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Review

The Carbon and Global Warming Potential Impacts of Organic Farming: Does It Have a Significant Role in an Energy Constrained World?

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Abstract: About 130 studies were analyzed to compare farm-level energy use and global warming potential (GWP) of organic and conventional production sectors. Cross cutting issues such as tillage, compost, soil carbon sequestration and energy offsets were also reviewed. Finally, we contrasted E and GWP data from the wider food system. We concluded that the evidence strongly favours organic farming with respect to whole-farm energy use and energy efficiency both on a per hectare and per farm product basis, with the possible exception of poultry and fruit sectors. For GWP, evidence is insufficient except in a few sectors, with results per ha more consistently favouring organic farming than GWP per unit product. Tillage was consistently a negligible contributor to farm E use and additional tillage on organic farms does not appear to significantly deplete soil C. Energy offsets, biogas, energy crops and residues have a more limited role on organic farms compared to conventional ones, because of the nutrient and soil building uses of soil organic matter, and the high demand for organic foods in human markets. If farm E use represents 35% of total food chain E use, improvements shown of 20% or more in E efficiency through organic farm management would reduce food-chain E use by 7% or more. Among other food supply chain stages, wholesale/retail (including cooling and packaging) and processing often each contribute 30% or more to total food system E. Thus, additional improvements can be obtained with reduced processing, whole foods and food waste minimization.

Keywords: GHG; GWP; organic farming; conventional farming and food systems; energy efficiency; biofuels

1. Introduction

Energy (E) is used throughout the food supply chain, including the growing of crops and livestock production, manufacture and application of agricultural inputs, processing, packaging, distribution and cold storage, preparing and serving, and disposing of waste. Recent studies of the US food system [1,2]. have shown that most (50–70%) of the average households' carbon footprint for food consumption comes from farm production and subsequent processing, with transport accounting for only an average of 11%, respectively, across all sectors or food products. Similar results, in which transport accounted for 9% of the food chain's greenhouse-gas emissions have been obtained recently in a British national study entitled Food 2030 [3]. However, in the USDA report by Canning *et al.* [1], energy costs of production vary widely between sectors. In addition, as household and food service food preparation activities continue to diminish and are outsourced to food processors, energy use at the food processing and farm level in the US is projected to increase a further 27% and 7% respectively, even when energy embodied in purchased inputs is excluded from the calculations. These studies suggest that a focus on farm level E use as impacted by farm management system, in this case, organic *vs.* conventional management, is very appropriate. Organic standards [4] impose a specific set of realities on farms that affects their energy efficiency and GHG emissions, realities that differ from those on most conventional farms. In comparison with conventional operations, organic farms typically have more diverse crop rotations, different input strategies, lower livestock stocking densities and different land base requirements, all of which affect energy consumption.

This study focuses on the state of international evidence in support of farm-level GHG and energy efficiency benefits of organic production, with a particular view to implications for Canada [5]. In an evidence-based policy world, decision makers understandably are reluctant to act in the absence of solid data supporting a policy position. We believe the state of evidence would need to be characterized in the following ways to warrant significant interventions by policy makers.

1. Clear and significant differences exist in energy and GHG emission performance between organic and conventional operations. No commonly accepted threshold of system differences currently exists but given variability in farming systems, our presumption is that average improvements of at least 20% by type of measurement would be required across all production areas to warrant claims of differences between organic and conventional systems. Below such a level, it would be legitimate to argue that system variability could just be an artifactual relationship.

2. There is a consistent approach to how emissions are reported. *i.e.*, whether on a per land unit basis or product basis. The latter, the 'intensity of emissions' (*i.e.*, per unit product) is also useful in pointing towards indirect methods of mitigation (*i.e.*, by increasing yields). Bertilsson *et al.* [6] argued further that while E use per unit yield expresses system E efficiency (and is often lower in organic systems), the measure is insufficient to compare E characteristics of farming systems, especially when yields are being reported on single crops rather than the productivity of the whole rotation. Net E production per unit land area is recommended as a more equitable measure. A counter argument to this approach is that while organic farming does generally require more land to produce the same total yield, it conserves soil, water, above and belowground biodiversity, and even maintains and restores multifunctional landscapes [7-9] and these key environmental benefits cannot be overlooked. Additionally, conventional production is associated with the degradation of hundreds of millions of hectares of land worldwide according to the FAO, and much farmland globally is assigned to non-food crops, suggesting that land availability is not as great a constraint as offered by organic critics.
3. A consistent approach to whether a credit for soil carbon (C) sequestration is included in the estimates. Soil C sequestration is discussed below.
4. A consistent approach with respect to N_2O emissions from biologically fixed N by legumes is essential in whole farm and cropping system estimates of GHG emissions [8]. Nitrous oxide (N_2O) emissions from soil are related to (i) the N cycle in the soil and losses from the processes of nitrification and denitrification and (ii) losses from the N contained in crop residues which ultimately decomposes releasing N through N cycle processes. Until recently, however, N_2O was assumed to be emitted also directly from standing legume crops fixing N_2 biologically from the atmosphere. Organic farming systems are highly dependent on legume N_2 from biological nitrogen fixation [10,11]. As N_2O emissions appear not to be directly derived from legume N_2 fixation as previously assumed by the Intergovernmental Panel on Climate Change [12], Rochette and Janzen [13] and Janzen *et al.* [14] have argued for a revised IPCC coefficient related to legume N_2 fixation. This concept has been implemented and acknowledged, particularly in more recent studies.
5. Accepted measures for determining differences. Gomiero *et al.* [7] highlight the main challenges of organic *vs.* conventional studies:
    - the degree to which a holistic analysis is employed over the long term, looking at integrated farming systems [15], and the related problem of comparability across systems that can differ significantly in crop mix and stocking rates
    - variability in energy accounting measures; many studies do not take a 'farm to fork' or Life Cycle Analysis (LCA) approach [16]
    - the extent to which the study addresses whether externalized costs are internalize Ideally, the conditions for a meta-analysis [17] of studies would exist; however, according to Mondalaers *et al.* [18], they do not for organic/conventional comparisons, so there is a current requirement for less robust approaches. At a minimum, there must be relative agreement on the elements and measurement of comparison to assure some consensus on the data and its meaning. In many cases, the measurement of baseline emissions from conventional operations is also variable which complicates the organic/conventional

comparison [19]. Such differences can result from the methodology or operational differences. Other sectors have these types of elements, for example, the World Resources Institute series of methods and tools [20]. At this point, no specific standard methodology is used for organic/conventional comparisons, though many may follow the related WRI standard on land use change [21]. Others being used include the guidelines of the IPCC [12] and the eco-balance guidelines (ISO 14040 and 14044) [22].

6. Generally, agreement that these differences are consistently realizable: in other words that they are not so variable by time and space that no consistent patterns emerge.
7. The changes represent a permanent improvement. The presumption of such comparisons is that the gap between organic and conventional in regard to these measures remains constant.
8. The differences actually mean something in the context of food system GHG mitigation and energy efficiency. For example, does it make more sense to have more farmers convert to organic, or have 50% of conventional operations dramatically reduce N fertilizer use? Should the focus be on conversion to organic or dramatic reductions in livestock densities and consumption? Or does supporting well managed organic farms, by demonstrating the practical and economic viability of both reduced livestock density and alternatives to N fertilizer use, broadly contribute to overall GHG mitigation and energy efficiency?
9. That some verification measures, at the sectoral or farm level, are feasible. It is not the purpose of this study to examine verification systems per se, but rather to identify if the current state of the data makes verification possible.

2. Results and Discussion

Given the current state of the literature, we start with a quick review of the conclusions of some meta-analyses, then, for each sector, we look at the data for energy use and the three main GHGs (carbon, methane, nitrous oxide) and also examine intensive *vs.* extensive production studies, with an eye to interpreting European results for the NA context.

In their recent meta-analysis of a wide range of global organic *vs.* conventional comparisons, Gomiero *et al.* [7] found …

> "lower energy consumption for organic farming both for unit of land (GJ ha^{-1}), from 10% up to 70%, and per yield (GJ/t), from 15% to 45%. The main reasons for higher efficiency in the case of organic farming are: (1) lack of input of synthetic N-fertilizers (which require a high energy consumption for production and transport and can account for more than 50% of the total energy input), (2) low input of other mineral fertilizers (e.g., P, K), lower use of highly energy-consumptive foodstuffs (concentrates), and (3) the ban on synthetic pesticides and herbicides".

In their study, all of the commodity-based analyses showed lower energy consumption in organic production per unit of land, but a few showed higher energy consumption per unit of product in the organic systems, particularly for potatoes and apples. For these crops, knowledge of organic production has not been as well developed as field crops and dairying, and consequently many operations were reporting significantly lower yields than in conventional production, a disparity that has been reduced over time. In these cases, even though gross energy use was lower, measured against yield, the comparison was less favorable to organic production.

Similar to their review of energy efficiency studies, Gomiero *et al.* [7] consistently found that organic systems had significantly lower CO_2 emissions than comparable conventional systems, when measured on a per area basis, though in some systems that benefit was lost when measured per tonne of production, depending on yield differences. Most of their review focused on European studies where the intensity of conventional production produces greater spreads in yields than those found in North American ones [23].

Mondalaers *et al.* [18] in their meta-analysis involving some studies not covered in Gomiero *et al.* [7] also concluded that emissions were significantly lower under organic production on a per area basis and the same on a per unit of production basis. The "per area" improvements were based on lower concentrate feeding, lower stocking rates and the absence of synthetic nitrogen fertilizer.

Kustermann and Hülsbergen [24], in a review of 33 German organic and conventional commercial farms examining direct and indirect energy inputs, GHG fluxes and C sequestration, found that energy use per ha in the organic operations was dramatically lower than conventional (2.75 time lower/area), but that, although the mean was significantly lower (72% of conventional), the higher variability in GHG emissions/ha on organic farms meant that the upper range of emissions on the organic operations was comparable to conventional ones, though the lower range was significantly lower (28 GJ ha^{-1} for the organic operation *vs.* 51 for the conventional operation). Nitrous oxide and carbon dioxide emissions were clearly lower on organic farms, with much higher C sequestration.

2.1. Field Crops

Snyder and Spaner [25] recently conducted a review of the sustainability of organic grain production on the Canadian Prairies, including many of the Canadian studies discussed in detail below. Notably, the authors conclude that management quality in either organic or conventional systems is key and well managed conventional systems may outperform organic systems, *i.e.*, that adoption of some organic technologies in conventional field crop production systems would likely ameliorate the general higher C cost of these systems.

In their recent survey of 250 Prairie-region conventional and organic grain growers, Nelson *et al.* [26] provided added evidence regarding the differences in agronomic practices between these management systems, particularly with respect to use of tilled summerfallow, compost and green manures (additional implications discussed below). A 12-yr study in Manitoba of two forage and grain crop rotations and two crop production systems (organic *vs.* conventional management) on energy use, energy output and energy use efficiency, found energy use was 50% lower under organic compared with conventional management [27]. Energy efficiency (output energy/input energy) was highest in the organic and integrated (*i.e.*, forage included) rotations. Tillage differed between crop production systems primarily with respect to alfalfa termination; by herbicide application in the conventional system *vs.* two to three cultivations with sweep cultivators in the organic system. Herbicides were also used to control weeds in the conventional system, while occasional light harrowing was required to control weeds in the organic system. The absence of inorganic N fertilizer was the main contributor to reduced energy inputs and greater efficiency. It could be argued that the relatively reduced degree of mechanical weed control required in the study by Hoeppner *et al.* [27] is somewhat atypical of many current commercial organic crop production systems.

An LCA modeling analysis of a Canada-wide conversion to organic canola, wheat, soybean and corn production concluded that under an organic regime, these crops would consume "39% as much energy and generate 77% of the global warming emissions, 17% of the ozone-depleting emissions, and 96% of the acidifying emissions [sulfur dioxide] associated with current national production of these crops. Differences were greatest for canola and least for soy, which have the highest and lowest nitrogen requirements, respectively."[28]. In general, the substitution of biological N for synthetic nitrogen fertilizer and associated net reductions in field emissions were the most significant contributors to better organic production performance. The authors concluded that organic yields had to be unrealistically below conventional yields before GHG emission reductions were eliminated, although their assumptions of organic field crop yields of 90–95% of conventional (as found in many USA studies) may not be realistic in all Canadian landscapes [23].

Zentner *et al.* [29], using data collected over the 1996–2007 period from a long-term cropping systems trial at Scott, Saskatchewan, examined (i) non-renewable energy inputs and energy use efficiency, and (ii) the economic merits of 9 cropping systems, consisting of 3 input management methods and 3 levels of cropping diversity. Input treatments consisted of (i) high input (HI)—conventional tillage with recommended rates of fertilizers and pesticides as required; (ii) reduced input (RI)—conservation tillage and integrated weed and nutrient management practices; and (iii) an organic input (OI) system—tillage, non-chemical pest control, and legume crops to replenish soil nutrients. The crop diversity treatments included (i) a fallow-based rotation with low crop diversity (DLW); (ii) a diversified rotation using cereal, oilseed and pulse grains (DAG); and (iii) a diversified rotation using annual grains and perennial forages (DAP). All crop rotations were 6 years in length. Total energy input was highest for the HI and RI treatments at 3855 MJ ha^{-1} and 51% less for the OI management system. Most of the energy savings under OI management came from the avoidance of use of inorganic fertilizers and pesticides. In addition total energy use was highest for the DAG treatments at 3609 MJ ha^{-1}, and similar but approximately 17% lower for the DAP and DLW treatments. Thus, the highest energy requirements (4465 MJ ha^{-1}) were associated with HI/DAG and RI/DAG treatments and OI/DAP had the lowest requirements(1806 MJ ha^{-1}). Energy output was typically highest for the HI input systems at 26,543 MJ ha^{-1} (and ~4% less with RI), and 37% less with OI management, due to lower crop yields. Energy use efficiency, measured as yield of grain plus forage produced per unit of energy input or as energy output/energy input ratio, was highest for the OI managed systems (501 kg of harvested production GJ ha^{-1} of energy input, and an energy output/energy input ratio of 8.85), and lower but similar for the HI and RI systems (377 kg per GJ^{-1} and 6.79 ratio). The authors conclude that organic management and a diversified rotation using perennial forages (DAP) was the most energy efficient cropping system, while RI/DLW and RI/DAG generally ranked lowest.

In most organic field crop systems, total N inputs to soil and the potential for N_2O emissions are reduced compared to conventional systems. However, an increased risk for N_2O emissions occurs in organic farms following the flush of soil N mineralization after incorporation of legume green manure or crop residues. As noted by Scialabba and Müller-Lindenlauf [9], however, when measured over the entire crop rotation, N_2O emissions are generally lower for organic field crop systems. The authors cite one German study in which emissions, while peaking at 9 kg N_2O ha^{-1} following legume incorporation, averaged 4 kg N_2O ha^{-1} for the organic system compared with 5 kg N_2O ha^{-1} for a conventional system. Also in Europe, Petersen *et al.* [30] tracked N_2O emissions from five rotation sequences [31] and found N_2O emissions were lower from the organic than conventional crop rotations, ranging from 4.0 kg N_2O-N ha^{-1} to 8.0 kg N_2O-N ha^{-1} across all crops as total N inputs increased from 100 to 300 kg N ha^{-1} yr^{-1}.

In the US, Pimentel *et al.* [32] examined the comparative average energy inputs (in millions of kilocalories ha^{-1} yr^{-1}) for corn and soybeans grown under three cropping systems; (i) an animal manure- and legume-based organic; (ii) a legume-based organic; and (iii) a conventional system, from 1981 to 2002. Fossil energy inputs averaged approximately 30% lower for both organic production systems than for conventional corn. Robertson *et al.* [33], in the Midwest USA, compared the net global warming potential (GWP) of conventional tillage, no-till, low input and organic management of a corn soybean-wheat system over 8 yrs. After converting the combined effects of measured N_2O production, CH_4 oxidation and C sequestration, plus the CO_2 costs of agronomic inputs to CO_2 equivalents (g CO_2 m^{-2} yr^{-1}) none of the systems provided net mitigation, and N_2O production was the single greatest source of GWP. The no-till system had the lowest GWP (14), followed by organic (41), low input (63) and conventional (114).

Cavigelli *et al.* [34] reported on GWP calculations for a no-till (NT), chisel till (CT) and organic (Org3) cropping systems at the long-term USDA-ARS Beltsville Farming Systems Project in Maryland, USA. Also calculated was the greenhouse gas intensity (GHGI = GWP per unit of grain yield). The contribution of energy use to GWP was 807, 862, and 344 in NT, CT, and Org3, respectively. The contribution of N_2O flux to GWP was 303, 406, and 540 kg CO_2e ha^{-1} y^{-1} in NT, CT and Org3, respectively. The contribution of change in soil C to GWP was 0, 1080, and –1953 kg CO_2e ha^{-1} y^{-1} in NT, CT and Org3, respectively. GWP (kg CO_2e ha^{-1} y^{-1}) was positive in NT (1110) and CT (2348) and negative in Org3 (–1069), primarily due to differences in soil C and secondarily to differences in energy use among systems. Despite relatively low crop yields in Org3, GHGI (kg CO_2e Mg $grain^{-1}$) for Org3 was also negative (–207) and significantly lower than for NT (330) and CT (153). Org3 was thus a net sink, while NT and CT were net sources of CO_2e. The authors concluded that common practices in organic systems including soil incorporation of legume cover crops and animal manures can result in mitigation of GWP and GHGI relative to NT and CT systems, primarily by increasing soil C.

Meisterling *et al.* [35] also in the US, used a hybrid LCA approach to compare the global warming potential (GWP) and primary energy use involved in the production process (including agricultural inputs) plus transport processes for conventional and organic wheat production and delivery in the US. The GWP of a 1 kg loaf of organic wheat bread was found to be about 30 g CO_2e less than that for a conventional loaf. However, when the organic wheat was shipped 420 km farther to market, the two systems had similar impacts. Organic grain yields were assumed at 75% of conventional average yields of 2.8 t grain ha^{-1}. Soil C storage potential was assumed the same for both systems and was omitted as a mitigation credit. Comparing just the farm level production and not including transport, the GWP impact of producing 0.67 kg of conventional wheat flour (for a 1 kg bread loaf), was 190 g CO_2e, while the GWP of producing the wheat organically was 160 g CO_2e. Tillage in the organic system accounted for 600 J of energy (or 42 g CO_2e) compared to 450 J (or 32 g CO_2e) for the conventional system. By comparison, N and P fertilizer production added a total of 820 J (or 57 g CO_2e) to the GWP total of the conventional system. N_2O emissions from soil were assumed to be a large contributor to GWP of both systems and were rated as equivalent at 96 g CO_2e. As noted by these authors, there is the greatest uncertainty with respect to soil C storage and N_2O emissions (uncertainty ranges were greater than the calculated GWP difference between the two systems) and 'uncertainty and variability related to these processes may make it difficult for producers and consumers to definitively determine comparative GHG emissions between organic and conventional production' [35]. Notably, when the transport of wheat was shifted to primarily rail, the life cycle GWP impacts were considerably decreased compared to truck transport.

Among categories of emissions, the highest uncertainty also is associated with direct soil N_2O emissions and indirect soil and manure N_2O emissions [36]. In support of the assumption of Meisterling *et al.* [35] of similar N_2O emissions from both organic and conventional wheat production systems, Carter *et al.* [37], after directly measuring N_2O emissions in spring, summer and fall-winter from a conventional and three different organic winter wheat production systems, found N_2O emissions related to a given amount of grain was similar in all systems.

Gomiero *et al.* [7], in their meta-analysis, drew upon three studies of winter wheat cropping systems in Europe, also reported in Stolze [38]. CO_2 emissions per land unit (kg CO_2 ha^{-1}) were lower in the organic systems by an average of 50%, while emissions per unit of grain production (kg CO_2 ha^{-1}) were found to be lower in two of the studies (by 21%) and greater in one (by 21%).

Deike *et al.* [39] in Germany compared, using data from a long-term replicated field experiment (1997–2006), one organic farming treatment (OF) and two integrated farming treatments (IF). Averaged across all years and crops, the E inputs in OF (8.1 GJ ha^{-1}) were 35% lower than in the IF systems (12.4 GJ ha^{-1}). The largest shares of energy input in IF were diesel fuel (29%) and mineral fertilizers (37%). Mineral nitrogen (N) fertilizers represented 28% of the total energy input in the IF systems. Halberg *et al.* [40] examined five European studies comparing energy use under conventional and organic farming, including some cash crop (grains and pulses) operations and concluded that energy use is usually lower in organic farming compared with conventional farming methods, both per hectare and per unit of crop produced.

Nemecek [41] reported in the study by Niggli *et al.* [42] found, after analyses of data from two long-term comparative cropping systems studies in Europe, that the GWP of all organic crops was reduced by 18% per unit product compared to the conventional production systems.

In a recent study in Spain, Alonso and Guzman [43] compared 78 organic crops and their conventional counterparts. About 25% were direct survey comparisons for arable crops including wheat, peas, barley, oats, rice and broad bean. The results indicated that non-renewable energy efficiency, at 8.27 MJ per MJ input, was higher in organic arable farming compared to 6.70 MJ per MJ input for conventional arable farming and showed a lower consumption of non-renewable energy. Notably this difference between production systems was much greater for arable crops than all other sectors, including field and greenhouse vegetables, and fruit production. The authors concluded that an increase in the land area dedicated to organic farming would considerably improve the energy sustainability of Spanish agriculture.

In summary (Table 1), while only a few Canadian studies have been conducted, the strong consensus of the data, across a range of jurisdictions and crops, indicates that organic field cropping systems (grains, grain legumes, oilseeds and forages) require less energy and improve energy efficiency, both per hectare and per unit product, compared to conventional arable production systems, and provide improvements above our suggested threshold of 20%. A subset of these studies (although none are Canadian) has assessed field cropping systems for GWP. Here again, while conclusions are less definitive then for E use, and given the qualifiers noted regarding the uncertainty associated with N_2O emissions and variation in study methodology and assumptions with respect to soil C storage, and N_2O emissions from legumes, the consensus is that organic field crop management also improves GWP both per ha and per unit product when compared to conventional production.

Table 1. Field crops—summary of organic *vs.* conventional comparisons (%Org-Conv/Conv).

Authors	**Region**	**Type of study**	**Measure**	**Org < Conv**	**Org > Conv**
Hoeppner *et al.* [27]	Manitoba, Canada	Comparative field trial	E use (MJ ha^{-1}) E efficiency (MJ per MJ input)	50%	 20%
Zentner *et al.* [29]	Sask, Canada	Comparative field trial	E use (MJ ha^{-1}) E efficiency (MJ per MJ input)	51%	 24%
Pelletier *et al.* [28]	Canada	LCA (of conversion)	CO_2e ha^{-1} CO_2e $product^{-1}$	61% 23%	
Robertson *et al.* [33]	US	Comparative field trial	GWP (g m^{-2})	64% [1]	
Pimentel *et al.* [32]	US	Comparative field trial	Non-renewable E use (MJ ha^{-1})	30%	
Cavigelli *et al.* [34]	US	Comparative field trial	E use (CO_2e ha^{-1}) GWP (CO_2e ha^{-1}) GWP (CO_2e unit $grain^{-1}$)	57% 69% [2] 42% [3]	
Miesterling *et al.* [35]	US	LCA	GWP (CO_2e) kg $bread^{-1}$)	16%	
Nemecek [41] (in Niggli *et al.*[42])	Europe	Comparative field trials	GWP (CO_2e) per unit product	18%	
Kustermann and Hülsbergen [24]	Germany	Meta-analyses	E use (CO_2e ha^{-1})	64%	
Gomiero *et al.* [7]	Europe	Meta-analyses (including 3 wheat studies)	GWP (CO_2e ha^{-1}) GWP (CO_2e kg $grain^{-1}$)	50% 21% (2 studies)	 21% (1 study)
Deike *et al.* [39]	Germany	Modeling from long term trial	E inputs (GJ ha^{-1})	35%	
Alonso and Guzman [43]	Spain	Meta-analyses of survey data	E efficiency (MJ per MJ input)		24%

[1]Note: The no-till system surpassed the organic, however, with GWP of only 14 compared to the organic at 41, and conventional at 114 [15].When compared to a no-till treatment this gain is 51% [16]. When compared to a no-till treatment this gain is 61%.

2.2. Livestock (Including Pasture/Forage as Appropriate)

For animal production, fewer studies have been conducted and the comparisons are more difficult because of the dramatic differences in operations, particularly for hogs and poultry. There is tremendous scope for expanded research on organic livestock systems and GHG emissions.

2.2.1. Beef

Beef production systems are well known to be much less efficient than crop production in terms of E, requiring seven times as many inputs for the same calorie output [44]. Correspondingly, GHG emissions are reported as greater in beef production than poultry, egg and hog production, milk and crops. As noted by Sonnesson *et al.* [45], however, there is usually great variation in the results of studies assessing the net GHG impact of beef, because of methodological differences, system boundaries, and differences in production systems.

Niggli *et al.* [42] summarized studies by Bos *et al.* [46], Nemecek [41], Fritsche and Eberle [47], and Kustermann *et al.* [48] and suggested that, in general, net GHG emissions from beef production are in the range of 10 kg CO_2e kg^{-1} meat product compared with 2–3 kg CO_2e kg^{-1} for poultry, egg and hog production, 1 kg CO_2e kg^{-1} for milk and typically less than 0.5 kg CO_2 equivalents kg^{-1} for crop production systems.

Sonesson *et al.* [45] reports, from a compilation of published studies from Europe, Brazil and Canada, a higher range (14–32 kg CO_2e kg^{-1} meat product). The one Canadian study included is that of Verge *et al.* [49]. In this and all the cited studies, methane emissions account for 50–75% of total GHG emissions. As noted by Niggli *et al.* [42] and others, however, while the methane emitted by ruminants is the major limitation of their use, by allowing efficient use of often marginal land they play a critical role in global food security. Furthermore, the methane emissions of ruminants consuming forages only are at least partially offset by the sequestration of CO_2 by those same perennial forages.

In Ireland, Casey and Holden [50] undertook a 'cradle-to-farm gate' LCA approach to estimate emissions kg^{-1} of live weight (LW) leaving the farm gate per annum (kg CO_2 kg LW^{-1} yr^{-1}) and per hectare (kg CO_2 ha^{-1} yr^{-1}). Fifteen units engaged in suckler-beef production (five conventional, five in an Irish agri-environmental scheme, and five organic units) were evaluated for emissions per unit product and area. The average emissions from the conventional units were 13.0 kg CO_2 kg LW^{-1} yr^{-1}, from the agri-environmental scheme units 12.2 kg CO_2 kg LW^{-1} yr^{-1}, and from the organic units 11.1 kg CO_2 kg LW^{-1} yr^{-1}. The average emissions per unit area from the conventional units was 5346 kg CO_2 ha^{-1} yr^{-1}, from the agri-environmental scheme units 4372 kg CO_2 ha^{-1} yr^{-1}, and from the organic units 2302 kg CO_2 ha^{-1} yr^{-1}. GWP increased in a linear fashion, both per hectare and per unit animal liveweight shipped as there was an increase in either farm livestock stocking density, N fertilizer application rate, or concentrates fed. The authors concluded that moving toward more extensive production, as found in organic systems, could reduce emissions per unit product and there would be a reduction in area and live weight production per hectare.

Flessa *et al.* [51] reported on a German research station comparison of two beef management systems: one a conventionally managed confinement fed system; the other an organic pasture based system. For both systems, N_2O emissions, mainly from soils, accounted for most (~60%) of the total GHG emissions, followed by CH_4 at 25% of the total emissions. Combined GWP per unit land base was 3.2 Mg CO_2e ha^{-1} and 4.4 Mg CO_2e ha^{-1} for the organic and conventional systems respectively. When compared per unit product (*i.e.*, per beef live weight of 500 kg), yield related GWP failed to differ between the two systems, primarily as productivity was approximately 20% greater for the confinement-based system, although emissions were also higher overall.

Peters *et al.* [52] in Australia using an LCA analyses considered three scenarios; (1) a sheep meat supply chain in Western Australia, (2) a beef supply chain in Victoria, Australia producing organic beef, and (3) a premium export beef supply chain in New South Wales which includes 110–120 days at a feedlot. Data were collected over two separate years for each supply chain. GHG emissions were estimated, including all aspects of red meat production such as on-farm energy consumption, enteric processes, manure management, livestock transport, commodity delivery, water supply, and administration. The study found that organic production may use less energy than conventional farming practices but may result in a higher carbon footprint, as the additional effort in producing and transporting feeds appeared to be offset by the efficiency gains of feedlot production, even though the feedlot stage accounted for 22% of the total GWP of the beef supply chain.

Sonesson *et al.* [45] noted that few systematic studies are available providing data on the GWP impact of different beef production systems in Sweden. Data on GWP per unit product, however, was presented from three studies of organic, 'ranch systems' and Swedish 'average beef' systems respectively, conducted by the same group of researchers (Cederberg *et al.* [53-55]). GWP impact averaged 22, 24 and 28 kg CO_2e kg^{-1} meat for organic, ranch and average production systems respectively.

Very limited analysis is available on which to base a conclusion for this sector (Table 2), particularly from North America. While organic beef production appears to reduce GWP per hectare, this is not consistently evident when calculated per unit of meat product. Numeric results specifically on energy use and efficiency were difficult to segregate from net GWP impacts presented in the studies available, but trended towards an improved outcome per land base and per unit product under organic management.

Table 2. Beef—summary of organic *vs.* conventional comparisons.

Authors	**Region**	**Type of study**	**Measure**	**Org < Conv**	**Org > Conv**
Casey and Holden [50]	Ireland	LCA	GWP (CO_2e ha^{-1})	57%	
			GWP (CO_2e kg meat^{-1})	15%	
Flessa *et al.* [51]	Germany	Comparative systems study	E use (CO_2e ha^{-1})	16%	
			GWP (CO_2e ha^{-1})	27%	
			GWP (CO_2e kg meat^{-1})	0%	
Peters *et al.* [52]	Australia	LCA	E use (MJ kg meat^{-1})	3%	
			GWP (CO_2e kg meat^{-1})		9%
Sonneson *et al.* [45]	Sweden	2 LCAs	GWP (CO_2e kg meat^{-1})	21%	

2.2.2. Dairy

A modeling study in Atlantic Canada examining 19 different dairy production scenarios found that a seasonal—grazing organic system was 64% more energy efficient and emitted 29% less greenhouse gases compared with the average of all other analyzed systems [56,57]. A different study comparing non-organic seasonal grazing compared with confined dairying did not find such significant differences between the two systems, suggesting that additional organic management requirements provide some significant efficiency opportunities [58]. This study conducted a LCA of dairy systems in Nova Scotia to compare environmental impacts of typical pasture and confinement operations. Use of concentrated feeds, N fertilizers, transport fuels and electricity were dominant contributors to environmental impacts. Somewhat surprisingly, grazing cows for five months per year (typical of pasture systems in Nova Scotia) had little effect on overall environmental impact. Scenario modeling suggested, however, that prolonged grazing is potentially beneficial.

A recent study of 15 organic dairy farms in Ontario found that farm nutrient (NPK) loading (imports-exports) and risk of off-farm losses to air and water are greatly reduced under commercial organic dairy production compared with more intensive confinement based livestock systems in eastern North America [10]. However, livestock density (and farm N surplus) on the organic farms varied and increased as self-sufficiency, with respect to livestock feeding, decreased. As noted below, farm N surplus has been suggested as a proxy for farm net GHG emissions per hectare [59]. It is unknown how much these differences in management approach, compared with farm management system (organic *vs.* conventional), influence farm GHG and E.

Olesen *et al.* [59] used the whole farm model, FarmGHG to analyse conventional and organic dairy farms, located in five European agro-ecological zones, on relative GHG emissions. Farms were assumed to have the same land base of 50 ha and, in each region, to achieve the same milk yield per cow. Livestock density (LD) was 75% higher on the conventional farms compared to the 100% feed self-sufficient organic farms. Livestock contributed an average of 36% of total emissions, while fields contributed about 39%. Of the GHGs, N_2O and CH_4 dominated, accounting for an average of 49% and 42% of total farm emissions. GHG emissions per hectare (Mg CO_2e ha^{-1}) increased with production intensity (*i.e.*, LD) and thus farm N surplus, for both types of farms and were thus usually higher for conventional dairy farms. GHG emissions per unit milk product (or metabolic energy, kg CO_2e kg milk^{-1}), however, were inversely related to farm N efficiency.

Bos *et al.* [46] assessed E use and GHG on organic and conventional model dairy farms in the Netherlands. Model farms were designed on the basis of current organic and conventional farming practices. Notably, on all dairy farms, indirect energy was much higher than direct energy with concentrates contributing the largest share to total energy use (~30%). Total energy use ha^{-1} increased with increasing milk production ha^{-1}, which was linked to stronger dependence on imports and higher animal densities. Energy use ha^{-1}, averaged over all conventional dairy farms (75 GJ ha^{-1}), was almost twice as high as that of all organic farms (39 GJ ha^{-1}). Energy use per Mg of milk produced ranged from 3.6 to 4.5 GJ on the organic farms and from 4.3 to 5.5 GJ on the conventional farms. Similarly, energy use per Mg of milk was positively correlated to milk production ha^{-1}. Energy use and total GHG emissions per Mg of milk in organic dairy farming were found to average approximately 80 and 90%, respectively of that in conventional dairy farming.

Thomassen *et al.* [60] in the Netherlands conducted a detailed ‘cradle-to-farm-gate’ LCA analysis, including farm environmental impact with respect to GHG and pollution impacts on water quality (*i.e.*, eutrophication). As also reported above by Oleson *et al.* [59], N_2O and CH_4 accounted for the bulk of emissions. In the conventional system CO_2, N_2O and CH_4 accounted for 29%, 38% and 34% of total GHG, compared to 17%, 40% and 43% respectively for the organic dairy farm system. Results indicated improved environmental performance with respect to energy use and eutrophication potential kg milk^{-1} for the organic compared to conventional farms (3.1 *vs.* 5.0 MJ kg^{-1} FPCM respectively). On the other hand, farming systems failed to differ with respect to GWP per unit milk produced. Overall recommendations from this study included reducing use of concentrates with a high environmental impact and reducing whole farm nutrient surpluses.

It should be noted that the studies of Oleson *et al.* [59], Bos *et al.* [46] and possibly Thomassen *et al.* [60] may have overestimated N_2O emissions associated with legume nitrogen fixation (a key component of organic farm systems) as older IPCC coefficients and methodology were used in these studies.

Flachowsky and Hachenberg [61] conducted a review of nine European studies reporting GHG emissions from conventional and organic dairy farms, and discussed at some length the gaps and uncertainties in the data. While one study [62] reported equivalent GWP per unit milk product (kg CO_2e kg milk^{-1}), for five of the studies, organic systems resulted in greater GWP (ranging from a 1%–27% increase), while organic reduced GWP (ranging from 5%–8%) in the remaining three studies.

Gomiero *et al.* [7] reviewed a number of European studies that report on comparative energy consumption and efficiency by organic and conventional dairy systems. Both energy consumption per land base (GJ ha^{-1}) and unit crop product (GJ t^{-1}) were reported as consistently lower in the organic compared to conventional dairy systems (ranging from 23–69% lower GJ ha^{-1} and 8% to 54% lower GJ t^{-1}). Using data from the study by Haas *et al.* [62] GWP also per hectare is reported as reduced under organic, but not when compared per unit product.

Organic ruminant livestock farms differ also from conventional with respect to the cross-breeding and management goals, which, as less intensive systems, often result in improved animal longevity. As noted by Niggli *et al.* [42], methane emissions can thus be reduced when calculated on the total lifespan of organic cows. As comparative data on relative longevity across dairy production systems is limited, this consideration has yet to be included in farm system GWP comparisons.

In a recent Austrian study, Hörtenhuber *et al.* [63] conducted a 'life-cycle chain' analyses of eight different dairy production systems representing organic and conventional farms located in alpine, upland and lowland regions. Notably, and rather innovatively, the authors included an estimate for GHG impacts of the estimated land use change (LUC) required to produce concentrates (which ranged from 13% to 24% of total feed intake for various farms), such as soybean production replacing tropical forests. Nitrogen fertilizer was assumed not to be used on any farms, and only partially during external-to-the-farm production of concentrates. About 8% of total GHG for the conventional farms was attributed to LUC associated with concentrates. In general, the study found that the higher yields per cow and per farm for the conventional farms did not compensate for the greater GHG produced by these more intensive systems, with organic farms on average emitting 11% less GHG (0.81–1.02 kg CO_2e kg milk^{-1} compared to 0.90 to 1.17 kg CO_2e kg milk^{-1}).

Sonesson *et al.* [64] summarized LCA studies from ten OECD countries that found emissions up to the farm gate ranged from 1.0–1.4 kg CO_2e kg milk^{-1}. While there were minor differences between conventional and organic farms, the contribution of each GHG differed. In general, organic systems had higher methane emissions kg milk^{-1} but lower emissions of N_2O and CO_2 per unit product.

On balance, organic dairy systems appear to reduce energy use and improve energy efficiency both per unit land base and per kg of milk produced, and the results available pass, on average, our threshold of 20% (Table 3). With respect to GWP per unit product, there is no consensus in the data available to suggest organic dairy systems management is significantly beneficial. It must be noted, however, that Canadian and North American data is particularly scarce.

Table 3. Dairy—summary of organic *vs.* conventional comparisons.

Authors	Region	Type of study	Measure	Org < Conv	Org > Conv
Main [56]	Atl. Canada	Modeling of farming systems	E use (GJ kg milk^{-1}) GWP (CO_2e kg milk^{-1})	64% 29%	
Olesen *et al.* [59]	Denmark/EU	Comparison of model farms	Mg CO_2e ha^{-1} kg CO_2ekg milk^{-1}	40%	11%
Bos *et al.* [46]	Netherlands	Comparison of model farms	E use (GJ kg milk^{-1}) GWP (CO_2e kg milk^{-1})	20% 10%	
Thomassen *et al.* [60]	Netherlands	LCA	E use (MJ kg FPCM^{-1}) GWP (CO_2e kg FPCM^{-1})	38% 0%	
Flachowsky and Hachenberg [61]	EU	Review of nine studies	GWP (CO_2e kg milk^{-1})	0% (1 study) 5–8% (3 studies)	1–27% (5 studies)
Gomiero *et al.* [7]	EU	Review of five studies	E use (GJ ha^{-1}) E use (GJ kg milk^{-1}) GWP (CO_2e kg milk^{-1})	23–69% 8–54% 0%	
Hörtenhuber *et al.* [63]	Austria	LCA	GWP (CO_2e kg milk^{-1})	11%	
Sonneson *et al.* [64]	Sweden	Review of LCAs	GWP (CO_2e kg milk^{-1})	0%	

2.2.3. Hogs

Organic hog production may be the least energy efficient of the major animal systems [65], possibly because of frequently lower than optimal levels of pasturing hogs, inappropriate breeds for organic systems, and the failure to find the most efficient roles for hogs in mixed farming operations. For example, hogs can play a useful role in weed control post-harvest or field renovation [66] and even compost aeration [67], with the potential to, therefore, reduce energy expenditures for weed control.

In a comparison of conventional, natural (Red Label) and organic hog production in France, van der Werf *et al.* [68] found, using a detailed LCA, that organic systems produced the lowest emissions of methane and carbon dioxide on a per ha basis, but not a 1000 kg pig basis, for which they were significantly outperformed by conventional production on nitrous oxide and carbon dioxide emissions. Only in methane production did organic maintain a reduction over conventional, but the natural system performed even better. Two Swedish LCA studies, in contrast, found emissions in the organic operations to be 50% less than this French study and concluded that reduced growth rates, inefficient feed production and composting of manure, with subsequent low nitrogen use efficiency and higher ammonia and indirect nitrous oxide emissions, likely explain the different results [19]. However, emissions kg meat^{-1} were higher in the organic studies compared to most of the conventional operations. Similar results were found for MJ kg meat^{-1}. Degre *et al.* [69] also looked at 3 comparable Belgian systems (organic, free-range and conventional) and found GHG emissions (CO_2e) pig^{-1} were the lowest for the organic system followed by free-range and conventional, with nitrous oxide the dominant gas. Organic system emissions were 87% of conventional, with slurry from conventional operations having much higher emissions than straw litter in the organic system. However, organic performance was inferior in some of the other environmental criteria assessed.

Williams *et al.* [70], modeling UK systems, in contrast found lower energy use and lower emissions on a per tonne basis for organic systems (13% fewer total MJ used and 11% lower GWP100 [71] emissions), but with 1.73 times greater land requirements t^{-1} of production.

Halberg *et al.* [40] modeled standard LCAs on 3 different Danish organic hog systems and compared the results with the literature on conventional operations [40]. They found higher levels of GHG emissions (CO_2e pig^{-1}) on all organic operations because of higher nitrous oxide emissions and lower feed conversion efficiencies, but concluded that if C-sequestration associated with the organic rotations were included in the calculations (11–18% reductions in CO_2e pig^{-1}), 2 of the 3 organic operations would outperform the conventional one [40,72].

Comparing the different conclusions of their work with those of van der Werf *et al.* [68], Halberg *et al.* [72] concluded that "methodological differences makes a direct comparison between the two studies problematic. The French study also found that organic pig production had a better environmental performance compared with conventional when calculated per ha but worse when calculated per kg pig product. But they did not include differences in the soil carbon sequestration as in our study."

Low meat yields of pork may be more efficient in terms of the ratio of human edible meat: human inedible feed. It is reasonable to postulate that too much reliance on high production will lead to crossing the ideal threshold ratio of meat: human inedible feed such that a low ratio should be flagged as likely to be unsustainable.

Sonesson *et al.* [19] concluded that although there are only a limited number of high quality studies on hogs, there was sufficient information to set out a workable protocol for the Swedish Climate Labeling for Food scheme, focusing on individual operations (whether conventional or organic) rather than the organic sector as a whole.

Table 4. Hogs—summary of organic *vs.* conventional comparisons.

Authors	Region	Type of study	Measure	Org < Conv	Org > Conv
van der Werf *et al.* [68]	France	LCA	CH_4 ha^{-1}	69%	
			N_20 ha^{-1}		33%
			CO_2 ha^{-1}	13%	
van der Werf *et al.* [68]	France	LCA	CH_4 pig^{-1}	46%	
			N_20 pig^{-1}		242%
			CO_2 pig^{-1}		58%
Sonneson *et al.* [19]	Sweden	2 LCAs	CO_2e kg $meat^{-1}$	6% (1 study)	2–35% (6 studies)
Sonneson *et al.* [19]	Sweden	2 LCAs	MJ kg $meat^{-1}$	1–4% (2 studies)	18–41 (4 studies)
Degre *et al.* [69]	Belgium	Expert ranking	CO_2e pig^{-1}	13%	
Williams *et al.* [70]	UK	Modelling	MJ t^{-1}	13%	
Williams *et al.* [70]	UK	Modelling	GWP100 t^{-1}	11%	
Halberg *et al.* [72]	Denmark	Modelled LCA	GHG100 kg^{-1} & C sequestration	4–33% for 2/3 org. farms	7% for 1/3 org. farms

On balance, comparison results were mixed for hogs (Table 4). Including carbon sequestration appears to create more positive comparisons for organic. However, many of the studies favouring organic did not pass our 20% threshold.

2.2.4. Poultry

There is some evidence that organic poultry systems are more efficient. For example, one solar emergy study, emergy being the solar (equivalent) energy required to generate a flow or storage [73,74], found that organic production resulted in a higher efficiency in transforming the available inputs into final products, a higher level of renewable input use, greater use of local inputs, and a lower density of energy and matter flows. Emergy flow for the conventional poultry farm was 724.12×10^{14} solar em joule cycle^{-1}, while for the organic poultry farm, it was just 92.16×10^{14}. The main reasons were the lower emergy cost kg meat^{-1} produced for poultry feed, veterinary drugs and cleaning/sanitization of the poultry barns between production cycles. Interestingly, the positive results were not a function of differences in housing systems [75].

Williams *et al.* [70] used standard LCA to model typical conventional and organic production scenarios in the UK. They found that organic poultry meat and egg production increased energy use by 30% and 15% respectively. Although organic feeds had lower energy requirements, these savings were outweighed by lower bird growth rates. GWP from organic poultry meat production was up to 45% higher than conventional production. Bokkers and de Boer [76] reached similar conclusions when examining Dutch organic and conventional operations; not necessarily surprising, given that some of their modeling was based on the work of Williams *et al.* [70]. The key comparative factor is the high feed conversion rates obtainable in conventional production. Sonesson *et al.* [77], from their review of 5 European studies including Williams *et al.* [70], found that nitrous oxide emissions from conventional feed, associated with N fertilizer and soil losses, presented the greatest opportunities for savings in well designed organic systems. The design of barn heating systems would be another significant area for efficiencies, especially in hatcheries.

Comparative data on poultry production are particularly sparse, especially for eggs [78]. In conclusion (Table 5), only on a solar emergy basis would organic currently appear to be more energy efficient that conventional production, but this is an area with very limited analysis.

Table 5. Poultry—summary of organic *vs.* conventional comparisons.

Authors	Region	Type of study	Measure	Org < Conv	Org > Conv
Castellini *et al.* [75]	Europe	Emergy analysis	solar em joule cycle^{-1} (kg meat^{-1})	13%	
Williams *et al.* [70]	UK	LCA modeling	Energy use kg meat^{-1} Energy use egg^{-1}		30% 15%
Williams *et al.* [70]	UK	LCA modeling	GWP kg meat^{-1}		45%
Bokkers and de Boer [76]	Netherlands	Multiple sustainability indicator modelling	Energy use kg meat^{-1}		30–59%

2.3. Horticultural crops

2.3.1. Vegetables

Four European potato studies summarized by Gomiero *et al.* [7] found that, on a ha^{-1} basis, organic fossil energy use was from –27 to –48% of conventional, but on a kg^{-1} basis, –18 to +29%. Gomiero *et al.* [7] also reported on input/output per unit of yield, with 3 German studies reporting organic at +7 to +29. A US study, however, reported more positive results for organic production, at –20 to –13 of conventional [79]. Williams *et al.* [70], reporting on $tonne^{-1}$ comparisons in the UK, found little difference in energy use for potato production and slightly lower GHG emissions in organic production, the largest difference being in reduced direct N_2O emissions.

Using a non-renewable energy balance approach that included embodied energy of inputs, structures and machinery [80], Alonso and Guzman [43] reported on numerous Spanish organic *vs.* conventional comparisons. Across 13 vegetable cases [81], they found non-renewable energy was 41% lower in the organic operation. Organic systems relied to a much greater extent on renewable energy which was critical to the overall analysis, since the organic systems used more energy of all kinds than the conventional operations.

Using a hybrid input-output economic and LCA analysis, Wood *et al.* [82] concluded that organic vegetable production in Australia had about 50% of the energy intensity of conventional vegetable production (measured as MJ $\$Australian^{-1}$). The main energy reductions were associated with on-site energy use and fertilizer.

A British MAFF study [83] found that energy input ha^{-1} in organic production was 54% of conventional potatoes, 50 %for carrots, 65% for onions, and 27% for broccoli. On a per tonne basis, results were less dramatically positive, essentially 16–72% lower across a range of vegetables.

Data on CH_4 and N_2O emissions suggest similar results to those for CO_2, though data are relatively more limited [38]. Interim research results from Atlantic Canada field trials comparing organic and conventional potato rotations, found lower nitrous oxide emissions ha^{-1} in the organic plots using biological N sources [11]. These results concur closely with a European study by Petersen *et al.* [30] that found N_2O emissions were lower per hectare from various organic than conventional crop rotations (some including potatoes).

Bos *et al.* [46] used a model farm approach and compared one organic and one conventional arable farm on clay soil (both growing potato, sugar beet, wheat, carrot, onion and pea) and one organic and conventional vegetable farm on sandy soil (leek, bean, carrot, strawberry, head lettuce and Chinese cabbage). They calculated direct and indirect energy use and GHG emissions with no net accumulation or depletion of soil C. Emissions of GHGs were expressed as 100-year GWP (CO_2e). Energy use (MJ t^{-1}) in organic head lettuce, potatoes and leeks was higher than conventional, in the 20–40% range depending on the crop, but dramatically lower in organic sugar beets and peas, and slightly lower in beans.

Similar results were found by Bos *et al.* [46] for GHG emissions (CO_2e t^{-1}), though the range of differences was narrower compared to those found for energy use. However, there is some likelihood that N_2O emissions from legumes in this study were overestimated (see also the dairy section above), although this may have been a small overall contributor to farm budgets.

De Bakker *et al.* [84], examining leeks in Belgium in a full LCA analysis, concluded “that the total climate change indicator score, Global Warming Potential, GWP100 is 0.094 kg CO_2-equivalents/kg leek for the conventional system and 0.044 kg CO_2-equivalents/kg leek for the organic system, revealing conventional leek production to have a substantially higher impact on climate change. The GWP depends mainly on the use of fossil fuels for on farm activities, energy use for the production of inputs and emissions of N_2O connected to the on-farm nitrogen cycle.” Diesel use kg^{-1} leek was actually higher in organic, but the on-farm nitrogen cycle and synthetic fertilizer use in the conventional system had a larger impact than fossil fuel use. The results favoured organic to an even larger degree on a per area basis, with organic production producing only 33% of conventional emissions.

An Oko-institut study conducted in Germany by Fritsche and Eberle [47] found a range of vegetables to have 15% lower GHG emissions measured as CO_2e kg^{-1} and for tomatoes and potatoes, the reduction in GHG emissions was 31%.

In summary (Table 6), with the exception of potatoes, organic vegetables show consistently lower energy use, higher energy efficiency and lower GHG emissions on a t^{-1} and ha^{-1} basis. Most results favouring organic exceed our 20% threshold.

Table 6. Vegetables—summary of organic *vs.* conventional comparisons.

Authors	Region	Type of study	Measure	Org < Conv	Org > Conv
Gomiero *et al.* [7]	Europe	4 studies using variety of methods	Potatoes, fossil energy use ha^{-1} Potatoes, fossil energy use kg^{-1}	27–48% 18%	 29%
Gomiero *et al.* [7]	Germany	3 Energy input/output	Potatoes kg^{-1}		7–29%
Pimentel *et al.*[79]	USA	Energy	Potatoes kg^{-1}	13–20%	
Williams *et al.* [70]	UK	modelling LCA	Energy use t potato^{-1} GHG t potato^{-1}	0 Slightly lower	
Alonso and Guzman [43]	Spain	13 vegetables, non-renewable energy balance	MJ input	41%	
Wood *et al.* [82]	Australia	Vegetables, hybrid LCA & economic input/output	MJ \$Aus^{-1}	50%	
MAFF [83]	UK	Direct and indirect energy inputs	Energy input ha^{-1} potato carrots onions broccoli	 46% 50% 35% 73%	
MAFF [83]	UK	Direct and indirect energy inputs	Energy input t^{-1} Potato, carrots, onions, broccoli, leeks	16–72%	

Table 6. *Cont.*

Authors	Region	Type of study	Measure	Org < Conv	Org > Conv
Bos *et al.* [46]	Netherlands	Model farm	($MJ\ t^{-1}$) lettuce, potatoes and leaks Sugar beets, peas Beans		20–40%
De Bakker *et al.* [84]	Belgium	LCA	$GWP_{100}\ CO_2e\ ha^{-1}$ Leeks $GWP_{100}\ CO_2e\ kg^{-1}$ Leeks	 67% 53%	
Fritsche and Eberle [47]	Germany		$CO_2e\ kg^{-1}$ Vegetables Potato, tomato	 15% 31%	

2.3.2. Fruit

Scialabba and Hattam [85] concluded that energy use in organic apple production was 90% of conventional apple production measured in GJ ha^{-1}, but 123% ton^{-1} of product. Reganold *et al.* [86], from a long-term Washington state trial, found that organic apple production had 14% lower energy use ha^{-1} basis, largely because of reductions in synthetic fertilizers and pesticides, but 7% higher per unit of production. In Europe, Geier *et al.* cited in Gomiero *et al.* [7] found even higher use in organic relative to conventional (23%) per product but comparable per area.

In a perennial orchard system in Washington State, Kramer *et al.* [87] found after nine years that the organically managed soil exhibited greater soil organic matter and microbial activity, and greater denitrification efficiency (rN_2O or $N_2O:N_2$ emission ratio) compared to conventionally managed, or integrated orchard management systems. While N_2O emissions were not significantly different among treatments, emissions of benign N_2 were highest in the organic plots.

Using a hybrid input-output economic and LCA analysis, Wood *et al.* [82] concluded that, even though on-site energy use was higher, in total, organic fruit (unspecified varieties) in Australia had about 30% lower energy intensity than conventional fruit production.

Alonso and Guzman [43], for a wide range of irrigated fruits [88] (18 cases), and rainfed fruit and nut production [89] (22 cases), found non-renewable energy efficiencies (MJ input MJ $output^{-1}$) of 5.89 for organic and 5.48 for conventional irrigated production and 2.82 and 2.14 for rainfed respectively. Organic systems relied again to a much greater extent on renewable energy.

Gündogmus and Bayramoglu [90] examined raisin production on 82 conventional and organic Turkish farms and concluded that even though human labour inputs were higher, on average, for organic farms, organically produced raisins consumed 23% less overall energy, on average, than conventional production and had a better input-to-output energy efficiency ratio. Gündogmus [91] also examined, on a largely on-site energy input/output basis, small holding apricot production in Turkey and found that conventional production ha^{-1} basis, used 38% more energy than organic production systems. The organic systems also had a 53% higher output/input ratio, measured as MJ of production, even though yields were about 10% lower in the organic systems.

Kavagiris *et al.* [92] examined direct and embodied energy and human labour on 18 conventional and organic Greek vineyards and found significantly lower energy inputs and GHG emissions in the organic operations, although emissions were measured in a limited way related to diesel fuel consumption. Energy productivity, measured as grapes produced inputs^{-1}, was equivalent.

A joint LCA-emergy analysis was used to compare the environmental impacts of growing grapes in a small-scale organic and conventional vineyard in Italy [93]. Despite 20% lower yields in the organic system, GHG emissions for organic grapes were lower than for conventionally grown ones. Fuel and steel consumption were respectively 2 and 6 times greater on conventional operations. This result counterbalanced the effects of the higher yields in this system. However, this LCA was limited in that production-related fertilizer emissions were only calculated for the conventional system, and field-level fertilizer emissions in both systems were excluded entirely. Using a bottle of wine as the functional unit in a partial LCA (limited by data availability), Point [94] found effectively no differences in GWP potential between Nova Scotia conventional and organic production, at two levels of organic yields, one at 20% below conventional, the other at par.

As summarized in Table 7, fruit results are mixed on both an energy and GHG basis. Organic is slightly favoured ha^{-1}, but not generally so t^{-1} production, unless the study takes a full emergy analysis approach or examines non-renewable energy use efficiency. In only a few studies does organic performance exceed our 20% threshold.

Table 7. Fruit—summary of organic *vs.* conventional comparisons.

Authors	**Region**	**Type of study**	**Measure**	**Org < Conv**	**Org > Conv**
Scialabba and Hattam [85]	Europe	Numerous energy	Apples GJ ha^{-1} GJ t^{-1}	10	23
Reganold *et al.* [86]	Washington, US	Energy	Apples Energy ha^{-1} Energy t^{-1}	14	7
Kramer *et al.* [87]	Washington, US	N_2O	Apples	0	
Geier *et al.* in Gomiero *et al.* [7]	Germany	Energy	Apples Energy ha^{-1} Energy t^{-1}	0	23
Wood *et al.* [82]	Australia	I/O-LCA hybrid	Fruit, energy intensity \$$^{-1}$	30%	
Alonso and Guzman [43]	Spain	Non-renewable energy efficiency	Fruit, MJ input MJ output^{-1}	Organic 7–32% more efficient	
Gündogmus [91]	Turkey	Energy I/O	Apricots, MJ t^{-1}	Organic 53% more efficiency	
Gündogmus & Bayramoglu [90]	Turkey	Energy consumed	Raisins	23%	
Kavagiris *et al.* [92]	Greece	Energy productivity	Grapes, energy produced/inputs	0	
Pizzigallo *et al.*[93]	Italy	joint LCA-emergy analysis	Grapes, solar emergy/l wine	34%	
Point [94]	NS	LCA	Grapes, GWP potential at 2 levels of output	0	

2.3.3. Greenhouse

The energy efficiency of organic *vs.* conventional greenhouse production has not been well studied, complicated by both differences in yield and technology preferences. Although organic yields appear to be lower, there is also evidence that organic producers frequently use less energy intensive greenhouse technology which may offset per output differences [95]. In the Alonso and Guzman [43] study of greenhouse vegetables, the differences between production systems were negligible when both used the same greenhouse technology as the high fixed energy use of the structures made production differences insignificant. Other studies have come to similar conclusions [96]. Williams *et al.* [70] found that the lower yields of UK organic tomatoes (about 75% of conventional) and the focus on more specialist varieties meant that energy use and emissions were almost double those of conventional production t^{-1} if the same heating and power systems were used in the greenhouses. All this explains, in part, why the BioSuisse organic standard includes a strict limitation for greenhouse heating [9]. For organic greenhouse production to warrant support as an energy efficiency or GHG reduction strategy likely means use of advanced ecological greenhouse designs or very low technology systems using waste heat from biological processes.

2.4. Issues that Cross Commodity Lines

In the following section, cross cutting issues such as tillage, compost, soil carbon sequestration plus the related topics of consumption choices (animal and processed foods), wasted food and potential energy offsets, are briefly reviewed. While a number of these topics are relatively poorly explored to date, the issues form an important context in which to place whole farm E and GWP results, and the resulting interactions, if still only understood poorly, warrant the attention and future inquiry of readers.

2.4.1. Tillage

Frequently, fuel usage for tillage is highlighted by organic farming critics but, as noted above in the section on field crops, fuel use increases relative to no-till operations are usually a relatively small part of total farm greenhouse gas fluxes [33,27]. Dyer and Desjardins [97] report that fuel used for farm fieldwork in Canadian farming systems typically contributes less than 10% of total on-farm GHG emissions. Dyer and Desjardins [97] report GHG emissions for secondary tillage operations, such as discing that would require more draft power than finger weeders, as low (~28 kg CO_2 ha^{-1}) compared to plowing (90~28 kg CO_2 ha^{-1}) and between two to three times that for spraying (~10 kg CO_2 ha^{-1}). Manure spreading is also a relatively low E requiring practice.

Organic carrot and potato production have been identified in several European studies as having high energy inputs per unit of output because of mechanical weeding [96]. In a limited number of systems, such as potatoes with mechanical weeding, the increased energy from tillage may mean energy use in the entire system is roughly comparable, but in most other production systems, even with tillage, energy use is often half of conventional [98]. Organic farmers have frequently shifted from deep to shallow tillage (e.g., finger weeders) and these shallow tillage operations likely do not consume more fuel than herbicide applications, and can frequently be lower users of energy, especially when herbicide manufacturing is included in the energy balance [99].

Zentner *et al.* [100] found that although the use of minimum and zero tillage practices provided significant energy savings in the form of fuel and machinery, these savings were largely offset by increased energy expended on pesticides and N fertilizers. In a study conducted in the Parkland region of the Canadian Prairies, they compared non-renewable energy inputs and energy use efficiency of monoculture cereal, cereal-oilseed, and cereal-oilseed-pulse rotations, each four years in length and each managed using zero, minimum and conventional tillage practices. Total energy use over a 12-yr period was largely unaffected by tillage method, but differed significantly by crop rotation.

Khakbazan *et al.* [101] reported from Manitoba on a comparison of 16 alternative management practices for a wheat-field pea rotation for economic returns, non-renewable energy use efficiency, and GHG emissions. While a strictly organic management system was not included, the study is informative as ‘low-input’ treatments for wheat with respect to N fertilizer (20, 40, 60 and 80 kg N ha^{-1}) and herbicide (reduced *vs.* recommended rate), along with high disturbance (HDS) *vs.* low soil disturbance (LDS) seeding options for both crops, were included. The LDS tillage system did increase the amount of soil C sequestered compared to HDS system, but method of tillage had a negligible overall effect on total farm E use.

2.4.2. Composting

There is some Canadian evidence [102] that composted cattle manure has significantly lower GHG emissions on balance than stockpiled manure and slurry, largely because of much lower methane emissions. In the study of Bos *et al.* [46], energy requirements for imported organic manures were restricted to those for transport and application only and a ‘zero energy’ price for organic manures themselves was assumed. Consequently, E use was lower for a crop fertilized mainly with organic fertilizers than for a crop fertilized mainly with mineral fertilizers. On farms, manure (or compost) application is a relatively low fuel and E cost (<10 kg CO_2 ha^{-1}) when compared with tillage operations (>80 kg CO_2 ha^{-1} and >28 kg CO_2 ha^{-1} for plowing and discing respectively) and harvesting (>33 kg CO_2 ha^{-1}) [97].

2.4.3. Soil C Sequestration

To produce a gain in carbon storage, a management practice or system must (a) increase the amount of carbon entering the soil as plant residues or (b) suppress the rate of soil carbon decomposition. Organic farmers generally add either more organic C or a more diverse range of materials relative to conventional and no-till operations. In their meta-analysis, Mondalaers *et al.* [18] did find statistically significant higher levels of soil organic matter on organic farms, but also reported on numerous studies that did not find convincing evidence of differences, largely they believe because of methodological limitations. There is evidence that adding diverse materials with suitable C:N ratios also creates a more stable pool of organic material [103,104]. This was confirmed in a long-term USDA study in Maryland directly comparing organic production with no-till conventional production. The study showed that organic farming built up soil C better than conventional no-till because use of manure and cover crops more than offset losses from tillage [105]. Animal manure, the diversity and C: N ratio of organic additions, and the decay rate may be important to this process [104]. Cavigelli *et al.* [34], for example, found improved GHG intensity (or GWP per unit grain yield) and GWP for an organic compared to no-till and chisel till systems in Maryland, USA to be due primarily to increased soil C [106] under the organic system compared to chisel or no-till systems. Sanchez *et al.* [107], in a long-term (7 yr) study of comparative grain management systems in Michigan, found the enhanced 'substrate diversity' of a transitional organic management system that combined green manures and compost enhanced both short ('active') and long-term soil C and N pools.

Research teams at Michigan State University compared corn-soybean-wheat systems under conventional tillage, no-till, low input and organic systems (with legumes, but without animals and manure). Using CO_2 equivalents (g m^{-2} yr^{-1}) as their measure for systems comparisons, they found that no-till had the lowest net Global Warming Potential (GWP) (14), followed by organic (41), low-input (63) and conventional tillage (114) [33]. The Michigan study also concluded that perennial crops (alfalfa, poplars) and successional communities all had much lower emissions and in fact most were net C sinks. The no-till system superiority over organic was a result of higher soil C sequestration (–110 to –29). However, there is some debate about the extent to which no-till systems actually sequester carbon and to the type of organic matter stored and its permanence. In some studies, soil C content increases within the top 7.5 cm of the soil profile, but results in no changes over the entire profile [108-110]. The Michigan study only measured soil C changes in the top 7.5 cm, so the C sequestration benefits of no-till may be overestimated relative to organic systems. No till, because it increases moisture in the profile, may also be increasing N_2O emissions in drier environments [111,112].

Recent surveys of Canadian grain producers suggest tillage may be offset by increased organic matter return. Nelson *et al.* [26] documented, through mail out survey responses (n = 225) from organic and conventional grain growers on the Canadian Prairies, that while organic farmers used more tilled summerfallow than conventional farmers (52% *vs.* 6%), they also had more forages and green manures in rotation (66 *vs.* 64% and 84% *vs.* 6%, respectively). The authors recommend further research to determine the net effect of these practices on soil C while developing alternatives to summerfallow suitable to organic production.

In Atlantic Canada, organic potato farms utilize extended (5-yr) rotations, including legume cover crops compared with much more frequent cropping of potatoes (and associated tillage) in conventional production systems [11,113]. Recent studies suggest these rotations confer marked benefits to soil organic matter and soil health including micro- and macro-fauna. In a study conducted on four farm sites over 2 years, indices of soil health, including earthworm abundance and biomass and soil microbial biomass, appeared to benefit particularly from these extended rotations, recovering from marked reductions during potato cropping to levels found in adjacent permanent pastures only 3 to 4 yrs after potatoes (comprising 1 yr of grain followed by forages) [114]. Soil organic C levels were also sustained at all sites (~30–38 Mg C ha^{-1} in the surface 0–15cm across all sites and rotation phases) with no significant change during the potato phase or relative to the reference fields.

Despite these positive results, innovative approaches to tillage reduction are being explored in organic production. Hepperly [115] reported on the substantial additional soil organic carbon (SOC) gains from a 'biological no-till' system that combines cover crops and a crop roller system at the

Rodale Institute when compared to conventional no-till, and standard organic management. No-till systems for organic vegetable production are also being explored [116]. In Canada research efforts are underway within the Organic Science Cluster research project to test no-till systems for organic grain production [117].

'Another key issue is all soils have a limited capacity for storage of soil C. Steady state permanence is usually reached within 15–33 years depending on soil and management, and measures must then be taken to avoid subsequent C declines'.

There are also significant debates about how to account for regional variability, measurement uncertainties, process uncertainties, identifying real additionality, reducing leakages, and appropriate pricing of stored carbon [112]. All this suggests organic farmers should not necessarily count on the development of well functioning carbon sequestration markets in the short term to finance improvements to their operations. Niggli *et al.* [118], however, argue that soil C sequestration is very cost effective, can be achieved relatively quickly, and because of its many ancillary benefits, should be given as a credit for improved soil management practices, as are common on many organic farms. Currently SOC credits are excluded from Clean Development Mechanisms and World Wildlife Fund for Nature programs.

The influence of livestock systems and the management of permanent grassland in particular on potential SOC storage has been less assessed compared with comparative studies of cropping systems' influence on SOC. Organic ruminant livestock producers are required under organic standards to rely on forage-based livestock feed including, in season, management of grazed pastures. Improved grazing management, including the use of legumes, and decisions on grazing intensity and stocking rate as practiced by organic farmers, can be a cost effective option that promotes substantial SOC gains on the extensive acreage of often degraded permanent grasslands in Canada [42,119,120].

2.4.4. Energy Offsets

To what extent might energy offsets from energy crops, residues and biogas production create a more favourable energy balance for organic farms? These questions must be examined against comparable conventional farming energy strategies. A review by MacRae *et al.* [121] suggests that energy crops and residues have a much more limited role on organic farms compared to conventional ones, because of the need to use organic material for nutrient and soil building purposes, and the high demand for organic food targeted to human markets. Similarly, biogas production will likely play a more limited role, given the limited amount of manure that can typically be directed towards on-farm biogas, and the degree to which anaerobic digestion is discouraged in organic standards [122]. Although energy offsets, even in a limited capacity, can improve the overall GHG reduction and energy efficiency of an organic operation, they are likely to be relatively smaller benefits than could arise from conventional operations.

2.4.5. Studies of Widespread Organic Adoption

There are only a few studies examining the energy implications of widespread adoption of organic farming systems. A Danish study of wholesale national conversion to organic farming found 10–51%

reductions in net energy use relative to 1996 conventional agriculture, depending on the scenario of wholesale conversion. Scenarios varied by yields of animal and crop production and extent of self-reliance in animal feed. As organic yields improved, there was greater potential for efficiencies. These reductions in net energy use were associated with significant reductions in greenhouse gas emissions, particularly N_2O emissions [123,124].

Few Canadian studies of the GHG and GWP implications of more widespread adoption of organic systems have been undertaken. The Pelletier *et al.* [28] study was summarized above. An unpublished and less complete analysis by World Wildlife Fund Canada [125], based particularly on assessments by Robertson *et al.* [33], reported total GHG reductions from limited conversion scenarios at 1.225 Mtonnes of CO_2 equivalents, a significant amount given Agriculture and Agri-food Canada's target at the time of the analysis for reductions from agriculture of 10–20 Mtonnes [126].

2.5. Consumption—Related Considerations

Here we consider consumption related issues that could impact on the interpretation of the conventional-organic production differences. Though not well studied in Canada, some recent work suggests that dairy and eggs, fresh and frozen meat and prepared foods were the biggest food household expenditure contributors to GHG emissions in 2003 [127]. Using US analyses that are more robust, we elaborate on some of these findings.

2.5.1. Processed Foods

In the US, processed foods account for 82–92% of food sales [128]. Many foods require minimal, or what is called primary processing, to be edible and to increase nutritional value, while others go through extensive secondary and tertiary processing that adds to convenience, though not necessarily nutritional value. In fact, much secondary and tertiary processing reduces some nutritional components, requires sophisticated packaging, and is very energy intensive. In recent years, households have effectively transferred energy use from the home to such processors [1]. Pimentel *et al.* [128] propose that the most effective method for decreasing energy inputs is to dramatically reduce consumer demand for these secondary and tertiary processed products that require large energy inputs. For example, a can of diet soda has only 1 kcal of food energy, yet requires about 500 kcal to produce, with a further 1,600 kcal to produce the 12 oz. aluminum can. Thus, 2,100 kcal are invested to provide zero to 1 kcal of consumable energy [129]. In addition, the energy input for transportation must be taken into account, although aluminum weighs less than glass and is readily recyclable in many jurisdictions.

2.5.2. Animal Products

Some analysts see the other population explosion—livestock—as a huge threat to global sustainability [130]. Land use changes to accommodate livestock, manure production, animal feed grown with synthetic nitrogen fertilizer, direct emissions from animals themselves, transport, chilling and heating in the processing and consumption chain may account, directly or indirectly, for 18–51%

of total GHG emissions on the planet [131,132]. An EU study concluded that half of all food-related emissions in the EU are associated with meat and dairy products [133]. It would appear that encouraging more plant-based diets, especially in combination with organic production, would pay significant dividends. Animal-based protein foods are 2–100 times more energy-intensive than plant-based protein foods, depending on the production system and commodity [134].

Eliminating livestock is not, however, a viable option, since they can play very important ecological roles on farms. But it is important to optimize both human and animal feeding systems by maximizing ruminant feeding on forages/grass, while monogastrics feed on residues and seeds of non-dominant crops. Other countries have more optimal balances. For example, the national share of grain fed to animals is only 5% in India, compared to 60% in the US [44]. Crop residues and wastes must be better maximized. One effective component of that strategy is to increase feeding on oil seed crush, processing residues, and lower quality feed grade crops. As well, more research on pasturing hogs and poultry can help determine optimal livestock levels on pasture. Reducing feed losses will improve overall system efficiency. While elimination may not be appropriate, significant reductions in consumption of livestock products may reduce environmental stressors and improve human health.

Related to this is the need to rationalize selection of animals. At present, much of the focus in organic meat production is on cattle, partly because of the pasture-related opportunities, partly because of current market realities. Pigs, however, have 40% lower energy requirements than would be anticipated from their size, largely because of low basal metabolism. Thus, from an energy perspective there is a logic to favouring hogs over cattle, which have much higher basal and reproductive metabolism. Pigs also tolerate a wide range of environments. Dairy animals do, however, have a favourable energy conversion ratio for milk.

As discussed above, how to best take advantage of these biological realities has yet to be fully explored in organic hog systems. Chicken and eggs are next most efficient on the energy conversion scale, suggesting that they warrant more attention in landscape level planning for energy efficiency. Ultimately, fish are much more efficient feed converters than farm livestock. Thus, it makes sense over the longer term for the organic sector to devote more attention to ecological herbivorous and omnivorous fish production systems.

2.5.3. Wasted Food

By some estimates, up to 40% of what gets planted and raised is never eaten [44]. Waste is generated at all stages of the supply chain—at harvest, during storage, distribution, retail, and as kitchen waste. For example, each phase of the grain handling process—from harvest to threshing, drying, storage and milling—can produce up to 10% losses, for cumulative losses of 40%. Fruit and vegetable losses run in the 10–70% range [135,136], though not all waste is of edible matter. But all of it, theoretically, could be used, either by humans, animals or as soil amendments. Given the immaturity of the organic waste handling system in Canada, with the exception of some provinces, most notably Nova Scotia, the system is likely not minimizing its losses.

Another type of waste arises from "unnecessary" consumption. The average person on the planet might need 2200 kcal/day (with an additional 800 kcal/day lost from production to consumption) [44]. The average North American is consuming substantially more than is required for optimal health, perhaps around 3700 kcal/day [128]. The average Canadian consumes more calories than is generally required for good health [137,138]. A more health-oriented approach to consumption, with a focus on more equitable global distribution of food resources, would ultimately reduce the pressure to increase crop and animal yields (and the associated use of high emissions nitrogen fertilizer) and dramatically reduce food system emissions per capita.

A key place to start would be reducing junk food consumption. The average American appears to consume 33% of their total calories from junk food. According to Pimentel *et al.*, "reducing junk food intake from 33% to 10% would reduce caloric intake to 2,826 kcal, conserve energy, and improve health" [129].

3. Conclusions

In the Introduction, we detailed that which needs to be in place to warrant significant public support for expansion of the organic sector to meet energy efficiency and GHG reduction targets. We discuss the results of our study in the context of those conditions.

1. Clear and significant differences exist in energy and GHG emission performance between organic and conventional operations.

   Organic generally has lower energy use and GHG emissions ha^{-1}, better energy input/output ratios per unit of product, but variable results for energy use and GHG emissions per unit of product. With some variability in results for field crops, hogs and some fruits and vegetables, organic systems are consistently more energy efficient, beyond a 20% threshold, than conventional systems, measured by land area and production. Similarly, GHG emissions are consistently lower, with again some variability in those same commodities, but in more cases than energy efficiency, the 20% threshold is not passed. This is especially the case when measured on a per product basis, where results are often highly variable. Poultry and fruit, however, are generally more favourable in conventional systems, or when organic is favoured, usually not beyond the 20% threshold, unless the results are from a solar emergy study. The main reasons for better organic performance are the lack of synthetic N fertilizers and lower use of feed concentrates. Tillage in organic farming does not appear to be a significant contributor with respect to on-farm E use, in contrast to common assumptions of organic critics. The study found no consistent evidence to support the view that tillage reduces soil carbon in organic systems. In fact, our review found that the inverse is usually true, *i.e.*, that green manures and forages increased soil C on organic farms regardless of added tillage. Equally, the criticism that organic producers are diesel farmers is not supported by the data.

2. Consistent approach in how emissions are reported. *i.e.*, whether on a per land unit basis or product basis.

   There is considerable debate in the literature about which measures are most appropriate and the variability in the comparative results means this is a significant issue that has yet to be resolved. Due to yield differences in intensive conventional production zones (*i.e.*, Europe), per product comparisons more commonly do not favour organic, especially when examining GHG emissions.

Although organic critics commonly argue that lower yields are sufficient reason to not support organic agriculture, many regions of the global south show better yield performance in organic compared to conventional systems [139]. In areas where conventional farming significantly out-yields organic, it is not obvious that this conventional "overproduction" is entirely beneficial, given on-going farm financial challenges, trade distorting measures that penalize producers in less "productive" regions, and overconsumption of food in those very regions that overproduce.

While efficiency improvements (per product) sustain food production, they may not in themselves be sufficient. The carrying capacity of the planet to provide food for humans is unknown, given the elasticity of consumption (including energy, water and other resources) per person and waste (including packaging, contaminated sewage and other by products) per person. Eventually, the product of excess population, consumption and waste could exceed global carrying capacity, even if food production becomes more efficient with more MJ output per MJ input, less energy use per kg food product and less CO_2e per kg food product. For all these intensity measurements, higher rates of production improve efficiency. The cautionary proviso to the argument that more efficient production will address carbon and global warming potential impacts is that if the total human impact is so large that we exceed carrying capacity, then increased efficiency will not be enough to avoid system collapse and may, in fact, drive us closer to the line. Units of production have an upper limit and system resilience depends on the continuation of regenerative inputs and sustainable consumption. It may be that efficiency assessed per unit land area is closer to a model of food production and consumption which will remain within the carrying capacity of the planet.

3. A consistent approach to credit for soil carbon sequestration in the estimates.

Although the comparisons consistently favour organic production, not all studies measure soil C storage. There is a mixed attitude to the permanence of agricultural soil sequestration and some reluctance to include agricultural soil sequestration in Clean Development Mechanisms (CDM) and other sequestration standards [42]. In some systems, only C sequestration appears to create a positive outcome for organic, especially when measured on the basis of output [42] so this is significant.

4. A consistent approach with respect to N_2O emissions from biologically fixed N by legumes.

Earlier studies, using then current IPCC coefficients, likely overestimated emissions from legumes in organic systems. However, until such study results are recalculated, the implications cannot be quantified.

5. Accepted measures for determining differences.

As Mondalaers *et al.* [18] have concluded, no consistent approach to meta-analysis exists for organic-conventional comparisons. Our review found 5–6 main approaches to doing such studies, and the results are not always comparable. Concluded Gomiero *et al.* [7], "Results from energy assessments are often difficult to compare because of the variety of methodologies and accounting procedures employed". Van der Werf *et al.* [68] used 5 different European approaches to tease out their efficacy related to organic/natural/conventional comparisons and found significantly different results across the evaluation schemes.

6. Generally, agreement that these differences are consistently realizable; in other words that they are not so variable by time and space that no consistent patterns emerge.

Results are variable by jurisdiction, usually determined by whether the conventional comparator is an intensive or an extensive production system. This means that global comparisons are more difficult.

7. The changes represent a permanent improvement. The presumption of such comparisons is that the gap between organic and conventional in regard to these measures remains constant.

Organic recidivism is low and the demands of annual inspection mean that most practices, once adopted for organic certification, are retained. However, debates over the permanence of soil C pools remain. Nevertheless, some conventional farms also use methods quite similar to those used on organic farms and some organic farms emphasize intensity, though still within the standards, to a greater degree than some conventional farmers.

8. The differences in E and GWP between organic and conventional farms do represent an incremental gain worth promoting within the context of overall food system GHG mitigation and energy efficiency.

Assuming, as found in the US study of Canning *et al.* [1] (Canadian data is sorely needed), that farm E use represents a gross average of 35% of total food chain E use and continues to increase, an improvement of 20% or more in E efficiency through organic farm management would represent a reduction in food-chain E use of 7% or more. In practice, farm E use as a proportion of total food chain E use varies widely by sector (ranging in the US study of Canning *et al.* [1] from 17% to 54%), thus benefits of organic farm management to total E use may be even greater. Among food supply chain stages other than agriculture, the wholesale/retail stage (including cooling and packaging) and the processing stage represent similarly large contributions to the entire food supply chain, often contributing 30% or more to total E costs. Thus, additional improvements in food system E use can be obtained by emphasizing reduced processing and consumption of whole foods. Organic processing protocols, through their emphasis on minimal additives, limited numbers of ingredients, and less degrading process techniques, may already offer efficiencies, an aspect that requires more study. Finally, reducing transport offers some additional, if smaller, potential for E and GHG gains (and again data for the Canadian food system is lacking) and a significant body of literature has examined relative E and GHG efficiency of various freight modes. Ultimately, it will be important for the organic sector to note that the improvements in efficiency gained at the farm level can be lost through inefficiencies further along the chain, including processing, transport and wholesale/retail. This is particularly important in the horticultural sector in North America, with heavy reliance on trucking (higher GHG emissions t^{-1} than rail and ship) and product cooling all along the supply chain (see [2,140,141]. In the US study of Miesterling *et al.* [35], the GWP of a 1 kg loaf of organic wheat bread was found to be about

30 g CO_2e less than that for a conventional loaf. However, when organic wheat was shipped 420 km farther to market, the two systems had similar impacts. Thus assuming local transport systems are efficient [142], promotion of local, whole, organic food offers the greatest gains combined in reducing E costs of providing organic food to the consumer.

Ultimately, the differences between organic and conventional production, while significant, may be relatively small compared to reductions that are possible at other levels in the food system such as through changes at a population level favouring lower levels of meat consumption [143] (see argument put forward by Weber and Matthews [2]). However, these farm level benefits are an incremental gain, which combined with significant improvements in processing E use and efficiency, and to a lesser degree by improvements in transport, cooling and packaging of conventional supply chains, will further add to farm scale benefits from organic management.

9. That some verification measures, either at the sectoral or farm level, are feasible.

Measures are being introduced and guidance documents are being produced. Climate change inspectors exist, though such work could only be described as being in its early stages of evolution. Farm energy audits are, in some jurisdictions, being provided through provincial environmental farm plans. Documentation of all inputs and often yields regularly recorded by organic farms provides an important component of any farm scale verification system with respect to farm E use and efficiency.

In summary, our review found significant variability in the volume and type of studies examining organic *vs.* conventional systems (see Table 8).

Table 8. Relative availability of literature.

Sector	**Literature Availability****
Field crops	√ √ √ √
Beef	√ √
Dairy	√ √ √
Hogs	√ √
Poultry	√
Vegetables	√ √ √
Fruit	√ √ √
Greenhouse	√

**From all sources/locations.

Only on-farm energy use would appear to offer sufficiently robust data to warrant immediate interventions, with poultry and fruit question marks given current evidence, albeit very limited, favouring conventional production or not surpassing our threshold of 20% organic advantage. Interventions based on GHG emissions reductions, given variability in study approaches and evidence, may be considered premature by decision makers. However, with more robust data on GHG emission comparisons, and attention to the most up-to-date emission coefficients, it is likely that measures to support organic production based on GHG emissions ha^{-1} would be feasible in the medium term. The longer term challenge regarding GHG emissions per product is to either (a) improve organic yields with better knowledge and farm-level performance; or (b) subject conventional production to cost internalization, thereby producing market signals that encourage producers to reduce yields to less damaging levels in conventional systems. Both options will only likely produce results in the longer term.

Note that in drawing the above conclusions regarding E and GWP benefits of organic production , we believe that reducing reliance on fossil fuels in agriculture is a critical national strategy, but not at the expense of the health of the sector itself. Some argue that further energy savings can be had if production is concentrated in regions with warmer climates. However, in our view, Canada needs a vibrant and ecologically appropriate agriculture sector because of the multiple social, economic and (potentially) environmental benefits that flow from it.

This inquiry has also identified a substantial future research agenda:

- Canadian data on organic/conventional comparisons is generally limited, except in field crops and dairy. But there are major needs for studies on other livestock and horticultural products.
- System-level analyses of energy use and GHG emissions, as opposed to BMP assessments, are also deficient.
- Refining GHG co-efficients in organic operations is particularly important to garner a full understanding of organic performance.
- Few studies examine organic food from inputs through production, distribution, processing and retail. Do organic supply chains outperform conventional ones? Also, given that wasted food is a huge energy inefficiency [44], is food waste as high in organic food chains as conventional ones?
- Ultimately, there are larger questions about the GHG and energy costs of simple rotations or confined single species livestock systems, whether conventional or organic. To the extent that conventional or organic farms deviate from a baseline of good agronomic or husbandry standard practice, they compromise capacity to avoid GHG and energy costs in the long term or become too brittle and not able to adjust as the cost of C and energy rise. It's important to better understand these dynamics.

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Disclaimer

On behalf of the Organic Value Chain Roundtable (OVCRT), the Organic Agriculture Centre of Canada (OACC) conducted a literature review to determine if sufficient evidence exists to substantiate organic branding and image development based on environmental benefits of organic farm management, with respect to farm level carbon footprint. The opinions expressed in the report are those of the respondents and do not represent those of the stakeholders involved in the survey, namely the Organic Agriculture Centre of Canada, the Organic Value Chain Roundtable and Agriculture and Agri-Food Canada.

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OR1 Spring barley Barley-pea/grass Rye Grass Grass
OR2 Grass-clover Barley/grass Pea + oat Wheat –
OR3 Winter wheat Beet roots Barley Alfalfa –
OR4 Potatoes Oat/grass Grass Maize –
OR5 Permanent meadow
CO1 Spring barley Barley-pea/grass Rye Grass Grass
CO2 Grass-clover Barley/grass Pea + oat Wheat –
CO3 Winter wheat Beet roots Barley Alfalfa –
CO4 Potatoes Oat/grass Grass Maize –
CO5 Permanent meadow
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