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Organic and Conventional Agriculture: A Useful Framing?

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Abstract

In this review, we examine the debate surrounding the role for organic agriculture in future food production systems. Typically represented as a binary organic–conventional question, this debate perpetuates an either/or mentality. We question this framing and examine the pitfalls of organic–conventional cropping systems comparisons. The review assesses current knowledge about how these cropping systems compare across a range of metrics related to four sustainability goals: productivity, environmental health, economic viability, and quality of life. We conclude by arguing for reframing the debate, recognizing that farming systems fall along gradients between three philosophical poles—industrial, agrarian, and ecological—and that different systems will be appropriate in different contexts. Despite evidence for lower yields in organic crop systems, we found considerable evidence for environmental and social benefits. Given these advantages, and the potential for improving organic systems, we echo calls for increased investment in organic and ecologically based cropping systems research and extension.

Contents

1. INTRODUCTION

According to the philosopher Paul Thompson (1), two distinct schools of thought, the industrial and the agrarian philosophies, characterize the debates heard in modern-day agriculture. The industrial philosophy embodies a utilitarian view of agriculture, viewing it as akin to an industrial process that produces various commodities. It emphasizes efficient production at low financial cost, with a reliance on external inputs for fertility and pest management, simplified monocultures, and economies of scale and specialization evident in large-scale farming businesses (2). In contrast, the agrarian philosophy recognizes that land stewardship and biological diversity have both social and environmental value. Emphasis is placed on small-scale and "family-oriented" farmers (1). Under the agrarian paradigm, management of ecological processes and services to cycle and provide nutrients, and to control pests and diseases, are central principles (3). Alternative agriculture movements fall to various degrees within this agrarian paradigm, including agroecology as a social movement (4). However, agroecology as an academic discipline seeks to integrate agricultural, ecological, and social knowledge across multiple scales, and as such can be applied to systems that fall along a spectrum from agrarian to industrial (5). Recent approaches that prioritize farm and landscape diversification, such as diversified farming systems (6), in many ways fit between the agrarian and industrial perspectives and may represent a third philosophical position, a point we return to in Section 5.

Diversified farming systems: farm practices and landscapes that intentionally include functional biodiversity at multiple spatial and/temporal scales to maintain ecosystem services critical to agriculture (6)

Conventional agriculture: typically uses synthetic pesticides, herbicides and fertilizers, may use organic soil amendments; fields are frequently planted in short rotations (2)

The most common representation of the industrial-agrarian dichotomy is the comparison between organic and conventional agriculture, the former usually aligned with the agrarian philosophy, the latter with the industrial approach. Organic agriculture, it is argued, presents a rationality in which economic profit is often not the motivation for producers (7), and implies "specific social relations, and relations to nature and technology" (8). Although many organic producers reflect this agrarian view, some substitute organically approved inputs for chemical fertilizers and pesticides and fit more of an industrial model (9). However, the industrial-conventional and agrarian-organic perspectives are frequently presented as diametrically opposed, each with its own proponents. Critics of the industrial view cite its overemphasis on productivity and cost efficiency irrespective of environmental and social outcomes (10), advocating instead for balancing production with environmental conservation and social well-being (11, 12). The agrarian approach, however, has been critiqued as producing inadequate yields, and its proponents have been accused of being dogmatic and misguided by certain agronomists (13–15).

This article examines the nature and utility of organic versus conventional comparisons—as examples of the agrarian-industrial debate on food production systems. We ask if this dichotomy is best able to reflect the complex suite of issues and implications for addressing future food production and sustainability goals. We divide our review into three sections: (*a*) a discussion of the merits and methodological challenges of comparisons between organic farming and conventional farming, (*b*) a critical examination of the state of knowledge about relative system performance across multiple sustainability metrics, and (*c*) concluding reflections on where to go from here. Our investigation considers primarily the past decade of cropping systems research and does not attempt to investigate animal production in a comprehensive way; instead, we direct readers to Herrero et al.'s (16) recent review on livestock and the environment. Here, we draw heavily from existing reviews and meta-analyses to ensure broad consideration of available literature, but this is not a systematic review. Rather, we discuss key issues using representative examples of systems comparisons, drawing from multiple geographic regions whenever possible—with the goal of identifying constructive avenues for future cropping systems research.

Organic farming: uses ecological processes and cycles; eliminates synthetic inputs; crop rotation required; soil organic matter additions, biodiversity, and biological pest control encouraged; farms certified as organic by third-party agencies (12)

2. MERITS AND METRICS OF COMPARISONS

2.1. Why Compare?

The following are some arguments favoring organic–conventional comparisons: (*a*) Organic agriculture is a rapidly growing segment of the food market, offering new and high-value markets to farmers in developing countries (17); (*b*) demand for some organic products is outstripping availability (18), suggesting further growth in organic production is likely; (*c*) advocates of organic agriculture cite its potential environmental, human health, and social benefits (11, 12); (*d*) the organic and conventional comparisons already made have resulted in a highly visible and polarized debate, with important implications for agricultural policy; and (*e*) certified organics is the predominant legally defined type of alternative system that can be contrasted against conventional production and that is available as a choice to consumers.

Nonetheless, contrary arguments can be made: (*a*) Organic versus conventional is a false dichotomy. Outside of researcher-managed experiments, both organic and conventional cropping systems fall along a gradient of input use intensity, scale, and diversification of crops and habitat. Such real-world variation among organic and conventional cropping systems is insufficiently considered in binary comparisons; (*b*) methodological issues with how comparisons are made can undermine the robustness of conclusions being drawn (see Section 2.2); (*c*) research investments may be better spent studying how to improve a range of cropping system types, including those that fall between the certified organic and industrial models; (*d*) finally, and perhaps most importantly, framing research questions around the relative superiority of organic or conventional production perpetuates an either/or mentality rather than consideration of where and how each type of management system can contribute to more sustainable agriculture and farmers' livelihoods (19, 20).

Organic–conventional comparisons are nonetheless debated in high-profile public and scientific arenas, and represent the bulk of studies comparing agrarian and industrial approaches (11). Furthermore, the performance of organic systems relative to conventional is frequently used to argue for, or against, research investments and extension efforts to support organic production (14, 20, 21). Therefore, one must be clear about what conclusions can and cannot be responsibly drawn from the work to date by critically examining the methods and metrics used to make the comparisons.

2.2. What to Compare?

As noted above, organic and conventional labels cover a range of cropping systems that vary widely; hence, the choice of what examples to compare and how the comparison is framed can greatly impact the results obtained. This is an issue particularly with organic systems, which, in our experience, can be more complex, variable, and knowledge intensive in terms of management, and which have less well-developed sets of common management practices used across multiple farms.

2.2.1. Experimental field plot comparisons. Most comparative studies, especially regarding productivity, come from replicated plot experiments where researchers decide on the design of each cropping system, sometimes with input from farmers (22), but rarely based on a rigorous survey of the predominant systems in the region. Indeed, on the basis of the longer history of research and extension, there is typically more information and experience available for selecting representative conventional treatments than for organic. Researchers have reported a steep learning curve when managing experimental organic systems, with impacts on performance (23), and the comparative lack of research in organic cropping systems has left knowledge gaps that may result in less than optimal organic system performance (20, 21).

Opinions differ on how to design comparisons in a scientifically rigorous way, with some arguing that it is necessary to compare systems with similar rotations, nutrient input levels, and cultivars (24). However, although scientifically appealing, such equalizing comparisons may not make sense for comparing realistic organic or conventional systems, if the goal is to contrast "best" management systems. Single-season yield comparisons that fail to account for the replacement of economic species with cover crops can also be misleading, suggesting that productivity is better expressed on a yield area^{-1} time^{-1} basis than as yield area^{-1} alone (15, 24). Selecting an appropriate time frame for making comparisons is also crucial to allow ecological interactions to fully develop (see Section 4.5).

The problem of arriving at inaccurate conclusions when scaling-up results from small-plot experiments is also a major concern. Authors have questioned if it is reasonable to assume that the performance of cropping systems in field experiments is comparable to when they are applied at a realistic farm scale where farmers divide their attention between multiple crops, fields, and often animal components (25). For example, in the absence of herbicide use, optimal timing of mechanical weeding is critical for maximum organic yields, but not always possible in commercial operations (26). Furthermore, surrounding land use and vegetation types can greatly impact the degree of biological control of arthropod pests (27), which is not accounted for in plot experiments.

2.2.2. On-farm comparisons. Given the limitations of experimental comparisons, monitoring and contrasting operating farms may be a suitable alternative. This approach accounts for variation in each management type if a similar range of locations, soil types, surrounding land use, cropping systems, and scale are represented (28). Potentially confounding variables can be measured and analyzed to discern important relationships. Comparing multiple examples of a given type of system can provide important insights into productivity and environmental impacts of specific management choices (29). Such on-farm studies highlight that farmers make management decisions based on a variety of criteria, such as market demand, cost of production, and ease of management, among others, and do not always aim to maximize yield. An example is when farmers plant at climatically suboptimal times to capture early or late season high produce prices, despite yield penalties (28). Using data obtained from yield surveys of operating farms as a measure of the relative productivity of organic or conventional farming as done by Kniss et al. (30) can therefore be misleading, unless the varied management objectives and marketing strategies used by farmers are explicitly accounted for. Yields of a crop in large-scale specialized conventional farms are likely to be higher than those from diverse organic operations where yield maximization is less important if the crop is a small component of overall production, is grown primarily for rotation value, or is grown as part of a diverse product supply for direct marketing avenues.

The choice between conducting experiments or monitoring farms depends on the attributes to be assessed. Impacts of cropping systems on soil microbial communities can be measured in small-plot experiments, as can disease or weed populations, if plots are large enough to avoid edge effects; but for highly mobile arthropods, birds, and bats, whole-farm and landscape-level studies are needed. Whole-farm studies may also be more suitable for comparisons of nutrient cycling where farms rely on crop residue or fodder processing through livestock and manure addition to fields. Such spatial and temporal complexity is hard to mimic in experiments. A third alternative is to use crop or farm models (31, 32); however, work to accurately reflect nutrient cycling and productivity in organic systems remains limited.

3. COMPARISONS OF SYSTEMS ACROSS DIFFERENT SUSTAINABILITY METRICS

Agricultural sustainability has been defined as the ability of a system to sustain movement toward socially agreed-upon goals, namely to (*a*) satisfy human food and fiber needs; (*b*) enhance environmental quality and natural resources; (*c*) assure economic viability of farms and agricultural businesses; and (*d*) improve quality of life for farmers, farmworkers, and society (2). Any single approach to farming is unlikely to optimize movement toward all four goals, but should be expected to generate some balance of each. Identifying the "best" balance is highly context dependent, and opinions differ on the relative priority to be given to each goal. Such disagreements reflect differing values—as illustrated in the different weight given to production, environmental, and social goals in the industrial and agrarian perspectives (1). Deciding an appropriate balance of goals is not the sole purview of science or scientists; rather, it requires broad societal discussion involving multiple stakeholders, including producers and consumers. Science, as discussed here, informs this debate by providing knowledge about the current state of the systems in question and comparative effects of alternative management options (2).

In the case of organic agriculture, most public debate has revolved around yield comparisons and the question, "Can organic farming feed the world?" The implicit assumption is that if the current answer is "No," then organic production deserves only limited space in mainstream agricultural R&D (13, 15). Others have made the counterpoint that conventional production systems have also failed to feed the world or meet many sustainability criteria (20, 33), and argue that if organic systems improve environmental quality, economic viability, and quality of life outcomes, then these considerations counterbalance some reduction in crop yields and justify the importance of organic systems (34). We argue that "How and where can organic, conventional, or other systems contribute to feeding the world in a sustainable manner?" is a more appropriate question.

4. SYSTEM PERFORMANCE ACROSS MULTIPLE SUSTAINABILITY METRICS

4.1. Productivity

Early studies of the productivity of organic compared to conventional systems found lower yield response ratios (YRRs) for organic (35), but subsequent systematic analyses posited that legumes can supply sufficient nitrogen to offset synthetic fertilizer use and that organic systems can provide sufficient calories to feed the global population (36). This work was criticized heavily for a variety of reasons, including failure to account for climatic constraints to cover crop production (13, 15). Meta-analytical methods have since been used to assess relative productivity and resulted in estimates of organic yields ranging from 5 to 34% less than conventional yields (34, 37, 38). Differing crop species, rotation systems, and environments explain considerable variation in YRRs, but patterns observed vary among these analyses due to differences in data selection and the statistical methods used (21). Yield gaps also appear to widen as conventional yield potential increases and organic systems encounter nutrient supply limitations (30, 38). Ponisio et al. (21) conversely showed that biological diversification in the form of rotations or multiple cropping can reduce yield gaps to 8–9%, compared to 19% for all studies combined, and suggested that increased investment in organic research could further reduce the remaining yield gap. Notably, they accounted for differences in nutrient input levels, use of cover crops, and crop rotations between systems in their analysis, unlike earlier studies.

These findings were, however, contested; for example, some critiques claimed organic practices may be unable to cope with rapidly multiplying and dispersing pests at the landscape level, and with “land sparing” arguments stating that lower-yielding organic systems would lead to greater expansion of agricultural land with detrimental effects for biodiversity (39). Ponisio & Kremen (34) countered with evidence of the positive effects of organic and ecologically managed farmland on pest suppression and pollination services at the landscape level, and they highlighted that where higher yields increase farmers’ profits, even conventional practices can drive land expansion and deforestation (40).

Most of the above YRR calculations are still derived from small-plot experiments that may not be representative of farm-scale functioning. Meta-analytical quality also suffers where calculation of YRRs includes data from truly experimental treatments rarely found on functioning farms. Examples include zero-tillage organic management or conventional systems with drastically reduced nitrogen inputs designed to examine performance under nutrient limitation. Cassman (15) therefore proposed that use of small-plot comparisons in systematic reviews should only be considered where best management practices are utilized for each system studied (15). We are, however, unaware of any meta-analyses that have explicitly addressed these issues, despite the substantial yield variation observed among farms managed as organic or conventional. Drinkwater et al. (28), for example, compared commercial organic and conventional tomato farms, finding a threefold variation in yields in both system types. An in-depth comparison of 13 organic tomato farms also found that YRRs relative to regional average conventional yields ranged from 0.27 to 1.34, reflecting widely different approaches to organic management, notably for nutrients (27).

Clearly, the scale of comparison studies is important to provide realistic assessments of productivity. Whole-farm studies coupled with life-cycle analysis (LCA), and attention to nutrient recycling patterns at landscape and regional scales, are also needed to assess productivity, limitations in input availability, and environmental costs. This calls for a redirection away from plot-scale and experimental research toward a more integrated systems agronomy.

4.2. Soil Carbon

The extent to which organic management increases soil carbon is of interest, in terms of both soil quality benefits and climate change mitigation (41). Soil organic carbon (SOC) is crucial for enhancing cation exchange capacity, soil physical structure (aggregate stability, water infiltration, water-holding capacity), and soil biological properties, with positive impacts on nutrient and water cycling and suppression of some soilborne pathogens (42–44). Multiple studies indicate that under organic management regular organic inputs can more than replenish carbon lost during tillage, such that SOC concentrations increase for some time after conversion to organic management (45–48), with some exceptions (46). Most organic practices increase SOC primarily in active labile pools in the top 0–15 cm of soil, as found in a multistate comparison where labile SOC increased 44% in organic treatments compared to conventional, over a four-year period, whereas total SOC increased only 16% (49).

Variation in tillage practices can, however, obfuscate differences between organic and conventional management. Tillage is strongly associated with increases in bulk density and decreases in aggregate structure and SOC (50). No-till systems concentrate SOC from a 0–20-cm depth, whereas tilled systems distribute SOC at deeper depths, such that no difference between systems is often found when all depths are considered (51). With limited development of organic reduced tillage systems to date, it is premature to speculate on the effects of organic reduced/no-till systems on SOC and carbon sequestration (52).

Only when the rate of SOC decomposition is reduced through increased chemical recalcitrance or physical occlusion can SOC be categorized as sequestered (50). Carbon sequestration through organic amendments and perennial cover is proposed as a viable method of reducing atmospheric carbon and mitigating the effects of global climate change (41), but the methods and metrics used to evaluate sequestration vary greatly. It is difficult to compare findings between studies, with many reporting SOC as a concentration (mg g^{-1} or %), whereas others report stocks (Mg C ha^{-1}). The latter is preferable for quantifying sequestration, given that it accounts for changes in bulk density. Gattinger et al.'s (48) meta-analysis attempts to separate out changes in SOC and sequestration, and shows that even in zero net carbon input organic systems SOC stocks and sequestration rates were higher than in equivalent conventional systems. However, there were a limited number of studies that provided all the necessary information (measured inputs, bulk density, and SOC), making it difficult to identify the main determinants of sequestration. Furthermore, changes in SOC with organic management at deeper depths are less clear, with stocks being reported as similar or lower than conventional (53).

4.3. Nutrient Cycling

Organic farming is frequently reported to reduce nutrient losses via leaching and runoff/erosion, especially where cover crops are used (54, 62), although this is not always the case. Conflicting conclusions relate to differences in location, systems, and management practices, making broad generalizations problematic. Organic management and increased soil organic matter (SOM) can decrease the rate of nutrient loss via leaching and/or erosion (55) and can also increase nutrient use efficiency (44, 56). A meta-analysis of ^{15}N isotope studies found that practices that couple C and N inputs (organic inputs, diverse and legume rotations) improved total ^{15}N retention in cereals and soil, more than modifications in synthetic fertilizer management (57). Another meta-analysis concluded that leaching losses were lower in organic systems on an area basis, but similar to conventional on a yield basis (58). Multiple studies in one watershed showed that SOM reduced nitrate leaching even in the case of overapplication of nitrogen (59), that lower N leaching losses occurred in organic than conventional farms (60), and an on-farm paired comparison found lower N leaching and N_2O losses with organic practices (30% area-scaled and 12% yield-scaled) (61). Greater landscape heterogeneity in the form of hedgerows and other perennial vegetation is important for reducing erosion and nutrient pollution (62).

Conversely, there are studies showing either no difference or greater N leaching with organic management, notably in northern temperate climates (63, 64). In these systems fall management, including the use of catch crops and minimization of fall tillage operations, is crucial for reducing leaching (65). A 12-year multisite study in Denmark showed, however, that N leaching decreased over time as SOM increased, and soil structure improved with use of catch crops (66).

4.4. Greenhouse Gas Emission and Life-Cycle Analysis

In 2008, the Intergovernmental Panel on Climate Change calculated that the agricultural sector produced 10–12% of global greenhouse gas (GHG) emissions, producing 84% and 52% of global N_2O and CH_4 emissions, respectively (67). Direct comparisons between organic and conventional management impacts on GHG emissions are hindered by inconsistent study periods and metrics, as well as confounding effects of tillage, soil type, and other factors. Lynch et al. (46) outlines these inconsistencies, including whether soil carbon credits are calculated and included, whether calculations are area- or yield-scaled, and whether LCA is employed. Some studies indicate that organic farms have higher GHG emissions related to greater machinery usage for weed control (62), whereas others have found the differences to be insignificant (46), or have found greater GHG emissions in conventional systems due to fertilizer and pesticide use (68). One study estimates that GHG emissions from fertilizer production account for 10% of the total GHG emissions from agriculture (62). Organic inputs that increase microbial activity can lead to greater N_2O and CO_2 (69), although there are few comparisons with equivalent fertilized conventional systems (54). Longitudinal studies using LCA approaches are rare, yet increasingly relevant. Most studies are for a single crop season only, providing limited understanding of emissions in rotational systems or at the farm scale. A meta-analysis concluded that due to variations between farms, energy efficiency comparisons ideally need sample sizes >100, which are difficult to obtain; nonetheless, their analysis suggests that organic farms tend to be more energy efficient and have lower GHG emissions compared to their conventional counterparts (70).

4.5. Pest Control Services

Crop losses to pests (including weeds and diseases) are estimated at between 26% and 40% for major crops, numbers which have changed little over the past 40 years despite large increases in pesticide use (71). An estimated 3.6 billion kg of active ingredients are applied globally per year (72), with serious, negative impacts on ecosystems (73) and human health (74). From a sustainability perspective, enhanced pest control services that reduce or eliminate the need for pesticide applications provide benefits in terms of human and ecosystem health.

Organic production relies primarily on systems-based nonchemical methods of control, although some organically approved pesticide materials are used for aboveground arthropod pests and foliar pathogens (75). Chemical control is the dominant approach in conventional systems, with varied degrees of integration of cultural and biological strategies (70). It is difficult to generalize about the effectiveness of pest control approaches given it is highly dependent on pest intensity, type, and distribution, as well as seasonal, geographic, and crop-specific factors (38). Furthermore, direct comparisons between management systems present significant design challenges. Synthetic pest control inputs disrupt biological control mechanisms (11), making experimental comparisons of pest control between management systems difficult to design spatially such as to avoid spillover effects from one treatment to another (pesticide drift, movement of arthropods) and to allow for different levels of habitat diversification among treatments. The time frame of comparisons is also important, given that organic systems may require multi-year rotations to achieve stable weed control (76), and effective biological control requires sufficient time to develop stable predator/parasitoid populations (77).

4.5.1. Plant diseases. There is a lack of information quantifying comparative effects of plant disease on crop productivity in organic systems. Letourneau & van Bruggen (9) state, "Our overall impression (and also that of organic farmers) is that diseases in organic agriculture are generally not so severe that they limit yield (except for downy mildews, late blight, and some other foliar diseases in conducive climates); other factors such as weeds and plant nutrition are usually more limiting." They also identify the challenge of assessing crop loss in organic systems when fungicide application cannot be used as a control treatment, and it is generally not practical to introduce different levels of pathogens to determine yield responses.

Organic disease management is built around maintaining crop and soil health, use of resistant cultivars, sanitation, and cultural controls (75). Although pesticide applications are infrequent in organic systems, they are important for control of key foliar pathogens. Notably, copper, sulfur, and bicarbonate-based compounds are frequently used for control of late blight, downy mildew, and powdery mildew (75), sometimes in conjunction with other measures, including temporal and spatial plant diversity (78), induced resistance (79), variety selection (80), and cultural management. Concerns regarding long-term accumulation of copper in organic systems have led some countries to prohibit or limit its use (80).

Soilborne diseases are generally well controlled in organic systems through good soil management and crop rotation with some key exceptions. Pathogens with wide host ranges are not easy to control with crop rotation, and damping off caused by *Pythium* spp. can be problematic if crops are planted into soil with freshly decomposing organic matter (75). In conventional systems, soilborne pathogens are typically controlled by coating seeds with fungicides, direct application of fungicides, or soil fumigants and disease-resistant crop varieties (75). Plant breeding is an important frontier for improving disease resistance in cultivars targeted specifically for organic production (81).

The creation of disease-suppressive soils (82, 83) is a cornerstone of organic disease management. Soil microbiome composition can greatly impact disease development (84) and root colonization by pathogens (85, 86). Conventional practices reduce the density of soil biota (87), whereas practices such as frequent use of organic amendments and biomass incorporation through cover crops increase the abundance and affect the structure of the soil microbiome (88, 89). Nonetheless, the relationships between microbiome structure and pathogen control across production systems and pathogen types remain unclear (90). Disease-suppressive soils can result from the deliberate use of management practices to manipulate soil microbiomes (85). Examples include use of brassicaceous seed meal amendment, as in the control of apple replant complex (84), or the creation of temporary anaerobic conditions and stimulation of anaerobic breakdown of added organic carbon, which has been shown to control a wide range of pathogens typically controlled by soil fumigation (91).

4.5.2. Weed management. The exceptional reliance on herbicide-resistant cultivars and herbicide applications for weed control in conventional systems is well known (76), as is the challenge weed management presents to organic growers in the absence of these tools (92). No single combination of cultural, mechanical, and biological methods is universally effective, so organic growers are dependent on a combination of practices (the aptly named "many little hammers" approach) to achieve suppression (93). Nonetheless, weed management is generally rated as a top priority for research by organic farmers. Heavy reliance on well-timed tillage for weed control makes organic systems vulnerable to yield loss if weather or other conditions delay tillage operations (26). The potential for breeding more competitive crop varieties is yet to be exploited, and adjustments in seeding rates, rotation design and plant spacing have shown promise in some systems (19).

Conversely, heavy reliance on herbicides has led to substantial problems with pollution of water sources, negative ecological impacts, and increases in herbicide-resistant weeds, leading to calls for a rediversification of management strategies (76) and consideration of the evolutionary dimensions of weed control (94). The rapid expansion of no-till in conventional crop production systems was facilitated by the availability of herbicides and herbicide-resistant cultivars. Reducing herbicide use and expanding conservation tillage approaches into organic systems requires improvements in seedbank management, integration of weed-suppressive mulches, and advances in mechanical implements for termination of cover crops (95) and mulch-tolerant weeding (96).

4.5.3. Arthropod pest management. Arthropod pest management in conventional systems relies heavily on synthetic pesticides, integrated to varying degrees with other cultural and biological strategies (72); however, effects of pesticides on nontarget natural enemies can lead to emergence of secondary pests (9). Organic farmers rely on a diversity of management practices, which sometimes include organically approved pesticides (75). Partitioning the effects of pesticides and other management practices on pest control services makes comparisons across organic and conventional systems challenging. Comparisons nonetheless suggest that natural enemies in organic systems provide a level of pest control comparable to pesticide use in conventional systems for many, but not all, pests (97, 98). Organic systems that incorporate biological diversification practices can lead to higher populations of natural predators and parasitoids, as well as improved biological control (75, 99). The linkages between habitat diversity, natural enemy communities, and biological control efficacy are complex and not well understood for many systems; however, a meta-analysis found that increased plant diversity in agricultural systems was associated with reduced levels of herbivory in the majority of cases (100).

Landscape characteristics also impact pest control, as seen by the negative effect of landscape simplification, which led to 46% lower pest control in simple compared to complex landscapes (27). Landscape and management also interact to affect pest control; for example, control of aphids was higher in organic fields in complex landscapes, and it declined with landscape homogeneity; however, landscape context had no effect on pest control in conventional fields (101). A large-scale study of wheat fields across Europe also found increased biodiversity and biological control of aphids as the proportion of diversified and organic farms in the landscape increased, whereas biodiversity and biological control were negatively correlated with intensity of pesticide application (102). Abundance and species richness of natural enemies are affected by multiple farming practices, however, and the distinction between organic and conventional may be less informative than knowledge of specific practices (103). For example, hedgerow length and configuration, distance to natural habitat, and landscape heterogeneity all positively impact natural enemies (103–105).

4.6. Biodiversity Conservation

Agriculture is a dominant form of land management, covering 40% of terrestrial land area, and is a major cause of global biodiversity loss (106). Numerous recent studies report greater species abundance or richness of many taxa in organic than in conventional systems (107, 108). It is apparent that species traits, specific farming practices, and surrounding landscape all influence on-farm biodiversity, making it challenging to determine under what circumstances targeted management practices could offer similar benefits to organic farming (108, 109). Furthermore, gains in species richness of some taxa in organic compared to conventional fields can be marginal at the farm scale, and higher species richness in organic systems can be partially explained by sampling more abundant species (108).

Practices that differ between organic and conventional farms and that impact biodiversity include habitat management (hedgerows, wildflower strips), tillage, and pesticide use. For example, weed cover, plant species richness, insecticide intensity, and tillage intensity all influenced spider diversity in South African vineyards (105). Hedgerows can also increase biodiversity and are often managed to provide habitat for beneficial insects (103). The effects of practices on biodiversity may take time to develop, as in the case of soil biota that benefit from no-tillage and cover crops (110). The intensive use of pesticides negatively impacts biodiversity across both aquatic and terrestrial ecosystems. Significant reductions in aquatic invertebrates were observed in Australia and Europe, even at pesticide concentrations below those considered by legislation to be environmentally protective (111). Similarly, diversity of plants, carabids, and ground nesting birds was consistently impacted by insecticides and fungicides in a multicountry European study (102). Declining plant diversity in farmland may be due to sensitivity of reproduction of nontarget species to herbicide exposure during flowering (112), and specialist birds, notably herbivore species, were greatly reduced in herbicide-treated fields (113).

To what extent can landscape diversity override differences in farm management remains an important question (114). A recent study shows that organic farming generally enhances species richness and abundance, but the effects depend on species traits and are mediated by landscape characteristics (115). In heterogeneous landscapes, natural habitat may already support such high levels of biodiversity that it may not be further increased by organic farming (116); in simple landscapes, however, organic management may increase landscape heterogeneity and biodiversity, but only if some minimum amount of seminatural habitat and species pools exists nearby (117). Indeed, plant species richness and functional diversity responded to landscape heterogeneity, with the strongest effect occurring on conventional farms (118).

Organic agriculture can thus be an important tool to protect biodiversity, but alone may not provide significant benefits to all declining or sensitive species, indicating that conservation of natural habitat in farm landscapes is also important. [Most comparisons of biodiversity are from Europe and North America (119), with little information for the tropics and subtropics, and studies are generally short term and do not address species persistence and population dynamics (120).] We have also not covered the rapidly evolving field of below-ground biodiversity and soil ecology, which has important implications for multiple ecosystem services, including nutrient cycling, soil structure, and pest and disease suppression. Many management practices encouraged in organic farming, including reduced pesticide use, crop rotation, use of cover crops, and habitat diversification, are associated with supporting soil biodiversity, but tillage intensity is also a critical factor. As a result, the relative benefits of organic management vary among reported studies, but it is clear that organic systems have potential to enhance soil biodiversity and food web structure (121).

There is a lack of consensus on how to best conserve biodiversity in relation to agriculture. Whether to promote diversified agricultural landscapes (land-sharing) or intensified simple landscapes that are presumed to be more productive and hence require less land to meet production demand (land-sparing) is debated. An inherent assumption in this debate is that land-sharing agriculture will be less productive than land-sparing, but this is not always the case. Arable crop yields were similar or increased in fields adjacent to habitat, such that overall monetary value and nutritional energy production was similar to that from areas without habitat set asides (122). Furthermore, analysis of the 54 major crops in France produced over the past two decades found that benefits of agricultural intensification decrease with increasing pollinator dependence, such that intensification failed to increase yields of pollinator-dependent crops and decreased the stability of yields over time (123). Woodland islets have been promoted in an attempt to reconcile restoration and intensive agriculture (124); however, Kremen (120) emphasizes that both protected areas and permeable matrices (as in diverse farm landscapes) that allow movement of wildlife are essential to the preservation of biodiversity. In agricultural landscapes, some species are winners (well-adapted to agriculture and benefit from agricultural resources) but others are losers (e.g., forest-dependent species, species sensitive to disturbance), whose persistence may require careful management (125).

4.7. Pollination Services

Given recent declines in global pollinator populations, many scientists have asked if organic practices promote greater pollinator diversity in comparison to conventional practices. Pollinator abundance and richness are often higher on organic farms and linked to vegetation diversity. In a quantitative review, wild bee abundance and richness were found to be higher in organic and diversified fields (123); however, differences in pollinator communities between organic and conventional farms also depend on species traits (126). Agrochemical inputs can also cause pollinator declines through direct toxicity and indirect effects via changes in floral abundances. Wild bees showed increased population extinction rates associated with exposure to neonicotinoid seed treatment use on oilseed rape (127), but pesticide intensity did not affect abundance or diversity of pollinators in South African mango orchards (128). Interestingly, increased natural habitat may buffer against pesticide-induced pollinator mortality (129).

Given the importance of floral resources and undisturbed habitat as refugia for pollinators, various vegetation management interventions are being tested. Diverse wildflower strips augment resource availability and increase bee abundance (130), and wild pollinator visitation and enhanced fruit set are positively correlated with flowering ground vegetation (131). Isolation from natural habitat is also associated with a decline in pollination services (128). Hedgerows replicated across a landscape can boost pollinator diversity to levels similar to some natural communities (34). In their global review, Kennedy et al. (132) found that wild bee abundance and richness were higher in landscapes with more high-quality habitats, but the benefits of landscape heterogeneity depended on both species traits and an interaction between local and landscape scales. For example, the taxonomic breadth of pollinator communities only declined with decreasing landscape heterogeneity on conventional, not organic, farms (126). Similarly, wild bee richness in conventional fields benefited most from high-quality surrounding land cover (132). These findings suggest that resources provided by organic farms and high-quality surrounding habitats are, to some extent, interchangeable.

Fewer studies measure actual pollination rates as opposed to richness and abundance of pollinators (115). Most studies report greater pollination services on organic than conventional farms (11, 133), suggesting that organic practices can bolster pollination, although not sufficiently to compensate for a lack of natural habitat in the surrounding area. Evidence suggests that organic management can enhance habitat connectivity (134), an important attribute for pollinators affected by both isolation and amount of seminatural habitat in the surrounding area. In some cases, pollination is not affected by organic practices, but it is positively associated with the amount of surrounding seminatural habitat (135) or distance to seminatural habitat (136).

4.8. Economic Viability and Quality of Life

Global sales of organic food and drink topped $80 billion in 2014, representing a fivefold increase since 1999, and there are several commodities where demand outstrips supply (137). There were an estimated 2.3 million organic producers in 2014, with 80% in developing countries and emerging markets where much of the production is for export to the United States and Europe. The continued growth in the organic sector will depend in part on its ability to compete economically with conventional agriculture, as well as how limitations in terms of market and technical infrastructure, certification requirements, policy, and inexperience with production methods are addressed (17). Here, we examine what is known about the economic performance of organic systems, their role in rural development, and impacts on various aspects of quality of life and human health.

4.8.1. Economics and profitability. A recent meta-analysis of 54 crops and their associated rotations concluded that organic farming is generally more profitable than conventional due to price premiums, and that to get comparable returns to conventional would require price premiums of only 5–7% (17). Organic practices that improve soil health, weed control, and water conservation can increase profitability over time (138). Multistate studies in India showed that farmers perceive that further expansion of organic production would increase profits, through potential economies of scale (139), and that organic can be more profitable despite yield penalties (140, 141). Increased profitability may trade off with local food production, however, where organic crops are grown for export markets (139). With low risk-to-return-ratio crops, such as bananas, (142), and systems with low labor needs, such as lemon orchards (143), organic systems can yield significant profits and create a competitive advantage. Although labor costs tend to be higher in organic systems, input costs are often lower (17), and when combined with price premiums, this can reduce financial risk for farmers (140). In developed countries, economies of scale and degree of market integration also influence profitability. Organic products are successful in niche markets with price premiums (144), and horizontal integration, or acquisition of competitive production units, can be important to the success of organic ventures (145).

Beyond profitability, various factors affect entry into and survival in the organic market. Access to knowledge, participation in training and extension, and access to resources have a large impact on entry and are frequent barriers to resource-poor farmers in developing nations (144, 146). In Nepal, proximity to market, age, level of training, affiliation with institutions, and larger farm size increased farmers' likelihood of choosing organic production (147); similarly, in the Philippines, training opportunities, resource access, and organizational support were influential (148). Human values and ideology, rather than financial gain, can also be influential (149), as with the ideological base of the organic movements in Brazil (150) and Iran (151).

Policies also influence organic farmers. In the European Union, for example, Common Agricultural Policy subsidies and organic price premiums increase profitability dramatically (152). Organic subsidies can, however, favor larger farms and create a cycle of dependency to maintain profitability. In Poland, public funds disproportionately influence farms over 20 hectares in size to convert to organic agriculture, doubling income per working person and quadrupling profitability (153). Furthermore, organic certification bodies can boost knowledge exchange and facilitate farmers' movement into organic production in both developing (154) and developed (155) countries. However, the costs of certification itself can be prohibitive and an insurmountable barrier to entry for small farmers (156, 157). To overcome financial burdens of certification, some have suggested an area-based certification process to encourage the community development and knowledge-sharing benefits of organic agriculture at lower cost (158).

Resilience: the capacity of a socio-ecological system to absorb a spectrum of shocks or perturbations and to sustain and develop its fundamental function . . . as a result of recovery or reorganization in a new context (208)

Overall, there is limited information on the quality-of-life impacts of organic and conventional agriculture (2), but there is some evidence that organic farming can provide positive benefits. Higher returns from organic production has led to rural economic revitalization in some regions. In Spain, loss of EU subsidies and profits for conventional citrus production led to widespread abandonment of farms, but restructuring of the sector to organic production resulted in higher farm profits and increased employment (159). In France, organic farmers were found to have higher levels of life satisfaction, including indicators such as income, profitability, work satisfaction, social recognition, and health (160). If rural prosperity is expanded to include social capital, innovation, social learning, and resilience, organic farming shows considerable promise (161). In Denmark, organic farms were ranked high relative to regional norms in terms of most quality-of-life indicators by farmers and farmworkers, but there was less satisfaction with income and salaries (162). Laborers on larger organic farms, however, tend to experience better working conditions than those on smaller farms. A study comparing organic fruit and vegetable production in California and various sized dairy farms in Wisconsin showed that laborers on larger farms tended to fare better or equal to their smaller counterparts, although white US-born workers received more benefits in both settings, signifying important and unresolved social justice issues (163).

4.8.2. Human health.

In the debate comparing organic and conventional agriculture, the negative impacts of agrochemical exposure for human health, especially farmworkers, receives surprisingly little attention. Although farmworker health is acknowledged as a globally important issue (164), most of the literature surrounding it originates from the United States and Europe, where exposures are likely to be lowest due to stricter safety regulations. The US Environmental Protection Agency estimates that annually, 10,000–20,000 pesticide poisonings are physician-diagnosed in US agricultural workers (165), although this likely underestimates actual exposures. Humans are exposed to pesticides in-field during application, through pesticide drift (166), or from contaminated food (167) and water (168). Numerous reviews identify important negative health effects of various pesticides, but they caution that limited data are available (74, 164, 169). Recent attention has focused on the most heavily used compounds (herbicides) with the recognition of glyphosate as a potential carcinogen (170) and atrazine in groundwater being implicated in birth issues (168).

Little work has investigated health effects of organically approved pesticides, but some studies address differences in exposure between organic and conventional farms. Parelho et al. (171) compared wild mice populations from organic and conventional farms, finding damaging effects of conventional farming practices on testicular health. A limited set of studies assess genetic damage in pesticide-exposed individuals compared to unexposed controls (172, 173), with one study finding higher levels of genetic damage in workers from conventional farms compared to unexposed control individuals and workers from organic farmers (174).

Pesticide drift is a significant and understudied source of exposure in rural communities (166), but diet can be another source of exposure for the general public. Urine of preschool children eating organic diets had significantly lower levels of organophosphate metabolites than those eating conventional diets (175). Other experimental studies using animals came to similar conclusions (176). Analysis of large data sets from multiple agencies have also suggested that organic foods may have up to a third less residues as conventional produce, across most crop types (177). The health impacts of the levels of residues found are unclear, however, but the lack of data, especially for children in developing countries, is a grave concern given exposure is likely to be much higher.

4.8.3. Food safety and nutritional quality.

Food safety refers to concern over the spread of disease-carrying pathogens such as *Escherichia coli*, *Salmonella enterica*, and other microbes between agricultural systems and humans. Literature comparing the incidence of foodborne pathogens and microbial contamination from conventional and organic farms is limited and equivocal. Bourn & Prescott (178) found no difference in organic and conventional foods in terms of microbial contamination. The distinction between organic and conventional farming practices may be less important for pathogen spread than specific practices common to both. For example, removing noncrop vegetation around farm fields was not only ineffective in preventing the spread of foodborne pathogens, but it may in fact exacerbate *E. coli*–related food safety issues (179), calling into question reforms that promote vegetation removal to improve food safety. Franz & van Bruggen (180) review the ways in which *E. coli* and *S. enterica* populations fluctuate throughout the leafy greens production system, suggesting that the use of high-quality manure in organic systems (high in organic matter and microbial diversity) can actually suppress pathogens and minimize outbreak.

Finally, there has been considerable debate about the nutritional value of organic versus conventional foods, with findings varying depending on methods used, crop type, and nutritional attributes being measured. There are several mechanisms whereby organic management might impact the nutritional quality of food crops (43), but effects of other factors may obscure the impact of management (181). An overriding effect of *cultivar* has been demonstrated for several crops and compounds (182–184); however, for spring barley, organic management produced higher levels of lunasin, a peptide with cancer-prevention health benefits across genotypes (185). Of the articles Reeve et al. (43) review, seven concluded that organically grown food has a greater content of minerals and vitamins, but these differences are generally minor; five concluded there was insufficient evidence to draw conclusions; and two meta-analyses concluded there were no differences in nutritional content between organic and conventional produce (43). Importantly, some authors pointed out that consumption of organic foods may, however, reduce exposure to pesticide residues and antibiotic-resistant bacteria (167).

Vulnerability: linked but alternative concept encompassing adaptability defined as the susceptibility of a system to disturbances determined by exposure and sensitivity to perturbations and the capacity to adapt (209)

Adaptability: a cornerstone of resilience theory, referring to "the capacity of actors to respond to, create, and shape variability in the state of the systems" (183)

4.9. System Resilience

The ability of agricultural systems to survive biophysical and socioeconomic stresses and perturbation is a crucial aspect of sustainability, especially in the context of global climate change. Terms such as vulnerability, robustness, resilience, or adaptability are widely used to describe a system's susceptibility and capacity to absorb, adjust to, or recover from environmental or socioeconomic stresses.

Resilience and vulnerability both have biophysical and social aspects operating across multiple scales. For example, in the biophysical sphere, soil type and management impact field-level wheat yield sensitivity to temperature (186, 187), ecological farm management can impact vulnerability to hurricanes (188), and the presence of riparian buffers and wetlands can increase landscape resilience to runoff and soil erosion during high-rainfall events (189). In the socioeconomic dimension, resilience can similarly be considered at the household/farm (190, 191), organization (161), community or regional (192), and food system levels (193).

When comparing the relative resilience of farming systems, the questions "Resilience of what, to what, and in what context?" must be addressed. Walker et al. (194) distinguish between specific and general resilience. The former can be measured as the response of a particular property to a specific stressor, for example, crop yield to drought, whereas the latter requires use of indicators (195) to capture the ability of a social-ecological system to survive and adapt to a range of shocks. This may include assessments of the ability of individuals and institutions to learn, adapt, and reorganize. There are circumstances when high resilience may be undesirable—as in the case of low-yielding resource-poor agriculture. Here, the challenge becomes how to shift states to a more productive system without increasing risks while still ensuring adequate resilience. Introducing expensive improved seed, fertilizer, and pesticides, for example, may potentially improve incomes but will also expose poorer farmers to fluctuations in input availability and cost, thereby increasing vulnerability and lowering resilience (194).

There have been few attempts to directly compare the resilience of organic and conventional systems, although there is evidence that practices associated more often with organic management may increase some types of specific resilience. For example, improving soil organic matter can increase water infiltration and retention, leading to greater yield resilience under low rainfall conditions (196, 197). Diversification is a key element of resilience, which for farming systems can take the form of enterprise, habitat, crop, or genetic diversification. Farms with higher genetic diversity had decreased risk of crop or economic failure (192), and long-term rotational studies also recorded greater yield stability with more diverse crop rotations (198). Other economic studies indicate that crop diversity can be a viable mechanism for risk reduction under uncertain conditions and that land use diversity can increase economic resilience in the face of unreliable markets and environmental conditions at the regional scale (192).

In the social realm, adaptive ability is central to resilience. Darnhofer's et al.'s (199) concept of an adaptive farming system highlights the importance of learning (sharing and expanding knowledge), flexibility (the pool of material and knowledge resources available), and diversity (the ability to cope with variability). At the local level, managerial ability; access to financial, technological, and information resources; infrastructure; and kinship networks can all influence a community's adaptive capacity, as well as more general socio-economic and political contexts such as the availability of state-subsidized crop insurance. Although availability of subsidized crop insurance can increase economic resilience, it can also support management and system designs that perpetuate vulnerability of farming systems to extreme weather events (200).

Studies that integrate examination of biophysical and social differences in the resilience of conventional and organic farming systems are nonetheless rare. Jacobi et al. (190, 191) provide two of the few in-depth studies of resilience of organic and conventional production. They found that organic cocoa farms, especially those using successional agroforestry, rated highest on a range of indicators including tree crop diversity, soil quality, yields and incomes, and social connectivity (from participation in local farmers' learning and certification organizations). The data were collected from a modest number of farms for one year only, but they underscore the potential improvement in resilience that may accrue under certain organic production systems. There is a clear need for further in-depth and longer-term studies addressing resilience across a diversity of cropping systems.

5. FINAL REFLECTIONS

When a broad set of sustainability indicators are considered, organic or ecologically based systems compare favorably against conventional across many environmental and socioeconomic metrics. Organic systems can also achieve similar levels of productivity for some but not all crops. Differences in system performance across sustainability metrics depend on multiple factors including crop rotation structure, landscape heterogeneity, organic price premiums, farmer knowledge and investment capability, and the appropriateness of each system given local agronomic and socio-economic circumstances. We find strong evidence for socioeconomic and environmental benefits from organic management, and we echo other calls for greater research investment to improve understanding of how organic systems function and can be improved upon. Furthermore, although organic represents a small proportion of global agricultural production, organic farmers are a source of innovation and information with relevance far beyond certified acreage (201).

Most organic–conventional comparisons focus on yield. Differences observed are cropping system and region specific, with several meta-analyses indicating an average organic yield reduction of ∼20%, although evidence is emerging that biologically diverse cropping systems can reduce this gap. Most studies, however, generate data from small-plot experiments that may not adequately reflect within-field yield variability, farm-scale resource constraints, or the diversity of management practiced by farmers. More work is needed to address the yield limitations of ecological cropping systems through experimentation and investigations of operating farms. In the case of organic farming, we are aware that research has often lagged behind farmer innovation and experience. Much could be learned by studying successful farms and by using this information to identify important research questions that can be addressed through experimentation. We also need to better understand potential trade-offs between specialization, yield maximization, and system resilience to biophysical or socioeconomic perturbations.

Evidence suggests that soil fertility and weed management problems are key constraints to higher organic yields, with exceptions for some crops and locations where pathogens (e.g., potato late blight) can cause major losses. Most organic farmers have to use cultivars that have been bred under and for conventional management, which may differ from organic systems in terms of lower weed pressure and larger pulses of mineral nitrogen availability from synthetic fertilizers. Traits including more efficient nutrient acquisition from slowly mineralizing organic matter, weed competitiveness, and enhanced resistance to pests and diseases may be lacking in cultivars bred under conventional circumstances. The continued development of breeding programs to address genotype × management system interactions remains an important research priority.

Many authors have questioned the feasibility of large-scale expansion of organic production due to physical and logistical limitations to nutrient supply from manure, and climate or economic constraints to cover cropping. Although a significant part of a crop's nitrogen requirement can be met through biological nitrogen fixation, inputs of P, K, and micronutrients are ultimately required to avoid negative nutrient balances. To the extent that organic crops are produced on farms lacking livestock, there can be logistical issues getting manure/composted manure to crop fields (202), but whether the amount of manure available is limiting will vary by region. To our knowledge, no adequate spatially explicit regional analyses of manure availability and organic production have been undertaken. Organic producers are increasingly using compost from urban waste, in addition to other amendments derived from animal and fish by-products. Concerns have been raised that such external amendments, and manure from conventional farms, are in essence subsidizing organic agriculture, but this contention misses the bigger-picture argument for encouraging closure of nutrient cycles by reusing multiple kinds of waste in any type of agriculture. If we are to reduce or even stabilize the rapidly increasing amount of reactive nutrients cycling in the environment globally (203), then it is imperative we find more effective ways to recycle nutrients back to farmland—both for organic farming and to reduce fertilizer use in conventional farms (204).

The potentially detrimental impacts of pesticides on both human and environmental well-being has surprisingly not featured prominently in the organic–conventional debate, although it remains a crucial issue. Demand for organic products continues to grow, which reflects consumer concerns for people's health and the environment. That in many cropping systems, organic management can yield within 20% or better of conventional yields, despite limited research, challenges the idea that intensive use of pesticides is essential for productive agriculture. Limitations related to weed management, especially in reduced tillage systems, and in control of certain foliar diseases and pests for which few alternatives to pesticide use exist, nonetheless remain. Further research and extension to improve integrated pest and weed management are urgently needed to reduce reliance on pesticides and slow the evolutionary development of resistance on conventional farms (72, 94).

5.1. Potential for Integrated Systems

Integrated production: combines principles of conventional and organic production; may use composts, cover crops and synthetic fertilizers, and pesticides in addition to biological and cultural pest control (2)

It is instructive to ask if the benefits of ecological management embodied in organic systems could be maintained with the addition of supplemental inputs to alleviate key constraints—for example, meeting late season nitrogen demand with supplemental synthetic fertilizer, or with occasional use of a fungicide to control a foliar pathogen. Our review uncovered many examples of integrated crop management systems that perform as well or better than organic in terms of yield, ecosystem services, cultural benefits, or reducing environmental externalities (12, 22). As discussed earlier, landscape diversification may be more critical than in-field management for pollinators, and it enhances biodiversity conservation and biological pest control without necessarily reducing crop output or income. A meta-analysis found that low external input systems yielded as well as (wheat), or slightly lower (maize) than, conventional, with reductions of 70% in pesticide use, and 28% less nitrogen fertilizer (205). The challenge then becomes how to make these systems economically viable, especially in developed countries where fertilizers and pesticides can comprise a small amount of total production costs, but where management costs of "hybrid" systems may be greater (22). Policies to support the integration of ecological practices and encourage reduced fertilizer and pesticide use may be needed for such hybrid systems to be widely adopted, although demands for more sustainable production practices from large retailers could also provide incentives. In parts of the developing world, combining ecological practices, such as manures or crop residues with modest amounts of synthetic fertilizer may be a viable option given farmers can rarely source or afford recommended rates. Integrating low-cost residue inputs or relay intercropping legumes (206) with modest amounts of fertilizer can significantly increase yields and profit. In addition, strategic use of limited toxicity pest control products or herbicides may also be advantageous (207). These suggestions fall within the vision of "sustainable intensification," which aims to integrate ecological crop management with sound socioeconomic practices and appropriate cultivars to reduce environmental externalities while raising crop productivity. Ecological crop management, however, should include crop and habitat diversification strategies to enhance critical ecosystem services and potentially system resilience.

We began this review by identifying the broad division between the industrial and agrarian philosophies of agriculture, while also recognizing increasing efforts to promote diversified farming systems that prioritize values of biodiversity conservation and provision of ecosystem services. Given that diversification can be applied to both agrarian and industrial modes of production, we propose adding this as a third philosophical pole, or vision of agriculture (**Figure 1**). Farming systems can theoretically fall anywhere between the three visions, reflecting different degrees of industrialization, agrarianism or diversification, although to what extent the values epitomized by the industrial and agrarian philosophies are fundamentally distinct remains an unanswered question (the unshaded area in the triangle in **Figure 1**). Using this framing organic systems vary widely, spanning the agrarian-industrial and the diversification-specialization spectra (see the green shaded area of **Figure 1**). Conversely, conventional systems tend to fall close to the industrial pole, but with efforts toward sustainable intensification and diversification strategies such as cover crops, and field margin habitats, etc. can move toward the ecological pole (orange area, **Figure 1**). This variation within both organic and conventional systems underscores the inability of simple binary comparisons to reflect real world complexity, and that metrics averaged across such different systems are of limited value. We believe that a spectrum of production system typologies that includes organic, integrated production, and diversified systems will play significant roles in achieving more sustainable food production systems, and that it is crucial to look for ways to improve multiple types of systems if we are to meet the critical sustainability challenges of the future.

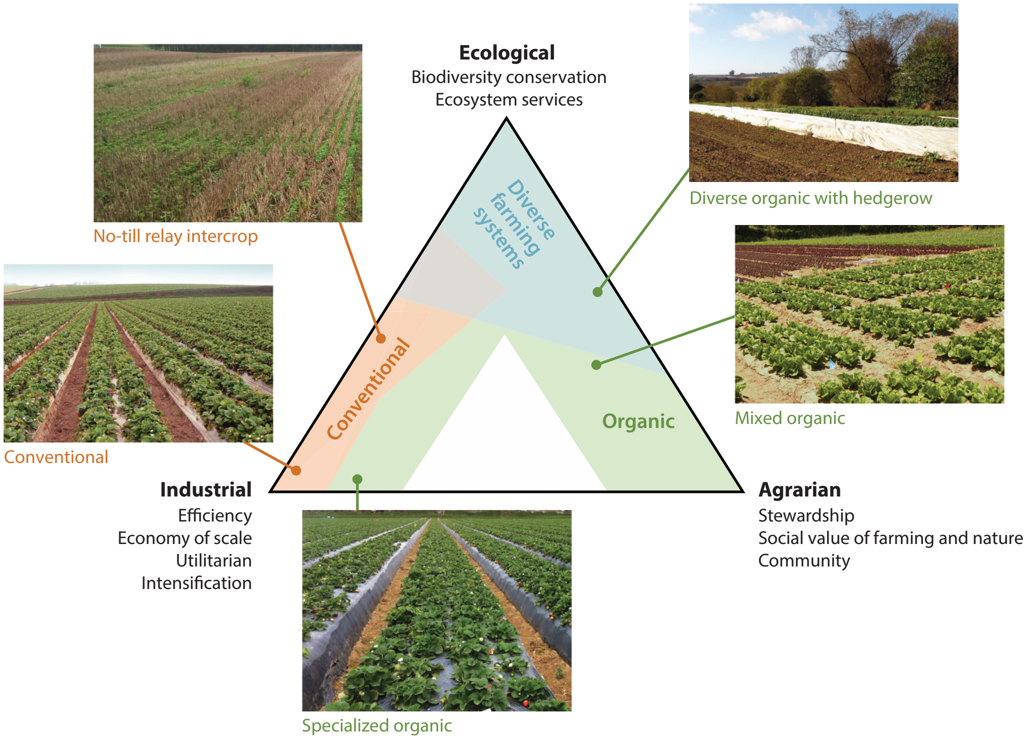

Figure 1

Three philosophical poles of agriculture (ecological, agrarian, and industrial) and zones where system types are located (*colors*). The midpoint between two poles reflects equal importance of both visions. Organic farms range from strongly agrarian and ecological to industrial, whereas conventional systems fall mostly along the industrial and ecological axes.

SUMMARY POINTS

1. Assessing how and where organic, conventional, or other systems can contribute to feeding the world in a manner that addresses multiple sustainable goals moves us beyond the either/or dichotomy of much of the organic–conventional debate. The multiple ecological and social benefits identified justify greater research investment in organic and ecologically managed systems.
2. Organic systems currently yield less than conventional, but differences vary among crops, locations, and management choices. Methodological issues with comparison studies, and limited research to improve organic systems, suggest that broad generalizations about the capability of any system type to feed the world are inappropriate.
3. Although organic management can increase SOC in shallow soil depths, improved understanding of management effects on labile SOC versus long-term sequestration is needed. Practices that increase SOC, use of catch and cover crops, reduced tillage, and landscape diversification contribute to reducing nutrient losses and protecting water quality. Insufficient information is available to responsibly evaluate differences in GHG

emissions or to quantify LCA measures of environmental impacts between conventional and organic crop systems.

4. All systems are challenged by pests and diseases, but there is little evidence to suggest they cause greater yield reductions in organic systems—with some exceptions. Weed control remains a major challenge for organic systems, whereas conventional systems face issues with herbicide-tolerant weeds and nontarget herbicide use effects. Serious human health and environmental impacts associated with intensive pesticide use remain a problem for conventional systems. Schemes that increase plant diversity at the farm scale, and more heterogeneous landscapes, tend to increase pest control services.
5. Organic systems typically support greater biodiversity, although conventional systems can be managed to improve biodiversity. Management effects are more pronounced in simple than heterogeneous landscapes, and productivity is not always reduced in diverse (land-sparing) landscapes. Greater abundance and diversity of pollinators on organic farms may be associated with habitat heterogeneity more than pesticide exposure. Without sufficient habitat, organic farming cannot fully sustain wild pollination services.
6. Organic markets continue to grow worldwide, and price premiums or policy subsidies make organic systems profitable in many developed and developing countries, even spurring rural revitalization. Limited data suggest positive quality of life benefits from organic farming, but inequalities persist for farmworkers and resource-poor farmers' ability to invest and enter into organic markets.
7. Data suggest few consistent differences in nutritional content of organic and conventional crops, and no difference in microbial pathogen contamination, although more antibiotic-resistant bacteria may be present in conventional crops.
8. Few studies compare the resilience of organic and conventional cropping systems, although improved soil organic matter, greater diversity of crops, habitats and enterprises, as well as social networks associated with organic certification have enhanced resilience in some contexts.

FUTURE ISSUES

1. Farmers manage cropping systems that fall along gradients between the industrial, ecological, and agrarian visions of agriculture. Changes in how conventional farmers manage their systems appear to be incremental, with increased attention to environmental and ecological goals, as opposed to more radical shifts away from the utilitarian values embodied in the industrial vision toward more agrarian values. Organic systems themselves cover much of the range between all three poles, rendering binary system comparisons poorly suited to capture real-world variations in management used by either organic or conventional farmers. Rather than focus on further analyses of the global benefits or constraints of either system, or presumptions that one system type will work in all contexts, greater efforts to improve the capacity for different types of management systems to strike a balance among sustainability attributes, and tailored for given contexts, are needed.

2. To realistically assess social, environmental, and productivity impacts of management systems, multi-scale and multi-year studies are needed. We must move beyond plot- and farm-scale studies to examine linkages among farm operations and between urban and rural landscapes. Such studies could develop innovative ways to recycle nutrients at landscape and regional scales; address landscape heterogeneity and connectivity; or examine roles of markets, policy structures, networks, and institutional arrangements in social well-being. Although this review focused on crop production, these investigations will need to incorporate linkages between crops and livestock at multiple spatial scales.
3. Food safety is a high-profile concern, especially in developed countries, yet exposure to agrochemicals present a higher risk to farmworkers, farmers, and rural communities. The relative lack of attention to these issues represents an important environmental (in)justice issue. More research is needed to discern agricultural management impacts on human health in both developed and developing countries, with a focus on reducing agrochemical (including organically approved materials) exposure to farmers, farmworkers, and the public.
4. In the face of climate change, the resilience and adaptive capacity of farming systems are increasingly important. Further work is needed to examine the merits of biological and enterprise diversification, as well as social networks and institutional arrangements, to enhance resilience. Other risk-reducing measures such as crop insurance or social safety nets have utility, although care must be taken to implement them in ways that do not reduce the incentive for adoption of strategies to build more resilient farming systems.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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