AGRICULTURE

Many shades of gray—The context-dependent performance of organic agriculture

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Organic agriculture is often proposed as a more sustainable alternative to current conventional agriculture. We assess the current understanding of the costs and benefits of organic agriculture across multiple production, environmental, producer, and consumer dimensions. Organic agriculture shows many potential benefits (including higher biodiversity and improved soil and water quality per unit area, enhanced profitability, and higher nutritional value) as well as many potential costs including lower yields and higher consumer prices. However, numerous important dimensions have high uncertainty, particularly the environmental performance when controlling for lower organic yields, but also yield stability, soil erosion, water use, and labor conditions. We identify conditions that influence the relative performance of organic systems, highlighting areas for increased research and policy support.

Agriculture today is a leading driver of environmental degradation (*1*), but despite major increases in production, one in eight people in developing countries remain malnourished (*2*). Organic agriculture is often proposed as a solution to this challenge of achieving sustainable food security. Although it only covers ~1% of global agricultural land and only contributes ~1 to 8% of total food sales in most European and North American countries (*3*), "organic" is a label that is recognized and purchased by many consumers, and organic agriculture is the fastest-growing food sector in North America and Europe (*3*). Given that organic agriculture is a current and rather widespread farming system and is one of the few legally regulated labels in farming, it is important to assess its performance and identify how we can improve it.

The benefits of organic agriculture are widely debated. Although some promote it as a solution to our sustainable food security challenges (*4*–*6*), others condemn it as a backward and romanticized version of agriculture that would lead to hunger and environmental devastation (*7*–*9*). Previous reviews (*4*, *6*, *10*–*14*) have focused on the benefits of organic management, asking the question whether organic agriculture is good or bad. Here, we address a more policy-relevant question, assessed across a suite of different criteria and contexts: Where does organic agriculture perform well, and where does it not? Unlike previous reviews, which only assessed the average performance of organic agriculture relative to conventional agriculture, we also evaluate the range around this central tendency, the contextual factors driving the upper and lower range of responses, and the uncertainty in our understanding.

We assessed the benefits and costs of organic agriculture across the following dimensions: (i) production, (ii) environment, (iii) producers, and (iv) consumers. Rather than starting from what is known in the literature on organic agriculture, we developed a framework that identifies important dimensions of agricultural sustainability and specific indicators within each. Accordingly, we also include indicators that have received limited attention in the organic literature to date (for example, water use and farm wages). Often farming system assessments only examine the impact per unit area. However, given that yields vary, and that a primary purpose of agriculture is production, it is important to also assess the performance of farming systems per unit output (*15*). Per unit output impacts are particularly relevant to the environmental dimensions because of the strong environmental impact of land conversion (*1*). For each dimension and each variable examined, we assess existing knowledge based on quantitative reviews of the scientific literature, where possible, including (i) average performance per unit area and per unit output (where relevant), (ii) uncertainty around the average performance, (iii) factors influencing low and high performance, and (iv) knowledge gaps.

The scope of this review is limited to an examination of impacts at the level of the farming system (including indirect impacts on consumers), with no consideration of other aspects of the food system such as processing and distribution, consumption, or recycling. Our assessment is also restricted to cropping systems, excluding livestock systems (except where integrated into mixed systems). Thus, animal welfare, in particular, is not addressed.

Organic agriculture is defined here as a farming system that follows organic certification guidelines (for example, avoidance of synthetic fertilizers and pesticides) and that is intentionally organic (that is, excluding organic-by-default systems that do not apply synthetic inputs due to lack of access). Conventional agriculture is defined as mainstream agriculture as dominantly practiced today. This can represent both high-input and low-input systems, depending on the region.

ORGANIC AGRICULTURE AND PRODUCTION BENEFITS AND COSTS

Yields

Crop (and animal) production is the primary reason that humans manage agroecosystems. Many studies point to the need to greatly increase food production to meet the needs of a growing human population and the shift to more meat-intensive diets (*16*). Although the need for increased food supply is still debated because of the inefficiencies and inequities in the current system (*17*), yields do matter not only for farmers whose incomes critically depend on the yield but also for many environmental outcomes. Even if food production does not need to increase, higher yields could still be environmentally beneficial because we could take land out of production and restore natural ecosystems, which typically are better at delivering ecosystem services than production systems.

Numerous meta-analyses have concluded that yields under organic management are, on average, 19 to 25% lower than under conventional management (Fig. 1 and fig. S1) (*18*–*20*), and a recent analysis of commercial organic crop yields in the United States reveals a similar average yield gap of 20% (*21*). However, the magnitude of this yield gap varies by crop type and depends on management practices [for example, crop

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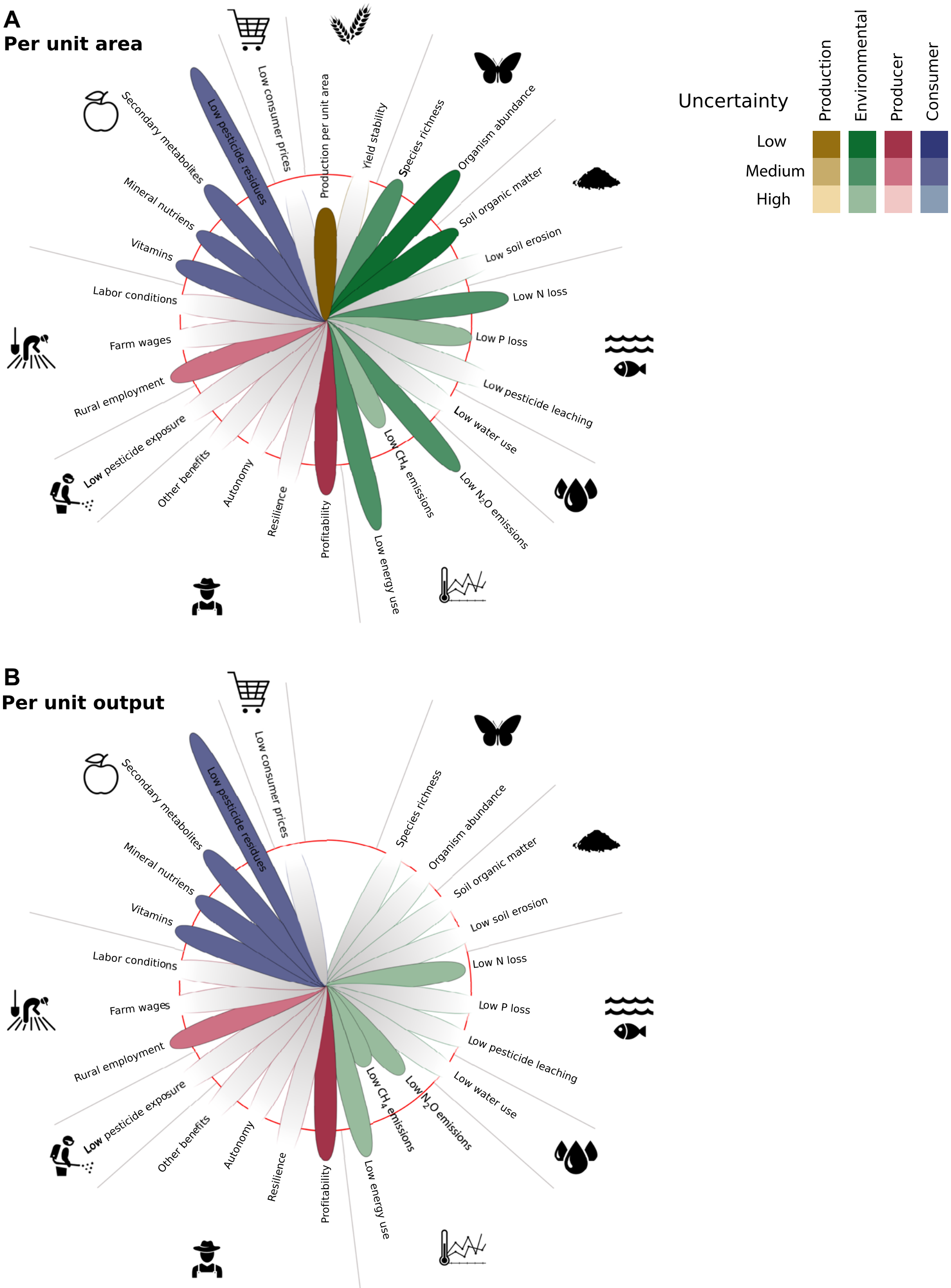

Fig. 1. Overall average performance of organic agriculture relative to conventional agriculture (indicated by the red circle). (**A**) Performance per unit area and (**B**) performance per unit output. Figure includes production (brown petals), environmental (green petals), producer (red petals), and consumer (blue petals) benefits (petals that extend beyond the red circle) and costs (petals inside the red circle). Dimensions assessed include (starting at the top, going clockwise) production, biodiversity, soil quality, water quality, water quantity, climate change mitigation, farmer livelihoods, farmer and farm worker health, farm worker livelihoods, consumer health, and consumer access. Larger petals represent superior organic performance (for example, a larger petal for N loss means lower N loss in organic). In addition, note that per unit output performance is only relevant for environmental variables; other petals are unchanged relative to per unit area performance. Shading of petals represents level of uncertainty for each variable, with uncertainty determined by the number of primary studies included in each assessment and the level of agreement between different quantitative reviews (see fig. S6 for details). Variables that could not be quantified are in gray. Length of gray petals also varies slightly depending on whether the qualitative assessment of each dimension (see Table 2) is uncertain or suggests no difference (that is, petal is on the red circle) or shows higher (that is, petal extends beyond the red circle) or lower (that is, petal is inside the red circle) performance. Means used to quantify each variable (also known as petal length) were calculated as weighted means (weighted by the sample size, typically the number of observations in each quantitative review) across estimates of response ratios (organic/conventional) from different quantitative reviews (see table S1 for sources and figs. S1, S2, and S5 for values used) and are represented on a log scale to treat changes in the numerator and denominator the same [with the red circle indicating no change, that is, log(org/conv) = 0]. Note that this approach does not account for double-counting of primary studies included in multiple quantitative reviews or meta-analyses. This double-counting might affect petal size but would not alter qualitative size relationships among petals.

rotations, amount of fertilizer inputs (Table 1) (*18–20*)]. The yield gap can be as low as 5 to 9% under some conditions, but as high as 30 to 40% under other conditions (*18*, *19*). Many cereals show, for example, a higher yield gap (*18*, *21*), while forage crops, such as hay, tend to have smaller yield gaps (*20*) or even higher yields under organic management (*21*). However, studies disagree on some of the factors that influence the yield gap (table S2), possibly because of the small sample sizes when individual factors are considered. An important caveat is that existing analyses are mostly limited to data from high-income countries (Fig. 2), which prevents a verdict on the relative yield performance of organic agriculture compared to different types of high-input and low-input conventional systems in low-income countries.

Studies have typically examined the annual output (in terms of dry matter) of single crop species per unit area of cultivated land (*18–20*). However, given the diversity of temporal dynamics (for example, fallow periods and multicropping) and the diversity of land uses (including nonedible crops and livestock), a more useful comparison would be of the total energy, caloric, or protein yield across an entire crop rotation available for human consumption [that is, whole system output per unit area-time (*9*, *20*)].

Yield stability

Most assessments of the productivity of agricultural systems focus on efficiency of production (that is, how much can be produced per unit area of land in a single year?) but ignore the resilience of production (that is, can the same production be achieved over longer time frames?). Yield stability, one measure of the resilience of food production, matters not only for farmer livelihoods but also for food production under a changing climate.

Organic agriculture is often said to be more resilient and have higher yield stability (*11*, *22*). A possible mechanism may be the use of organic amendments leading to higher soil organic matter, resulting in higher yields under drought conditions (*23*). In addition, more diverse crop rotations can increase yield stability (*24*). However, organic systems are sometimes more prone to pest outbreaks (*25*), can experience high weed pressure (*26*), or be characterized by highly variable N availability (*25*), which all can lead to higher yield variability. The relatively few comparisons of yield stability in organic versus conventional systems conducted to date have therefore shown both higher (*23*, *24*) and lower yield stability under organic management (Table 1) (*25–27*).

ORGANIC AGRICULTURE AND ENVIRONMENTAL BENEFITS AND COSTS

Biodiversity

Not only is agricultural land use one of the leading drivers of biodiversity loss (*28*), but food production also depends on many regulating and supporting ecosystem services (such as pest regulation, crop pollination, and soil nutrient cycling) from biodiversity (*29*). The benefits of organic management for biodiversity of wildlife on farmland are clear, with a typical increase in organism abundance of 40 to 50% across different taxa (*30*, *31*). The influence on species richness is less clear (ranging from 1 to 34%; see Fig. 3 and fig. S2) because some have argued that the often-observed species richness effect (*31*, *32*) might be driven by an underlying sampling effect at higher organism densities (*30*).

Generally, it appears that plants (*32*) and bees (*33*) benefit the most from organic management, although other arthropods and birds benefit to a smaller degree (Table 1 and table S3). Landscape context is an important factor, and higher benefits of organic management are found in simplified landscapes with high agricultural land cover (*32*) and lower habitat quality (*33*) and in regions with intensive agriculture (*34*). Some evidence also suggests that organic agriculture has a stronger effect on biodiversity in arable systems (for example, cereal) than in grassland systems (*32*, *34*), and a stronger impact within individual fields than at the farm scale (*34*).

Because of the importance of habitat conversion for biodiversity loss, an assessment of the impact of farming systems on biodiversity has to control for yields, which few studies have carried out to date (Fig. 1B) (*35*, *36*). Both Gabriel *et al.* (*35*) and Schneider *et al.* (*34*) suggested that there are trade-offs between the biodiversity benefits of organic management and yields. Gabriel *et al.* (*35*) further argued that although earlier studies had shown higher organic benefits for biodiversity per unit area in simplified landscapes (see Table 1), biodiversity per unit output might benefit most from organic management in mixed and low-productivity landscapes because of a smaller yield difference between organic and conventional farms.

Soil quality

Soil health has always been at the core of organic philosophy (*37*). The formation of soil and soil nutrient cycling are important supporting services for food production (*29*). Soil degradation and soil erosion, which affect large areas of land today because of the intensive use of croplands and rangelands, threaten current and future food production and are a key sustainability challenge for agriculture (*38*).

Several meta-analyses and quantitative reviews have found that soils managed with organic practices have higher organic carbon content (Fig. 1A) (*39–42*). Studies have also typically found reduced soil erosion from organic farms due to improved soil structure (Table 2) (*43–45*), but more studies are needed to quantify this variable (Fig. 1A). Primary studies have also often shown improvements in other soil health and fertility parameters (such as soil nutrient status or soil physical properties) under organic management (*46–48*). Despite these generally positive impacts of organic management on soil parameters, the soil fauna does not appear to be more species-rich (*31*, *32*), but it is more abundant in organically managed soils (*31*).

One of the most important factors influencing the impact of organic management on soil organic carbon content is the amount of organic matter inputs; the higher the organic inputs such as composts or animal manure, the higher the organic matter content in organically managed soils (Table 1) (*39*, *40*, *42*). However, we have a poor understanding of other potential important drivers, such as the presence of legumes in the crop rotation (*39*), or of the impact of organic agriculture on soil quality per unit output (Fig. 1B).

A common criticism of organic farming is the use of increased tillage to control weeds because of the prohibition of herbicides (*7*), which can enhance organic matter loss and soil erosion (*49*). However, the typically higher organic matter content of organically managed soils suggests that tillage under organic agriculture is no more intensive than under conventional management (*39*). Furthermore, reduced tillage systems seem to be feasible under organic agriculture, as evidenced, for example, by the large number of U.S. organic farmers reporting the use of reduced tillage [that is, 41% (*50*)], which is the same proportion as for conventional farmers in the United States (*51*) and also highlighted by a recent meta-analysis that suggested that some organic reduced tillage systems (for example, shallow noninversion tillage) can lead to higher soil organic matter content without incurring yield penalties relative to intensive tillage (*52*).

Climate change mitigation

Agriculture, which is responsible for ~22% of global anthropogenic greenhouse gas (GHG) emissions [including deforestation (*53*)], is a

Table 1. Factors influencing the low and high performance of organic agriculture across some production (brown), environmental (green), producer (red), and consumer (blue) dimensions. Shading represents the strength of the evidence base (that is, dark shade, based on meta-analyses and quantitative reviews; medium shade, based on qualitative reviews or large-scale primary studies; light shade, based on primary studies or authors' opinion). Some key references supporting the assessment of each effect are indicated. Note that numerous variables (for example, yield stability, water use, pesticide leaching, resilience, or farm wages) could not be assessed. For the level of agreement between different studies for production and biodiversity, see tables S2 and S3. org, organic; conv, conventional.

Variable	Low performance	High performance	References
Production per unit area	Cereals	Fodder crops	(*18, 20, 21*)
	Nonlegumes and annuals	Legumes and perennials	(*18, 21*)
	Lower N inputs in org	Higher N inputs in org	(*18, 19*)
	No rotation	More rotation in org	(*18, 19*)
	Strong acidic and alkaline soils	Neutral soils	(*18, 19*)
Species richness and abundance	Arthropods and Birds	Plants	(*32, 34*)
	Predators, herbivores, and decomposers	Pollinators and producers	(*32, 33*)
	Pastures	Cereal fields	(*32, 34*)
	Extensive agriculture in region	Intensive agriculture in region	(*34*)
	Complex landscapes	Simple landscapes	(*32, 33*)
	Outside fields/at farm level	Within fields	(*34*)
Soil organic carbon	Same organic matter inputs in org and conv	Higher organic matter inputs in org	(*39, 40, 42*)
Energy use	Fruits and vegetables	Other field crops	(*58*)
GHG emissions	Multicropping systems	Monocropping systems	(*58*)
N loss	High N inputs in org	Low N inputs in org	(*60*)
P loss	Organic amendments	Legume-based systems	(*65*)
N and P loss	Horticultural systems	Arable systems	(*63*)
Profitability	No access to premium prices	Access to premium prices	(*81*)
	Regions with high labor cost	Regions with low labor costs	(*81*)
Autonomy	Reliance on export markets	Participation in alternative food networks	(*82, 87*)
Pesticide exposure	Crops with low pesticide use and/or regions with strong pesticide regulation and enforcement	Crops with high pesticide use and/or regions with weak pesticide regulation and enforcement	—
Rural employment	—	Regions with high rural unemployment	—
Pesticide residues	Crops with low pesticide use and/or regions with strong pesticide regulation and enforcement	Crops with high pesticide use and/or regions with weak pesticide regulation and enforcement	—
Nutritional content	—	Regions with micronutrient deficiencies	(*101*)
	—	Low-income groups	(*109*)
Consumer prices	Regular wholesale	CSA	(*110*)

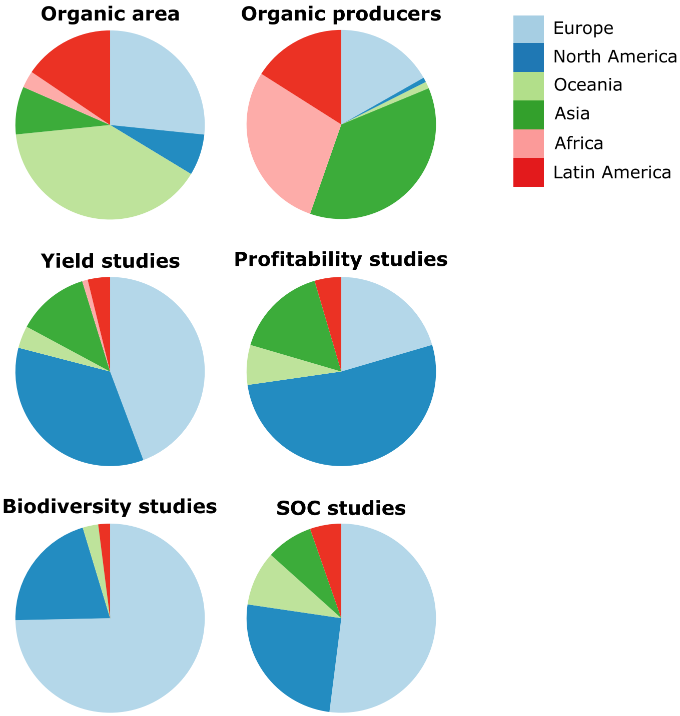

Fig. 2. Regional distribution of organic area, organic producers, as well as studies included in key meta-analyses on organic agriculture. "Organic area" represents data on total organic agricultural area (in hectares) for 2014 (*3*). "Organic producers" represents data for 2013 (*3*). "Yield studies" represents all studies (n = 210) included in the works of Seufert *et al.* (*18*), Ponisio *et al.* (*19*), and de Ponti *et al.* (*20*). "Profitability studies" represents all studies (n = 44) included in the work of Crowder and Reganold (*81*). "Biodiversity studies" represents all studies (n = 150) included in the works of Crowder *et al.* (*30*), Bengtsson *et al.* (*31*), and Tuck *et al.* (*32*). "SOC (soil organic carbon) studies" represents all studies (n = 75) included in the work of Gattinger *et al.* (*39*).

major contributor to climate change. Agricultural GHG emissions from croplands and pasture (excluding livestock systems) are mostly in the form of N_2O emissions from agricultural soils (from fertilizer and manure application and crop residue management), CH_4 emissions from paddy cultivation, and CO_2 emissions through energy use [for example, for fertilizer production and machinery use (*53*)].

Overall, both N_2O and total GHG emissions per unit area appear to be lower under organic management for most crops (Figs. 1 and 3) (*40*, *54*, *55*). Studies of organic performance for CH_4 emissions from rice paddy are limited [the review by Skinner *et al.* (*54*) is based on a single-field study (*56*)]. However, the limited evidence suggests higher CH_4 emissions from organic paddy management (*56*). Organic agriculture generally leads to reduced energy use due to avoidance of synthetic fertilizers (Fig. 1A) (*12*, *40*, *55*). Organic agriculture typically increases soil organic carbon content (*39*), which is often argued to contribute to carbon sequestration (*22*). Because of uncertainties about the ultimate fate of the stored carbon (that is, for how long this sequestration will continue and whether it will be permanent) and the counterfactual (that is, how the carbon inputs would otherwise have been used), the potential for climate change mitigation through carbon storage in agricultural soils is heavily debated (*57*). Therefore, we do not consider soil carbon storage as a climate change mitigation option here.

Because of the importance of land conversion for GHG emissions [that is, deforestation for agriculture represents ~7% of global anthropogenic GHG emissions (*53*)], per unit output impacts are particularly important for climate change mitigation. Evidence on GHG emissions per unit output mostly comes from modeling and life-cycle analysis studies and shows high variability in outcomes (*40*, *55*). N_2O emissions per unit output appear to be higher under organic management because of lower yields (*54*), whereas CH_4 emissions from paddy soils per unit output might be even higher than per unit area (Fig. 1B) (*56*). Energy consumption per unit output tends to remain lower, but with high variability (Fig. 1B) (*12*, *40*, *55*).

Few studies to date have identified contextual factors driving GHG emissions in organic versus conventional systems. Lee *et al.* (*58*) found that the benefit of organic management in terms of energy consumption is lowest for vegetables and fruits, whereas the benefit in terms of GHG emissions was higher in monocropping systems (Table 1).

Water quality

Agriculture is a major threat to water quality, which affects both human water security and freshwater (and marine) biodiversity (*59*). Agricultural management influences water quality through losses of nitrogen (N) and phosphorus (P) (which lead to eutrophication and hypoxia), as well as pesticide leaching, and soil erosion leading to sediment loading (*59*).

The impact of organic management on water quality is one of the environmental dimensions with greatest uncertainty (Figs. 1 and 3). On average, N leaching per unit area in organic agriculture appears to be lower (*40*, *41*), but variation is high (Fig. 3). Some have argued that the variation within organic systems is as high as the difference between organic and conventional systems and that the magnitude of N loss depends more on the specific management practices used (*60*).

Lower N losses from organic systems are typically associated with lower N inputs (*60*) and higher N losses with lower nitrogen use efficiency (NUE) due to the low availability of organic N to crops and asynchronies between crop N demand and N availability from organic sources (*47*, *60*, *61*), as well as the use of cover crops or leys that are not harvested (*62*). However, N application rates and NUEs of organic systems can vary widely (*63*), depending, for example, on whether systems are legume-based or use external organic amendments (such as composts or animal manures) for nutrient management. In addition, organically managed soils often have higher organic matter content (see discussion above), which can lead to higher N holding capacity (*47*, *61*).

Although organic farms typically have positive N budgets because they apply more N than they remove through harvest (*63*, *64*), organic yields are still often N-limited because of the low NUE of organic inputs (*47*, *61*). On average, nitrogen leaching per unit output might therefore be higher in organic systems (Fig. 1B) (*40*, *41*).

The limited number of studies (*40*, *41*, *63*) and the large variation in results do not permit reliable conclusions on P loss from organic versus conventional systems, although we can discuss factors that influence P loss. Because of the low N:P ratios of many organic inputs, organic farmers often overfertilize for P while trying to match crop N requirements (*65*). High-value organic horticultural systems, which often apply large quantities of external organic matter to avoid N limitation, typically have the highest P surplus, whereas organic arable systems, which rely more on BNF (biological N fixation) for N management, often have a P deficit (*63*–*65*). P surpluses in agricultural fields do not necessarily lead to P losses (or P deficits to crop P limitation) because of the high P buffering capacity of many soils and depend on erosion rates and the P solubility in organic amendments (*65*).

Although we have reviewed the impact of organic management on local- and regional-scale N and P loss, it is the amount of new reactive N

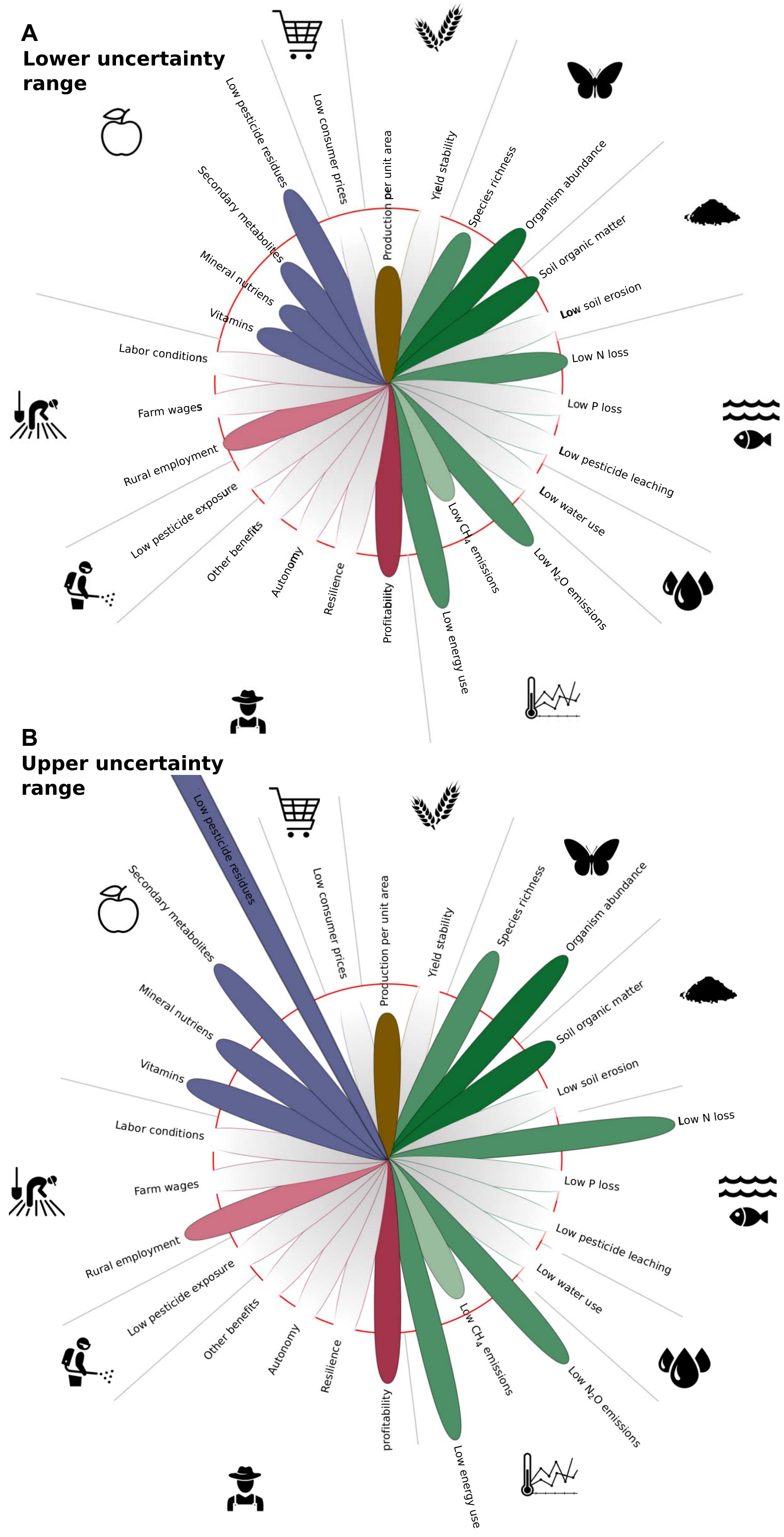

Fig. 3. Uncertainty range around the average (per unit area) performance (depicted in Fig. 1A) of organic agriculture relative to conventional agriculture (indicated by the red circle). (**A**) Lower and (**B**) upper uncertainty range. Figure includes production (brown petals), environmental (green petals), producer (red petals), and consumer (blue petals) benefits (petals that extend beyond the red circle) and costs (petals inside the red circle). See Fig. 1 for details on variables depicted. Shading of petals represents the level of uncertainty for each variable (see Fig. 1 for legend and fig. S6 for details). Variables that could not be quantified are shaded in gray. Upper and lower ranges represent the lowest and highest values (typically low or high confidence intervals), represented as log response ratio (organic/conventional), from different quantitative reviews or meta-analyses (see table S1 for sources and figs. S1, S2, and S5 for values used).

Table 2. Impact of organic management on different production, environmental (per unit area), producer, and consumer variables that could not be quantified (see Fig. 1). The direction of the arrows indicates the direction of impacts (that is, positive, up; negative, down; no change, right; uncertain, up and down). Shading of arrows represents the level of uncertainty for each variable (dark shade, low uncertainty; medium shade, medium uncertainty; light shade, high uncertainty), with uncertainty being determined by the number of primary studies examining each variable and the level of agreement between different studies (see fig. S6 for more details). Some key references supporting the assessment of each effect are indicated.

Dimension	Variable	Direction of impact	References
Yields	Yield stability	↑↓	(*23*–*27*)
Soil quality	Low soil erosion	↑	(*43*–*45*)
Water quality	Low pesticide leaching	↑	(*69*, *70*)
Water quantity	Low water use	↑↓	(*74*, *75*)
Farmer livelihood	Resilience	↑	(*88*)
	Autonomy	↑↓	(*82*, *83*, *87*)
	Other benefits	↑	(*84*, *92*)
Farmer and farm worker health	Low pesticide exposure	↑	(*69*, *70*, *94*, *95*)
Farm worker livelihood	Farm wages	↑↓	(*93*, *96*)
	Labor conditions	→	(*93*, *96*)
Consumer access	Low consumer prices	↓	(*109*, *111*)

(Nr) fixed through human activity and the amount of newly mined P that matter at the global scale. Organic management has a clear advantage in this regard because it more likely relies on recycled N and P inputs (such as composts and animal manure) and less on newly fixed Nr or mined P (*66*).

Many pesticides used in conventional agriculture have negative impacts on nontarget aquatic organisms and can compromise the drinking quality of surface and groundwater supplies (*67*). Although organic management is often assumed to reduce pesticide loads (*4*, *13*), critics argue that some organic pesticides are more hazardous than synthetic pesticides (*7*). The few assessments that were carried out find that organic pesticides typically have lower toxicity (*68*) and often lower persistence in the environment (*69*). However, some organic pesticides, such as sulfur and rotenone, can have a higher total impact because of the higher dosages and the higher frequency of application required, despite lower toxicity quotients (*68*). In practice, however, organic farmers typically use integrated pest management (*69*, *70*) or use pesticides that are less harmful (*71*, *72*). Therefore, it is likely that pesticide leaching from organic agriculture is lower than that from conventional agriculture (Table 2).

Water quantity

Agriculture is the single biggest user of fresh water, and water shortages pose important risks to future food production (*73*). Improving irrigation efficiency and crop water management thus represent key strategies for moving toward sustainable food production.

Water use in organic agriculture has received little attention [(*4*, *13*, *40*), but see related studies (*74*–*76*)]. In general, organic soils show higher water holding capacity and water infiltration rates due to higher organic matter content (*23*, *76*). This can lead to higher yields and water use efficiency under drought and excessive rainfall conditions (*23*) and to lower water limitation of organic yields (*77*). A farm survey in Australia showed considerably lower water use on organic farms, potentially due to higher grazing and cropping densities as well as environmental motivations of farmers (*74*). Wheeler *et al.* (*75*) found similar water use per unit farm area but higher water use per unit output as a result of lower yields on organic farms. In other words, while improved soil quality from organic management provides some advantages for water management, lower organic yields implies unclear impact per unit output. An overall conclusion on the benefits of organic management for water use is not possible. This dimension, which is of considerable importance for the sustainability of agriculture, requires greater attention.

ORGANIC AGRICULTURE AND PRODUCER BENEFITS AND COSTS

Farmer livelihoods

Many farmers across the world have difficulty making a living from agriculture and often rely on off-farm income (*78*, *79*). However, a farmer's livelihood goes beyond the income. We use the sustainable livelihoods framework (*80*) to examine how organic agriculture influences farmer livelihoods through (i) its relative profitability (determined by yields, cost of production, and prices received), (ii) its relative resilience, (iii) the degree to which it gives farmers autonomy, and (iv) its influence on other livelihood benefits (such as access to knowledge, access to credit, access to inputs, or access to markets).

A recent meta-analysis of studies from North America, Europe, and India concluded that organic was more profitable than conventional because of the higher premium prices received (Fig. 1) (*81*). Total management costs were similar; organic had higher labor costs but lower input costs. Income without premium prices was lower under organic management because of lower yields. However, premium prices compensated for lower yields, which are typically higher than needed to match profits from conventional agriculture.

Although organic agriculture might be more profitable, making ends meet might still be challenging (*82*–*85*). Many authors have criticized organic agriculture for mimicking models of conventional industrial production, arguing that small organic and conventional producers face similar challenges (*82*, *85*–*87*).

Organic systems are often thought to have higher socioecological resilience than conventional systems (*88*). Organic systems, which are often diverse mixed farming systems (*89*), can minimize risk by reducing the economic dependence on a single crop. In addition, organic price premiums can sometimes buffer against low prices and price volatility [especially when coupled to Fair Trade certification (*84*, *89*)], and farming systems following agroecological principles have sometimes been shown to provide more stable yields and to be more resilient to extreme weather events (*23*, *90*) (also see previous discussion on yield stability).

Three-quarters of organic farmers are located in low-income countries (Fig. 2), while 96% of organic food sales take place in European and North American markets (*3*). Certified organic agriculture in low-income countries is therefore an export-oriented farming system, typically dependent on exporting companies to access international organic markets and associated premium prices (*84*, *89*). International organic trade has therefore been criticized for reproducing the inequalities of conventional north-south trade by concentrating market power in the hands of transnational organic buyers and certifiers and by imposing additional certification costs on producers (*87*). In high-income countries, instead, organic farmers are often part of alternative (local) food networks and often sell directly to consumers, which typically has positive impacts on farmers' autonomy (*82*, *83*, *91*).

Finally, organic agriculture can provide other livelihood benefits, especially for farmers in low-income countries, such as the organization of farmers in cooperatives, building of social networks, integration of traditional knowledge, providing training, and access to health and credit programs through the certifying and exporting agency (*84*, *92*). Access to such services as well as organization in farmer groups is sometimes considered one of the most important benefits of organic agriculture for smallholder farmers (*92*).

Farmer and farm worker health

Farm work is considered to be one of the most dangerous occupations, and an important reason for this is the exposure to often toxic agrochemicals (*93*). Pesticide poisoning of farm workers and other people handling pesticides causes an estimated 1 million deaths and chronic diseases each year (*67*). Because of the lower use of pesticides in organic agriculture (see discussion under "Water quality"), it is very likely that pesticide exposure is lower on organic farms (Table 2), and this could be one of the most important advantages of organic management for farm workers, particularly in crops (such as fruits and vegetables) with typically high pesticide application rates, as well as in regions with weak pesticide regulations, such as India (Table 1) (*67*). Organic farmers in low-income countries often report reduced health risks from pesticide exposure as one of their key motivations for adopting organic agriculture (*94*, *95*).

Farm worker livelihoods

The social issues concerning farm workers are numerous—both in the Global North, where farm workers are often precariously employed, farm wages are declining, and farm labor is increasingly dependent on migrant workers (*93*), and in the Global South, where farm workers are often among the poorest of society. Organic regulations do not include clear labor guidelines. The limited research on farm worker livelihoods on organic farms suggests that, for the most part, farm workers on organic farms are faced with the same problems as those on conventional farms.

The clearest distinction is that organic management typically requires more labor (*81*, *96*), attributed not only to more labor-intensive management practices (such as preparation of compost or weeding) but also to a higher share of labor-intensive commodities, such as vegetables and fruits, and often smaller farm sizes (*83*, *96*). Although this increases employment opportunities for farm workers (Fig. 1), it can also be an obstacle to adoption of organic farming in regions with labor shortage (*96*). Because of the premium prices received (*81*), some studies have concluded that organic agriculture leads to higher returns on family and hired labor and therefore better remuneration of labor (*96*). However, evidence on the difference in wages of farm workers is anecdotal and highly variable (Table 2).

Labor practices on organic farms vary widely, typically at the discretion of the farmers (*93*), because of the lack of concrete labor guidelines in organic regulations. Large-scale organic agriculture is often criticized for reproducing the inequities of the conventional system (*83*, *93*). However, there is little consistent evidence in high-income countries on differences in labor conditions between organic and conventional farms or between small and large farms; both can entail different types of exploitative labor practices [for example, migrant versus voluntary labor (*82*, *83*, *85*, *93*, *97*)]. In low-income countries, it appears that organic certification mostly provides benefits to farm workers when coupled to Fair Trade certification of smallholder farmers (*98*). Instead, large-scale organic production often does not provide any benefit for farm workers because it is typically not Fair Trade–certified (*98*). However, in general, there are even fewer studies on labor relations in organic agriculture in low-income than in high-income countries.

ORGANIC AGRICULTURE AND CONSUMER BENEFITS AND COSTS

Consumer health

Consumers buy organic food predominantly because of health concerns, to avoid contamination from chemical residues, and because organic food is associated with higher nutritional value (*99*). Accordingly, this topic has received great attention (we identified 22 reviews, including 11 quantitative reviews and meta-analyses), although most of the comparisons included in these quantitative reviews are from Europe (and a few from North America).

The quantitative reviews and meta-analyses greatly disagree; some found a significant difference in nutrient content between organic and conventional crops (*100*–*103*), but others did not (*104*–*106*). These disagreements can be traced to four factors: (i) differences in results for individual food components (see figs. S3 and S4); (ii) whether nutrient content was measured on a dry matter or fresh weight basis [because organic foods are often said to have higher dry matter content, which could lead to a dilution in nutrient contents when measured on a dry matter basis (*100*, *101*)]; (iii) differences in interpretation of similar results [partly due to different grouping of compounds; see, for example, conclusions from Hunter *et al.* (*100*) and Dangour *et al.* (*104*) on mineral nutrient contents]; and (iv) uncertainty in whether an observed difference in composition between organic and conventional food actually provides any health benefits [see, for example, conclusions from Barański *et al.* (*102*) and Smith-Spangler *et al.* (*105*) on the health effect of increased phenolic compound content]. Few studies have examined actual health outcomes of increased consumption of organic foods to date (*105*, *107*). It is important to note that the health benefits of different food components can be highly context-dependent [for example, micronutrient differences may matter more in low-income countries, while in high-income countries, the most important health benefit of plant foods is most likely related to the antioxidant activity of secondary metabolites and vitamins (*101*) (Table 1)].

Overall, average effects across different quantitative reviews and meta-analyses suggest that organic plant foods have higher amounts of secondary metabolites, vitamins, and mineral micronutrients and macronutrients (Fig. 1) but with high uncertainty and disagreement between studies (Fig. 3 and fig. S5). For secondary metabolites, the evidence for higher amounts in organic food is strongest (figs. S3 and S5) and only the oldest and smallest (*104*) of four quantitative reviews and meta-analyses (*101*, *102*, *104*, *105*) did not find an effect. The only entirely unequivocal benefit of organic foods is reduced contamination from pesticide residues (Figs. 1 and 3); although this might not matter for consumers in high-income countries, where pesticide contamination on conventionally grown food is far below acceptable daily intake thresholds (*67*), it could provide an important health benefit for consumers elsewhere.

Consumer access

Organic food typically has a substantial price premium, which benefits producers (*81*), but at the expense of consumers. Higher organic prices are due to limited supply relative to demand (*108*), the need to maintain separate distribution channels (*109*), and lower yields and sometimes higher production costs (*81*). Although direct organic marketing initiatives such as farmers markets and Community Supported Agriculture (CSA) aim to be more accessible to low-income consumers, they usually mostly reach middle-class consumers (*91*). However, some studies suggest that CSA shares in an organic farm can provide considerable cost savings to consumers, even compared to conventional produce (Table 1) (*110*).

A study estimated that the costs of a fully organic diet in the United States would be ~50% higher than a conventional one (*109*). However, organic retail prices vary considerably between stores, years, and products, ranging, for example, from 7% for spinach to 60% for salad in the United States in 2010 (*111*). Data on organic consumer prices for Europe are not available (*108*). It is important to note that breakeven premiums needed to allow organic farmers to match profits of conventional farmers are only 5 to 7% (*81*), and that if the organic sector is to increase further, and distribution costs are lowered, organic consumer prices could potentially decrease considerably. However, to date, no strong decrease in organic consumer prices over time has been observed in European or U.S. markets owing to demand outstripping supply for many products (*108*, *111*).

SCALING UP ORGANIC

So far, we have mostly discussed the impact of organic management on a single field or farm. A system-level transition to organic farming would potentially have different effects from those discussed until now, both due to positive and negative feedbacks. A fair assessment of organic versus conventional farming systems should thus be conducted at the food system level and, for example, consider feedbacks with other sectors (such as the livestock or consumer sectors), issues of nutrient availability, and off-farm impacts (*66*).

Some authors have argued that the yield gap between organic and conventional agriculture would increase if more farms were converted to organic because of problems in nutrient availability (*9*, *20*). Organic agriculture today often relies on nutrient inputs from conventional farms and is highly dependent on the livestock sector (*112*), and it is unclear whether there would be sufficient non-BNF organic nutrient inputs (from animal manure, municipal solid wastes, or crop residues) if organic were to be scaled up (*9*, *20*). Smil (*113*) estimated that, currently, only ~11% of total N inputs to croplands are from animal manure and ~8% are from crop residues, and that crop residues (if left in the field) could supply the equivalent of 30% of current global synthetic N fertilizer. The use of sewage sludge, currently not permitted by most organic regulations, could potentially increase nutrient availability and recycling. However, it is unlikely that global food production could be met only through recycled N because some N losses from the system are inevitable (*114*). Some amount of new N will thus need to be used, either through synthetic fertilizer inputs or through BNF.

Whether sufficient nutrients could be available through BNF is another concern. Many organic systems require long fallow periods and (nonedible) leguminous crops in the rotation to manage soil fertility. This implies that the output of edible calories over the course of an organic rotation might be lower than that in conventional systems (*9*) (although the legumes or leys in organic rotations are often used as fodder for livestock and can thus also contribute to calorie production). Some studies estimate that BNF on cropped land provides about half of the N required to feed the current world population (*113*). Badgley *et al.* (*5*) estimated that BNF through additional leguminous cover crops on current cropped land could replace current synthetic fertilizers, but their analysis was criticized as a gross overestimate (*9*). Whether sufficient organic nutrient sources from recycled N and BNF would be available to grow enough food to feed the global population into the future without requiring considerably more land area remains an important question (*66*).

In addition to the question of whether organic could be scaled up, we also need to consider the question of how scaling up would influence the performance of organic agriculture. Current organic farms are often situated on marginal lands (*21*, *43*, *115*). Adoption of organic management on more fertile lands and more beneficial production climates could potentially increase the productivity of organic farming. In addition, organic agriculture has received limited research to date, and modern crop varieties bred for high-input conventional management often do not perform well under organic management (*116*) because organic crops require different traits (*116*, *117*). It is estimated that 95% of organic production relies on crop varieties bred for conventional systems (*117*). Widespread adoption of organic management could lead to increased research and development of crop varieties adapted to organic management, as well as development of management practices addressing yield-limiting factors [for example, improved organic pest control, which has also received limited attention (*69*), or the use of bioeffectors such as mycorrhiza or rhizobia], and could thus potentially reduce the organic-conventional yield gap. On the other hand, it is argued that organic farms are currently benefitting from pest control on neighboring conventional farms and that pest pressure would increase under more widespread adoption of organic management and thus further reduce yields (*118*). To date there is no theoretical, observational, or experimental evidence to support this hypothesis, and there also could be an opposing effect: Increased crop diversity under organic management could potentially decrease the susceptibility to pest outbreaks, whereas increased biodiversity on organic fields could increase natural pest control.

In terms of environmental impacts, some studies suggest that an increased density of organic farms has strong additional benefits for biodiversity (*119*, *120*) and for some soil quality parameters (*121*). However, others observe no impact of scaled-up organic agriculture on regional biodiversity (*34*). Large-scale adoption of organic agriculture could potentially reduce nutrient losses at the regional or global scale because of its enhanced use of recycled nutrient sources and its increased linkages between crop and animal production systems (*66*).

An important caveat to consider when evaluating whether results from individual studies on organic agriculture can be scaled up is the appropriateness of study design and management practices used in these studies. Most assessments of organic versus conventional agriculture typically only examine a single factor (for example, yields or biodiversity) and over a limited time period. This fails to account for synergies or trade-offs between different outcomes of organic agriculture (for example, between yields and biodiversity), and it also fails to account for long-term consequences (for example, land degradation, water availability, or climate change) that may affect future food production. Better assessments of organic agriculture should conduct multidimensional long-term studies that consider local, regional, and global feedback between different variables (*66*). In addition, the representativeness of management practices used in studies requires attention. Seufert *et al.* (*18*) have shown that relative organic yield performance is higher when best practices (rather than typical practices) are used by both systems, suggesting a stronger dependence of organic agriculture on the use of best practices, probably because it is a more knowledge-intensive system. Although this suggests that there is substantial room for improvement of current organic practices, it also questions how transferable the results of many scientific studies are because farmers usually do not use best practices.

Several modeling studies have simulated scenarios of large-scale conversion to organic agriculture (*122*–*125*). However, their results depend strongly on underlying assumptions, which are based on uncertain empirical evidence (see Figs. 1 and 3). These studies mostly conclude that wholesale conversion to organic would lead to reductions in food production (*122*, *124*, *125*), which would lead to slight increases in food insecurity (*122*), or require changes in diet (*123*, *125*). On the other hand, conversion to organic agriculture would decrease the eutrophication of local waterways (*124*). An important caveat to consider is that most of these modeling studies (*122*, *123*, *125*) do not consider questions of nutrient availability. Given the large uncertainties on many environmental and social dimensions (Fig. 3) and our limited understanding of system-level feedback, potential outcomes of large-scale conversion to organic agriculture are also highly uncertain.

KNOWLEDGE GAPS

Our review of the performance of organic agriculture across multiple dimensions has highlighted substantial knowledge gaps (Fig. 1). Some dimensions have received considerable attention but with no consensus to date [for example, species richness and food quality (lower right quadrant in fig. S6)]. For others, the direction of impact appears to be clear, but better quantification through additional studies is needed [for example, pesticide residues, rural employment, and N_2O emissions per unit area (upper left quadrant in fig. S6)]. Numerous other dimensions have received limited attention [for example, N and P loss and CH_4 emissions (lower left quadrant in fig. S6) or variables that could not be quantified, for example, soil erosion, pesticide leaching, farmer resilience, and farm wages (see Table 2 and Fig. 1)] or no attention at all (for example, calorie production per unit area-time or global Nr creation). For those variables that could not be quantified and included in Fig. 1, some have not yet been examined sufficiently (for example, yield stability, soil erosion, pesticide leaching, water use, farm wages, labor pesticide exposure, and consumer prices), whereas others are difficult to quantify (for example, farmer resilience, farmer autonomy, farmer benefits, and labor conditions). Only for production per unit area, organism abundance, soil organic matter, and profitability there seems to be ample evidence and consensus supported by a sufficiently large number of studies (lower right quadrant in fig. S6).

In addition to specific dimensions that require additional research, there are other knowledge gaps to be addressed. First, more research on organic farming systems in low-income countries is greatly needed; the vast majority have been conducted in North America and Europe (Fig. 2). However, three-quarters of organic producers are located in low-income countries (Fig. 2), and sustainable food security challenges, as well as farm management and socioeconomic and biophysical contexts, differ substantially between low- and high-income countries.

The second knowledge gap deals with the challenge of clearly identifying factors that drive the range of organic performance (Table 1). An improved assessment requires more studies covering a wide range of conditions (for example, different climates or soils, different management practices, farm sizes, and marketing channels) and also primary studies collecting better contextual information (for example, reporting study location and farm characteristics).

Finally, another important knowledge gap is the environmental performance of organic agriculture per unit output (Fig. 1B). This requires environmental scientists studying organic agriculture to measure yields; and agronomists, who typically examine yields alone, to measure environmental variables. These multidimensional studies of organic agriculture (ideally including socioeconomic assessments as well) are particularly important to assess synergies and trade-offs between different production, environmental, and socioeconomic dimensions under different contexts [for example, as highlighted by one of the few biodiversity studies that included an analysis of yields (*35*)].

CONCLUSIONS

Critics and advocates of organic agriculture often seem to describe different realities (*5*, *7*). Although there is some evidence supporting arguments from both sides, neither side is entirely right, and there is great uncertainty in many dimensions. Organic agriculture has some clear benefits and promising characteristics, for example, its positive influence on local biodiversity, high productivity in some circumstances, or a livelihood for poor farmers in some situations. However, many unresolved questions and concerns remain, such as N availability and the total land area required, accessibility, and influence on N losses from the system.

It is also important to point out that the relative performance of organic agriculture compared to conventional agriculture varies considerably and is highly dependent on context and that estimates of the average performance have limited practical use. The studies we reviewed show superior organic performance for yields of forage crops, for biodiversity of plants and pollinators in arable systems and simple landscapes, for water quality in arable systems using low N inputs, for livelihoods of farmers who participate in alternative food networks and who are located in regions with low labor costs, for the health of consumers in regions with micronutrient deficiencies and high pesticide residues on food, and for consumer prices in CSA markets (Table 1). On the other hand, organic agriculture performs less well for yields of cereal crops, for biodiversity of birds in pastures and extensive agricultural regions, for water quality of horticultural systems using organic amendments, for the livelihood of farmers without access to premium prices, and for consumer prices in regular wholesale markets (Table 1). Note that there can also be trade-offs between these contextual factors. For example, yield performance benefits from high N inputs, but water quality does not; similarly, organic horticultural systems show particular benefits for the health of producers due to reduced pesticide exposure, but perform poorly on energy use and N and P loss (Table 1).

The stated goal of organic agriculture is "achieving optimal agroecosystems which are socially, ecologically and economically sustainable" (*126*). Our review highlights potential policy targets to improve organic performance to match this ambitious goal, including (i) targeted research programs to develop new crop varieties for conditions specific to organic management and development of efficient and selective organic pesticides; (ii) an improved focus on environmental best practices in organic regulations; (iii) enhanced research and extension services on organic best practices; (iv) development of domestic organic markets and organic certification, especially in low-income countries; (v) subsidies for organic farmers to alleviate higher production and labor costs during the transition period; (vi) regulation of labor rights; (vii) development of (domestic) Fair Trade labels coupled to organic certification; and (viii) improving accessibility of organic to low-income consumers by lowering organic premiums through farmer or consumer subsidies. Finally, the adoption of organic agriculture could be particularly beneficial under those conditions and contexts where it has been shown to perform well (Table 1).

However, organic agriculture cannot be the Holy Grail for our sustainable food security challenges. First, the outcomes are uncertain (given the ambivalence about the social and environmental benefits of current organic practices). Second, being primarily a production system, organic agriculture has limits in its ability to transform the food system. From an environmental perspective, other changes to the food system (for example, reducing food waste and changes in diet) might have greater benefits (*1*). From an equity perspective, organic agriculture faces similar agricultural labor, farmer livelihood, and consumer access challenges as conventional agriculture, and we require more fundamental changes in the way we produce, distribute, and consume our food to improve these conditions. The question remains on whether organic agriculture, embedded in alternative visions of the food system and conceived as a movement rather than as a production practice, could contribute to a more just food system.

From a broad policy perspective, we conclude that organic agriculture offers many benefits and could be an important part of a suite of strategies to improve the sustainability and equity of our food system. In addition, the influence of organic agriculture extends beyond the ~1% of agricultural land it covers at present. Many conventional farms have, in recent years, increased the use of organic practices such as conservation tillage, cover cropping, or composts (*51*). A further expansion of organic agriculture and integrating successful organic management practices into conventional farming are important next steps.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/3/3/e1602638/DC1

Supplementary Materials and Methods

fig. S1. Impact of organic agriculture on production, farmer livelihood, farm worker livelihood, and consumer access (as depicted in Figs. 1A and 3), as well as water quality and climate change mitigation variables per unit output (as depicted in Fig. 1B), as observed by different meta-analyses and quantitative reviews [that is, de Ponti *et al.* (*20*), Ponisio *et al.* (*19*), Seufert *et al.* (*18*), Crowder and Reganold (*81*), Mondelaers *et al.* (*41*), Tuomisto *et al.* (*40*), Skinner *et al.* (*54*), and Gomiero *et al.* (*12*)].

fig. S2. Impact of organic agriculture on biodiversity, soil quality, water quality, and climate change mitigation variables per unit area (as depicted in Figs. 1A and 3), as observed by different meta-analyses and quantitative reviews [that is, Bengtsson *et al.* (*31*), Crowder *et al.* (*30*), Tuck *et al.* (*32*), Tuomisto *et al.* (*40*), Mondelaers *et al.* (*41*), Gattinger *et al.* (*39*), Skinner *et al.* (*54*), and Gomiero *et al.* (*12*)].

fig. S3. Difference in content of individual secondary metabolites, and vitamin groups in organic versus conventional plant foods, as observed by different meta-analyses and quantitative reviews [that is, Barański *et al.* (*102*), Brandt *et al.* (*101*), Dangour *et al.* (*104*), Hunter *et al.* (*100*), and Worthington (*103*)].

fig. S4. Difference in content of individual mineral micronutrients and macronutrients in organic versus conventional plant foods, as observed by different meta-analyses and quantitative reviews [that is, Barański *et al.* (*102*), Dangour *et al.* (*104*), Hunter *et al.* (*100*), and Worthington (*103*)].

fig. S5. Difference in content of aggregated secondary metabolites, vitamins, mineral micronutrients and macronutrients, and pesticide residues in organic versus conventional plant foods, as observed by different meta-analyses and quantitative reviews [that is, Barański *et al.* (*102*), Brandt *et al.* (*101*), Dangour *et al.* (*104*), Hunter *et al.* (*100*), Smith-Spangler *et al.* (*105*), and Worthington (*103*)].

fig. S6. Uncertainty in different variables (per unit area) on production benefits and costs (brown), environmental benefits and costs (green), producer benefits and costs (red), and consumer benefits and costs (blue), based on quantitative reviews of the organic literature.

table S1. Sources used for variables that could be quantified in Figs. 1 and 3.

table S2. Variables influencing the organic-conventional yield gap according to different meta-analyses [that is, Seufert *et al.* (*18*), de Ponti *et al.* (*20*), and Ponisio *et al.* (*19*)] and large-scale census data analyses [Kniss *et al.* (*21*)].

table S3. Variables influencing the difference in biodiversity between organic and conventional agriculture according to different meta-analyses [that is, Tuck *et al.* (*32*) and Kennedy *et al.* (*33*)] and large-scale primary studies [that is, Schneider *et al.* (*34*)].

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