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The energy efficiency of organic agriculture: A review

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Abstract

Growing populations and a constrained fossil-manufactured energy supply present a major challenge for society and there is a real need to develop forms of agriculture that are less dependent on finite energy sources. It has been suggested that organic agriculture can provide a more energy efficient approach due to its focus on sustainable production methods. This review has investigated the extent to which this is true for a range of farming systems. Data from about 50 studies were reviewed with results suggesting that organic farming performs better than conventional for nearly all crop types when energy use is expressed on a unit of area basis. Results are more variable per unit of product due to the lower yield for most organic crops. For livestock, ruminant production systems tend to be more energy efficient under organic management due to the production of forage in grass–clover leys. Conversely, organic poultry tend to perform worse in terms of energy use as a result of higher feed conversion ratios and mortality rates compared to conventional fully housed or free-range systems. With regard to energy sources, there is some evidence that organic farms use more renewable energy and have less of an impact on natural ecosystems. Human energy requirements on organic farms are also higher as a result of greater system diversity and manual weed control. Overall this review has found that most organic farming systems are more energy efficient than their conventional counterparts, although there are some notable exceptions.

Key words: energy, emergy, fossil fuel, organic, biodynamic, agro-ecological, life-cycle assessment

Introduction

Non-renewable (mainly fossil) energy inputs have played an important role in increasing the productivity of our food systems and sustaining the exponential rise in the world's population witnessed over the past century[1]. At the same time, the dramatic rise in production levels required to support increased populations has created a dependence on mined sources of so-called 'stored-solar energy'[2] within the developed world. This, in turn, has led to agricultural systems that are more exposed to fluctuations in the prices of fossil fuels, whether caused by political instability or increasing demand. A range of environmental catastrophes caused by the pursuit of ever-more scarce sources of fossil energy have also caught the media and public's attention in recent years. These include the Deepwater Horizon oil rig disaster in 2010 and the Exxon natural gas project disaster in Papua New Guinea in 2012. Such events have served to underline the risks associated with our reliance on these energy sources[3]. With this growing awareness, our vulnerability and the continuation of 'agri business as usual' have been questioned[4].

In this context, organic agriculture has evolved as a farming system that focuses on the preservation and recycling of resources, with the aim of creating more sustainable production systems[5–8]. This has been encouraged through the development of an underlying set of internationally accepted principles, and legally binding standards in some jurisdictions, that define organic agriculture[9–12]. With the focus on reducing inputs within the organic sector, it should follow that the adoption of organic production methods will result in farming systems that are less dependent on fossil-fuel inputs. Recent reviews by Lynch et al.[13], Gomiero et al.[14] and Lampkin[15] report that organic agriculture consistently has lower energy use and greenhouse gas emissions when results are expressed on a per hectare basis. The results were more variable when presented per kilogram of product, and conventional production was found to have the highest levels of net energy production. The above studies also found that the variety in energy assessment methods make direct comparisons between studies difficult. The magnitude of difference between organic and conventional production varied greatly depending on whether 'conventional' production within a given region is of an intensive or extensive nature[13].

The aim of this review is to build on the work of Gomiero et al.[14], Lynch et al.[13] and Lampkin[15] by assessing the results from studies comparing the energy use and energy efficiency of organic and conventional farming systems. Unlike previous work, the review presented here provides an overview of the energy use according to the type of input (e.g., fuel for machinery, embodied energy in feed and fertilizer) instead of the farm type. A more complete overview of studies that have considered the embodied energy associated with inputs and ecosystem services is also presented (i.e., results from emergy studies). In addition, the results from more recent published work have been included here. This review also explores the extent to which the results from these studies vary according to the scope of the assessment, the unit of measurement and the farm or production system.

Method

A literature review of organic/conventional energy use studies was carried out in 2012 using a range of web-based search engines (ISI Web of Knowledge, Scopus, Google Scholar, BIOSIS Previews, SCIRUS, ScienceDirect, Organic Eprints). The following or similar terms were used in a combination with the Boolean operators AND, OR:

- Energy, emergy, fossil fuel
- organic, biodynamic, agro-ecological
- life cycle assessment (LCA), emergy, thermodynamic
- comparison, compare.

Only studies based on pairwise comparisons were selected for inclusion and publications had to contain energy use data on both organic and conventional agriculture. Non-certified production systems were also included, for example where experimental farms were using organic methods. In these cases a judgment was made as to whether the farming practices on the experimental farm being assessed adhered to the IFOAM (International Federation of Organic Agriculture) principles. Countries in the developing world were excluded and the review focused on modern agricultural systems (e.g., excluding the use of draught animals for cultivation). Studies compared were drawn from Europe, North America, Canada, Australia and New Zealand. Gray literature was included within the search, including PhD theses, government and non-governmental organization (NGO) reports and research project reports.

Comparisons were made for each product group in relation to the amount of energy required per unit of product (e.g., kilograms or liters) in addition to the amount used per unit of land (e.g., hectares or acres). This approach follows the suggestion of Van der Werf et al.[16] who propose that the unit of area comparison reflects a farming system's function as a producer of non-market goods (e.g., biodiversity), whereas the unit of product comparison reflects agriculture's function as a producer of market goods (e.g., food and fuel). Comparisons of environmental performance based solely on the amount of product can also present an issue when dealing with foodstuffs that vary greatly in nutritional and water content (e.g., milk and meat)[17]. Furthermore, Cherubini and Strømman[18] highlight that displaying results per unit of agricultural land can provide a useful indicator of land-use efficiency. The same study highlights the need to identify the limiting factor of the system being assessed and that this should be used as the reference indicator of the assessment. With competition for agricultural land purposed to be one of the main drivers affecting food and farming in the future[19], assessing energy use per unit of land can be a useful tool to compare the energy efficiency of agricultural systems.

Types of study considered

Most of the studies considered within this review have taken what Jones[20] describes as a 'mechanistic' or 'process analysis' approach, i.e., assessing the fossil energy use associated with the various production stages of an agricultural product. This includes the assessment of energy associated with production processes on case study farms[21,22] or through the application of LCA. This is a method used to calculate the burdens associated with one unit of a food commodity, e.g., 1 kg of wheat, area of land or livestock unit (LU) defined as the 'functional unit'[23]. Within the LCA approach, inputs to the system are usually traced beyond the farm gate to the primary resource. For example, this can include the coal or uranium used to generate electricity or the energy required to produce steel, plastic and other materials required for the manufacture of tractors[24]. LCA has the distinct advantage of being able to determine efficiency within supply chains in a manner that can be easily understood[25]. In addition, the broad principles for the application of LCA have been standardized, e.g., through the International Organization for Standardisation 14044 standard[26]. This has helped to make LCA the most widely used method for the assessment of energy use within supply chains in the agriculture sector[27]. It is important to note, however, that these standards are not prescriptive about boundary conditions, the functional unit or the purpose of the study, which can make comparisons between studies difficult.

Other studies considered here have followed a 'thermodynamic approach'[20] through the adoption of emergy accounting[28]. Emergy has developed as an alternative to the 'traditional' fossil energy focused approach of energy accounting. It takes an eco-centric approach that accounts for the contribution of natural services (e.g., rain, pollination, soil formation) in delivering agricultural products[29]. In a similar manner to LCA, the emergy approach measures the energy previously used in the creation of a product. However, it also accounts for the amount of available energy that sits within the assessed product or system. The units of energy are expressed in a common unit (i.e., 'solar energy' or 'emjoules')[28]. The emergy approach also takes into account natural/ecological inputs and human activities. It calculates natural inputs, based on the distribution of solar energy in the biosphere and the energy output potential of the various processes (e.g., rainfall, total wind energy and total wave energy)[30]. Human labor and services can also be accounted for, both in terms of the energy used to support human life and the energy associated with the accumulation of information[28]. In this sense, emergy allows for an assessment of 'energy quality' through considering the importance of inputs and outputs in a web of relationships[31]. A limited number of studies have used the emergy approach to assess the efficiency of organic and conventional agriculture. The results from these studies will be described in a separate section below.

A number of studies within this review have also taken the nominally dimensionless 'energy ratio' approach to determine the efficiency of production systems (i.e., dividing the energy output in food sold by the energy input of fossil fuels). This approach is nominally dimensionless in that the gross energy of fuels is compared with the metabolizable energy of foods or feeds. Lampkin[15] highlights that this method can be a useful determinant of the efficiency of agricultural systems in capturing solar energy and transforming this into feedstuffs for growing populations. Halberg et al.[32] also highlight the potential of this approach to allow farmers and advisors to compare the efficiency and environmental impacts of crop and livestock enterprises, in order to identify areas for improvement.

A limitation of the study is that there are insufficient data to perform a statistical analysis. The wide variation in the scale of the studies and the methods used prevents this. In addition, the wide geographical variation in the studies and the resultant wide range of soil types and climates makes it difficult to draw definitive conclusions that will apply to each country or region (Appendix 1 shows the list of studies, their location and energy assessment method used).

Results from the Literature Survey: On-Farm Energy Use

The efficient use of fossil-fuel energy on farm is of increasing concern for farmers and stakeholders within the supply chain, in light of fluctuating input prices[33,34] and the effects of climate change and pollution[1]. A number of process-oriented and LCA studies have compared the on-farm resource efficiency for a range of organic and conventional crop and livestock systems, to explore the relative efficiency of these production systems. In addition, a number of studies have assessed human energy, using empirical methods or system modeling; the results from studies in both of these areas will be outlined below.

On-farm fuel use

A common criticism of organic agriculture is that reliance on mechanical tillage (e.g., for weed control) results in lower energy efficiency overall[35]. A process-oriented modeling study carried out by ADAS[36] supported this criticism, finding higher machinery energy use within organic systems (i.e., energy associated with the manufacture, distribution and repairs to mechanical equipment). This increase was, however, offset by higher indirect energy use under conventional management. Most of the additional fuel use within the ADAS study was associated with weed control. Organic carrot production compared particularly poorly due to the energy-intensive process of flame weeding. Organic wheat production was also associated with higher machinery energy, a potentially significant finding in view of the dominance of wheat in the European arable sector and the importance of this crop as a staple of Western diets. Venkat[37] also found higher on-farm energy use on organic farms for certain vegetable crops (see Fig. 1) within an LCA comparison, suggesting that this is due to systematically higher levels of mechanical weeding. Unlike the ADAS study, Venkat found that this difference was enough to offset the impact of fertilizer manufacture in the conventional system. Greater use of tractor diesel per liter of milk produced was also reported for an organic farm in an LCA of two large dairy units in Sweden[38]. Higher fuel use per functional unit on the organic farm was a result of the larger area of fodder production and lower yields within this study. Jørgensen et al.[39] also found that the levels of on-farm energy use were 28% higher for organic crop production in Denmark. This was a result of higher fuel consumption for weed control in addition to the energy-intensive practice of manure spreading (compared to spreading fertilizer). In common with the ADAS study, the authors found that the higher on-farm energy use was offset by the energy requirements for the manufacture of inputs in the conventional system.

The need for moldboard plowing in organic systems, for the removal of crop residues and control of weeds, can also contribute to greater on-farm energy use in comparison to reduced tillage with herbicides, as identified in a comparison of organic, integrated and conventional farming systems[40]. A study by Michigan State University also found a lower fuel use for a corn, soybean, wheat rotation under conventional no till, compared to the same rotation under low-input and organic conditions, although the savings were offset by the energy associated with fertilizer and lime inputs[41]. Zentner et al.[42] also found that gains in on-farm fuel use from reduced tillage were offset by the embodied energy associated with inputs of pesticide and fertilizer within an energy analysis of direct and indirect energy associated with nine cropping

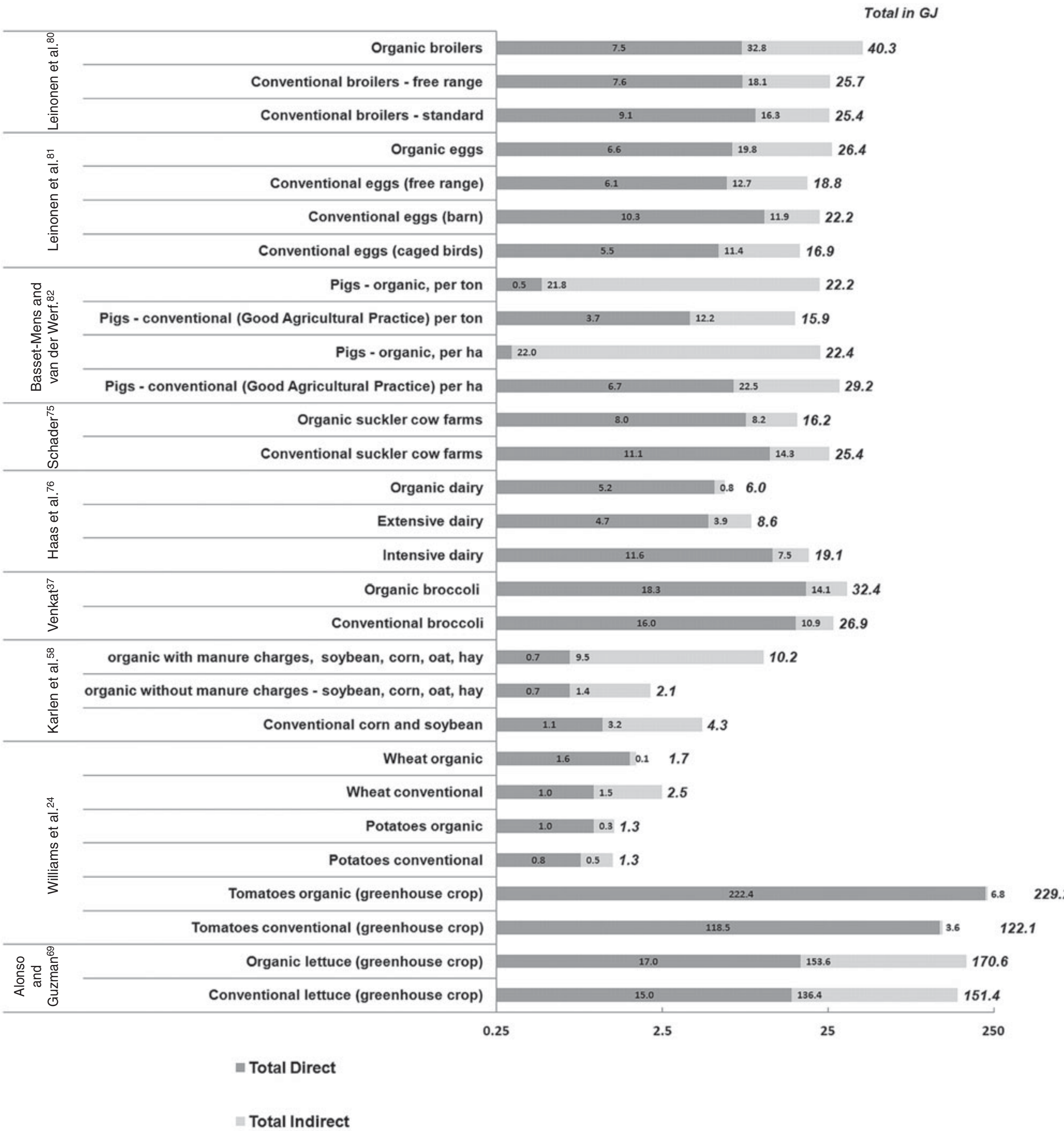

Figure 1. Distribution of 'direct' (i.e., on-farm) and 'indirect' (i.e., off-farm) energy use from seven studies comparing organic and conventional production. Owing to variation in the scale for the products reported, a log scale has been used on the *x*-axis. Most studies took a 'cradle-to-gate' approach (i.e., considering energy use associated with production but not retail consumption and disposal); for more details on boundaries and functional unit of each study, see Table 1.

systems in Canada. Despite this, Snyder and Spaner[43] note that high-input costs are supporting a shift toward reduced-input systems, where reduced tillage is applied, and it has been suggested that such tightly controlled conventional systems may rival organically managed farms with regard to energy efficiency, even when the costs of inputs are taken into account[44]. However, reduced tillage is no longer exclusive to conventional farms. Recent studies show that this technique can be applied successfully under organic conditions for cereal crops[45,46] with significant energy savings as a result[46]. Lockeretz et al.[47] also found that organic farmers in the 'corn belt' of the USA were more likely to use chisel plowing methods, as opposed to the moldboard plow. This was to help conserve organic matter and water, instead of exposing the soil to wind erosion, a common problem in the area studied. It is also important to consider that reduced tillage is not always possible for farmers. The possibility

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for implementation will depend greatly on the soil type, topography and the available power of the machinery[48]. Increased herbicide leaching and greater population of certain perennial weeds and grasses have also been reported in some reduced tillage systems[49,50], which could result in increased requirements for cultivation and fuel use to remove pernicious weeds. Reduced yields within no tillage systems have also been observed in some soil and climate conditions[51], reducing the overall energy efficiency per unit of product.

In contrast to many of the above studies, some authors have found the similar or even lower levels of on-farm diesel use for organic production. For example, Refsgaard et al.[52] found little difference between the amounts of diesel required for the production of conventional and organic crops. However, the organic systems within the process models used in this study tended to require more fuel for handling and spreading of manure. A farm system monitoring project in Switzerland also found very similar levels of diesel in a long-term comparison of an organic and conventional farm, although the conventional systems used as a comparator within this study were of a relatively low intensity[22].

Labor

With regard to human energy (or labor), organic systems have been associated with higher numbers of staff on the farm due to increased livestock, reduced machinery use and diversity in farm enterprises[21,53,54]. El-Hage Scialabba and Hattam[55] also report a higher share in the production of labor-intensive crops (e.g., vegetables) and on-farm marketing and processing on European organic farms. In a modeling study of four organic and conventional crops, Pimental et al.[56] also found lower labor productivity for organically produced crops (i.e., kilogram output per hour of labor input). This was due to a need for increased cultivations, in addition to greater losses from pests and disease and high cosmetic standards, which prevent sale of certain crops, in particular organic apples. Nguyen and Haynes[57] also compared the labor productivity of three pairs of mixed cropping farms in the Canterbury region of New Zealand, with labor requirements calculated in hours per hectare for the entire rotation and the cropping part (i.e., peas, barley and wheat) separately. The labor productivity was also measured as a ratio of harvested grain to the number of hours per hectare. Although labor inputs per hectare for most grain crops were higher on the organic and biodynamic sites, the total labor use was lower as a result of the 3–4-year fertility-building period. This balanced out the higher requirement for the cropping phase. Despite this, the grain crops grown within the biodynamic and organic systems had a lower labor productivity (0.4–1.1 $\mathrm{ton\,h^{-1}}$) compared to the conventional (1.3–1.6 $\mathrm{ton\,h^{-1}}$), as a result of higher labor inputs and lower yields. The additional labor requirement within the organic systems was partly due to the additional field and manual operations plus the additional labor requirement for the manufacture of cow-horn manure (a homeopathic preparation for improving soil health) within the biodynamic system. Karlen et al.[58] took a similar approach in calculating the number of field-work hours required for crop production and harvest in a comparison of four 40-acre fields in the ‘Corn belt’ of the USA. Within the ‘alternative’ system, labor requirements were substantially increased (between 178 and 183% of the conventional). This was primarily as a result of the additional time required for spreading manure, weed control and through the incorporation of a hay crop within the rotation, which required multiple harvests.

An attempt was also made to compare the labor requirements of organic and conventional farms by comparing calendars of work of conventional and organic farmers in addition to measuring heart rates and constructing an energy budget based on their food intake[59]. The relatively high energy and effort expenditure on the organic farm led the author of this study to suggest that ‘the annual activity of organic farming is characterized by physical stress and fatigue’. Unfortunately the study was flawed in that it compared an organic farmer using hand tools with a conventional livestock and arable farmer who spends most of the heart rate assessment period driving a tractor. The farms were therefore not comparable, and as the author notes, the organic farmer cannot be considered representative of the sector. Having said this, the study does contribute to addressing the methodological difficulties of comparing mechanized systems with manual operations.

Indirect, off-farm energy use

Indirect energy use (i.e., energy use associated with the production and transport of inputs) typically exceeds on-farm energy use within modern farming systems in developed countries, with fertilizer and imported feeds for livestock comprising the two major sources of energy inputs used for agricultural products[27]. The importance given to on-farm or local resources within the IFOAM organic principles[12] suggests that organic farms could be less reliant on external inputs of fertility and animal feed, and a number of studies have explored the extent to which this applies in practice.

Fertilizer inputs

The energy intensive manufacture of nitrogen (N)-based fertilizers represents the most energy expensive input for modern farming, accounting for about half of agriculture’s energy use[19] and approximately 1.1% of energy use globally[60]. Instead of relying on manufactured fertilizers, organic farms source the bulk of their N through biological fixation by temporary, legume-based leys. The use of leys can also further the production of soil organic matter[61] in addition to providing an energy source for the soil biota, which enables humus production through transformation of organic material. In this, sense the organic system aims to develop soil health over the long term, rather than providing a short-term nutrient supply through application of soluble plant nutrients[62]. Refsgaard et al.[52] state that in this context 'one might think of organic farming as a systematic replacement of fossil-fuel N fertilizer production with solar-driven N fixation in legumes', with fossil fuels being used to help this process. This was illustrated by Gomiero et al.[14] who found that the main reason for increased energy efficiency under organic management was the lack of synthetic inputs, in particular fertilizers and pesticides.

Despite the reliance on biologically fixed N within organic agriculture, organic farmers still make use of mineral sources for other nutrients, in particular rock phosphate (P), which is mined from natural stores. Trewavas[63] argues that when this aspect is taken into account, the energy efficiency of organic farming is lowered considerably, when compared to integrated no-till systems. Low solubility of rock phosphate may also make it less effective than manufactured P fertilizer (superphosphate) particularly in low rainfall areas[64]. Co-application of rock phosphate with elemental sulfur or manure could, however, help to enhance availability[65,66]. Use of rock phosphate may also help to maintain a stable supply of readily available P over time, compared to use of water-soluble phosphate fertilizer[67]. Pelletier et al.[68] found in their LCA of organic and conventional wheat and soybean production in Canada, that the cumulative energy demands of producing phosphate fertilizer were on average four times higher than those associated with producing rock phosphate used in organic agriculture. Sourcing fertility from outside of the farming system also applies to farms producing large quantities of crops, which depend on external sources of compost and manure. Alonso and Guzman[69], for example, found higher energy use for organic crops grown in Spain, as a result of the energy associated with production of large quantities of compost. Karlen et al.[58] found that without charging for the energy associated with the manure nutrients (i.e., assuming that the manure is a 'cost' incurred by the livestock enterprise) an 'alternative' system required about half of the energy of the conventional; however, if the energy costs for the nutrients were included, the alternative system used twice as much energy as the conventional (see Fig. 1). Duesing (1995) in Rigby and Cáceres[70] also refer to North Californian organic farmers using manure from South Californian dairy farms, which in turn used imported feed grain from the Midwest. Rigby and Cáceres[70] note that such practices have serious implications in terms of energy use and that the methods used do not necessarily sit well with some people's perceptions of organic production or the organic principles.

Despite evidence that some organic farmers are importing fertility and are therefore 'robbing Peter to pay Paul', Alonso and Guzman[69] point out that inputs of manure and compost help to promote the long-term health of the system, and cannot be compared in the same way to non-renewable energy sources. They also highlight that organic farmers are able to reduce levels of compost application as soil humus levels develop. Moreover, when a comparison was made of non-renewable energy use (i.e., fossil fuels) within this study, the energy use was significantly lower within all of the organic production systems. El-Hage Scialabba and Müller-Lindenlauf[71] also highlight that the pollution and soil degradation problems associated with landless livestock production systems can be reduced through the co-operative use of farmyard manure between crop and livestock operations on organic farms. With landless livestock production systems currently supplying over 50% of pig and poultry meat worldwide[72], the relative advantages of a more integrated approach to production are an important consideration. Reviews comparing nutrient budgets on organic and conventional farms have also found that nutrient surpluses and N leaching are generally smaller for organic farms. This suggests a more efficient use and recycling of nutrients between enterprises[73,74].

Livestock feed

As mentioned above, organic farms try to maintain a closed production system as far as possible with regard to all inputs, not only those relating to soil fertility. Assessments of energy use within beef and dairy production by Schader[75] and Haas et al.[76] found that this approach manifests through a reliance on home-grown sources of feed for livestock (see lower energy inputs associated with imported feed within these studies in Table 1). Lower energy use associated with concentrate feed has also been reported in comparisons of organic and conventional dairy production in Sweden, Denmark and the Netherlands[38,39,77]. Within an assessment of the environmental impacts of a 1996 'baseline' and a number of 100% organic conversion scenarios in Denmark, Dalgaard et al.[78] also found that domestically produced, organic grass/clover was energetically cheaper than conventional forage, due to a lack of fertilizer application. The increased efficiency contributed to lower energy use overall per LU.

For poultry, most organic production systems have longer production cycles. This not only can have a positive effect in terms of animal welfare (e.g., lower prevalence of limb disorders, through use of slow-growing breeds[79]), but also results in lower energy efficiency through higher levels of feed use per unit of product (e.g., Leinonen et al.[80] see Fig. 1). In addition, mortality rates of caged poultry systems have been shown to be lower than organic or free-range systems[80,81]. For pig meat production, recent studies have shown that organic systems tend to import not only less feed, which contributes to lower energy use and greater efficiency per unit of land, but also lower levels of output and a possible increased energy use per kilogram of product, depending on the assessment method used[82,83]. Williams et al.[24] also reported a considerable increase in the area of land used for the production of pig feed within organic systems, in an LCA study of UK production. This led to a reduced energy output per hectare, compared to conventional production.

Effect of functional unit when comparing studies

As found by Lynch et al.[13], the unit of comparison affects the performance of organic farming systems with regard to environmental assessment criteria such as energy use. In common with this study, we have found that for most product types, organic performs better than conventional per unit of product, with over 75% of the product comparisons in Figure 2 reporting lower energy use. In particular, Figure 2 illustrates the efficiency of organic grazing systems due to the lower energy impacts associated with forage production for beef and sheep production (organic energy use ranges from 21 to 94% of conventional for these systems, depending on the system intensity). In common with Lynch et al.[13], we have also found that organic systems tend to compare less favorably for poultry systems. Energy use under organic management was found to range from 125 to 160% of conventional for broilers. For egg production, energy use also tended to be higher, between 120 and 127% of the conventional barn and cage-based systems, respectively. There was less difference between the energy requirements of organic and conventional free-range systems (with organic requiring 103–105% of the energy used on the conventional systems[24,81]).

With regard to crops, most organic systems perform better than conventional in energy use terms, mainly as a result of an absence of manufactured N fertilizer. Energy use for cereal cropping is approximately 80% of conventional per unit of product, despite the lower yield. Vegetable production energy requirements also tend to be lower on organic farms, requiring approximately 75% of the energy used under conventional. There are some exceptions, in particular glasshouse vegetables, apple and potato production exhibit reduced yields and similar levels of energy inputs, which can result in more energy use per unit weight of product overall. In particular, this is a result of greater losses from insect pests and diseases for potatoes and apples. Reduced yields in organic vegetable production glasshouse systems were partly due to an increase in specialty cropping (e.g., vine tomatoes) on organic farms[24].

It is also clear from Figure 3 that the difference between conventional and organic systems is greater when comparisons are made on a per hectare basis, over 80% of the comparisons showing a lower energy use associated with organic production. This is to be expected due to the lower intensity of production on most organic holdings, resulting in fewer inputs, and a reduced yield. Despite this, organic performs less well when the energy content of the organic matter/compost used on organic holdings is taken into consideration. Average energy inputs per unit of land area were approximately double that of the conventional farms when this was taken into account[58,69]. For the reasons outlined above, however, this renewable energy input cannot be compared in the same way to fossil-fuel-based energy.

A number of studies have compared organic and conventional systems in terms of energy efficiency (energy out/energy in). A range of approaches to measuring energy have been used, with some authors expressing production of organic/non-organic systems in terms of combustion energy[56] and other authors using metabolizable energy output values[36]. In addition, some studies have included energy use associated with the production of farm infrastructure (e.g., buildings and machinery), whereas others have only focused on energy use associated with feed, fertilizer and other variable inputs[69,84]. Despite the variation in methods, it is possible to see that organic production outperforms conventional for nearly all of the products listed in Table 2. Again, lower levels of inputs are the main reason for the increased efficiency of organic farming within these studies. There are some exceptions, however, for instance the Cormack and Metcalfe[36] study found that the lower yield and the inclusion of fertility-building crops within stockless arable farms resulted in a lower energy efficiency overall. Guzmán and Alonso[85] also found that net efficiency is lower in organic olive production, mainly due to incorporated organic material originating from other ecosystems, although the organic systems performed better in terms of non-renewable energy use efficiency. Nguyen et al.[86] also reported greater machinery use for weed control in organic pea production, which resulted in a lower energy efficiency overall, in a comparison of mixed farming systems in New Zealand.

Emergy studies

Most of the studies referred to above have concentrated on fossil-fuel use when comparing the efficiency of organic and conventional systems. A limited number of studies have taken a different approach, using the emergy method to account for all energy inputs to the system, including human activity and ecosystem services[28,29]. Emergy accounts for these inputs through an assessment of total amount of energy used for their creation. Scienceman (1989) therefore explains emergy as a calculation of the 'energy memory' of systems[30]. A common unit (i.e., solar emjoules—sej) is used within emergy assessments, to express the amount of emergy required to produce a gram (sej g^{-1}) or joule (sej J^{-1}) of a particular resource, commodity or service. This is referred to as the 'solar transformity'. The emergy efficiency of different agricultural production systems can be

Table 1. Distribution of 'direct' (i.e., on-farm) and 'indirect' (i.e., off-farm) energy use from nine studies comparing organic and conventional productions.

Author(s)	Product	Type of study	Unit	System boundary	Fuel and electricity	Purchased feed (indirect)	Fertilizer, compost, pesticides (indirect)	Machinery and buildings (indirect)	Other	Total
Leinonen et al.[80]	Chickens—broilers—organic	LCA	GJ ton^{-1}	Cradle to gate. Manure treated as energy credit due to fertilizer production offset	7.5	32.8	−0.5	0.5	0.0	40.3
	Chickens—broilers—conventional, free range	LCA	GJ ton^{-1}		7.6	18.2	−0.4	0.3	0.0	25.7
	Chickens—broilers—conventional, standard	LCA	GJ ton^{-1}		9.1	16.4	−0.4	0.2	0.0	25.4
Leinonen et al.[81]	Chickens—layers—organic	LCA	GJ ton^{-1} of eggs	Cradle to gate. Manure treated as energy credit due to fertilizer production offset	6.6	19.9	−0.4	0.3	0.0	26.4
	Chickens—layers—conventional, free range	LCA	GJ ton^{-1} of eggs		6.1	12.9	−0.5	0.3	0.0	18.8
	Chickens—layers—conventional, barn	LCA	GJ ton^{-1} of eggs		10.3	12.1	−0.4	0.2	0.0	22.2
	Chickens—layers—conventional, caged	LCA	GJ ton^{-1} of eggs		5.5	11.6	−0.4	0.3	0.0	16.9
Basset—Mens and van der Werf[82]	Pigs—organic	LCA	GJ ton^{-1} of pig	Cradle to gate	0.0	21.3	0.0	0.5	0.5	22.2
	Pigs—conventional	LCA	GJ ton^{-1} of pig		0.0	11.8	0.0	0.4	3.7	15.9
	Pigs—organic	LCA	GJ ha^{-1}		0.0	21.6	0.0	0.4	0.3	22.4
	Pigs—conventional	LCA	GJ ha^{-1}		0.0	21.7	0.0	0.8	6.7	29.2
Schader[75]	Beef suckler cow farms—organic	LCA	GJ ha^{-1}	Cradle to gate	8.0	1.5	0.1	6.4	0.2	16.2
	Beef suckler cow farms—conventional	LCA	GJ ha^{-1}		11.2	3.9	2.2	7.8	0.4	25.5
Haas et al.[76]	Dairy—organic	LCA	GJ ha^{-1}	Cradle to gate. Excluded energy in buildings/ machinery	3.4	0.8	0.0	0.0	1.8	6.0
	Dairy—extensive conventional	LCA	GJ ha^{-1}		4.1	3.7	0.2	0.0	0.6	8.6
	Dairy—intensive conventional	LCA	GJ ha^{-1}		4.5	3.8	3.7	0.0	7.1	19.1
Venkat[37]	Broccoli—organic	LCA	GJ acre^{-1}	Cradle to gate. Excluded energy in buildings/ machinery	18.3	0.0	2.6	0.0	11.5	32.4
	Broccoli—conventional	LCA	GJ acre^{-1}		16.0	0.0	5.5	0.0	5.4	26.9

Table 1. (*Cont.*)

Karlen et al.[58]	Soybean, corn, oat, hay rotation, with manure charges, organic	Farm study	GJ field^{-1}	Cradle to gate includes labor but excluded energy in buildings and machinery	0.7	0.0	9.5	0.0	0.0	10.2
	Soybean, corn, oat, hay rotation, without manure charges, organic	Farm study	GJ field^{-1}		0.7	0.0	1.4	0.0	0.0	2.1
	Conventional corn and soybean	Farm study	GJ field^{-1}		0.8	0.0	3.2	0.0	0.3	4.3
Williams et al.[24]	Potatoes—organic	LCA	GJ ton^{-1}	Cradle to gate	1.0	0.0	0.2	0.2	0.0	1.3
	Potatoes—conventional	LCA	GJ ton^{-1}		0.8	0.0	0.4	0.1	0.0	1.3
	Bread wheat—organic	LCA	GJ ton^{-1}		1.4	0.0	0.2	0.0	0.1	1.7
	Bread wheat—conv.	LCA	GJ ton^{-1}		0.8	0.0	1.5	0.0	0.1	2.5
	Greenhouse tomatoes—organic	LCA	GJ ton^{-1}		222.4	0.0	1.2	2.0	3.6	229.2
	Greenhouse tomatoes—conv.	LCA	GJ ton^{-1}		118.5	0.0	0.7	1.0	1.9	122.1
Alonso and Guzman[69]	Lettuce—greenhouse crop, organic	Farm surveys	GJ ha^{-1}	Cradle to gate, includes labor and embodied energy in machinery/buildings within 'other'	7.5	0.0	31.4	3.1	128.7	170.6
	Lettuce—greenhouse crop—conventional	Farm surveys	GJ ha^{-1}		4.7	0.0	3.5	3.1	140.1	151.4

compared through their relative solar transformities, with a lower transformity value per unit indicating a greater efficiency.

In addition to exploring the solar transformities of production systems, some emergy studies have also investigated the emergy yield ratio (EYR). This is an expression of the total emergy (in sej) within a system to the emergy purchased on the market (e.g., fossil fuels). In this sense, the EYR is a 'measure of the systems net contribution to the economy beyond its own operation'[28]. Other studies have also explored the environmental loading ratio (ELR), which is the ratio of purchased and non-renewable local emergy to renewable environmental emergy. This measure can be used as an indicator of environmental stress and technological level[28]. Emergy flow and emergy density are also used to explore levels of environmental stress through comparing the spatial and temporal concentration of emergy within different systems (e.g., emergy per unit of time or area)[87].

Castellini et al. used the emergy approach to assess the efficiency of organic and conventional poultry production systems in Italy[87]. Their study found that the solar transformity was lower within the organic system assessed, despite a lower level of production. This was due to the avoidance of chemical fertilizers and pesticides for the production of feed. In addition, the study found that the emergy costs for cleaning/sanitization of buildings were lower in the organic system, as a result of organic regulations only permitting molecules for sanitization that have a low environmental impact. Through an assessment of the energy yield ratio, the same study revealed a reduction in external inputs and in ecosystem stresses under organic management. The organic system also had a higher use of renewable energy, as expressed through the ELR (see Table 3). In particular, this was through its reliance on organic sources of fertility (poultry and cow manure) as opposed to synthetic fertilizer. The emergy density within the conventional system was also approximately eight times higher than the organic, as a result of much greater use of non-renewable inputs.

Pizzigallo et al.[31] also found a higher ELR for conventional systems of wine production in Tuscany, Italy, finding that the use of non-renewable resources on the conventional farm was approximately 15 times greater than that of renewable, whereas for the organic farm this level was only 10 times greater. The higher ELR for the conventional system was a result of the increased soil erosion and the use of manufactured fertilizers. Furthermore, the conventional system used a higher amount of agricultural machinery and fuel, plus a greater amount of glass for bottling (the organic farm used bottles that were lighter). The difference is thus not intrinsic to the farming system. The organic farm also had a lower solar transformity indicating a less resource-intensive production system. However, the conventional farm was disadvantaged by a greater amount of on-farm processing and the fact that only the best grapes were harvested[31].

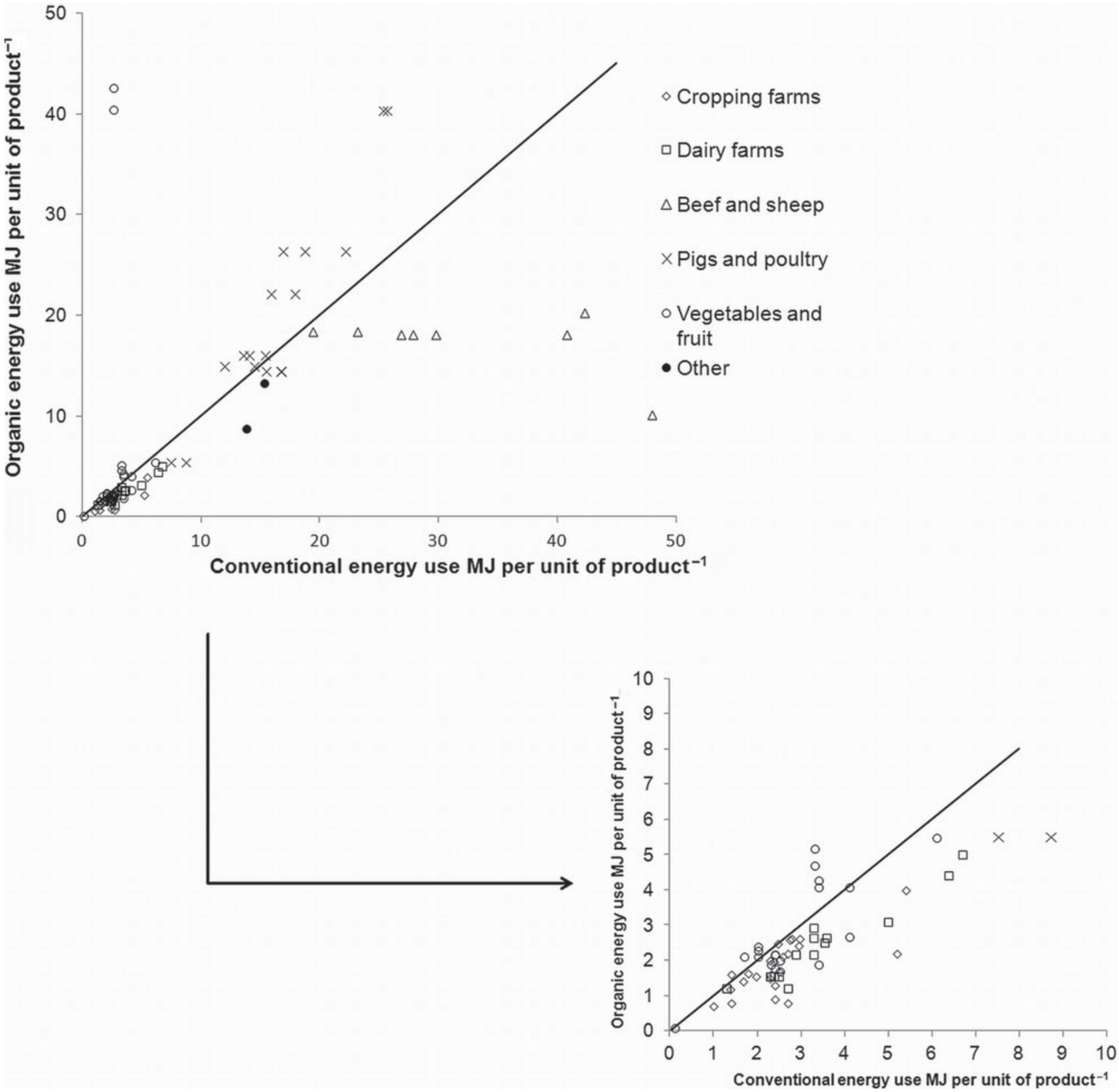

Figure 2. Organic versus conventional energy use per unit of product with expanded selection. Organic performs better below the line, worse above the line. Please note the 'trend-line' is x = y for the purposes of illustrating the relative performance for each product type and is not a line of best fit. Production units were not constant across the studies compared.

La Rosa et al.[88] also used the emergy approach to compare organic and conventional red orange production from four Sicilian farms; this study also found a higher renewable energy use on the organic farm assessed, which contributed to a higher EYR and a much lower ELR. This was the result of a greater reliance on organic sources of fertility within the organic system, compared to the energy-intensive manufactured fertilizer inputs used on the conventional farm. Furthermore, the conventional system used a greater amount of electricity per hectare. Conversely, the same study found a higher solar transformity (sej g^{-1}) associated with two of the three organic farms assessed, as a result of the lower product yield.

In a comparison of wheat production in Denmark, Coppola et al.[89] also found a lower emergy flow in organic production systems (i.e., lower sej ha^{-1} yr^{-1}) due to an absence of man-made fertilizers. Organic seed production was found to be more resource-intensive than conventional, and more field operations and greater machinery use were reported for the organic system. The study also reported a lower solar transformity for the organic wheat crop, suggesting a reduced efficiency per unit of biomass (straw and grain) despite the lower environmental impact, as expressed within the reduced ELR in Table 3. Ghaley and Porter[90] also used the emergy method to compare two farming systems in

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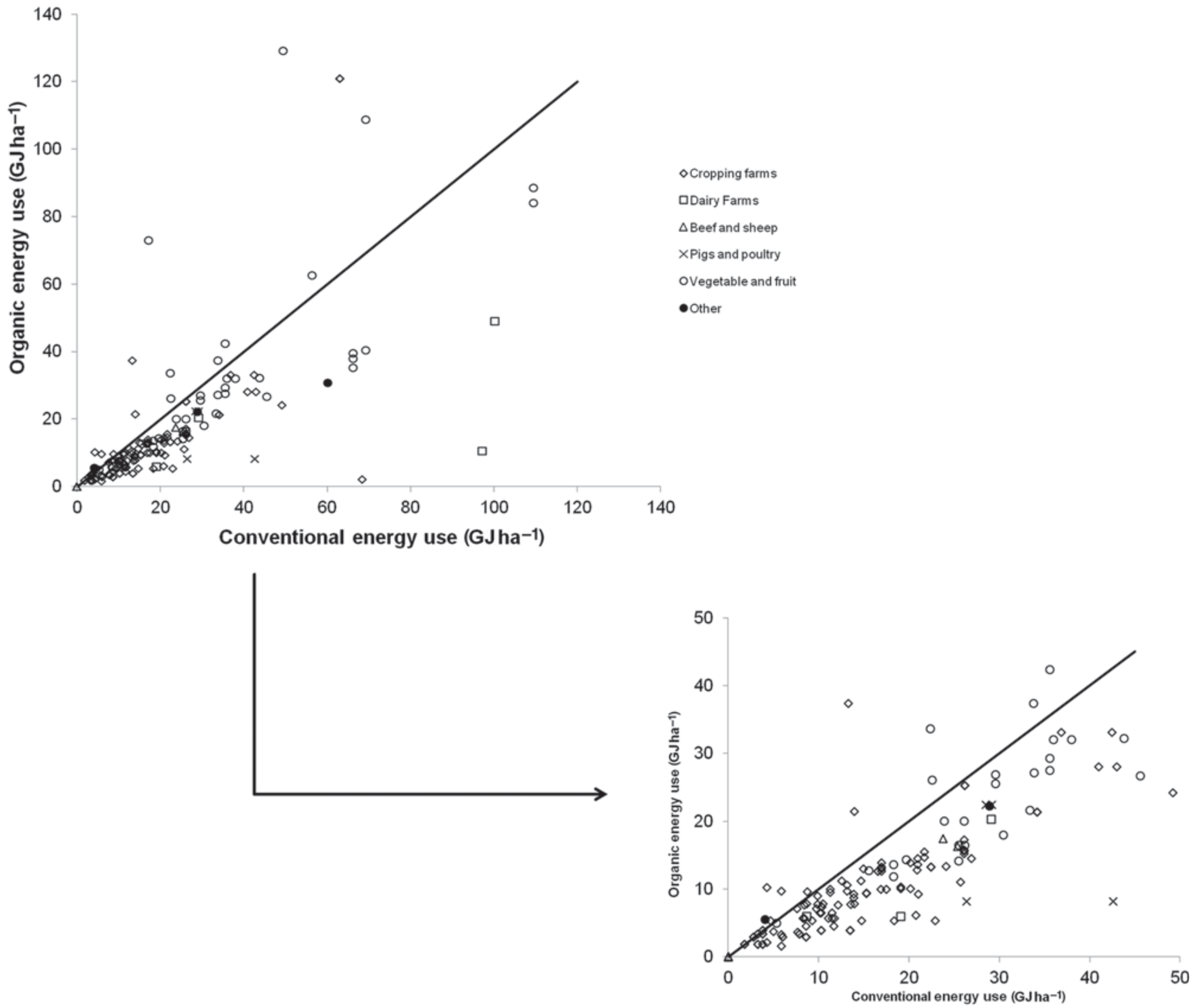

Figure 3. Organic versus conventional energy use per hectare with expanded selection. Organic performs better below the line, worse above the line. Please note the 'trend-line' is $x = y$ for the purposes of illustrating the relative performance for each product type and is *not* a line of best fit.

Denmark; a conventional wheat production system and an organically managed combined food and energy (CFE) system consisting of mixed arable cropping, clover ryegrass swards and woody biomass production. The emergy use in the conventional wheat system was 7.4 times higher than in the CFE, as a result of increased use of manufactured fertilizer and higher rates of soil erosion. The multiple yield components of the CFE system resulted in a greater output and a higher EYR. A lower ELR was also reported for the CFE system due to the reliance on renewable inputs (e.g., biologically fixed N). This study concludes that the CFE system provides a greater contribution to the economy compared with a wheat monoculture. The authors also suggest that such a diverse system could provide a suitable way forward for food and energy production, if an appropriate economic and policy environment could be provided.

Emergy is clearly a useful method that presents a more complete picture of the energy and ecosystem costs and benefits associated with a range of farming systems[14]. Unlike energy accounting, the emergy approach allows for an assessment of a productive system's relationship with the environment, in terms of energy flows. It takes into account environmental inputs that are usually treated as 'free' (e.g., ecosystem services)[29,31], assessing the amount of natural 'labor' required to obtain a given product[79]. Despite these perceived advantages, the emergy approach has been criticized on the basis of the subjective judgments and associations that lead to the allocation of solar energy values to inputs such as wind and rain[20]. The lack of a sufficiently detailed explanation behind the underlying methodology within many of the calculated solar transformities has contributed to this criticism[91], although recent attempts have been made

Table 2. Energy ratios (energy output divided by input) for conventional and organic crops and livestock. All of the studies cited here contain statistical uncertainties; some authors have calculated these and others not, where individual values are presented these represent the average energy ratio. Ranges are presented where different treatments or sites have been used to compare the production systems (e.g., Nguyen and Haynes[57]).

Farm system or crop/livestock	Country	Org. OUT/IN	Conv. OUT/IN	Source	Notes
Corn	USA	5.7–7.6	4.5	Pimental et al.[56]	Includes indirect energy, transport of products and embodied machinery energy. Organic management results are range from different fertilization treatments (i.e., livestock manure, sewage sludge, alfalfa, soybean and sweet clover)
Spring wheat	USA	3.2–3.5	2.4	Pimental et al.[56]	
Potatoes	USA	1.0–1.2	1.3	Pimental et al.[56]	
Stockless arable farm	UK	4.4	5.2	Cormack and Metcalfe[36]	Energy associated with transport of products included within study
Wheat	New Zealand	14.9–16.5	11.2–17.4	Nguyen and Haynes[57]	Range presented from three sites. Includes energy associated with on-farm labor
Barley	New Zealand	15.4–17.5	9.9–16.3	Nguyen and Haynes[57]	
Peas	New Zealand	9.0–9.1	8.8–11.5	Nguyen and Haynes[57]	
Arable rotation	Canada	10.4	6.8	Hoeppner et al.[35]	Gross energy content in harvested products divided by energy inputs
Arable and alfalfa rotation	Canada	33.5/11.9	19/7.4	Hoeppner et al.[35]	Higher energy output value due to high dry matter/energy yield from alfalfa. Lower energy efficiency calculation assumes alfalfa:meat conversion factor of 9:1
Arable rotation: situation-related pesticide use (2002–2006 experiment period)	Germany	20.7	17.4	Deike et al.[92]	Included energy content of straw harvested
Arable rotation: reduced pesticide use (2002–2006 experiment period)	Germany	20.7	16.9	Deike et al.[92]	
Arable farms	Sweden	4.3	5.9 Int: 5.9–6.5	Helander and Delin[84]	Includes energy used to produce machinery, diesel, electricity, fertilizers, pesticides and seed
Arable crops	Spain	1.8–8.2	4.5–6.7	Alonso and Guzman[69]	
Vegetables and fruits					
Vegetables	Spain	0.4–2.0	0.7–1.3	Alonso and Guzman[69]	Lower energy ratio values include energy embodied in renewable energy inputs (e.g., compost/organic matter)
Greenhouse vegetables	Spain	0.13–0.22	0.21–0.28	Alonso and Guzman[69]	
Irrigated fruits	Spain	1.7–5.8	4.8–5.4	Alonso and Guzman[69]	
Rain-fed fruits	Spain	1.3–2.8	1.8–2.1	Alonso and Guzman[69]	
Apples	USA	1.2	1.1	Reganold[93]	Includes indirect energy associated with farm infrastructure and on-farm labor
Apples	USA	0.06	0.89	Pimental et al.[56]	

Table 2. (*Cont.*)

Olive groves (without compost allocation)	Spain	2.4–5.2	2.2–4.2	Guzman and Alonso[85]	Includes energy use associated with on-farm labor
Olive groves (with compost allocation)	Spain	0.6–2.2	1.4–2.9	Guzman and Alonso[85]	
Livestock and mixed farms					
	Sheep meat and wool	New Zealand	8–15	9.1–12	Nguyen and Haynes[57]
Includes energy associated with on-farm labor					
Upland livestock (beef and sheep)	UK	2.5	1.1	Cormack and Metcalfe[36]	Energy associated with transport of products included within study
Dairy	UK	1.7	0.4	Cormack and Metcalfe[36]	
Pig farms	France	1.6	1.2	van der Werf et al.[16]	Values calculated using the DIALECTE approach for calculating on-farm energy efficiency
Arable and livestock	UK	5.5	3.6	Cormack and Metcalfe[36]	Energy associated with transport of products included within study

to apply uncertainty calculations to the emergy approach[94]. Hülsbergen et al.[95] also state that inclusion of solar radiation in the energy balance can mask the variation of fossil energy input influenced by different husbandry techniques, as fossil energy is often a small proportion of the total emergy use when considering solar inputs. Conversely, it can also be misleading to focus only on the use of energy on-farm (i.e., without accounting for the embodied energy associated with inputs and natural services), providing an advantage to farms dependent on external sources for the maintenance of higher levels of production[96]. It has been suggested that a combined approach of using LCA and emergy analysis may help both the methods to improve, allowing LCA to account for ecosystem services, and overcoming problems with allocation (i.e., partitioning energy inputs between multiple outputs) found within the emergy approach. This combined method was adopted by Pizzigallo et al.[31], who used LCA methods to comprehend and disaggregate the productive systems assessed, together with the application of emergy to account for the energy contribution of ecosystems.

Discussion

Comparisons by farming system

When making comparisons of the energy efficiency of organic and conventional systems, it is difficult to draw definitive conclusions, partly due the variation within each of the sectors, which makes performance very site and system dependent[97]. For example, Williams et al.[98] found that wheat grown on sandy soils uses about 20% more energy than that grown on clay soils, within an LCA of organic and conventional arable crops grown in the UK. Refsgaard et al.[52] also found that differences in soil type had a greater effect on energy efficiency than organic or conventional farming practices. Nevertheless, in common with the findings of Lampkin[15], Lynch et al.[13] and Gomiero et al.[14] it is possible to state that for most grazing systems, organic farming will result in a lower energy use, on a unit area or weight of product basis. This is a direct result of the use of clover and other forage legumes within leys, which results in more efficient forage production compared to the conventional practice[35,92,99]. Similarly, for dairy systems, organic production tends to result in lower energy use per liter of milk produced, due to greater energy efficiency in the production of forage and reduced reliance on imported concentrates[38,76,77].

With regard to poultry, meat and egg production tends to require more energy per kilogram of product under organic management, as poorer overall feed conversion ratios and higher mortality rates reduce overall efficiency[24,80].

With regard to cropping systems, the absence of fertilizer inputs tends to more than compensate for a lower yield within organic cereal production, resulting in

Table 3. Results from five 'emergy' studies comparing organic and conventional production. Results expressed as 'sej' = solar emergy joules or emjoules, i.e., units of solar energy that would be required to generate all the inputs to the farming system defined (expressed in sej J^{-1} or sej^{-1} or sej ha^{-1}).

	Castellini et al.[87]		Pizigallo et al.[31]		La Rosa et al.[88]		Coppola et al.[100]		Ghaley and Porter[90]	
	Poultry (meat) production: Italy		Wine production: Italy		Red orange production: Sicily		Wheat production: Denmark		Conventional wheat and organic CFE system: Denmark	
	Conv.	Org.	Conv.	Org.	Conv.	Org.	Conv.	Org.	Conv. (wheat)	Org. (CFE)
Solar transformity (sej J^{-1})	6.1×10^5	5.7×10^5	N/A	N/A	N/A	N/A	$3.9–5.8\times10^4$	$4.6–7.1\times10^4$	8.63×10^4	6.40×10^3
Solar transformity (sej g^{-1})	4.3×10^9	4.1×10^9	4.7×10^{15} (ton^{-1})	3.0×10^{15} (ton^{-1})	1.2×10^9	$0.6–2.2\times10^9$	N/A	N/A	N/A	N/A
Emergy flow (sej ha^{-1})	N/A	N/A	N/A	N/A	N/A	N/A	$6.6–6.9\times10^{15}$	$5.4–5.6\times10^{15}$	N/A	N/A
Empower density (sej yr^{-1}) m^{-2}	7.8×10^{14}	3.6×10^{12}	1.9×10^{16}	1.0×10^{16}	N/A	N/A	N/A	N/A	N/A	N/A
EYR	1.1	1.5	N/A	N/A	1.5	1.6–11.7	N/A	N/A	1.0	1.2
ELR	5.2	2.0	15.4	10.5	43.0	3.8–30	7.3–8.5	2.3–2.4	37.7	4.2

lower energy use per kilogram of product[24,68] or little difference overall[101]. Organic management can also be better in terms of energy use for field vegetable production, as a result of fewer inputs in manufactured fertilizers and herbicides, although in some cases the energy used for flame weeding can make it worse[36]. For organically produced potatoes, energy use tends to be greater due to yield losses from pests, causing lower yields overall[24]. Pimental et al.[56] found that organic potato yields were only 50% of conventional as a result of a lack of control of blight (*Phytophthora infestans*) resulting in much lower energy efficiency per kilogram of product.

With regard to on-farm energy use, in common with the study by Lynch et al.[13] this review has found that in many cases organic farmers' diesel requirements are comparable to conventional; although for some crops this energy use may be greater through increased reliance on mechanical tillage, e.g., for broccoli[37], wheat and potatoes[24]. The reduced tillage systems commonly found on conventional farms will also require less diesel than the 'traditional' moldboard plowing technique commonly used on organic farms, although the difference may be offset by indirect energy, depending on the rate/efficiency of usage[41,44]. With regard to indoor crops, a greater amount of energy is used for greenhouse production under organic management on a kilogram of product basis, as a result of lower yields but similar energy requirements for heating or building construction[24,69].

The 'human energy' aspect is missing from many of the studies considered here. This is a result of the absence of a widely accepted and applied methodology for its inclusion, in addition to the relatively small contribution of labor to total energy use in modern cropping systems. Borin et al.[102], for example, calculated that this aspect accounts for <0.2% of the total energy input in modern cropping systems. Relatively higher energy input is likely, however, in other systems, such as fruit, vegetable and livestock. The limited number of studies that have included this aspect found that organic farming will generally result in greater levels of on-farm energy from human labor[56–58]. Although this may have negative effects on the productivity per labor hour, some authors have taken an optimistic view of the increased labor requirements associated with organic production systems. For instance, Pretty[103] in Cobb et al.[21] found that a shift toward an organic production scenario in the UK could create 100,000 jobs in addition to encouraging more added value through on-farm processing of products and direct sales.

Productivity versus energy efficiency

It is also important to note that most of the studies and farming systems mentioned above found higher levels of productivity in conventional systems, despite organic systems having greater resource-use efficiency. In this context, Deike et al.[92] point out the large yield losses that would result from a widespread switch to organic production. The lower yields from organic management have led some authors to conclude that organic farming is incapable of feeding the world in a sustainable manner[63,104]. Others have claimed that the apparent benefits of organic production, such as reduced fertilizer manufacture and pesticide use, are a poor exchange for a potential lack of productivity[105]. Despite this, a recent meta-analysis by Seufert et al.[97] found that under good management practices, some organically grown food crops can nearly match conventional yields. Specifically, organically produced legumes and perennials on rain-fed, weak acidic to alkaline soils were found to have small yield differences of <5%, although the authors of this study note the small sample size and high uncertainty for these crops. On the other hand, for vegetables and cereals, a greater, statistically significant yield reduction was found for organic systems (− 33 and −26%, respectively). The authors note that when only the most comparable organic and conventional systems are used, organic yields can be up to 34% lower. Conversely, a study based at the Rodale Institute's experimental farm in the Northeastern United States demonstrated that under drought conditions, crops in organically managed systems can produce higher yields than conventional crops. Yield increases within this study ranged from 137 to 196% of conventional depending on the crop and method of fertilization[106]. The main reason given is the increased water-holding capacity of the soil, as a result of increased organic matter content. Smolik et al.[107] also found that yields within an organic system were more stable in the face of diseases and weather variation over a 7-year period.

Whatever the yield differences between organic and conventional production, it is clear from both an environmental and economic perspective that we need to reduce our reliance on fossil fuels, per unit of food produced, whether under an organic or conventional production scenario. Although the use of these reserves has clearly had a positive impact in terms of increasing productivity throughout the 'Green Revolution'[108] and fertilizer manufacture efficiency is increasing[34], it has been highlighted that oil and gas reserves are only sufficient to meet our needs for another 50–100 years[109]. Moreover, the negative effects of our dependency on non-renewable inputs are already being witnessed (e.g., through food price riots in 2008, in part caused by increasing costs of fertilizer and fuel[110]). The wisdom of putting our faith in the development of an unproven or unknown energy source to maintain or increase levels of production in the future has also been questioned[109]. In addition, recent assessments have found that vast increases in yield seen in recent years have been at the expense of increases in soil erosion, reductions in biodiversity and a large increase in agriculture's reliance on manufactured fertilizers and pesticides[111,112]. In this context, Gomiero et al.[14] highlight the usefulness of methods such as emergy accounting, which can present a more complete picture of agricultural systems' impact on the natural environment. The current application of emergy approaches to comparisons of organic and conventional farming systems has been limited, however, and more work comparing the two approaches using this method would be helpful.

It should also be noted that in their current form, organic systems do not offer a radical alternative to the fossil-fuel reliance of modern agricultural systems. The reduced use of energy in organic production and increased energy efficiency compared to conventional production is often marginal. These systems often still depend on the same sources of (fossil) fuel for tractors, machinery and buildings, etc. While organic production can make a contribution to a more resource-efficient agriculture, in its present form it does not provide a complete solution.

Some have suggested that a 'happy medium' for the development of more fossil-fuel-efficient farming systems would be to pursue lower-input conventional farming systems (e.g., reducing man-made fertilizer inputs, increased use of legumes for N fixation and organic manures)[19]. Indeed, recent work has highlighted that well-managed conventional systems with reduced input levels can outperform organic production in terms of resource-use efficiency, when measured on an energy output/input basis[113]. In this context, the recent International Assessment of Agricultural Knowledge, Science and Technology for Development[4] and Foresight[19] reports outline a number of key challenges to maintain the production of food while decreasing dependence on fossil energy, none of which would seem to exclude or preclude a conversion to organic standards:

- The development of decentralized, locally based production and distribution systems.
- Improving nutrient use, in particular more exact timings and amounts of fertilizers (organic and inorganic).
- Increasing productivity through increasing the marketable/edible yield from crops, improved animal breeding, feeding, and pest and disease control.
- Recycling of urban and industrial wastes.
- Increased use of renewable energy throughout the supply chain.

In addition, the need to improve the synchrony between N supplied by legumes and N demand from crops is highlighted by Myers et al.[114]. However, even with developments in this area, it will be difficult to match the synchronization with crop demand to the same extent as through targeted application of soluble N through manufactured fertilizer[109,115]. Crews and Peoples[109] also highlight the importance of reducing the amount of grain fed to livestock, thereby freeing up land for legumes and reducing agriculture's current dependence on manufactured fertilizer. This would, however, particularly reduce the output of eggs and poultry meat and, to a lesser extent, pig meat, given the nutritional requirements of these stocks. Kumm[116] also highlights the importance of focusing meat production on landscapes that cannot be used for arable cropping, and using by-products that can contribute to food supply only through the refinement of meat-producing animals. Although Kumm[116] also highlights that, in situations of energy shortage, there might be competition between meat production and the bioenergy sector.

Conclusion

Organic production systems focus on the development of closed cycles of production as far as this is possible, as espoused by the IFOAM principles. This naturally creates systems, which are less productive in terms of crop and livestock yields. Results from studies considered within this review, however, have illustrated that the reduced yields are matched by greater energy efficiencies for most ruminant livestock and field crops. The difference is greatest when comparisons are made on a unit of area basis, although substantial increases in energy efficiency can also be observed per unit of product within most of the comparative studies. The difference between organic and conventional production tends to be greatest for grassland systems, due to the relative efficiency of producing grass in conjunction with clover, a practice encouraged within the organic sector. There are some important exceptions where organic performs worse. For example, potatoes, where a lower yield reduces efficiency, and other vegetables that require flame weeding. Within livestock production, organic pig and poultry production systems also perform worse where poor feed conversion and higher mortality rates can lead to lower energy efficiency overall. With regard to human labor productivity, organic farms will also tend to perform worse than conventional, primarily as a result of greater requirements for weeding, spreading of manure and composts, and greater system diversity. The limited number of emergy analyses comparing the two production systems to date have also found a lower environmental loading and increased renewable energy use on organic farms. Overall it would appear that the energy efficiency of most cropping and ruminant livestock farming systems can be enhanced through the adoption of organic management. However, in many cases this will be at the expense of crop or livestock yields.

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Appendix 1. List of comparative studies.

Author of study	Country	Production system/farm types	Method
Alonso and Guzman[69]	Spain	Vegetables, arable crops, fruit	Input/output assessment using farm data
Bailey et al.[48]	UK	Arable	Data collected from 5 years of field trials
Basset Mens and van der Werf[82]	France	Pigs	Modeling of farm systems using published and expert data using LCA
Bos et al.[117]	Netherlands	Arable, dairy, vegetables, mixed	Direct/indirect energy use modeling
Cederberg and Mattsson[38]	Sweden	Dairy	LCA using measured farm data and published data
Clements et al.[44]	Canada	Arable	Experimental farm data and farm survey
Cormack and Metcalfe[36]	UK	Arable, dairy, vegetables, beef and sheep, mixed	Modeling based on book values
Dalgaard et al.[78]	Denmark	Arable, dairy and pig production	Direct/indirect energy modeling
Deike et al.[92]	Germany	Arable	Long-term field experiment
Flessa et al.[118]	Germany	Beef and arable	Experimental farm data
Geier et al.[119]	Germany	Apple production in Hamburg (organic intensive, organic extensive and integrated)	LCA using farm data and published data
Grönroos et al.[120]	Finland	Dairy	LCA using statistics and expert opinions
Gündoğmuş and Bayramoglu[121]	Turkey	Raisins	Structured interviews and direct/indirect energy model
Guzman and Alonso[85]	Spain	Olive oil production	Calculated energy balances using data collected through farmer interviews
Haas et al.[76]	Germany	Dairy	LCA using published agricultural planning data
Helander and Delin[84]	Sweden	Arable	Results from research farm-based comparison
Hoeppner et al.[122]	Canada	Arable	Crop rotation experiment
Kaltsas et al.[123]	Greece	Olive oil production	LCA using data collected through interviews
Karlen et al.[58]	USA	Arable	Farm level comparison
Kavargiris et al.[124]	Greece	Grapes	Energy analysis using data collected through farmer interviews
Klimeková and Lehocká[125]	Slovakia	Arable	Field experiment data
Küstermann et al.[126]	Germany	Arable	REPRO model and data collected from farms
Leinonen et al.[80]	UK	Poultry—meat, standard	LCA, structural model of industry
Leinonen et al.[81]	UK	Poultry—eggs, caged	LCA, structural model of industry
Mäder et al.[127]	Switzerland	Farm comparison—conventional FYM/biodynamic	Data collected from experimental farms
Meisterling et al.[128]	USA	Wheat	LCA modeling study
Nemecek et al.[101]	Switzerland	Arable	Swiss Agricultural Life Cycle Assessment method (SALCA)
Nguyen and Haynes[57]	New Zealand	Arable and livestock	Farm comparison
Pelletier et al.[68]	Canada	Wheat	LCA Scenario modeling
Peters et al.[129]	Australia	Beef and sheep	LCA using collected and public/published data
Pimental et al.[56]	USA	Arable, apples	Modeling based on published data
Pimental et al.[130]	USA	Arable	Recorded energy use from experimental farm at The Rodale Institute
Refsgaard et al.[52]	Denmark	Arable, dairy, forage	System modeling using farm data
Reganold et al.[93]	USA	Apples	Farm comparison
Schader[75]	Switzerland	Arable, beef, sheep, dairy, vegetables, poultry, pigs, mixed	LCA using farm and public/published data

Thomassen et al.[77]	Netherlands	Dairy	LCA using farm data
Van der Werf et al.[83]	Brittany, France	Pig production	Modeling of farm systems using published and real farm data
Venkat[37]	USA	Arable, vegetables, fruit, nuts	LCA modeling using production data
Williams et al.[24]	UK	Arable, beef, sheep, dairy, vegetables, poultry, pigs, mixed	LCA using public/published data
Williams et al.[98]	UK	Arable	LCA using public/published data
Wood et al.[131]	Australia	Sheep, arable, vegetables, fruit	Hybrid LCA incorporating a farm survey
Castellini et al.[87]	Italy	Poultry—meat	Emergy
Pizzigallo et al.[31]	Italy	Wine production (including processing post farm-gate)	Emergy and LCA
La Rosa et al.[88]	Italy	Red orange production	Emergy
Coppola et al.[100]	Denmark	Wheat	Emergy
Ghaley and Porter[90]	Denmark	Wheat and CFE system comparison	Emergy