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Review

Environmental impacts of organic agriculture in temperate regions

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Abstract

Can organic agriculture elaborate a scientifically based, resource-efficient and agroecological approach to low-input farm management? This review examines the literature from temperate regions, with a particular emphasis on Canadian and US studies that relate to environmental and ecological impacts of organic agriculture with respect to (i) soil organic matter storage, (ii) soil quality/soil health, (iii) nutrient loading and risks of off-farm nutrient and agrochemical losses, (iv) biodiversity and (v) energy use and global warming potential. The context and implications of semi-arid conditions and low soil P levels, common to many organic farms in North America, and widespread adoption of genetically engineered crops in conventional production, is also considered. The consensus of the data available to date indicates the distinctiveness of cropping, floral and habitat diversity, soil management regime, nutrient intensity and use efficiency, and energy, and pesticide use in organic farming confer important environmental and ecological benefits. These include maintenance of soil organic matter and added return of carbon to soil, improved soil health, reduced off-farm nitrogen and phosphorus losses, enhanced vegetative and wildlife (bird) biological diversity, extended sometimes to other taxa depending on landscape context, improved support for pollinators and pollination and reduced energy use and improved energy efficiency. The continued evolution of organic agriculture to a more outcomes-based, agroecological production system will require an expanded multi-disciplinary research effort, linked ideally to support from consumers and policy-makers on the basis of renewed understanding of its potential contribution to global environmental sustainability.

Keywords: Organic agriculture, Farming system, Soil organic matter, Soil health, Nutrients, Biodiversity, Energy

Introduction

Agriculture is a key driver of environmental pressures and ecosystem degradation globally, through its impact on water use, loss of habitat, climate change and pollution (particularly with nitrogen (N) and phosphorus (P)) [1, 2]. Over the past 60 years, humans have had a more rapid and extensive impact on ecosystems than during any comparable period in history. This is substantially attributable to the exponential increase in the human population. Over 38% of the world's land and 70% of use of global freshwater supplies are now used by agriculture, and many agricultural processes, in contrast to many industrial processes, have an inherently low efficiency of resource use [2]. Habitat loss through landscape modification, combined with the intensification of production and use of agrochemicals, has become a major cause of biodiversity loss [3–6]. In addition, widespread and intensive use of synthetically produced N fertilizer, and the impact of this massive increase in reactive N on target and non-target ecosystems, is producing an 'N-saturated planet' [7]. If unabated, further 'unintended consequences' of this N saturation include reduced biodiversity, polluted water and air, increased human health risks and an even more perturbed greenhouse-gas balance [2, 7, 8]. Besides these environmental consequences, many farming practices do not sufficiently maintain soil health [9], thus undermining global long-term food production capacity.

We can no longer claim to be unaware of the consequences, and reduction of global environmental impact must be one of the main drivers for future innovation [2, 7]. Thus, in agriculture and food, a scientific approach to develop and assess efficient organic and low-external input production systems, framed with a broader multidisciplinary agro-ecological approach to farming (i.e. 'agroecology' [10], 'eco-functional intensification' [11], 'sustainable intensification' [12] and landscape management or 'farmscaping' [13]) is essential. Against this backdrop, a review of the current documentation of the environmental impact of organic production systems in temperate regions is timely.

An overreaching goal of organic standards, globally, is to develop farm enterprises that are 'sustainable and harmonious with the environment'. In Canada, for example, five of the seven guiding principles of the national standard for organic production [14] refer to environmental and ecological goals of organic farm management, including minimizing soil degradation and erosion, decreasing pollution, optimizing biological activity and 'health' and maintaining biological diversity, and recycling materials and resources within the production system. These principles are in line with the motivations of many organic producers. A survey of more than 600 Canadian organic farmers found improving holistic management, including rotations, soil quality and soil life, ecological interactions and energy (E) use, as their top ranked research priorities [15]. In the USA, a study found that an Iowa organic beef producers' first priority was to protect wildlife habitat and water quality, nurture plant diversity and gain 'an ecological profit' [16]. However, surveys suggest most North American consumers, in contrast to those in Europe, who purchase organic foods do so mainly as they perceive this to be primarily a healthier choice for themselves or their families [5, 17], with only a few respondents (11 and 2% respectively) identifying farm environmental or animal welfare attributes as motivating their purchases. In contrast, across five European countries, consumers exhibited a positive willingness-to-pay more for 'animal welfare', 'regional production' and 'fair prices to farmers' arguments, which were considered 'well communicated' to the consumer in these markets [18]. Results such as this are encouraging for organic farmers in North America and elsewhere, suggesting that improved environmental stewardship and animal husbandry, if well-documented and communicated to the consumer, is a promising strategy to further differentiate organic products in the market.

Maintaining acceptable yield levels within organic agriculture can be challenging. Often, organic yields average 20% below conventional crop and livestock production systems, respectively [19–24]. However, the yield difference depends on the crops, the farming system, the degree of intensification in local conventional farming and agro-ecological conditions [25]. A significant interaction was found between observed yield differences on comparable organic and conventional farms and the potential yield for the location (i.e. yields in conventional crops under no nutrient limitation and good pest control) [26]. Yield differences varied between years and were smaller on relatively poorer sandy soils. Organic farm gross margins often still remain greater [21, 27, 28]. In Denmark, organic cash crop producers, dairy and pig keepers also had higher income per hour of labour in most years between 2005 and 2009 [29]. However, there are certainly studies providing exceptions to this point regarding system profitability [30]. The challenges of providing adequate N and controlling weeds are key limitations to organic stockless cash crop production [31]. As discussed also below, in North America, potential P deficiencies may be as important [32–35]. However, and as noted elsewhere [5] , the distinctive characteristics (cropping, floral and habitat diversity; nutrient intensity; soil management; and E and pesticide use) that are generally common to organic management can in turn be key drivers conferring important environmental and ecological benefits from these systems. Thus, in any region, the trade-offs between single crop yields, efficiency of resource use and ecological benefits must be considered when evaluating organic production systems [5, 19].

It can be hypothesized that if the true costs, externalized to the environment, of food production, were internalized, organic systems would be more economically competitive and command a larger market share in the food marketplace when combined with additional social and financial benefits derived from organic farming, these systems could potentially solve broad multiple policy goals for agriculture [21, 36]. Currently, organic agriculture is seen as a political tool for reducing the environmental impact of farming in Europe. Thus, in Europe, organic producers have received, for decades, direct government payments through agri-environmental schemes (AES) for environmental stewardship services to society (protection of water, biodiversity, etc.) [37, 38]. Whether AES schemes are effective in promoting biodiversity and other objectives, and whether in turn organic farming is necessarily deserving of support has been the focus of a substantial body of research and debate [8, 38–43]. To date, North America generally, and Canada in particular, lags other OECD countries in providing AES-related support to agricultural producers.

The topic of environmental and ecological impacts of organic management has received increasing attention in recent years. Lynch [5] provided a review of emerging information while highlighting relevant Canadian studies. Mondelaers *et al.* [44] conducted a meta-analysis of comparative environmental impacts of organic and conventional farming. More recently, Gomiero *et al.* [4] comprehensively examined comparative performance of organic production with respect to soil biophysical

Table 1 Comparison of soil organic carbon storage of organic (org) and conventional (conv) farming systems

Reference	Region	Type of study	Study period (years)	Org < conv	Org=conv	Org>conv
[135]	Canada	Comparative field trial	12		√[1]	
[113]	USA	Comparative field trial	22			20–25%[2]
[22]	USA	Comparative field trial	9			19%[3]
[23]	USA	Comparative field trial	11		√	
[137]	USA	Comparative field trial	8	12%[3]		
[54]	Switzerland	Comparative field trial	27		√	
[53]	Sweden	Comparative field trial	18			16%
[56]	England	Paired farm study	1–58[4]		√	
[71]	Denmark	Comparative field trials	11		√	

[1] SOC not measured but assumed no difference between farming systems.
[2] Higher gains (25%) were recorded for the 'organic animal' then 'organic legume' (20%) system.
[3] Compared with a no-till treatment.
[4] Variation in length of time in which organic farms (n=16) were managed organically.

and ecological characteristics, biodiversity, E use and greenhouse gas (GHG) emissions. There are other specific detailed reviews on topics such as E, and global warming potential (GWP) footprint of organic systems [20, 45], while earlier reviews focused on the topic of biodiversity [46, 47]. Until recently, few empirical studies in the USA and Canada examined environmental benefits derived from organic agriculture, although with expanded national funding for research in organic in these countries in recent years this situation is fortunately changing. The semi-arid ecosystems characteristic of much of the organic hectarage, extensive management of grazing lands, emerging potential resource limitation with respect to P availability, plus widespread use of genetically engineered (GE) crops in conventional production, in the USA and Canada, however, are conditions which differ substantially from those of temperate regions of Northern Europe, and which may substantially influence the outcomes of such studies. Our objectives are to complement the existing literature by highlighting key additional findings from temperate regions, with particular reference to U.S. and Canadian studies, which relate to the broad environmental/ecological impacts of organic agriculture, and to compare these results with those from other temperate regions, notably Europe. Key findings are presented and discussed within the indicator categories of: (i) soil organic matter storage, (ii) soil quality/soil health, (iii) biodiversity, (iv) nutrient loading and risks of off-farm nutrient and agrochemical losses and (v) energy use and global warming potential, with the additional aim of suggesting important areas of insufficient knowledge and/or areas where the organic sector needs to improve in order to be of significant relevance for solving environmental problems related to agriculture.

Soil organic matter storage

Soil organic matter is a key attribute of soil quality and soil health. In agricultural soils, the soil organic C (SOC) level is a function of the influence of a given management system on the net effect of the processes of C deposition from crop residues and organic amendments versus C losses from soil respiration and SOC decay [48]. In Canadian and U.S. agricultural systems generally, gains in SOC over the past few decades have been attributed to a reduction in the use of summer fallow, and in particular to the adoption of no-till and minimum tillage practices [49]. Organic farming systems, within this context, are criticized for their continued reliance on mechanical tillage for incorporation of green manures (GMr) and weed control. Can organic systems be promoted as viable options for storage of SOC or does the added tillage deplete SOC? Or alternatively, are organic systems possibly neutral with respect to SOC storage, but does the added C return (and decomposition) in these farming systems play a key role in stimulating nutrient dynamics and soil biological life? Indeed, surveys of Canadian organic farmers [15], found a greater interest in research focused on soil quality rather than SOC sequestration, suggesting organic producers regard the soil as a dynamic system as opposed to just a sink for SOC.

Many authors have proposed organic management systems as a means of promoting SOC gains. The consensus of the data suggests organic systems at least do not deplete SOC when compared with conventional production (Table 1). Mondelaers *et al.* [44] concluded that organic farms have 'on average' higher SOC content, while Smith [50] and Gomiero *et al.* [4] proposed adoption of organic farming as one of a suite of practices to improve soil conservation and SOC sequestration. A report to the Food and Agriculture Organization (FAO) [51] concludes that reducing GHGs through SOC sequestration in soil has great potential to mitigate climate change and is desirable in both low- and high-yield crop and animal systems. In a U.S. maize–soyabean cropping systems study, qualitative differences in crop residues in the organic system, which included a vetch GMr, were considered critical to SOC gains [52]. In contrast, a long-term (18-year) study in Sweden reported that SOC concentrations decreased in both organic and conventional systems, but less so in the organic because of higher C inputs and lower soil pH values [53]. They concluded, however, that organic farming appeared not to be an option for sequestering SOC. Leifeld *et al.* [54] conducted a detailed study (including soil fractionation, radiocarbon dating, and modelling with the carbon model RothC) of SOC levels within the DOK trial in Switzerland [55]. The DOK study includes three organically fertilized treatments under conventional, organic and biodynamic management, and two systems with or without mineral fertilizer. After 27 years, topsoil (0–20 cm) SOC levels had declined equally for all treatments. In England, farm management (organic versus conventional), in contrast to soil texture and cropping (arable versus grassland), failed to influence soil (0–20 cm) SOC concentration [56]. All soils have a limit to SOC storage, a capacity strongly influenced by soil texture [57], which may limit any gains through organic management. In addition, accurate comparisons of farming system gains in SOC ideally should also monitor changes in soil bulk density in order to compare on an equivalent soil mass basis, or document SOC levels throughout the entire soil profile. Finally, where manure or compost is imported into the farm system under study, appropriate recognition of this transfer, rather than actual gain, of C must be acknowledged (i.e. chosen manure or compost input rates must be credible and correspond to the production systems' capacity for assimilating C [54]). Soil carbon results from systems comparison trials where the organic plots receive large amounts of imported organic matter (e.g. manure from a disproportionate livestock production that could not have been sustained by the crop production in the tested crop rotation) should be interpreted with caution, because the import of such a carbon source might have resulted in less SOC maintenance in other locations. Perhaps in recognition of the complexity of accurate SOC measurement and lack of consensus on gains with organic production, in studies conducted to gauge E efficiency and GWP of organic versus conventional production systems, SOC changes are sometimes considered neutral and not included in calculations [20, 28, 58]. When modelled SOC changes were included in LCA comparisons within pig and soybean production sectors, the differences between farming systems became larger [59, 60].

A recent survey of 225 Canadian Prairie-region grain growers [61] found that while organic farmers used tilled summer fallow more than conventional producers (52% versus 6%) the use of GMrs was much more prevalent among the organic producers (84% versus 6%). Few empirical studies, however, have gauged the net effects on SOC of such added C return, combined with added tillage, within organic management systems [5]. A 9-year comparison of selected minimum-tillage strategies for production of maize, soybean and wheat was conducted by [22] at USDA-ARS Beltsville, MD. Four management systems, including: (i) an organic system using cover crops and manure for nutrients and reliant on chisel-plough for tillage and post-planting mechanical cultivation for weed control, (ii) a standard no-tillage system with recommended N inputs and herbicides, (iii) a no-till cover crop (hairy vetch and rye) system with reduced herbicide and N inputs and (iv) a no-tillage crown vetch living mulch system, were compared. Despite the use of tillage in the organic regime, at the end of the study SOC and N concentrations were greatest at all depth intervals (to 30 cm) in the organic system, and 19 and 23% greater, respectively, than found for the no tillage system. This was reflected in improved soil productivity under the organic plots. Wortman *et al.* [23] report a long-term (11-year) cropping systems study in Nebraska, in which the conventional system consisted of fertilized soybean, winter wheat, maize and sorghum, while organic systems utilized composted beef manure (applied once only) in place of fertilizer, or an alfalfa forage, prior to maize and sorghum. At the end of the study (SOC levels were reported for 0–15 cm depth only) treatments had largely equivalent SOC concentrations.

Innovative approaches to termination of GMrs that reduce reliance on tillage, are increasingly being explored in organic systems. Hepperly [62] reports on the substantial additional SOC gains from a 'biological no-till' system that combines cover crops and a crop roller (also known as blade rollers or roller crimper) system at the Rodale Institute when compared with conventional no-till and standard organic management. Vaisman *et al.* [63] compared the impact of rolling or tilling or a combination of rolling and tilling, at flowering, of a pea (*Pisum sativum* L.) GMr or pea and oat (*Avena sativa* L.) on soil N dynamics, weeds and yields of the subsequent wheat crop in Manitoba, Canada. The added soil cover (50–90% cover) provided by GMrs mulches following rolling compared with tillage (< 5% cover) can provide important soil and water conservation benefits, although the impact of potentially reduced soil temperatures and spring available N needs further examination. No-till systems for organic vegetable production are also being increasingly explored such as no-till or rolled hairy vetch and fall rye cover crop systems for field tomatoes, cucumber, zucchini and bell pepper production in the USA and Canada [64–67].

Few studies have examined the influence of livestock systems and management of permanent grassland on SOC. Under organic standards, organic ruminant livestock producers are required to rely on forage-based livestock feed including, in season, management of grazed rangeland or pastures. Some studies suggest that improved grazing management, including the use of legumes, can be not only a cost-effective option but can also promote substantial SOC gains on the extensive acreage of often degraded, permanent grasslands in North America [16, 68, 69].

Soil Quality/Soil Health

As noted by [70] the routine return of C to soil in organic systems through the increased use of perennial crops and GMrs is perhaps most important in its ecological effect in maintaining soil health and biodiversity, mitigating the disruptive effects of more intensive cropping in conventional systems on micro- and meso-fauna communities. Convincing evidence for such enhanced microbial activity, but not necessarily SOC gain, is provided from Europe [71]. In an 11-year study in Denmark, an organic rotation (including GMrs, catch crops and manure) was compared with an inorganic fertilizer based rotation. While organic management treatments returned C to soil at rates 18–91% greater than the conventional rotation, after 11 years, SOC levels (0–30 cm depth) were similar across all systems, attributable to increased microbial biomass and activity (respiration) correlated with C input rates. This is consistent with many studies demonstrating that soil health and biodiversity appears to benefit from the unique characteristics of organic production regimes [4, 5, 19, 55]. Organic farming correspondingly tends to achieve improved outcomes with respect to preserving or improving soil quality (see studies cited within Gomeiro *et al.* [4]). In Atlantic Canada, organic potato farms utilize extended (5-year) rotations, including legume cover crops, compared with much more frequent cropping of potatoes (and associated tillage) in conventional systems [72, 73]. On four organic farm sites, earthworm abundance and biomass, and soil microbial quotient, was shown to particularly benefit from these extended rotations, recovering from marked reductions during potato cropping to levels found in adjacent permanent pastures after 3–4 years of the rotation [74]. SOC levels were also sustained, ranging from 30 to 38 Mg C/ha for surface (0–15 cm) soil, across all farm sites and rotation phases. Irmler [75] similarly found changes in earthworm populations during conversion to organic farming were not related to SOC or soil pH alone. Organic management may also influence C resource utilization efficiency by the soil microbial community [55] attributable to shifts in soil microbial functional diversity.

Documenting a minimum dataset of parameters to assess soil quality or soil health *in situ,* as in the above studies, is complex, time-consuming and costly. Nelson *et al.* [76] assessed whether a lab method, based on the response of a sole bioindicator, may have promise as a method to gauge the health of agricultural soils. The bioindicator used, the Collembola *Folsomia candida* (FC), is an established standard laboratory-based soil eco-toxicology test [77]. Intriguingly, results, following a series of test modifications, indicated a more positive FC response (with respect to changes in body growth and reproduction) when exposed to organically managed compared with conventionally managed soils.

Biodiversity

A growing body of literature, primarily European in origin, suggests species abundance and richness, across a wide range of taxa (including arable flora, birds, mammals and invertebrates), benefits from organic management [5, 19, 46, 47]. Gomiero *et al.* [4] provide a comprehensive review of this area of study, and that report and others [13, 78, 79] also explore the complexity of linking biodiversity with ecosystem services. In Canada and the USA, the increasing specialization in intensive arable cropping, expanded herbicide use and reduced need for rotations, has strongly affected the composition, heterogeneity and interspersion of habitats in agricultural landscapes. Farm fields have become characterized by low within-field and between-field variability, while field margins and other-non crop habitats have been reduced or eliminated. Strong evidence exists that these changes have had substantial adverse effects on wildlife, including beneficial insects and birds [3]. Corresponding increases in N input use have likely also negatively impacted on farmland biodiversity [8]. Is there evidence that organic cropping systems in the USA and Canada increase farmland biodiversity and how do these results compare with those found to date in Europe?

Vegetative diversity

Boutin *et al.* [80] conducted a study on 16 conventional and 14 organic farm sites in Ontario, Canada, inventorying plant species in crop fields and woody hedgerows and found clear differences in vegetative species richness and composition between the organic and conventional sites. More native and exotic plant species were found in fields and woody hedgerows on organic sites. Numerous species, including several long-lived herbaceous forest species were only found in organic hedgerows. Older fields tended to promote prevalence of exotic species, while farm type was a significant predictor of native species richness. Similarly, in a study conducted on commercial farms in Estonia, organic farming promoted richness of ‘nature-value’ species less tolerant of contemporary agricultural practices [81]. However, both field boundary type and width, along with landscape structure, rather than farming system, accounted for most of the observed vegetative diversity. In a comprehensive recent study conducted across 153 farms in Europe, Winqvist *et al.* [79] found the abundance and species richness of wild plants were enhanced by both organic farming and more complex landscapes.

In conventional production in the USA and Canada, farmer adoption and use of GE crops has been very high (over 80% of canola (*Brassica napus* L.) grown in Canada, and 80% of cotton (*Gossypium* spp.) and soyabean (*Glycine max* L.) in the USA were GE by 2004). The greatest risks from GE production relate to GE-intraspecific (within-species) movement of transgenes within and among farming systems. Among documented cases, intraspecific transgene movement in canola has been the most common, producing volunteer herbicide tolerant canola, canola-weed hybrid 'superweeds', and ultimately the loss of organic canola production on the Canadian prairies [82]. Organic production, by banning the use of GE technology and trying to limit cross-contamination in seed and during production and marketing, attempts to limit the ecological impacts that may relate to further escape to the environment of transgenes (whether from crops with current herbicide-tolerant traits or future GE crops with broader physiological traits such as salt or drought tolerance). More broadly, organic producers have a continued disproportionate interest in use and preservation of heritage crop varieties and their seed stocks.

Few studies have examined the impact of organic management of rangelands and grasslands on vegetative biodiversity. The oversupply of N and P is considered a major driver of biodiversity loss in temperate grasslands [2]. The avoidance of this causal factor and reduced likelihood of overgrazing in organic management may promote the establishment of more diverse and multifunctional swards, as reported from Iowa [16]. There is a need also for more farmland biodiversity studies under semi-arid conditions common to much of North America, as results from more temperate regions such as Northern Europe may not transfer to these different climatic and ecological conditions. In Nebraska, [83], above ground weed biomass (primarily grass species), was greater after 12 years of organic compared with conventional grain rotations, and particularly so for the GMr (alfalfa) rather than manure-based organic system. This was largely reflected also in weed seed bank diversity, evenness and richness. In dryland conditions in Spain, greater differences (abundance 202%; richness 176% and diversity 133%) in weed communities found between 28 pairs (organic and conventional) of farms compared with studies from Northern Europe were attributed to richer weed flora and weed seed availability under their conditions and management regime [84].

When assessing biodiversity, the time from transition to organic farming or adoption of beneficial practices appears also to be an important factor. In California, Smukler *et al.* [13] found 'farmscaping' (i.e. the management of non-production areas to enhance biodiverse habitats and landscape heterogeneity) of an organic farm in the Sacremento Valley in California, over a short time frame was more likely to affect plant diversity when compared with below-ground biodiversity (earthworms, nematodes and microbial diversity).

Farmland birds

The presence of non-crop habitats and landscape heterogeneity are increasingly recognized to be as important as farming system in determining the distribution, composition, abundance and richness of different organisms on agricultural landscapes [4, 79, 85–87]. Freemark and Kirk [88] counted birds over a breeding season on 72 field sites, across 10 organic and conventional farms in southern Ontario. Sites were matched for crop and non-crop habitat characteristics, including crop type, adjacent non-crop habitat, and when possible, field size and shape to enable effects of agricultural practices to be detected. Of 68 bird species recorded, species richness, abundance and frequency of occurrence was significantly higher on the organic than the conventional sites. Local habitat and agricultural practices each contributed roughly equally to the variation in bird species among sites. Differences found between farm types were considered most likely to be the result of reduced availability of nesting sites and food supply, because of lower plant species richness, cover, seed availability and soil invertebrates on conventional farms. These results appear to concur with those conducted in Europe where agricultural intensification is considered the main cause of a drop of 52% in farmland bird populations [89]. Winqvist *et al.* [79] found breeding birds were enhanced by both organic farming and more complex landscapes (as measured by percentage arable crops within 1 km of the study area).

Lepidoptera

Lepidoptera, primarily butterflies, have been studied extensively across farmlands in Europe but much less so in North America, although results there differ as to whether farming system is a significant predictor of biodiversity. Boutin *et al.* [90] examined the contribution of crop fields and woody hedgerow habitats to regional moth diversity within eight pairs of farmlands managed organically or conventionally near Peterborough, Ontario. Only hedgerows which were structurally similar on both farm types were selected. Out of 26 020 individuals representing 408 moth species captured, the study found no difference in moth assemblages between organic and conventional farming systems (except for species richness of the Notodontidae family). However, habitat-type greatly influenced average species richness, abundance and composition of moths, with hedgerows harbouring more species than fields did.

Soil biology

An earlier study, in the same Canadian province, on beneficial and phytophagous arthropods, found that the former were more abundant in woody hedgerows, while the latter were more abundant in crop fields [91]. Overall abundance was influenced by farming systems, while family richness was not. While local factors (plant composition and management regime) strongly influenced arthropod composition so also did habitats in the surrounding landscape. In Europe, Ponce *et al.* [84] found abundance and richness was 43% and 6% greater, respectively, under organic management and observed a strong link between plant (especially insect-pollinated weeds) and arthropod diversity, while Purtauf *et al.* [87] found landscape complexity (quantified as percentage grassland cover) more important than farmland management to carabid beetle diversity. In their review, Winqvist *et al.* [79] found no difference in ground beetle abundance and richness between farming systems.

The link between soil ecology and production system has been recently reviewed by Gomiero *et al.* [4], while soil health is discussed above. Nelson *et al.* [61], in their review of soil microbial communities as influenced by semi-arid grain cropping systems as found on the Canadian prairies, concluded that systems that have reduced tillage, diverse crop rotations or intercrops, low applications of inorganic fertilizers and pesticides, and some organic fertility inputs tend to encourage a large and diverse microbial community. As also discussed below, at the long-term Glenlea grain cropping systems study in Manitoba [121] found that while organic crop management decreases labile P, it promotes mycorrhizal colonization, and increases mycorrhizal spore populations. More recent research, utilizing molecular techniques found significant differences in mycorrhizal species composition on paired organic and conventional dairy farms in Ontario [92]. Is soil biota also influenced by both local and landscape factors and their interaction, as found for aboveground taxa? Flohre *et al.* [85], in Germany, examined this question on 12 pairs of farms across landscapes varying in structural complexity and found microbial biomass and earthworm species richness increased under organic farming as landscape simplified, and predation pressure reduced, while the opposite was true under conventional farming. As organic farming consistently enhanced species richness of weeds, it was concluded that this farming system is more efficient at conserving aboveground rather than below-ground diversity.

The above studies, primarily of North American origin, suggest that among taxa, plants followed by birds show the most consistent and pronounced responses to the use of organic systems *per se*, while responses of other taxa are more variable and dependent on interactions with habitat-type and landscape. These results are in general agreement with others [4, 47, 79, 86] and studies conducted in Europe.

Linking biodiversity to ecosystem services

While the above advances in understanding of the relationship between farming system, landscape and biodiversity are encouraging, we are just beginning to understand the relationship between such biodiversity and ecosystem services such as pollination, pest control, SOC storage or water quality maintenance [13, 79, 93–95]. Under semi-arid conditions in California, Smukler *et al.* [13] reported that environmental variables (including SOC, infiltration rates and dissolved organic C), associated with non-crop habitats on an organic farm explained the on-farm distribution of plant and soil taxa. These locations, including hedgerows, drainage ditches, a riparian corridor and tailwater ponds, in turn, provided the ecosystem services of enhanced plant biodiversity, water regulation and SOC storage. Crowder *et al.* [96] argue that organic farming promotes evenness of species, or communities, of natural predators. In work validated under organic potato production systems in the USA, they suggest a high level of evenness of natural predator species, rather than species richness alone, provided the strongest degree of pest control and crop growth. In Europe, after 30 years of the Swiss DOK trial, Birkhofer *et al.* [19] found organic management enhanced soil quality, microbial and faunal decomposers and fostered natural enemies and biological control of aphids. Garratt *et al.* [93] conducted a meta-analysis of pests and natural enemies as affected by farming systems and concluded that performance and abundance of all groups of natural enemies, except the coleopterans, consistently showed a positive response to organic agriculture. This impact was more pronounced at the farm than field scale and indicated larger-scale characteristics, including habitat heterogeneity on organic farms was facilitating natural enemies, in agreement with Krauss *et al.* [78]. In their comprehensive study on 153 European farms, Winqvist *et al.* [79] examined predation on aphids placed within cereal fields as an index of biological control potential. This service was affected by farming system and landscape and their interaction, being greatest in organic fields within complex landscapes, while the opposite was true for conventional fields.

Over 66% of crop species globally require pollination. In northern Alberta, Canada, Morandin and Winston [97] examined native wild bee abundance and pollination deficit (the difference between potential and actual pollination) in organic, conventional (non-GE), and herbicide-resistant GE canola fields. Bee abundance at bloom was greatest (342) in the organic fields followed by conventional (230) and GE (101). Correspondingly, there was no pollination deficit in organic fields, moderate (−16%) in conventional fields and the greatest deficit (−22%) in GE fields. The results with respect to bee abundance and pollination success for the GE fields were attributed to markedly reduced weed diversity and abundance (and thus forage for bees) in these fields in particular. In Germany [78, 98] and Ireland [99], insect-pollinated plant species in arable crops and grasslands and insect pollinators benefited disproportionately from organic farming.

Evidently, much more needs to be done to improve our understanding of the mechanisms underlying shifts in biodiversity at work at the field and farm scale as affected by type and intensity of organic production, and in turn the link to ecosystems services. Oelofse *et al.* [100] recently reported on case studies from Brazil, China and Egypt and found organic niche market crops with a high-value influenced organic farmers' management decisions, with a willingness to opt for input substitution for fertility and pest management rather than prioritizing cropping system diversity for agroecological purposes, a trend they termed the 'conventionalization' of organic production. More broadly, can we envisage in North America an effective targeted approach that builds on a link between biodiversity and ecosystem services, and a corresponding development of appropriate policy mechanisms and AES programmes for producers? In California, Smukler *et al.* [13] demonstrated that both enhancement of biodiversity and provision of multiple ecosystem functions on organic farms can be effectively implemented through a targeted enhancement of non-crop habitat on-farm. In Europe, both Winqvist *et al.* [79] and Gabriel *et al.* [101] recommend that both local farm management and regional landscape complexity must be considered when developing AES schemes targeting biodiversity and a range of ecosystem services. Currently, AES programmes in North America, particularly in Canada, have lagged behind other OECD countries in providing support for on-farm efforts targeting biodiversity and linked ecosystem services. An interesting exception is a new provincial pilot programme in the province of Quebec, which provides financial support to producers to enhance the 'multifunctionality' of their farms, including the establishment and maintenance of non-production habitat such as hedgerows [102].

Nutrient Loading and Risks of Off-farm Nutrient and Agrochemical Losses

The increase in agricultural intensification over the past 40 years has greatly increased the risk and incidence of contamination of surface and ground waters by nutrients (especially N and P) [2] and pesticides. In eastern Canada, for example, an increasing acreage of agricultural soils has been classified as at high risk of being a source of nitrate N losses to water [103, 104]. The off-farm costs of mitigating such soil and water degradation typically far exceed the costs of appropriate on-farm soil conservation and nutrient management practices [21].

Nutrient loading

On organic cropping farms, environmental benefits with respect to reduced off-farm nutrient impacts are closely linked to reliance on more complex rotations, legume biological nitrogen fixation and organic matter inputs and reduced overall nutrient intensity [5, 105, 106]. In turn, and as noted above under 'Soil Health', extended rotations within organic systems can enhance soil biological pools, which may contribute to nutrient dynamics in these systems in ways not fully yet appreciated [55, 74, 107]. Legume crops in organic crop systems, also act as an 'N buffer', reducing the risks of large excesses or deficits of N, and by accommodating lower application rates of organic amendments, reduce soil P and K accumulation [108]. A study of 15 organic dairy farms in Ontario, Canada found farm nutrient (NPK) loading (imports–exports), was greatly reduced under commercial organic dairy production compared with more intensive confinement-based livestock systems [35]. Annual farm nutrient surpluses averaged 75 (N), 1 (P) and 11 (K) $\mathrm{kg\,ha^{-1}\,yr^{-1}}$. Interestingly, organic farm nutrient surpluses were positively related to farm livestock density and negatively related to farm feed self-sufficiency. As noted above, N- and P-loading negatively impacts biodiversity of grasslands and whole farms [2, 8]. Mondelaers *et al.* [44], following a meta-analysis, concluded there was generally less nitrate and P losses through leaching from organic systems per hectare when compared with conventional systems but that differences were less apparent if expressed per unit product from each farming system, in agreement also with Korsaeth [109].

Nitrogen

The challenge of managing N in organic systems to sustain adequate productivity and nitrogen-use efficiency (NUE), while minimizing N losses, should not be understated [4, 5, 31, 106]. While sufficient N for the crop rotation is relatively easily supplied in mixed crop and dairy farms [110], the lack of a commercial purpose for grass-clover crops often reduces the use of GMr crops in organic cash crop rotations [29, 110, 111]. Synchronizing N availability with crop demand in organic cash crop systems is difficult as the supply of N from organic amendments, GMrs and crop residues, plus residual soil mineral N (RSMN), to the crop varies with climatic conditions and among years [106] and for winter cereals often is available later in the season than the start of crop N uptake. Lynch *et al.* [106] reported on results of a series of studies in Atlantic Canada on organic potato production, including on commercial organic farms. Following legume GMr of red clover or hairy vetch, potato yields and N uptake ranged from 30 to 35 Mg/ha (~20% lower than conventional) and 100–125 kg N/ha, respectively, while post-harvest RSMN, which is most likely be lost through leaching overwinter, remained low, especially when compared with conventional potato systems in the region [73, 112]. Combining N supplementation (with composts or dehydrated manures) with GMr consistently increased total and marketable yield although RSMN increased with manure use. In the USA, Pimentel *et al.* [113] found sporadic increases, over a 12-year period, in nitrate leached under maize following a hairy vetch GMr, especially when drought conditions reduced maize growth and N uptake. However, over all 12 study years, differences in annual nitrate leached were not significant, as found also in Sweden [53].

In orchard systems in Washington State, Kramer *et al.* [114] found 4.4–5.6 times greater annual nitrate leaching in conventional compared with organic plots. In irrigated processing tomato and maize production systems in California's Sacramento Valley, Poudel *et al.* [115] found similar crop yields across organic, low-input and conventional farming systems over 5 years, but a lower potential risk of N leaching in the low-input and organic systems. In Denmark, Askegaard *et al.* [31], reporting on a 12-year study conducted at three locations, found inclusion of a grass-clover GMr in organic cereal rotations did not increase N leaching. Inclusion of fall catch crops [31] and modifying the timing of GMr incorporation [106] are further important management options for minimizing leaching losses of N from organic systems.

Agriculture is relatively inefficient with respect to the amount of N retrieved in food produced per unit of N applied (NUE) [7]. In Sweden, Kirchmann *et al.* [53], following an 18-year trial, found the organic management system was less efficient with respect to NUE as N leaching was not reduced and weed competition reduced crop N uptake. In contrast, in Germany, both Finckh *et al.* [116] and Möller *et al.* [117] found that NUE can be improved under low input or organic potato production systems, possibly linked to improved crop light use efficiency when N is limiting. Halberg [110] and Halberg *et al.* [118] found significantly higher NUE in organic versus conventional dairy farms and lower N surplus per hectare. Askegaard *et al.* [31] and Halberg [110] demonstrated a high NUE from supplemental spring applied manure (when applied at a moderate rate of 70 kg N/ha) with no added N leaching. Development of new practical soil tests and plant bioassay tools to gauge soil N supply will be an important element in further improving NUE in organic systems [106]. More broadly, greater understanding is needed of the potential environmental trade-offs at play in these systems associated with improved soil quality on the one hand but possibly greater N losses to leaching and GHG on the other [105].

Insect pest dynamics may also be significantly affected by N availability and intensity [4, 93, 119, 120]. In potato production systems, Colorado potato beetle (CPB) (*Leptinotarsa decemlineata* (Say)) is the most destructive defoliating insect pest in Canada and North America. Boiteau *et al.* [120] found excessive rates (300 kg N/ha) of fertilization with a commercial organic fertilizer derived from poultry manure, promoted more rapid CPB larval development and earlier peaks of abundance of beetle larvae. But as the influence of fertilizer on overall potato beetle populations was limited, fertility management would only have a secondary role in control of this pest. In Maine, Alyokhin *et al.* [119] found CPB density was greater following full rates of synthetic fertilizers compared with when following reduced fertilizer rates combined with manure inputs. Garratt *et al.* [93] concluded that pests respond differently to the type of organic fertilizer, specifically manure and composts, while natural enemies responded positively to all organic fertilizers. For further discussion of this 'mineral balance' hypothesis see Gomiero *et al.* [4].

Phosphorus

In many organic production systems in North America, low farm P imports, and potential P deficiencies, may be as important a management consideration as the challenges of optimizing N use [32–35, 121]. Constraints with respect to P release efficacy of mined phosphate rock, especially as they are sparingly soluble in the alkaline calcareous soils common to the northern Great Plains of North America, make this issue a further challenge [34, 122]. In addition, livestock-based manure and compost sources are often in limited supply. Indeed as a reflection of this reality on many organic, particularly grain farms, in North America, long-term rotation studies, such as that of Wortman *et al.* [83] (Nebraska); [Entz, personal communication, 2011] (Manitoba); and Lynch *et al.* [106] (Nova Scotia), tend to use manure or compost supplements as an intermittent P source rather than as a routine N source. For example, Wortman *et al.* [23] in Nebraska used composted beef manure (~30 Mg/ha applied once in 11 years) to offset potential P deficiencies in their organic perennial-grains cropping system. While novel organic amendments such as source-separated municipal solid waste (or 'green waste') composts may be an effective source of soil P (and N) supply [106, 123], their use remains limited at present. Turmel *et al.* [124] and Welsh *et al.* [121] reported on the first 13 years of the Glenlea Long-term Crop Rotation and Management trial in Manitoba which compared, a conventional and organic annual grain rotation and perennial forage and grain rotation. Under the organic system, no fertility inputs were applied until a very recent application of compost on half of the perennial plots. While alfalfa in the rotation, managed as a hay crop, provided sufficient N supply to enhance yield and protein content of organic wheat, it also had the effect of more dramatically drawing down soil test P levels (< 5 ppm) and wheat grain P content, compared with the organic annual grain system. Ongoing research in Eastern Canada is gauging whether P supply in organic forage production systems is adequate to sustain forage legume biological nitrogen fixation [92, 125]. Organic management, and these low soil P levels, however, generally promotes mycorrhizal association of crops [92, 121, 124], and provides the added benefit of substantially reduced risks of off-farm P losses.

Agrochemicals

Very little research globally has directly examined the comparative impact of nutrient and agrochemical losses from organic and conventional farming systems on water quality and aquatic ecosystems. In England,

Table 2 Comparison of energy use, energy efficiency and global warming potential of organic (org) and conventional (conv) field cropping systems (%Org-Conv/Conv)[1]

Authors	Region	Type of study	Measure	Org < conv (%)	Org>conv (%)
[132]	Canada	Comparative field trial	E use (MJ/ha)	50	
			E efficiency (MJ/MJ input)		20
[135]	Canada	Comparative field trial	E use (MJ/ha)	51	
			E efficiency (MJ/MJ input)		24
[134]	Canada	LCA (of conversion)	CO_2e/ha	61	
			CO_2e/product	23%	
[137]	USA	Comparative field trial	GWP (g/m)	64[2]	
[144]	USA	Comparative field trial	Non-renewable E use (MJ/ha)	30	
[146]	USA	Comparative field trial	E use (CO_2e/ha)	57	
			GWP (CO_2e ha^{-1})	69[3]	
			GWP (CO_2e unit/grain)	42[4]	
[58]	USA	LCA	GWP (CO_2e) kg/bread)	16	
[51]	Europe	Comparative field trials	GWP (CO_2e) per unit product	18	
[133]	Germany	Meta-analyses	E use (CO_2e/ha)	64	
[45]	Europe	Meta-analyses	GWP (CO_2e/ha)	50	
		(incl. 3 wheat studies)	GWP (CO_2e kg/grain)	21 (2 studies)	21 (1 study)
[130]	Spain	Meta-analyses of survey data	E efficiency (MJ/MJ input)		24
[136]	Spain	Comparative field trials	E use (GJ/ha)	71[5]	
			E efficiency (MJ/MJ input)		128[6]

[1] Modified from [20].

[2] Note: The no-till system surpassed the organic, however, with GWP of only 14 compared with the organic at 41, and conventional at 114.

[3] When compared with a no-till treatment this gain is 51%.

[4] When compared withy a no-till treatment this gain is 61%.

[5] When compared with a no-till treatment this gain is 67%.

[6] When compared with a no-till treatment this gain is 125%.

Hathaway-Jenkins *et al.* [56] found agrochemicals (including pesticides, herbicides and total N, P and K) in soil (0–20 cm) water were lower on organic farms that had been managed organically from 1 to 58 years. In New Zealand, Magbanua *et al.* [126] compared the effects of organic, conventional and integrated beef and sheep farming systems on water quality and stream macroinvertebrate communities. Conventional production led to more pronounced levels of fine sediment, nitrates and glyphosate concentrations in streams, with adverse consequences for invertebrate densities and biological trait representation, and the occurrence and density of sensitive groups.

Energy Use and Global Warming Potential

There has been expanded interest in recent years in evaluating the E efficiency of the entire food chain at national levels [127–129] along with comparative studies of E efficiency of farming systems [24, 113, 130–135]. Farm E use often exceeds 50% of total food chain E use [128]. In addition, a subset of studies have attempted to integrate data, where it exists, on GHG emissions to provide a more comprehensive assessment of farming system impact on total GWP of food products. Comprehensive reviews of E and GWP (which combines both E use and GHG emissions) of organic farming systems have been recently provided [20, 44, 45]. The reader is refereed to these studies for more a detailed discussion, including of methodological challenges, than can be provided here. In general, organic farming systems have been found to have significantly lower CO_2 emissions with respect to E use than comparable conventional systems, when measured on a per area basis, though in some systems or sectors that benefit is lost when measured per unit of production [4, 20, 45], often depending on assessed yield differences (Table 2). For example, Gomiero *et al.* [45] focused on European studies where the intensity of conventional production produces greater spreads in yields than found in North America [21]. The higher E efficiency found under organic systems is primarily the result of: (i) lack of input of synthetic N-fertilizers (which require a high E consumption for production and transport and can account for more than 50% of the total E input) and (ii) much lower use of highly E-consumptive foodstuffs (concentrates) and low input of other mineral fertilizers (e.g. P and K) [20, 45]. Added tillage required for GMr and weed management on organic farms has been shown to be a negligible contributor to farm E use [20]. In general, the lack of evidence regarding GHG emissions as affected by management system limits definitive conclusions regarding GWP as affected by farming system, although it can be expected GWP per hectare will be lower for most organic sectors [20].

Lynch *et al.* [20] assessed farm level E use and GWP by organic sector including field crops, beef, dairy, hogs, poultry, vegetables, fruit and greenhouse production. Data tended to be most sparse for organic greenhouse, poultry and hog production. In field crops (grains, grain legumes, oilseeds and forages), which is one of the largest organic production sectors in North America, the strong consensus of the data, even if limited solely to the North American studies (n=7) reviewed, indicated that organic systems require less E and improve E efficiency both per hectare and per unit product compared with conventional production (Table 2). The quality of the studies further strengthens confidence in this conclusion. For example, in Canada, Zentner *et al.* [135] recently published the results of their 12-year study from Scott, Saskatchewan, comparing nine cropping systems varying in input management and crop diversity with respect to non-renewable E use. The authors conclude that their results support the 'current movement of producers toward organic management as a means of reducing the reliance on non-renewable E inputs and improving the overall E use efficiency of their cropping systems'. Improved water use and resilience to drought sometimes observed for organic production under non-irrigated and dryland conditions [4, 5], may have also played an important role in this study (growing season precipitation averaged just 181 mm over the 12 years, combined with severe droughts in 4 of these years). Results similar to those of Zentner *et al.* [28] for E efficiency of organic grain production under semi-arid conditions were reported from Europe (Spain) [136]. Lynch *et al.* [20] found organic systems also less E-intensive and more efficient for hogs, dairy, beef and some vegetables. In contrast, for poultry and fruit, conventional systems appear more favourable at this time.

With a few exceptions [114, 137], there is a scarcity of studies in N. America which have examined the impact of rotations characteristic of organic management on temporal variability of N_2O emissions and overall GHG budget. Differences in the synchrony of N supply and crop demand between inorganic N and organic N (legume, compost) fertilized regimes will affect N_2O emissions. Organic farming systems are highly dependent on legume N_2 from biological nitrogen fixation but few studies internationally have examined N_2O emissions from unfertilized pure forage legume stands, a common feature on organic livestock and arable crop farms [35]. Lynch [5] reported on interim data from organic potato production studies in Atlantic Canada which concurred closely with data provided from Europe [138]. That study found N_2O emissions were lower for various organic than conventional crop rotations, ranging from ~4.0 to ~8.0 kg N_2O-N/ha across all crops as total N inputs increased from 100 to 300 kg N/ha/yr. In contrast, Chirinda *et al.* [139], in Denmark, found that despite the lower N input in organic rotations, annual N_2O emissions did not differ between farming systems (although inorganic N fertilizer rates to winter wheat were relatively low at ~170 kg N/ha). In comparison with the EU [59, 133, 140] no North American studies to date have attempted to model GHG emissions on a whole farm basis as affected by organic management.

To what degree does transportation add to E and GWP embedded in food products? As noted by Lynch *et al.* [20], national studies in the USA [128] and the UK [127] indicate transport to be a relatively small contributor to the E or GWP footprint of food products. No comparative Canadian national study is available to date, although Gan *et al.* [141] recently assessed conventional Canadian Prairie region grain production and concluded 60–95% of the product GWP (CO_2e) impact occurs prior to farm gate. However, there are undoubtedly exceptions to this generalization regarding the contribution of transport, given the expanded global trade in organic products. Production of internationally traded goods is considered to account for 30% of global CO_2 emissions, a figure that is increasing [2]. While the vast majority of exported goods continue to be transported by ship, incurring a lower transport related GWP impact compared with air freight or truck transport [142, 143], for selected organic products transport may still be a major contributor to its GWP footprint. Truck transport of organic products, such as California organic lettuce, across large distances in North America, when combined with E-intensive production creates high GWP footprints for these products [144]. Knudsen *et al.* [145] recently conducted an LCA assessment of organic (*Citrus sinensis*) juice imported to Denmark from small-scale farmers in Brazil. Transport, especially the truck transport of fresh oranges in Brazil and of reconstituted orange juice in Europe contributed 58% of its GWP, while the farm stage contributed just 23% of GWP. At the same time, SOC storage and E use was lower, and crop and vegetative diversity greater, on the organic than the conventional farms in Brazil.

MacRae *et al.* [142] suggest a series of production and consumption-side initiatives to further improve organic farming E use and efficiency and reduce GHG emissions. These include a continuing focus on enhancing productivity, nutrient recovery and recycling, and, if demonstrable gains in productivity, agroecological sustainability and efficiency can be shown, flexibility in adapting and modifying the Permitted Substances Lists within organic standards.

Conclusion

In summary, a growing body of literature of Canadian and US origin generally appears to concur with that found in Europe and other temperate regions, namely that the cropping, floral and habitat diversity; nutrient intensity, soil management regime and reduced E and pesticide use in organic farming in temperate zones confer important environmental and ecological benefits. These include maintenance of soil organic matter and added return of C to soil, enhanced soil quality and soil health, reduced off farm nutrient losses of reactive N and P, enhanced vegetative diversity, sometimes extended to birds and other taxa depending on management of non-crop habitat on farms and the broader landscape context, and reduced E use and improved E efficiency. The somewhat unique conditions highlighted here of semi-arid conditions and emerging low soil P levels, common to many organic farms in the U.S. and Canada, does not appear to have influenced these generally positive outcomes. Novel technologies discussed, such as GMr crimper rollers being explored in organic cropping systems show promise for further improving organic tillage and soil management regimes. Organic production in the U.S. and Canada is also conducted against a backdrop of widespread use of GE crops on surrounding conventional farms. One Canadian study presented here showed enhanced support for pollinators and pollination under organic compared with GE canola management, likely to be the result of enhanced vegetative diversity (and forage for pollinators) under organic management.

In the current review, we have contrasted studies comparing organic agriculture broadly with conventional agriculture. However, there is increasing appreciation that within all organic sectors a spectrum of farm management exists (diversity of cropping, nutrient intensity and livestock density, management of non-crop habitats, etc.) that can also strongly influence environmental outcomes. If organic agriculture is to continue to be seen as a tool to achieve public goals for environmentally friendly agriculture further improvements should reflect this more comprehensive understanding of this variation within organic production systems. Given the understanding of the key role of field margins and non-production areas in promoting biodiversity, revised organic regulations also need to consider outlining requirements for their establishment and maintenance. This will need to be done in the context of improved understanding of which non-farmed elements are more important, the relationship to landscape factors for various taxa, and even more broadly the sustainability of the farming system in relation to the agroecosystem carrying capacity within a region [4, 95, 101]. In general, the expansion of research examining ecological and environmental impacts of organic agriculture, sometimes tied to AES programmes (farmscaping and multifunctionality), is an important step in the evolution of organic agriculture as it shifts to a more outcomes-based system more in line with its founding principles rather than a farming system defined by permitted inputs and regulation of farming practices alone.

If organic agriculture is to increasingly move towards a more agroecological production system of 'ecological intensification' the complexity of the accompanying research will require multidisciplinary teams capable of drawing linkages between biodiversity and provision of ecosystem services [70, 147]. Whole-farm models coupling biophysical, economic and environmental data for carrying out multiple criteria analysis of new production systems will be required [30]. Current LCA models are challenged in attempting to integrate biodiversity parameters, and to move towards a more integrative tool that combines both carbon and water use 'footprinting' [2, 60]. More broadly, as organic production expands globally, whether an agroecological approach is adhered to, encompassing system redesign to mimic ecological processes, rather than input substitution [142, 148] will be critical to whether organic farms can be promoted as 'biodiversity reservoirs' [101], and this farming system be promoted as a credible approach to 'ecological intensification' [11]. Continuing credibility and support will depend on the trustworthiness of the organic sector vis-à-vis adhering to its basic principles while at the same time continuously intensifying production based on agro-ecological principles. This will put substantial pressure on the sector's ability for innovation and adaptation, which again needs to be supported by research. Moreover, political interests may identify organic agriculture as a single policy intervention that can deliver a number of societal benefits, from animal welfare to biodiversity and water protection. It will thus be important to further research this multicriteria aspect of organic agriculture and target the development of organic systems to meet such specific requirements.

However, in order to promote the adoption of a multifunctional organic agricultural systems the economic viability of various organic farming systems will also have to be further examined (see review in the introduction and [21, 27–30].). The broader cultural and socio-political context in Canada and the U.S. must also be considered. Recent surveys, noted in this review, emphasize the relatively poor current understanding of the multifunctional benefits of agriculture in general and organic specifically. In agreement with Jordan and Warner [148], an integrated social vision that integrates all stakeholders is needed to advance organic agriculture and the multifunctional benefits derived from it.

In closing, there seems to be an increased understanding that the challenges of producing enough food and biomass while preserving soil, water and biodiversity necessary for ecosystem services cannot be solved by prevalent types of conventional agriculture and that agroecological approaches and ecological intensification is fundamental for our future food production. Thus, terminologies such as agro-ecological approaches, ecological or eco-functional intensification are being used more and more frequently by international (FAO, United Nations Environment Programme, United Nations Conference on Trade And Development) and transnational (EU) organizations and NGOs and this could pave the way for support to further research and development of farming systems and methods based on organic principles. An evolving organic agriculture has a critical role to play in elaborating a scientifically based, resource efficient agroecological approach to sustainable and environmentally friendly farming systems.

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