrogen (N) use efficiency in organic and integrated conventional plots in Michigan over 12 years	N use efficiency Soil C and N Leaching (nitrate) Crop yield	Organic management significantly sustained soil fertility, increased soil carbon (36%), enhanced N retention (50% decrease in nitrate-N leaching) and improved N use efficiency compared to conventional, integrated management. Biodiverse rotational systems produced lower yields, but the grain was of high quality	82
Studied one conventional, one full organic, and 4 different reduced-input strategy (transitional) farming systems replicated 3 times on 18 experimental plots in North Carolina over 3 years	Soil microbial biomass carbon and nitrogen	Soil microbial carbon and nitrogen were significant greater in the organic and transition farming systems in comparison to the conventional system	83

A recent comprehensive study of organic and conventional strawberry ecosystems suggested that organic production methods resulted in both higher quality soil and higher quality strawberries.⁶⁸ The organically farmed soils were higher in carbon (an indicator of SOM) and nitrogen and had greater microbial biomass and activity and greater functional gene abundance and biodiversity. In addition, the organic strawberries had lower concentrations of phosphorus and potassium; higher concentrations of antioxidants, ascorbic acid, and phenolic compounds; longer shelf life; and greater dry matter content.⁶⁸

METHODS

A literature review was conducted to answer the question: How do organic agriculture management systems and conventional agriculture management systems differ in regard to their impact on biodiversity and ecosystem services? Articles were identified by searching Agricola, PubMed, and Science Direct databases using the keywords *organic agriculture* and *biodiversity*.^{84,85,86} In Science Direct, due to the large number of articles that resulted from this first keyword search, articles were narrowed down by using additional keywords: *ecosystem services* and *species richness* and searching within the results. Articles were included if they (1) were published from January 2000 to June 2010 in peer-reviewed journals, (2) compared organically managed farms to conventionally managed farms, and (3) measured biodiversity or ecosystem services between organic and conventional production. In addition to the articles identified in the aforementioned database search, references cited in review and published research articles were reviewed.

Conventional farming systems employ a variety of management practices and no exact meaning exists. For the purpose of this review, *conventional systems* were defined as those that use external inputs to achieve high yields. *Organic production systems* were defined as farming systems that employ practices characteristic of organic agriculture such as crop rotation, use of legume-based green manures or manure-based fertilization systems, prohibition of synthetic or soluble mineral fertilizers, and prohibition or reduction in the use of synthetic pesticides.

RESULTS AND DISCUSSION

Twenty-two articles were found that met the criteria described in the Methods section. Eighteen articles were original research^{7,29,30,63,64,71–83} and four were reviews.^{39,40,45,87} The purpose of all articles was to evaluate how

organic and conventional agricultural systems differ in regard to their impact on various indicators of biodiversity and ecosystem services.

The original research identified (see Table 2) evaluated the effect of farming systems on indicators of soil quality, such as soil carbon and microbial biomass; above- and below-ground farm biodiversity, such as soil microbes, predator insect communities, birds, and native plants; and indicators of enhanced ecosystem services, such as pollination of crops by native bees. Summaries of the variables measured and complete research results are listed in Table 2. All articles identified in this review reported a significant increase in at least one variable that indicated enhanced biodiversity and/or ecosystem service on sites farmed using an organic farming system compared to sites farmed using a conventional farming system.

Bengtsson and colleagues⁴⁰ conducted a review, using a meta-analysis of 42 studies published before December 2002, that analyzed the effects of organic farming (versus conventional) on species richness and abundance. Species richness was 30% higher on organic farms, but results were highly variable between studies and organism groups. In 2005, Hole and colleagues³⁹ reviewed the impact on biodiversity of organic versus conventional farming in 76 studies. Comparing the effect of farming system on individual taxon, Hole and colleagues found that organic farming systems fostered greater species abundance and/or richness in 66 taxa, 25 had neutral or mixed outcomes, only 8 taxa showed a negative outcome.

In 2008, Letourneau and Bothwell⁸⁷ performed a review of the literature to assess the evidence for enhanced insect pest control as a consequence of greater biodiversity on organic farms. The authors argued that although biodiversity is clearly enhanced on organic farms compared to conventional farms in most studies, there was not enough research that measured how the enhanced biodiversity affects pest control and yield. The authors urged ecologists to clarify the links between biodiversity and ecosystem services.

A meta-analysis of more than 100 studies from Brazil in 2009⁴⁵ measured microbial biomass and biological activity in soils under various soil management practices, including organic farming. The majority of studies reviewed on organic agriculture indicated that organic agriculture improved soil quality by increasing soil microbial biomass and biological activity probably as a result of organic manure amendments and removal of agrochemicals application. The majority of studies showed that no-till, rotated pastures, permanent organic farming, and crop rotations improved soil quality, whereas overgrazing, agrochemicals, and burning disturbed soil microbial communities. Similar to the conclusions of Letourneau and Bothwell,⁸⁷ these authors found that the direct relationships between biodiversity and ecosystem services were unclear and that more research was needed to evaluate how enhanced biodiversity on organic farms affected ecosystem services.

Soil Quality and Soil Biodiversity

As discussed previously, SOM is an essential component of soil and critical to maintaining soil quality. Soil microbial biomass carbon (microbial biomass-C) is a measure of the living portion of SOM. Soil microbes perform numerous processes vital to soil quality, including carbon cycling, nutrient cycling, solubilization of nutrients, and biological control of plant pathogens.^{45,64} One of the most important services provided by soil is the breakdown of SOM by soil microorganisms.⁵⁵ Decomposition of SOM is fundamental to soil quality because it provides resources in the form of nutrients that are required for plant growth.³⁷ Six of the articles in this review measured variables associated with SOM decomposition, such as soil microbial biomass-C, soil biological activity, and litter decomposition.^{63,64,75,76,82,83} All found a significant increase in at least one variable associated with enhanced SOM and soil quality in organic production systems compared to conventional.

Biological Pest Control and Pollination Services

Ninety-nine percent of agricultural pest populations and diseases are controlled by their natural enemies—predators, parasites, and pathogens.⁸¹ Three studies reviewed showed significant enhancement in indicators of biological pest control in organic systems.^{63,72,75} Geiger and colleagues³⁰ did not find a significant difference in biological control potential between farms but did find reduced potential with insecticide use. Macfadyen and colleagues²⁹ found significantly increased insect diversity on organic farms, but simulated measures did not find enhanced pest control.

Three studies showed that pest control relationships in the food web depend on general soil biodiversity and that natural pest control is enhanced in biodiverse agroecosystems.^{29,72,75} Deikötter and colleagues⁷² found that biological pest control was enhanced and natural enemy populations were higher in complex landscapes versus simple landscapes. Native landscapes are naturally complex. Organic farming, which includes more diverse crops and frequent crop rotations, also results in complex landscapes.⁷² A recent review⁸⁷ has also indicated that non-crop habitats can be a source of natural enemies for farmlands. Birkhofer and colleagues⁶³ showed that long-term organic farming and the application of farmyard manure promoted soil quality and microbial biomass and fostered natural enemies and earthworms, suggesting enhanced nutrient cycling and pest control.

Pollinating animals, particularly bees, are essential for 15% to 30% of all food production and valued at \$5 to \$14 billion per year in the United States.⁷ Kremen and colleagues⁷ found that on organic farms near native habitat native bees could provide full pollination services. However, all conventional farms and the organic farms isolated from natural habitat experienced

greatly reduced diversity and abundance of native bees with insufficient pollination services.

Limitations

Although it is clear that organic agriculture increases biodiversity especially when compared to conventional agriculture,^{39,40,45,87} the direct link to specific ecosystem services has been harder to tease out.³⁷ For example, though it is known that microbes are needed for SOM formation, the exact microbial species and mechanisms involved is still unclear.³⁷ Similarly, a 2008 review⁸⁷ found that the effect of biodiversity on insect pest control on organic farms has not been fully tested and concluded that more research was needed to delineate the steps involved.

A recently published meta-analysis helps answer the aforementioned research gaps.⁸⁸ In farmlands, pest outbreaks are often the result of altered food web structure and communities dominated by a few common species.⁸⁸ Crowder and colleagues⁸⁸ found high species evenness (the relative abundance of species) of above- and below-ground natural pest enemies in organic potato fields, which resulted in larger plants and decreased pest outbreaks. In contrast, pest densities were high and plants were smaller when pest species evenness was disrupted, as is common in conventional agriculture. Although the specific mechanism by which organic agriculture fosters greater evenness remains unclear, the prohibited use of broad-spectrum pesticides, used in conventional agriculture, may be a factor. Broad-spectrum pesticides kill many species of pests, including beneficial predators.⁸⁸ These researchers noted that evenness may promote resilience to a disturbance by ensuring sufficient densities in key functional roles, which is analogous to the “insurance effect” seen in the species richness literature.⁸⁸ This is an important finding because reduced species richness and evenness can result in reduced ecosystem functioning and services.³¹ Because this meta-analysis was published only after the above-noted literature review was completed, its results were not included in Table 2.

CONCLUSIONS

US organic agriculture certification is likely the most well-established food standard related to ecosystem concerns in the United States. Organic production regulations have been administered and enforced by the United States Department of Agriculture (USDA) National Organic Program (NOP)⁴⁶ since 2002 when rules from the Organic Foods Production Act of 1990⁴⁷ were promulgated. The NOP’s mission is to facilitate trade and ensure the integrity of organic agricultural products by consistently implementing organic standards and enforcing compliance with the regulations throughout the world.⁸⁹

The resulting US program focuses on health and environmental issues but generally does not address labor, social, economic, or community welfare goals, which are often cited in international standards (see International Federation of Organic Agriculture Movement [IFOAM] definition Table 1). Additionally, organic producers themselves often cite other principles of organic farming, such as animal welfare, as important.⁹⁰

Despite the current distressed state of the economy, US sales of organic food products continue to grow. A recent industry survey by the Organic Trade Association found that organic food sales grew by 5.2% (compared to a general food sales increase of 1.6%) in 2009, reaching \$24.8 billion.⁶² To meet this increasing demand, producers have increased acreage, but at 4.6 million acres in 2008 this acreage is still less than 1% of the total agricultural acreage and not enough to meet demand.⁶² This low level of adoption of organic farming in the United States may be attributed to several factors, including lack of technical assistance through research and extension, resources, and capital to assist farmers with production and marketing of organically produced foods.⁴⁸ This is likely a result of the poor public investment through policy in organic agriculture, from research to payments for programs. However, the Food, Conservation, and Energy Act of 2008 (2008 Farm Bill) directed the USDA to make major increases in support of organic producers through (1) help for producer certification costs, (2) access to federal credit, (3) trade assistance, (4) crop insurance programs, (5) access to conservation programs, and (6) funding for research on production, marketing, and data collection.⁹¹ For example, in September 2010 the USDA announced that the Organic Certification Cost Share Program would pay up to 75% of certification costs for organic farms.⁹² To help organic farmers with crop insurance, in August 2010 the USDA released reports outlining improvements to crop insurance programs for organic farmers.⁹³ The USDA's Natural Resources Conservation Service (NRCS) implemented a new conservation initiative, the Environmental Quality Incentive Program (EQIP) Organic Initiative, aimed at assisting organic and transitional farmers by making conservation practices related to organic production and transition to organic production eligible for payments under the EQIP conservation program.⁴⁸ The program enrolled over 300 000 acres in 2009, obligating over \$36 million in conservation assistance. Additionally, organic producers can participate in the Integrated Organic and Water Quality Program,⁹⁴ the Conservation Stewardship Program (CSP), and the Conservation Innovation Grants Program.⁹⁵ Organic research dollars increased significantly in the 2008 Farm Bill through the Organic Agriculture Research and Extension Initiative (OREI), administered by the USDA's National Institute of Food and Agriculture, which devoted \$19 million in 2010 to fund projects that enhance the ability of producers and processors to grow and market high-quality organic agricultural products.⁹⁴ This funding is part of the Know Your Farmer, Know Your Food Initiative led by USDA Deputy Secretary Merrigan.

Organic Farming Systems and Ecosystems Services

Environmental and health benefits (ecosystem services) from organic production practices, including but not limited to improved water quality, soil biodiversity, and increased carbon sequestration, are often indirect and undervalued. As a result, producers are not compensated for their efforts.² However, the 2008 Farm Bill included a provision to facilitate the participation of farmers and landowners in environmental services markets (eg, carbon markets, see Table 1)⁹⁶ by requiring the USDA to establish technical guidelines for measurements, reporting and data registry of ecosystem services.⁹⁷

Studies show that establishing a successful payment for ecosystem services (PES) is a complex undertaking that requires not only scientific understanding but also consideration of social, economic, political, institutional, and power relationships.² For PES programs to work, buyers want documentation and assurance that they are getting what they paid for and that sellers (ie, farmers and ranchers) are getting a fair price for what they produce.

Implications for Research

Drinkwater⁹⁰ argued that 3 fundamental characteristics of organic agriculture have important implications for research. First, organic agriculture has evolved through a grassroots-based, farmer-dominated process. Second, organic farming systems apply an integrated-systems-based management strategy. And third, the goals of farmers practicing organic agriculture are multidimensional and go beyond maximizing yield or economic return (eg, soil quality or health). Farmer-participatory programs for promoting soil health have successfully included earthworm abundance as an indicator of soil quality and health.⁹⁰ Finally, as observed elsewhere,^{37,40} future studies comparing different aspects of organic and conventional agricultural production need to conduct such comparisons in a more integrated fashion, as demonstrated by Reganold and colleagues.⁶⁸

Roles for Food and Nutrition Professionals

The platform of a sustainable food system rests on food production. Eighteen original research articles and 4 reviews identified in this article support the view that organic agriculture holds much promise for maintaining soil quality, preserving biodiversity, and helping to ensure sustainable food production. This review underscores the importance of and need for further research on biodiversity, soil quality, and sustainable agriculture to future food production. The findings presented also highlight the need for dietitians to consider ecology and farming systems when making food recommendations to the public.

Food and nutrition professionals can have significant roles in organic food systems through education, research, policy, and direct participation. This supports the American Dietetic Association's (ADA) position "to encourage environmentally responsible practices that conserve natural resources, minimize the quantity of waste generated, and support the ecological sustainability of the food system." Specific roles for food and nutrition professionals are outlined in this position statement in addition to a report produced for the ADA House of Delegates on sustainable food systems, of which organic production is an important segment.^{93(p1033)} For example, roles for food and nutrition professionals can include educating eaters on organic production's health and ecological benefits, researching organic production's influence on the eating behaviors of individuals, research on organic production's influence on human or ecosystem health, and influencing food policy through work on food policy councils to support through participation by the purchase of organic foods in institutional settings. Regardless of the area of dietetic practice, food and nutrition professionals are involved in the food system and in turn in organic production. The roles are numerous, as outlined in these ADA resources, whether professional or personal.

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