

Organic Agriculture, Food Security, and the Environment

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Abstract

Organic agriculture is often perceived as more sustainable than conventional farming. We review the literature on this topic from a global perspective. In terms of environmental and climate change effects, organic farming is less polluting than conventional farming when measured per unit of land but not when measured per unit of output. Organic farming, which currently accounts for only 1% of global agricultural land, is lower yielding on average. Due to higher knowledge requirements, observed yield gaps might further increase if a larger number of farmers would switch to organic practices. Widespread upscaling of organic agriculture would cause additional loss of natural habitats and also entail output price increases, making food less affordable for poor consumers in developing countries. Organic farming is not the paradigm for sustainable agriculture and food security, but smart combinations of organic and conventional methods could contribute toward sustainable productivity increases in global agriculture.

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1. INTRODUCTION

Organic food is increasing in popularity. The growing demand is mainly attributable to consumer concerns about negative implications of conventional agriculture for human health and the environment. Especially in developed countries, most consumers consider organic food to be safer and healthier than conventionally produced food (Funk & Kennedy 2016). Rich-country consumers often also perceive organic farming to be better for the environment, climate protection, and animal welfare (Seufert et al. 2017). In Europe in particular, organic farming has such a positive public image that it is commonly touted as the paradigm for sustainable agriculture (Mercati 2016). A representative survey carried out in Germany showed that approximately 50% of the population considers wider adoption of organic agriculture as an important strategy to fight global hunger (Klümper et al. 2013). The same survey revealed that agrochemicals and genetically modified organisms (GMOs) are often perceived as major threats to food security. In developing countries, the awareness of organic agriculture is still lower, but European perceptions and food preferences are also starting to gain ground, especially among better-off urban consumers (Greenpeace 2015, Probst et al. 2012).

In the academic literature, the views are more nuanced, but the conclusions about the role of organic agriculture for global sustainable development differ widely. Some consider organic agriculture as inefficient and mainly driven by ideology (Connor & Mínguez 2012, Lotter 2015, Trewavas 2001). Others see great potential in organic farming to feed the world in an environmentally friendly way (Badgley et al. 2007, Reganold & Wachter 2016).

Over the last several decades, green revolution technologies, including high-yielding crop varieties and complementary inputs such as synthetic fertilizers, pesticides, and irrigation water, have contributed substantially to productivity growth in agriculture and improvements in global food security (Evenson & Gollin 2003, Qaim 2017). Nevertheless, approximately 800 million people are still chronically undernourished, most of them living in Asia and Africa (FAO 2017). Over the next few decades, the demand for food will increase further due to population and income growth. In addition, plant-based products are increasingly being used as renewable resources. To keep up with this rising demand, it is estimated that global agricultural production will have to increase by at least 60% and possibly up to 100% until 2050 (Godfray et al. 2010, Hertel 2015). This is a major challenge because land, water, and other natural resources are becoming increasingly scarce. Furthermore, the input-intensive agricultural production systems observed in many parts of the world are responsible for—or at least contribute to—major environmental problems, such as land degradation, biodiversity loss, water pollution, and climate change (Foley et al. 2011). Increasing production while reducing the environmental footprint will require profound changes in food and agricultural systems and the types of technologies used. But is organic agriculture the solution? This question is addressed here by reviewing the extensive literature on various aspects of certified organic farming, including economic, social, environmental, and health effects.

2. PRINCIPLES AND ADOPTION OF ORGANIC AGRICULTURE

2.1. Historical Background

The idea of organic agriculture evolved in the early twentieth century in the context of urbanization and the increasing use of agrochemical inputs in farming. The organic movement started in German- and English-speaking countries and was influenced by different groups that promoted rural traditions and the use of biological (instead of synthetic) fertilizers (Vogt 2007). For

Table 1 Summary of prohibited and required activities in organic agriculture

	Crop production	Animal husbandry
Prohibited activities	Use of synthetic fertilizer Use of chemical pesticides Use of genetically modified organisms (GMOs) Use of sewage sludge	Use of growth hormones Prophylactic administration of antibiotics Use of genetically modified organisms
Required activities	Use of organic seeds and locally adapted varieties Use of measures to improve soil fertility (e.g., crop rotation, organic fertilizer, erosion control) Pest/weed control only through mechanical/biological/thermic measures	Animal housing that allows for natural behavior (e.g., natural light, sufficient space) Use of organic fodder Access to pasture/outdoor areas

several decades, the organic movement remained very small, but it has gained popularity since the 1970s with rising public concerns about health and environmental effects of industrialized farming (Lockeretz 2007). In the following decades, governments in several rich countries started to subsidize the organic sector. As a result, the market share of certified organic products increased. In the European Union and the United States, policy measures to support organic farming include governmental regulations and standards, direct subsidies to organic producers, research funding, and sponsorship of communication instruments such as promotion campaigns and organic labeling. The rationale for government interventions is to reward organic farmers for their superior environmental performance and compensate for related increases in production costs or decreases in yield (Stolze & Lampkin 2009). More recently, policy support has also facilitated the adoption of organic standards in developing countries. Domestic governments and western development agencies have launched a number of projects to link smallholder farmers to organic export markets.

2.2. Principles of Organic Agriculture

Today, more than 100 countries publicly support organic standards (Seufert et al. 2017). Additionally, several private organic standards exist. Governmental and private standards are typically based on the standards developed by the International Federation of Organic Agriculture Movements (IFOAM) (<http://www.ifoam.bio/en>). Hence, most organic standards are similar, even though they can differ in specific details.

Organic standards cover different areas such as crop production, animal husbandry, wildlife collection, beekeeping, aquaculture, and processing, among others. The standards involve activities that are prohibited or restricted and other activities that are required or recommended (Table 1). The cornerstones of organic production systems are balanced crop rotations with legumes, recycling of nutrients (e.g., through mixed farming), and the use of organic fertilizers. Use of synthetic fertilizers and chemical pesticides is prohibited. In livestock production, the animals must be fed with organic fodder, preferably from the same farm, and provided with sufficient space and access to outdoor areas.

Compliance with organic standards is verified on an annual basis through farm inspections undertaken by accredited certification agents (Seufert et al. 2017). For this purpose, records on all farming activities must be kept. In developed countries, certification of individual farms is commonplace. In developing countries, certification is often group based, especially in the small farm sector. Group certification reduces the costs for individual farmers as well as the transaction costs for certifiers and buyers (Jena et al. 2012, Meemken et al. 2017b).

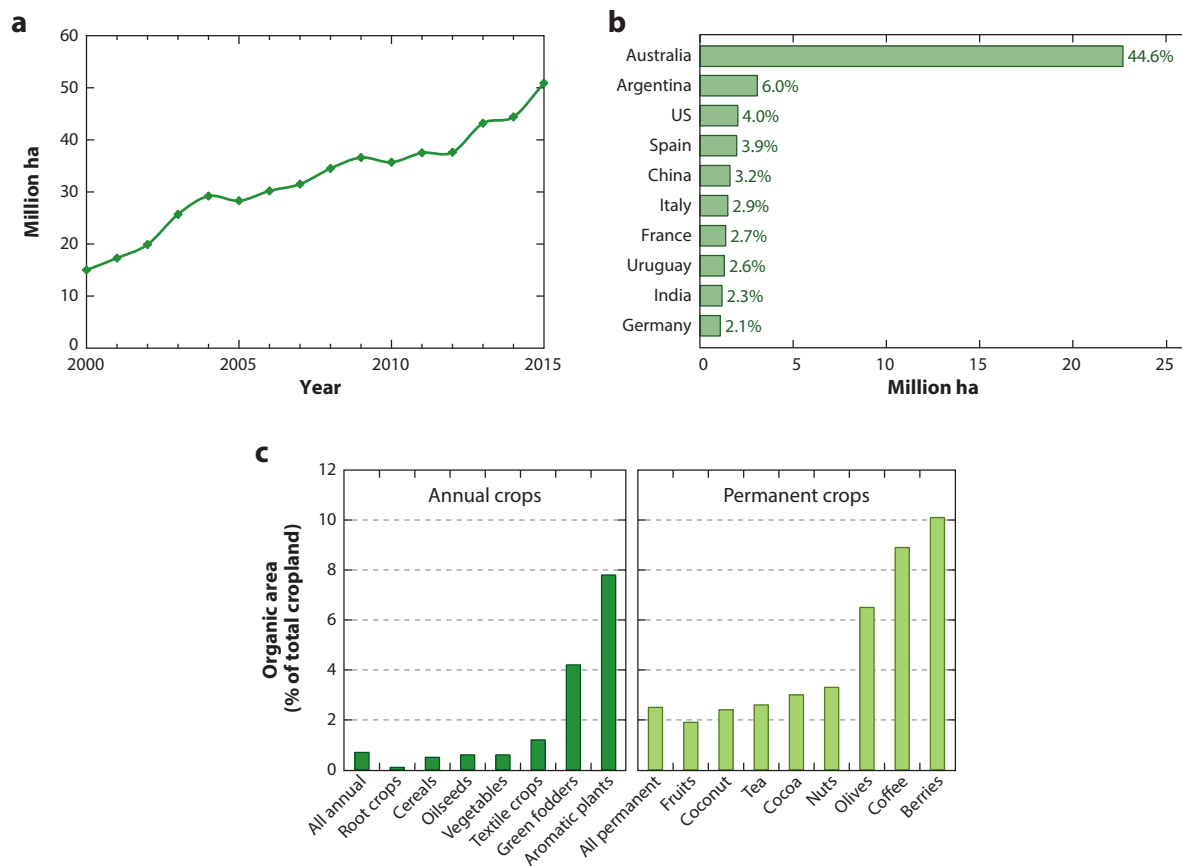


Figure 1

Adoption of organic agriculture. (a) Development of certified organic area worldwide from 2000 to 2015. (b) Top ten countries with the largest certified organic areas in 2015. Figures indicate the percentage of total worldwide organic area. (c) Certified organic area by crop in percentage of total cropland worldwide in 2015. Based on data from Willer & Lernoud (2017).

2.3. Adoption of Organic Agriculture

Over the past 15 years, the global area under certified organic agriculture has increased substantially, from 15 million ha in 2000 to 51 million ha in 2015 (**Figure 1a**). Nevertheless, in 2015, organic agriculture accounted for only 1% of the total agricultural land worldwide. With almost 23 million ha, Australia is the country with the largest certified organic area; most of the organic area in Australia is extensively managed grassland. Other countries with relatively large organic areas include Argentina, the United States, and Spain (**Figure 1b**). A breakdown by crop species shows that organic production plays a larger role for permanent crops, such as berries, coffee, and olives, than for annual crops such as cereals and vegetables (**Figure 1c**).

While the largest share of the global organic area is found in developed countries (**Figure 2a**), 88% of the organic farmers (2.1 million out of 2.4 million) live in developing countries in Asia, Africa, and Latin America (**Figure 2b**). The countries with the largest number of organic farmers are India (0.6 million), Ethiopia (0.2 million), and Mexico (0.2 million). Organic farmers in developing countries mainly produce traditional export crops, such as coffee and tea (Willer & Lernoud 2017).

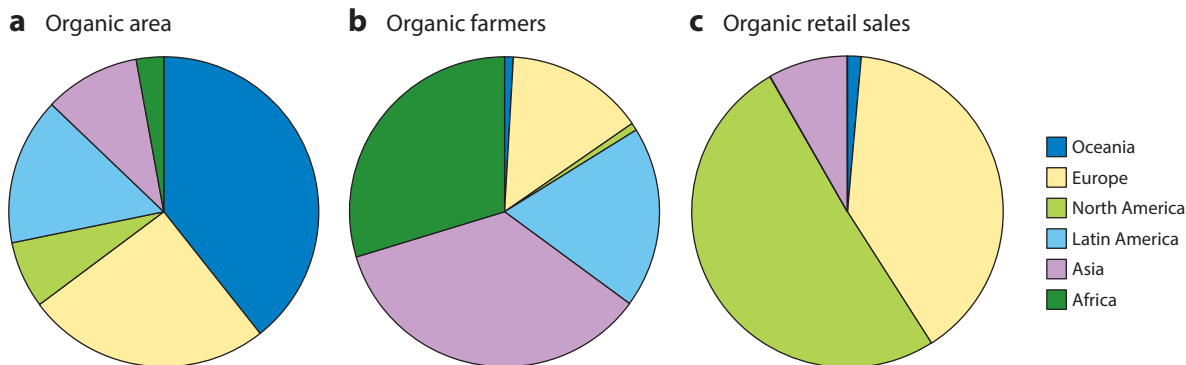


Figure 2

Production and consumption of organic food by geographic region in 2015. (a) Distribution of certified organic area by region. (b) Distribution of certified organic farmers by region. (c) Distribution of organic retail sales (in value terms) by region. Based on data from Willer & Lernoud (2017).

Several studies have analyzed factors that influence farmers' decisions to switch from conventional to organic practices in developed and developing countries. Access to government subsidies for organic farming tends to play an important role (Brenes-Munoz et al. 2016). However, government subsidies can also add to policy risk, which may reduce adoption under certain conditions (Kuminoff & Wossink 2010). In addition to policy risk, organic farming may be associated with higher production risk, because certain risk-reducing inputs are not allowed (Serra et al. 2008). For instance, chemical pesticides help to reduce pest damage but are prohibited in organic agriculture. Indeed, studies showed that adopters of organic practices tend to be more risk loving than non-adopting farmers (Kallas et al. 2010, Serra et al. 2008). Other important adoption determinants include access to information and to high-value certified markets in which buyers are willing to pay significant price premiums for organic products (Läpple 2010, Wollni & Andersson 2014). Especially in the small farm sector of developing countries, adoption of organic standards crucially depends on development initiatives to provide training and marketing support to farmers (Bolwig et al. 2009).

In line with the increase in the global organic land area, sales of organic products have also increased. Since 2000, global organic retail sales have quadrupled, reaching US\$82 billion in 2015. Demand for organic products is concentrated in North America and Europe (Figure 2c). In Europe, the largest organic markets in terms of total retail sales are Germany and France. However, in terms of per capita expenditures on organic products, the leading countries are Switzerland, Denmark, and Sweden (Willer & Lernoud 2017). In most developing countries, demand for organic products is negligible, although increasing in certain high-income segments of the population. Poor people can hardly afford organic products due to significantly higher prices. On average, organic products are priced 50% above conventional products, reflecting higher costs in production, processing, and distribution (Seufert et al. 2017). Price differences between organic and conventional tend to be more pronounced for animal products than for fruits, vegetables, and processed foods (Carlson & Jaenicke 2016).

3. YIELD EFFECTS

3.1. Estimated Yield Gaps

When evaluating the potential of organic agriculture to contribute to sustainable development, a central question concerns the yields obtained in comparison to conventional farming. Estimating

yield effects of organic practices is not easy, as confounding factors have to be controlled for. For instance, when organic farmers obtain lower yields, this may be due to the organic practices, but it is also possible that the farmers are less talented or operate in less-favorable environments than their conventional colleagues. In the latter case, organic farmers would have lower yields anyway, even when applying the same technology, so the yield gap of organic farming practices would be overestimated. On the other hand, it is also possible that organic farmers are systematically more talented than their conventional counterparts, which would lead to underestimated yield gaps when simply comparing observed organic with conventional yields. Surprisingly little research has tried to control for such selection bias in estimating yield effects of organic farming based on observational data.

Nevertheless, numerous studies have tried to estimate yield effects of organic farming, often using data from trials on experimental stations. Experimental data help to avoid bias through confounding factors but have their own problems in terms of external validity (see below). Available studies show a wide range of results, depending on the particular context. In some situations, organic yields were found to be higher than conventional yields, whereas in other situations they were considerably lower.

More recently, a few review papers have tried to synthesize the evidence. A first attempt in this direction was a study by Badgley et al. (2007). The authors used results from various sources to conclude that organic agriculture had 33% higher average crop yields than conventional agriculture at the global level. In developed countries, organic yields were 9% lower than conventional yields, but in developing countries, the authors claimed that organic practices would increase crop yields by 74% (Badgley et al. 2007). However, this study was heavily criticized on various grounds (Cassman 2007, Connor 2008, Goulding & Trewavas 2009). Many of the studies included in the review by Badgley et al. (2007) did not meet minimum scientific standards in terms of experimental design (Cassman 2007). Other relevant studies were simply ignored (Goulding & Trewavas 2009). For developing countries, Badgley et al. (2007) mostly compared yields of crops that had received high levels of organic nutrients as the organic version with crops that had received very little or no fertilizer as the conventional version (Connor 2008). Hence, despite being highly cited, the results of Badgley et al. (2007) are not reliable and meaningful.

Three scientifically more rigorous meta-analyses of organic-conventional crop yield comparisons were published in the last few years (de Ponti et al. 2012, Ponisio et al. 2015, Seufert et al. 2012). Results of these analyses are summarized in **Table 2**. Across all crops, mean yield gaps of organic agriculture are in the magnitude of 19–25%. Considerable differences can be observed across different crop species, with legumes and fruits showing smaller yield gaps than cereals and root and tuber crops. There is some evidence that the yield gap increases as conventional yields increase (de Ponti et al. 2012). Under best management practices for both systems, yield gaps

Table 2 Mean organic crop yields in comparison to conventional yields (results from global meta-analyses)

Crop	Meta-analyses		
	Seufert et al. (2012)	de Ponti et al. (2012)	Ponisio et al. (2015)
Cereals	–26%	–21%	–22%
Roots and tubers	Not included	–26%	–29%
Oilseeds	–11%	–26%	–12%
Legumes/pulses	–10%	–12%	–15%
Fruits	–3%	–28%	–8%
Vegetables	–33%	–20%	–13%
All crops	–25%	–20%	–19%

do not seem to differ significantly between developed and developing countries (Ponisio et al. 2015). However, in all three meta-analyses, observations from developing countries are heavily underrepresented (Seufert & Ramankutty 2017), so statements about geographic differences of yield gaps need to be interpreted with caution. Longer-term research was recently started to improve knowledge about the productivity effects of organic farming in developing countries (Forster et al. 2013).

One relevant issue when comparing yield levels between organic and conventional agriculture is the time period that the original studies cover. It is sometimes assumed that yields would decline shortly after conversion to organic practices but would then recover after a while due to gradually improving soil conditions in organic farming. However, the evidence to support this assumption is weak. While some studies report organic yield increases over time, others find no changes or even decreasing yields in longer-term studies (de Ponti et al. 2012, Mäder et al. 2002).

3.2. Explaining Yield Gaps

Apart from sunlight and favorable temperatures, plants need a range of different nutrients to grow well, especially nitrogen, phosphorus, potassium, and several micronutrients. In addition, soil texture and composition, water availability, and problems due to pests and diseases matter. Almost all of these parameters may differ between organic and conventional practices; hence, it is not surprising that yield levels differ as well. As mentioned, organic standards prohibit the use of synthetic fertilizers. Although all the required nutrients can, in principle, also be provided through organic fertilizers, nutrient management is more difficult in organic production systems (Niggli 2015).

Organic systems are often found to be limited in nitrogen and phosphorus (Berry et al. 2002, Oehl et al. 2002). The release of plant-available nitrogen from organic sources is slow and can often not keep up with the nitrogen demand during peak crop growth periods (Seufert et al. 2012). The amount of phosphorus provided in organic systems is also sometimes insufficient to replenish the quantities lost due to harvest (Oehl et al. 2002). In general, providing the right mixture of nutrients to optimally support plant growth is more complicated in organic systems because the nutrient ratio of organic inputs can only be influenced to a very limited degree (Seufert & Ramankutty 2017).

Nutrient limitations are an important factor to explain the observed yield gaps in organic agriculture. Against this background, lower-than-average yield gaps observed for legumes and fruits are plausible. Legumes can fix atmospheric nitrogen and are hence less dependent than other crops on externally added nitrogen. Fruits grow on trees that have longer growing seasons and extensive root systems and are hence better able to absorb nutrients in synchrony with crop demand (Seufert et al. 2012).

In terms of water availability and use, organic systems tend to have an advantage because soils managed with organic methods show better water-holding capacity and higher rates of water infiltration. This is also one reason why organic systems are often said to be more resilient and have higher yield stability, even under drought conditions (Gomiero et al. 2011, Niggli 2015). On the other hand, organic systems are sometimes more susceptible to pest outbreaks, which can lead to yield losses and higher yield variability (Seufert & Ramankutty 2017). The ban of chemical pesticides and GMOs in organic agriculture limits the tools available to farmers for effectively controlling weeds, insect pests, and plant diseases. Hence, in high pest pressure environments, and where pests and diseases that are difficult to control with biological methods are found, yield gaps of organic agriculture are higher than in low pest pressure environments.

3.3. External Validity of Estimated Yield Gaps

Most of the data that rigorously compare crop yields in organic and conventional agriculture stem from experimental trials carried out on research stations. Experimental yields are often higher than

those in real-world agriculture because farmers are not always able to fully replicate recommended management practices. If yield differences between experimental stations and farmers' fields would be the same for organic and conventional agriculture, yield comparisons between the two systems would not be systematically biased. However, there is increasing evidence that yield differences between experimental stations and farmers' fields are larger for organic than for conventional practices (Kravchenko et al. 2017). The reason is that organic farming is more knowledge intensive, and yields depend more on timely management interventions (Seufert et al. 2012, Taheri et al. 2017). Hence, while the reported yield differences between organic and conventional agriculture may be true under experimental conditions, they may possibly underestimate the yield gaps that occur in real-world farming situations.

To test the external validity of results obtained from studies on experimental stations, Kniss et al. (2016) compared data from a large number of commercial farms in the United States. For cereals, they found yields on organic farms to be approximately 20% lower than on conventional farms, which is similar to the yield gaps reported in the meta-analyses (**Table 2**). However, for certain vegetables, Kniss et al. (2016) reported yield gaps of 50% and more, which is significantly higher than what the meta-analyses reported. Under practical conditions in some parts of Europe, Pimentel et al. (2005) reported organic cereal yields to be 50% lower than conventional yields. These results should not be extrapolated, as unbiased evidence about organic yield effects under real-world conditions is limited (Kravchenko et al. 2017, Leifeld 2016). In any case, given the higher knowledge requirements for successful organic farming, it is likely that the average yield gaps would rise if an increasing number of farmers would adopt organic practices.

Another interesting question is how yield gaps between organic and conventional agriculture may further develop in the long run, when factoring in technological change. Available studies do not provide a clear answer to this question (Seufert & Ramankutty 2017). As mentioned, yield gaps tend to increase with increasing conventional yields. In addition, over the coming decades yield gaps may potentially widen due to slower plant genetic improvements in organic farming. Organic standards ban the use of GMOs and genome editing techniques, which have significant potential to further increase crop yields and yield stability (Qaim 2016). On the other hand, organic agriculture has received limited research until now (Niggli 2015); increasing the research efforts could possibly contribute to reducing the research gaps over time.

4. NUTRITION AND HEALTH EFFECTS OF ORGANIC FOODS

Consumers often perceive organic foods to be more nutritious and healthier than conventional foods (Seufert et al. 2017). In principle, this could be due to lower contamination of organic foods with unhealthy components or higher contents of nutritionally desirable ingredients. A large body of literature has analyzed whether there are indeed significant differences between organic and conventional foods in terms of chemical composition.

Several systematic reviews suggest that organic food contains lower levels of chemical pesticide residues (Barański et al. 2014, Dangour et al. 2010, Huber et al. 2011). Whether this difference is relevant for human health depends on the types and quantities of pesticides used in conventional farming. In developed countries, where pesticide regulations are relatively strict, differences in risk for exceeding maximum allowed limits are generally negligible (Magkos et al. 2006, Smith-Spangler et al. 2012). In terms of other unhealthy components, some reviews conclude that organic foods contain lower concentrations of nitrate and cadmium (Barański et al. 2014, Huber et al. 2011). No significant difference was found in terms of fungal or bacterial contamination in most studies, although some suggest higher microbial concentrations in certain organic products such as fruits (Mditshwa et al. 2017).

Regarding nutritionally desirable components, most reviews suggest that organic plant products contain moderately higher concentrations of secondary metabolites such as phenolics (Barański et al. 2014, Brandt et al. 2011, Smith-Spangler et al. 2012). Concerning vitamin C and carotenoids, the results are mixed (Barański et al. 2014, Hunter et al. 2011, Smith-Spangler et al. 2012). Higher levels of omega-3 fatty acids were found in organic milk and chicken (Barański et al. 2017, Huber et al. 2011, Smith-Spangler et al. 2012). On the other hand, slightly lower concentrations of proteins and amino acids were found in organic foods (Barański et al. 2014). However, it is not clear whether these differences in nutritionally desirable components between organic and conventional foods are clinically relevant (Barański et al. 2017, Dangour et al. 2010, Forman & Silverstein 2012, Smith-Spangler et al. 2012).

Certain differences in the composition of organic and conventional foods may not be surprising, as farming practices can affect plant chemistry (Brandt et al. 2011). Lower cadmium and nitrate levels in organic plants are linked to synthetic fertilizers not being allowed in organic farming (Barański et al. 2014). Nitrogen fertilization promotes vegetative growth (associated with the formation of proteins and carbohydrates) while limiting generative growth (associated with the formation of secondary metabolites) (Huber et al. 2011). Regarding animal products, higher levels of omega-3 fatty acids are potentially linked to outdoor grazing and larger biodiversity in pastures on organic farms.

However, plant chemistry depends not only on the production system but also on weather conditions, soil type, genotype (variety), ripening stage of the product at harvest, and postharvest conditions (Brandt et al. 2011, Huber et al. 2011). For instance, cadmium levels are highly dependent on soil type and may therefore also be high in organic products (Barański et al. 2014). Furthermore, management practices within both organic and conventional systems can vary (Huber et al. 2011, Smith-Spangler et al. 2012). Organic cattle are not necessarily kept on biodiverse pastures, and conventional cattle are not always raised indoors with silage. As a result, the variation in the composition of foods can be larger within organic and conventional systems than between the two systems (Brandt et al. 2011).

Beyond the chemical composition of foods, several studies have examined possible human health effects of organic diets through observational data from consumers. A few studies suggest that the consumption of organic foods can be associated with a lower risk of allergies and eczema in infants (Alfvén et al. 2006, Kummeling et al. 2008). A cohort study carried out in France showed that regular consumption of organic food is associated with lower rates of obesity (Kesse-Guyot et al. 2013). However, a systematic review did not find differences in health outcomes (Dangour et al. 2010). Generally, it is difficult to prove causality with observational data. Organic consumers are known to make different—often healthier—food and lifestyle choices (Huber et al. 2011, Kesse-Guyot et al. 2013), which can lead to selection bias in impact evaluation. Given the limited evidence, general conclusions about health effects of organic food consumption cannot be drawn (Barański et al. 2017, Dangour et al. 2010, Forman & Silverstein 2012).

5. ENVIRONMENTAL EFFECTS OF ORGANIC FARMING

Agricultural production contributes to various environmental problems such as climate change, biodiversity loss, soil degradation, and water pollution (Foley et al. 2011). It is widely believed that organic agriculture causes fewer negative environmental externalities than conventional agriculture, which is also the main reason why many governments subsidize the organic sector. In this section, we review the evidence of the effects of organic farming on various environmental aspects.

5.1. Land-Use Efficiency

Approximately 40% of the global ice-free land is used for agricultural production (Foley et al. 2011). Continuous land-use change (e.g., deforestation) is associated with various environmental problems, especially the loss of biodiversity and the release of soil carbon into the atmosphere. Thus, balancing food production and environmental goals will increasingly require using land and other natural resources more efficiently. Organic systems have lower land-use efficiency than conventional systems. As discussed above, organic crop yields are lower than conventional yields on average. In addition, organic crop rotations typically include crops that are not suitable for human consumption. Finally, organic animal husbandry is characterized by longer production cycles and lower animal growth rates, meaning that larger quantities of fodder and more land for fodder production are required per unit of organic meat (Treu et al. 2017).

Land-use requirements are also relevant when assessing other environmental effects of organic and conventional production systems. Therefore, environmental impacts are typically expressed per unit of land and per unit of output, where the latter tries to account for lower land-use efficiency in organic systems. Given the rising demand for food and agricultural products, measuring per unit of output seems more relevant to assess environmental impacts from a global perspective. However, even this approach probably underestimates the environmental effects that large-scale conversion to organic agriculture might have. Today, only a marginal share of the global agricultural land is certified organic. Large-scale conversion to organic would likely require bringing more natural habitats into agricultural production. Such additional land-use change would be associated with environmental costs that are not fully accounted for by simply expressing per unit of output (Leifeld 2016).

5.2. Energy Use and Greenhouse Gas Emissions

Approximately 25% of the anthropogenic greenhouse gas (GHG) emissions are attributable to food production (Edenhofer et al. 2014). Carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) emissions accrue during the combustion of fossil fuels (e.g., for the production of mineral fertilizer and the use of agricultural machinery), soil chemical processes, and animal digestion, among others (Gomiero et al. 2011). Energy use and GHG emissions from agriculture are typically evaluated through life cycle assessments until a product leaves the farm (Meier et al. 2015, Smith et al. 2015).

The evidence suggests that organic agriculture uses less energy per unit of land, and to a lesser extent, also per unit of output than conventional agriculture (**Table 3**). This difference is mainly attributable to the nonuse of synthetic fertilizers and pesticides in organic systems. Fuel use for agricultural operations is similar across systems. However, for certain crops (especially vegetables) more fuel is sometimes required in organic production, when repeated mechanical or thermal weed control becomes necessary (Lynch et al. 2011, Scialabba & Müller-Lindenlauf 2010, Smith et al. 2015). This may also lead to higher overall energy use in organic systems in certain situations (Lee et al. 2015).

Concerning GHG emissions, most studies conclude that organic farming has lower impacts when expressed per unit of land but not when expressed per unit of output (**Table 3**). Generally, organic systems are characterized by lower nitrogen inputs, and thus lower N₂O emission potential. However, balancing nutrient supply and plant demand is typically more challenging in organic systems; oversupply of nitrogen from organic fertilizer may also lead to significant N₂O emissions, while undersupply leads to lower yields (Clark & Tilman 2017, Lynch et al. 2011, Skinner et al. 2014). In crop production, soil carbon stocks and sequestration rates were found to be significantly

Table 3 Environmental effects of organic versus conventional agriculture

Effect category	Per unit of land	Per unit of output
Land use	Not applicable	Land use 20–110% higher ^{a,b,c} Land use for organic diets 40% higher ^d
Energy use	Energy use 10–70% lower ^c	Energy use 15–21% lower ^{a,b}
Greenhouse gas (GHG) emissions	Nitrous oxide emissions 14–31% lower ^{a,c} GHG emissions 39% lower ^c	Nitrous oxide emissions 8% higher ^a GHG emissions 0–10% lower ^{a,b,c} GHG emissions of organic diet equal to conventional diet ^d
Nutrient leaching/ eutrophication potential	Nitrate leaching 30–31% lower ^{a,c} Ammonia emissions 18% lower ^a Phosphorus losses 1% lower ^a	Nitrate leaching 5% lower globally ^c and 49% higher in the EU ^a Ammonia emissions 11% higher ^a Eutrophication potential (phosphate equivalents) 36% higher ^b Acidification potential (sulfur dioxide equivalents) 13% higher ^b
Soil quality	Soil organic matter 6–7% higher ^{a,c,g} Larger and more active soil microbial communities ^f	Not applicable
Biodiversity	Species richness 30–34% higher ^{h,i} Organism abundance 50% higher ^h Species evenness higher ^k	Biodiversity loss through indirect land-use change not evaluated in available studies

^aTuomisto et al. (2012).

^bClark & Tilman (2017).

^cMondelaers et al. (2009).

^dTreu et al. (2017).

^eGomiero et al. (2008).

^fLori et al. (2017).

^gMäder et al. (2002).

^hBengtsson et al. (2005).

ⁱTuck et al. (2014).

^kCrowder et al. (2010).

higher in organic than in conventional systems (Gattinger et al. 2012, Lori et al. 2017). In livestock production, less intensive organic husbandry systems lead to larger quantities of manure per unit of meat, and thus higher methane and N₂O emissions (Treu et al. 2017). Overall, the evidence does not support the widely held notion that organic agriculture is more climate friendly than conventional agriculture (WBA 2016).

5.3. Nutrient Leaching and Water Quality

Nutrient leaching is a problem, especially in regions with intensive agriculture, as it causes eutrophication of water bodies and marine ecosystems (Halberg 2012). Nitrate (NO₃⁻) leaching under organic management was found to be lower per unit of land but not per unit of output (Table 3). The overall eutrophication potential per unit of output, measured in terms of phosphate (PO₄) equivalents, and the acidification potential, measured in terms of sulfur dioxide (SO₂) equivalents, were even found to be higher in organic systems (Clark & Tilman 2017). Nonuse of synthetic fertilizers is generally associated with lower leaching potential (Lori et al. 2017, Niggli

2015), but again, avoiding mismatches between nutrient supply and plant demand can be challenging in organic systems, potentially leading to greater nutrient losses (Gomiero et al. 2011, Halberg 2012, Tuomisto et al. 2012).

Concerning pesticides, as synthetic pesticides are banned in organic farming, the risk of pesticide pollution of water bodies is lower (Reganold & Wachter 2016). However, certain nonsynthetic pesticides, which are used in organic farming, can also have negative effects for aquatic life. For instance, in organic horticultural production copper-based solutions are widely used to control fungal diseases (Niggli 2015).

5.4. Soil Quality

Millions of hectares of previously fertile land have become unsuitable for agricultural production because of soil degradation (e.g., erosion), often as a result of mismanagement (Halberg 2012). Organic practices such as the application of organic matter (e.g., green or animal manure) and longer and more diverse crop rotations with cover and catch crops can help to reduce soil erosion and fertility decline (Lori et al. 2017, Niggli 2015). Meta-analyses and results from long-term field trials confirm that organically managed fields have higher contents of organic matter and larger and more active soil microbial communities (**Table 3**), both key indicators of soil quality.

5.5. Biodiversity

Agricultural intensification and homogenization of landscapes have significantly contributed to biodiversity loss (Bengtsson et al. 2005, Halberg 2012). There is large agreement that organic farms are more biodiverse (Hole et al. 2005, Mäder et al. 2002, Pimentel et al. 2005, Schneider et al. 2014, Tuck et al. 2014), which is due to lower pesticide use, longer crop rotations, and more seminatural landscape elements (e.g., hedges) (Niggli 2015). Meta-analyses suggest that species richness (number of species) and species evenness (relative abundance of different species) are both significantly higher on organic farms than on conventional farms (**Table 3**). Large differences were found when high-intensity conventional systems were taken as the reference (Bengtsson et al. 2005, Tuck et al. 2014). However, the biodiversity benefits diminish with increasing intensity of organic production systems (Gabriel et al. 2013). Disagreement exists whether the benefits of organic farming also diminish with increasing scale (Bengtsson et al. 2005, Schneider et al. 2014, Tuck et al. 2014).

As mentioned, because of lower yields, large-scale conversion to organic agriculture would likely imply further loss of natural habitats. It is largely agreed that the biodiversity gains from organic production cannot offset the biodiversity loss associated with additional land-use change (Gabriel et al. 2013, Green et al. 2005, Mondelaers et al. 2009, Schneider et al. 2014). The “land sharing” versus “land sparing” debate is complex and requires site-specific solutions, which is why simplistic global prescriptions are inappropriate (Phalan et al. 2011, Tuck et al. 2014).

5.6. Summary of Environmental Effects

Overall, the environmental benefits of organic agriculture are less clear than widely believed. Often, the environmental performance of organic systems is better than that of conventional systems when compared per unit of land, but the difference vanishes when measuring per unit of output (**Table 3**). Consequently, organic agriculture seems to be more suitable to address local environmental problems (e.g., soil degradation) than global problems (e.g., land-use change, climate change) (Mondelaers et al. 2009).

It should be mentioned that some of the findings on environmental effects are not yet fully conclusive. Limited data are available from developing countries, so existing results may not be globally representative (Clark & Tilman 2017, Gattinger et al. 2012, Lee et al. 2015, Skinner et al. 2014). Furthermore, available studies mostly compare organic and conventional systems without controlling for confounding factors, so that observed differences cannot necessarily be interpreted as causal effects of organic standards. Finally, it needs to be stressed that large heterogeneity in environmental impacts exists within both conventional and organic systems (Bengtsson et al. 2005, Halberg 2012, Lori et al. 2017, Meier et al. 2015, Skinner et al. 2014, Treu et al. 2017). Environmentally friendly farming practices (e.g., sound management of nutrients, longer crop rotations, seminatural landscape elements) are particularly encouraged by organic standards, but they are also used by many conventional farmers (Lynch et al. 2011, Pimentel et al. 2005).

6. CAN ORGANIC AGRICULTURE FEED THE WORLD?

Many see organic agriculture as the most sustainable form of farming and as the paradigm for global food production in the future. Hence, the question of whether organic agriculture alone could actually feed the world with its 7.5 billion people today, and likely over 9 billion people by 2050, arises time and again (Badgley et al. 2007, Connor 2008, Erb et al. 2016, Seufert & Ramankutty 2017, Muller et al. 2017, Taheri et al. 2017). Given that organic farming today only accounts for 1% of the agricultural land, a total conversion to organic agriculture does not seem to be a realistic scenario in the foreseeable future, but it is nevertheless an interesting thought experiment.

6.1. Food Production Quantities

As discussed, average crop yields are lower in organic than in conventional agriculture. Consequently, total conversion to organic practices would require more land to produce the same quantity of food. Section 3 discussed the average organic yield gaps of 19–25%, which would mean additional land requirements of 23–33%. But in Section 3 we also discussed that yield gaps could increase if more farmers adopted organic agriculture. Organic farming is more knowledge intensive than conventional farming; therefore, there is little reason to assume that organic yields obtained on experimental stations or on 1% of the agricultural area could be extrapolated to all agricultural land worldwide. Larger yield gaps are especially likely when it comes to upscaling organic agriculture in the developing-country small farm sector, where levels of formal education are often low, and access to agricultural training is limited. Average yield gaps of 30–40% would already mean that 43–67% of additional land would be required to produce the same quantity of food with organic practices, implying a significant loss of natural habitats.

Another relevant question is whether sufficient nutrients from organic matter would be available if all of the world's agriculture were converted to organic practices (Tomich et al. 2011). Today, organic agriculture often relies on nutrient inputs from conventional farms and heavily depends on the livestock sector (Nowak et al. 2013). But would there be enough animal manure available to supply nutrients to a much larger area under organic production? Currently only about 11% of the nitrogen inputs to global crop production come from animal manure, and another 8% are from crop residues (Seufert & Ramankutty 2017). Completely replacing synthetic fertilizers, which are banned in organic farming, would mean significantly increasing the number of farm animals kept. Given the climate effects of animal husbandry and the additional land required for fodder production, this would hardly be a sustainable scenario. Alternatively, more leguminous cover crops could be grown to restore nitrogen in the soil. However, providing sufficient nitrogen would require a legume cover crop on each field every year, which would not be possible without

reducing the area available for food production (Connor 2008). Providing insufficient nutrients would mean additional yield gaps.

In summary, providing sufficient food for the growing world population through organic farming alone might be possible but not without taking significantly more land into production. The expansion of agricultural land is a major contributor to biodiversity loss and climate change (Foley et al. 2011, Green et al. 2005). As discussed in Section 5, the biodiversity gains from organic production cannot offset the biodiversity losses associated with additional land-use change. In other words, complete conversion to organic agriculture would likely be associated with additional GHG emissions and a net loss in biodiversity.

6.2. Sustainable Consumption

When calculating the food quantities that have to be produced to feed the world population, current patterns and trends of food consumption are typically assumed. However, a significant share of the food produced is lost or wasted along the value chain, including foods thrown away by the end-consumer (FAO 2011). Moreover, the high consumption of meat and dairy products in many parts of the world is associated with considerable resource inefficiencies. In other words, much less food production would be required if food losses and waste were reduced and if all people became vegetarians or vegans. Such a scenario could certainly change the conclusions about the potential of organic agriculture to feed the world. Indeed, in recent simulations, Erb et al. (2016) and Muller et al. (2017) showed that the predicted world population in 2050 could be fed even with lower yields and without the loss of additional natural habitat if only vegan diets were consumed.

However, completely vegetarian or vegan diets are not realistic and also not desirable from a nutritional perspective (Seves et al. 2017, White & Hall 2017). Nor do vegetarian or vegan diets fit together with increased organic production, as organic practices depend on the availability of animal manure. But with or without organic agriculture, changes in people's consumption habits toward less resource-intensive diets will have to be an important part of sustainable development strategies (Foley et al. 2011). Especially in rich countries, this should also involve less consumption of animal products. In several countries in Europe, the per capita consumption of meat is actually decreasing, but the decrease is slow. Behavioral change processes are not easy to instigate and accelerate through political measures, and the global trend goes in the opposite direction. Especially in Asia and Africa, the demand for animal products is rapidly rising, and the situation is similar in terms of food losses and waste. Although reductions are desirable, a zero waste scenario is hardly realistic in the foreseeable future.

6.3. Food Prices and Food Security

Mainly owing to lower average yields, organic production is associated with higher costs per unit of output and thus higher prices (see Section 2). Currently, the higher prices only apply to the small certified organic market segment, but total conversion to organic agriculture would mean significantly higher food prices in the entire market. In developed countries, most consumers are sufficiently rich so that higher food prices would not jeopardize their food security. But in developing countries, the situation is different. Many poor households spend over 50% of their income on food. In such situations, food price increases are associated with higher levels of food insecurity and undernutrition, especially in urban areas (Ecker & Qaim 2011). For farming households, higher agricultural prices are welcome as such, but when higher prices are the result of lower yields, they do not necessarily lead to higher incomes. The socioeconomic effects of organic agriculture for farming households are analyzed in the following section.

7. SOCIOECONOMIC IMPLICATIONS FOR ORGANIC FARMERS

Organic farming can only contribute to sustainable agricultural development when it is economically viable for farmers, meaning that the income derived from organic production is at least as high as that from conventional farming. A recent meta-analysis has analyzed this issue and includes studies from 14 different countries (Crowder & Reganold 2015). Results show that organic farming is 22–35% more profitable than conventional agriculture on average. While organic yields are significantly lower, organic farmers receive higher prices for their products in certified organic markets. Average price premiums at the farm level are on the magnitude of 30%. Without price premiums, organic farming would be less profitable than conventional farming (Crowder & Reganold 2015).

Whereas the meta-analysis by Crowder & Reganold (2015) includes data from different parts of the world, most of the original studies refer to the United States and other developed countries. Only a few of the studies refer to developing countries, and no single study looked at the situation in Africa. In terms of absolute numbers, most organic producers are smallholder farmers in developing countries. Moreover, smallholder farmers comprise a large share of the world's poor and hungry people (FAO 2014, Qaim 2017). Hence, a better understanding of what organic farming can mean economically for farmers in developing countries is important (Jouzi et al. 2017). A review of studies focusing on socioeconomic aspects of organic farming in Africa, Asia, and Latin America is provided below.

7.1. Smallholder Farmers and Organic Yields

As discussed in Section 3, yields obtained with organic production methods tend to be lower than those in conventional agriculture. However, yield differences depend on the particular context. In situations where most farmers have limited access to modern production technologies and apply low quantities of purchased inputs anyway, organic yields can be similar to conventional ones (Beuchelt & Zeller 2011, Jena et al. 2017, Kramol et al. 2013, Parvathi & Waibel 2016). This is not an untypical situation of smallholders in developing countries, especially in Africa. With intensive training and a substantial increase in the use of organic fertilizers, organic yields can even be significantly higher than those obtained from low-input conventional farming (Bolwig et al. 2009, Ibanez & Blackman 2016, Wollni & Andersson 2014). Employing organic soil management practices can also reduce yield variability and vulnerability to drought and other weather extremes (Niggli 2015, Scialabba & Müller-Lindenlauf 2010). However, where modern inputs are available and more commonly used, organic farmers typically have lower yields than conventional farmers. Yield gaps tend to increase during the process of economic development (Valkila 2009).

7.2. Price Premiums

Most organic farmers in developing countries produce cash crops (e.g., coffee, tea, cocoa, tropical fruits) for export to rich countries, where consumers pay a significant price premium for certified organic products (Raynolds 2004, Willer & Lernoud 2017). However, the price premium at the retail level is not necessarily reflected in the price that farmers receive for their organic produce because various actors along the value chain also capture some of the benefits (Minten et al. 2018). In some cases, prices received by organic farmers in developing countries are not higher than those in conventional markets (Chiputwa et al. 2015, Parvathi & Waibel 2016). Nevertheless, most studies find that organic premiums at the farmer level range between 6% and 44% (Beuchelt & Zeller 2011, Bolwig et al. 2009, Ibanez & Blackman 2016, Jena et al. 2017, Jones & Gibbon 2011, Kleemann et al. 2014, Mitiku et al. 2017, Valkila 2009).

However, oftentimes organic smallholders do not sell all of their harvest in certified markets (Jena et al. 2012, 2017; Kleemann et al. 2014). There are several reasons why they may decide to sell some or all of their crops in conventional markets. First, sometimes the quality requirements of certified markets cannot be met (Bolwig et al. 2009, Weber 2011). Second, there can be situations when the farmer organizations lack the capacity to handle the large supply of certified crops delivered by their members (Jena et al. 2012, Snider et al. 2017). Third, price premiums vary and can be small during certain periods (Snider et al. 2017). Finally, even when price premiums are more significant, selling in certified markets is often associated with payment delays. When facing urgent cash needs, organic farmers sell to local traders at lower prices but in return for immediate cash (Bacon 2005, Beuchelt & Zeller 2011, Valkila 2009). Given these conditions and constraints, the average price that organic smallholders receive may be lower than what the reported price premiums may suggest.

7.3. Production Costs

In the small farm sector, certification fees and related administrative costs are typically covered by farmer cooperatives, exporters, or development organizations. However, meeting certification requirements is often associated with certain investment costs (e.g., new equipment) that farmers have to bear individually (Kleemann et al. 2014). Also, organic certification involves a three-year transition period, which can be understood as a sunk cost. During this transition period, farmers cannot yet benefit from an organic price premium, but yields are often particularly low due to learning and experimentation with the new production methods (Caldwell et al. 2014, Ruben & Fort 2012, Weber 2011).

Organic certification can also influence variable production costs. Although costs for chemical inputs are saved, maintaining and increasing yields requires large quantities of organic material (e.g., manure). The organic matter available at the farm itself may not suffice, so that additional material has to be purchased (de Ponti et al. 2012). The cost can be substantial, especially when local market supply of organic matter is limited (Jena et al. 2017, Kloos & Renaud 2014). Furthermore, organic farming is typically more labor intensive, as manual labor is needed for weeding, application of organic fertilizers, and other operations (Valkila 2009). Consequently, households have to hire additional labor or use more family labor (Beuchelt & Zeller 2011, Kleemann et al. 2014, Ruben & Fort 2012). Most studies focusing on developing countries do not account for the opportunity cost of family labor. With the increasing availability of off-farm income opportunities, this may lead to underestimation of the total production costs in organic farming.

7.4. Indirect Economic Benefits

In addition to possible price premiums, organic certification may also be associated with indirect economic benefits. In developing countries, certified farmer organizations (or buyers) usually offer services, such as price information, training, credit, or value addition, to help farmers meet certification requirements and produce the quality demanded in international organic markets (Bolwig et al. 2009, Jones & Gibbon 2011). As smallholder access to rural services is generally low, such initiatives by certified organizations can improve the situation more broadly and result in income gains (Mitiku et al. 2017, Parvathi & Waibel 2016). However, the range and quality of services to be provided is not specified in organic standards, so the relevance of such indirect benefits varies (Jena et al. 2012, Meemken et al. 2017a).

Collective marketing or contractual arrangements are also commonplace in smallholder organic value chains. Such arrangements can be beneficial for farmers irrespective of organic certification

(Bellemare 2012, Fischer & Qaim 2012). But as new marketing institutions are often established as part of certification initiatives, related gains for individual farmers can also be considered as indirect benefits of participating in organic agriculture.

7.5. Overall Profitability and Income

The previous subsections showed that yields, prices, and production costs in organic farming are highly context specific. As a result, studies come to different conclusions regarding the overall profitability of organic certification. Some studies find that the price premium is insufficient to compensate for lower yields and/or higher production costs (Barham & Weber 2012, Ibanez & Blackman 2016, Mitiku et al. 2017). Other studies suggest that organic certification contributes to higher profitability in the small farm sector (Bolwig et al. 2009, Kleemann & Abdulai 2013, Kleemann et al. 2014). We conclude that the profit effects of organic farming are less clear cut in developing countries than what the global meta-analysis of Crowder & Reganold (2015) suggests.

However, a narrow focus on the profits from one certified crop alone may yield an incomplete picture of the overall economic impacts of organic farming. This is especially true in the small farm sector, where households usually engage in multiple farm and off-farm activities. For instance, when households decide to allocate land, labor, and capital to organic production, the income from other economic activities may also be affected through resource reallocation and other types of spillovers. Several studies have analyzed the effects of organic certification on total household income, thus implicitly capturing spillovers. Again, the results are mixed and context specific. While some studies suggest that organic certification has no effect or even negative effects on income and the likelihood to be poor (Barham & Weber 2012, Beuchelt & Zeller 2011, Chiputwa et al. 2015, Jena et al. 2017, Mitiku et al. 2017, Valkila 2009), others find exactly the opposite (Ayuya et al. 2015, Jones & Gibbon 2011, Kleemann & Abdulai 2013).

7.6. Broader Social Development Goals

Unlike other sustainability standards, such as Fairtrade, most organic standards do not include specific certification requirements related to social issues, such as child labor or gender equality (Meemken & Qaim 2018, Seufert et al. 2017). Nevertheless, studies suggest that organic certification can affect social outcomes in positive and negative ways. If it improves income, organic certification may enable households to make beneficial investments in human capital formation. For instance, Gitter et al. (2012) show that double organic-Fairtrade certification has a positive effect on child education in Mexico. Such investments in better child education are unlikely to occur in the absence of income gains, as Meemken et al. (2017a) show with data from organic coffee producers in Uganda.

Several studies have also analyzed nutrition effects, suggesting that organic certification helps to improve food security and dietary quality in farming households (Becchetti et al. 2012, Chiputwa & Qaim 2016, Meemken et al. 2017a). Positive effects on dietary diversity can even occur in the absence of income gains (Meemken et al. 2017a). One reason is greater production diversity on organic farms, which is known to affect household dietary diversity through the subsistence pathway (Sibhatu et al. 2015).

Organic farming can also reduce occupational health hazards, as farmers and farm workers are less exposed to chemical pesticides (Asfaw et al. 2010, Forman & Silverstein 2012, Shreck et al. 2006). The ban of chemical pesticides can also have interesting gender implications. On the one hand, pesticide bans can increase women's workload, as women are often heavily involved in labor-intensive activities such as weeding (Bolwig 2012, Lyon et al. 2010). On the other hand,

pesticide-free production can promote women's participation in cash cropping (Kloos & Renaud 2014). The reason is that the handling of pesticides is primarily considered a male task in many parts of Africa and Asia. More generally, organic certification can have effects on labor markets and employment conditions in the farming sector and also further downstream (Taheri et al. 2017). Such effects are not yet sufficiently understood.

7.7. Summary of Socioeconomic Effects

The results on socioeconomic effects of organic farming in developing countries are mixed. In some situations, organic certification contributes to significant welfare gains. But switching to organic is not always beneficial for smallholders and should therefore not be considered a general strategy for poverty reduction. The benefits of organic production methods tend to be larger in regions where conventional crop yields are low, due to farmers' limited access to modern inputs and production technologies. With better access to markets and technologies, yield gaps between organic and conventional production increase, and the benefits of organic production tend to get smaller.

However, the evidence on causal effects is still limited. Most available studies use cross-section observational data, and not all control for possible selection bias (exceptions include Bolwig et al. 2009, Chiputwa et al. 2015, Ibanez & Blackman 2016, Kleemann & Abdulai 2013, Weber 2011). Very few studies use panel data models (Meemken et al. 2017a), and to our knowledge, no study thus far has used randomized experiments to evaluate the socioeconomic impacts of organic farming in developing countries.

One aspect that needs to be kept in mind is that much of the research in developing countries involves case studies of communities where organic farmers received support through specific development projects. Project support typically includes intensive training in organic agricultural practices, facilitation of links to certified markets, and sometimes financial subsidies (Chiputwa et al. 2015, Jouzi et al. 2017, Stolze & Lampkin 2009). Hence, even when farmers benefit significantly under such conditions, upscaling of these benefits will be difficult, unless the same intensive support is provided to other farmers and communities as well. Organic farming is not a practice that spreads automatically in developing countries simply by other farmers copying what successful early innovators have done.

Another important aspect to remember is that most organic farmers in developing countries so far produce cash crops for the export market. Results from these examples cannot be transferred to the production of food crops for the domestic market. Positive socioeconomic effects for farmers are most likely when significant price premiums for organic products can be obtained. While some high-income consumers in developing countries are willing and able to pay more for organic foods, many domestic consumers are poor and unable to pay significant price premiums.

8. CONCLUSIONS

Many rich-country consumers consider organic foods to be healthier and organic agriculture to be more environmentally friendly than conventional farming methods. These perceived benefits are influencing food and agricultural policies. Sometimes organic farming is promoted as the paradigm for sustainable agriculture and food security. In this article, we have reviewed the available literature about the economic, social, environmental, and health effects of certified organic agriculture from a global perspective.

In terms of health effects, clear conclusions cannot be drawn. Although some studies show differences between the chemical composition of organic and conventional foods, others do not,

and where differences are found, these are small and may not be clinically relevant. In terms of environmental and climate effects, organic farming is less polluting than conventional farming when the effects are measured per unit of land but not when measured per unit of output. As the demand for food and agricultural products is high and growing, expressing environmental and climate effects per unit of output seems more relevant from a global perspective.

The reason why organic farming is more environmentally friendly than conventional farming per unit of land but not per unit of output is the lower average yield obtained with organic agriculture. The bans of synthetic fertilizers, pesticides, and GMOs in organic farming make plant nutrition and pest control more difficult and often less effective. So far, organic farming accounts for only 1% of the global agricultural land. Due to the higher knowledge requirements in organic farming, currently observed yield gaps between organic and conventional methods might further increase if a larger number of farmers would switch to organic practices. This is especially true in developing countries, where smallholder farmers tend to have relatively low levels of education and limited access to agricultural training.

The yield gaps imply that more land would be required to produce the same quantity of output with organic methods. Expanding agricultural production further into natural habitats would lead to additional GHG emissions and loss in biodiversity. Depending on the context, such indirect land-use change effects could outweigh the positive environmental effects of organic farming per unit of land. Against this background, organic farming is not the paradigm for sustainable agriculture and food security. Widespread upscaling of organic production methods would also entail significant output price increases, thus making food less affordable for poor consumers in developing countries.

The conclusion that organic farming is not the global blueprint for sustainable agriculture does not mean that organic methods cannot be useful in specific situations. Under certain conditions, organic farming can be clearly positive for the environment, even when the effects are measured per unit of output. Experience shows that farmers can benefit as well when they are linked to certified markets in which consumers are able and willing to pay a significant price premium for organically produced foods. This is the case in certain high-value niches but less so in mass markets catering to lower-income population segments.

However, the environmental footprint of agricultural production needs to be reduced for mass markets as well. This will require new technologies and production methods that conserve natural resources and make farming more resilient and less dependent on chemical inputs. Solutions have to be locally adapted, taking into account all promising areas of science. Neither conventional nor organic methods currently have perfect answers to these challenges. Sustainable production systems will likely require smart integration of both types of agriculture. Organic methods are well suited to reduce land degradation and improve soil quality, but in many situations, crop productivity and environmental efficiency could be further improved if these methods were combined with moderate levels of synthetic fertilizers and the newest insights into plant genetic improvement. Ideological barriers between supporters and opponents of organic agriculture need to be overcome to pave the way for developing and implementing more sustainable forms of farming.

There are several areas that deserve more research to further improve our understanding of the effects of organic agriculture. First, many of the available studies on yield performance and environmental effects refer to developed countries. Additional studies under typical conditions in developing countries would be very useful. Second, many of the existing studies with farm survey data have not properly controlled for selection bias. More rigorous empirical studies are needed. Third, while several studies showed that organic farming can be profitable with the existing support through subsidies and development projects, it is less clear whether organic farming could also be profitable without such external support. Fourth, the net food price effects of organic agriculture

are not sufficiently understood. Although it is clear that organic foods are more expensive than conventional foods, it is less clear how much of the price markup is attributable to differences in farming practices as opposed to other factors such as scale effects, market structure, and efficiency. Finally, it would be interesting to analyze how the productivity, environmental, and profitability effects of organic farming might change through slight adjustments in the definition of what is allowed and disallowed in certified organic production.

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