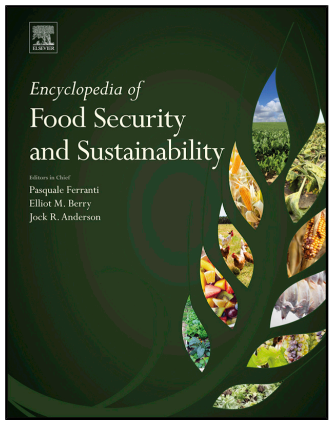

From Seufert, V., 2019. Comparing Yields: Organic Versus Conventional Agriculture. In: Ferranti, P., Berry, E.M., Anderson, J.R. (Eds.), Encyclopedia of Food Security and Sustainability, vol. 3, pp. 196–208. Elsevier.
ISBN: 9780128126875

Comparing Yields: Organic Versus Conventional Agriculture

Verena Seufert, Institute of Meteorology and Climate Research - Atmospheric Environmental Research (IMK-IFU), Karlsruhe Institute of Technology (KIT), Garmisch-Partenkirchen, Germany

Abstract

Yields of organic agriculture have been the center of many debates about the advantages or disadvantages of organic management. Recently, evidence has been accumulating that yields under organic management are, on average, 19%–25% lower than under conventional management. But there remain many open questions, including (1) the factors contributing to low or high yield gaps between organic and conventional agriculture, (2) whether yields on organic farming system trials can be replicated on farmers' fields, (3) the impact of organic management on yield stability, and (3) the comparative yields of organic agriculture at the cropping system level. This chapter provides an overview of the existing evidence on each of these points, while also highlighting important knowledge gaps. In addition, this chapter highlights that - given the limited attention from agricultural research and extension that organic agriculture has received to date - there is ample room to address yield-limiting factors in organic systems and to improve organic yields.

Introduction

In many countries organic agriculture represents one of the fastest growing sectors of the food industry (Willer and Lernoud, 2017), driven by a growing consumer demand for organic food (Seufert et al., 2017). Consumers buy organic food not only for reasons of personal health and taste, as well as animal rights, but also because they believe organic farming to be more sustainable and better for the planet (Yiridoe et al., 2005; Hughner et al., 2007). But some critics argue that organic agriculture may actually not be more sustainable than conventional agriculture, and that it would not be viable if practiced at larger scales (Trewavas, 2001; Connor, 2008, 2013; Kirchmann et al., 2008; Connor and Mínguez, 2012; McGuire, 2017). Many of the criticism of organic agriculture center around its lower productivity (Connor, 2008; Kirchmann et al., 2008). Because organic regulations do not allow the use of chemical fertilizers, chemical pesticides and herbicides, yields under organic management are typically lower than under intensive conventional agriculture (de Ponti et al., 2012; Seufert et al., 2012; Ponisio et al., 2015). But advocates of organic agriculture, on the other hand, argue either that the jury on comparative organic yields in developing countries is still out (Badgley and Perfecto, 2007; Badgley et al., 2007; Chappell et al., 2009), or that yields are not the right metric to assess farming systems by (Loos et al., 2014; Garibaldi et al., 2017). The yields of organic agriculture are thus at the center of the debate about the pros and cons of organic agriculture. In the following I will briefly portray this debate, followed by a review of the evidence on organic crop yields and other measures of productivity, as well as a review of factors limiting organic crop productivity, concluding with some thoughts on the future development of organic yields.

Do Yields Matter?

Crop (and animal) production is the primary reason for which humans manage agroecosystems. Many studies point to the need to greatly increase food production into the future due to a growing human population and shifts to more meat-intensive diets (Kearney, 2010; Tilman et al., 2011; Alexandratos and Bruinsma, 2012). But the need for (and magnitude of) required increases in food production is still debated due to the inefficiencies and inequities in the current system (Smith, 2013; Loos et al., 2014). People on

 https://doi.org/10.1016/B978-0-08-100596-5.22027-1

Encyclopedia of Food Security and Sustainability, 2019, 196–208

the one side of the debate argue that we need to close yield gaps and increase crop production on current agricultural land, to avoid further cropland area expansion and deforestation while providing sufficient food for everyone (Foley et al., 2011; Tilman et al., 2011; Van Ittersum et al., 2013). One the other side of the debate, people argue that we are already producing sufficient food for everyone and that malnutrition and hunger is not caused by a lack of food availability but by problems of distribution and food access (Chappell and LaValle, 2011; Holt-Giménez et al., 2012; Loos et al., 2014), and that if we adopted less meat-intensive diets and reduced food waste, projected increases in food production would not need to happen (Cassidy et al., 2013).

Both sides of this debate have valid arguments, and these arguments do not necessarily exclude each other – we do have enough food for everyone, and we could feed many more people without requiring further increases in food production if we distributed this food more equitably and consumed it more efficiently. But given that we do not live in a perfect world, it is very likely that we will need to increase food production to avoid food shortages in regions with high population growth and to meet growing meat demand. But even independently from this debate about whether we need more food to feed people in the future or not, yields do still matter. Yields do matter not only for farmers, whose incomes directly depend on how much they produce, and who often cite productivity as one of the most important factors guiding their decision-making (Wandel and Smithers, 2000; Schneeberger et al., 2002; Best, 2009) but yields also matter for the sustainability of the food system. Even if we did not have to increase food production, higher yields could still be beneficial for the environment, as we could take land out of production and restore natural ecosystems, which typically are better at delivering ecosystem services than agricultural systems (Foley et al., 2005). The land sharing-land sparing framework has highlighted the important point that productivity of agricultural land matters for the conservation of biodiversity, as it influences the amount of land required to produce a certain food production target, and thus the area that can be 'spared' for conservation purposes (Green et al., 2005). Similarly, the productivity of a farming system matters for other environmental impacts as well - be it for water quality or greenhouse gas emissions. In fact, yields (and per unit output measures of environmental impacts) matter for all those environmental variables that have trade-offs with yields or that perform better in natural ecosystems (Seufert and Ramankutty, 2017). As an example – let's assume that a low-input farming systems has, on average, lower nitrate leaching to waterways than intensive conventional agriculture. But if this low-input system also has lower yields, nitrate leaching per unit product might be higher under low-input than under conventional management. It might thus be more beneficial for water quality to farm a smaller area of land with intensive high-yielding conventional methods, while setting aside some land for water protection (*land sparing*), than it would be to farm the entire area with extensive low-input methods that have lower nitrate leaching, but also lower productivity (*land sharing*).

While yields should never be seen in isolation – as they often have been in the past, when efforts to improve farming systems were often focused solely on yields (e.g. through crop breeding or herbicide development) – yields are still an essential component of the assessment of the social and environmental sustainability of a farming system.

How to Measure Yields

Most assessments of the productivity of agricultural systems focus on efficiency of production (i.e. how much can be produced per unit area of land in a single year) but ignore the resilience of production (i.e. can the same production be achieved over longer time frames). The resilience of food production and stability of yields matters not only for farmer livelihoods (Scott, 1977) but also for food production under a changing climate (Ray et al., 2015). In addition to average yields, yield stability is thus also an important variable to consider.

Another issue when assessing agricultural productivity solely in terms of production of a single crop per unit area is that it often does not do justice to systems with more diverse crop rotations or multi-cropping patterns, where different crops (or animals) are grown within the same season, same year, or between years in the same piece of land. In addition, production per unit area also does not consider the end use of the crops produced, and whether, for example, crop production is used for biofuels or animal feed (Cassidy et al., 2013), or for nitrogen fixation (Connor, 2013). A more holistic assessment of agricultural productivity would therefore examine the food calorie (or energy) output per unit area time.

Evidence on Organic Yields

Crop Yields

Average Organic-Conventional Yield Gap

Until rather recently, claims about the difference between organic and conventional yields ranged widely, for example from −50% (Trewavas, 2001; Kirchmann et al., 2008) to +32% (Badgley et al., 2007). But recently, several large-scale studies have synthesized the scientific knowledge, as well as empirical data on the average organic-conventional yield difference and came to rather similar conclusions (**Figs. 1** and **2**): In scientific studies conducted to date, yields under organic management are, on average, about 19%–25% lower than yields under conventional management (de Ponti et al., 2012; Seufert et al., 2012; Tuomisto et al., 2012; Ponisio et al., 2015). While an analysis of United States (US) census data has shown that on actual farms in the US the yield difference appears to be similar – about −26% across all crops (Kniss, Savage and Jabbour, 2016a).

It is, however, important to point out that this average yield gap masks substantial variability (**Fig. 2**) and that organic yields in individual experiments, or on individual farms, can be up to −100% lower than conventional yields but can also sometimes - i.e. in

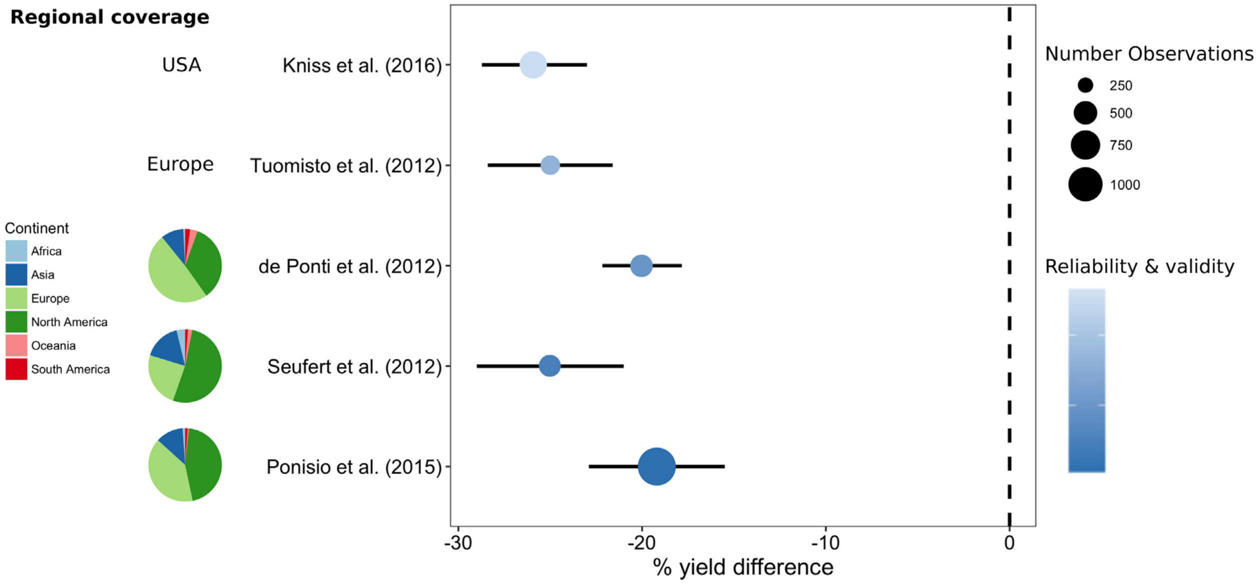

Figure 1 Average yield difference (%) between organic and conventional agriculture, as observed by five large-scale studies (de Ponti et al., 2012; Seufert et al., 2012; Tuomisto et al., 2012; Ponisio et al., 2015; Kniss, Savage and Jabbour, 2016a). Studies are arranged according to their level of reliability and validity – ranging from the Kniss et al. (2016a) study, which is a summary of agricultural census data that, by nature of its design, is poorly controlled and not replicated, to the meta-analysis of Ponisio et al. (2015), which represents a systematic statistical summary of typically well-controlled and replicated experimental data. Both Tuomisto et al. (2012) and de Ponti et al. (2012) represent systematic quantitative summaries of the scientific literature but they do not perform a full meta-analysis (including e.g. weighting of effect sizes according to precision, or assessment of between- and within-study variability) but they simply average values across studies and are thus rated as having lower reliability and validity. While Seufert et al. (2012) is rated as having lower reliability and validity than Ponisio et al. (2015), as it does not control for study- and sampling dependence and thus most likely underestimates the size of confidence intervals (CIs). The size of the dot shows the number of yield comparisons included in each study; the pie charts on the left show the regional distribution of yield comparisons for each study. Error bars represent 95% CIs. Note that for Kniss et al. (2016a) the average yield gap across all crops (and corresponding CIs) were re-calculated using their dataset and the methods described in their paper (i.e. weighted least-squares intercept-only model on the natural logarithm of the crop yield ratio), given that the average yield gap reported in their study appears to be incorrect (Kniss, Savage and Jabbour, 2016b). Data sources: Kniss - own calculations based on data provided in S1 Data; Tuomisto – Table 2; de Ponti – Text, p. 4; Seufert – Text, p. 229; Ponisio – Text, p. 3.

22% of yields observations from Kniss et al. (2016a), 21% from Ponisio et al. (2015), 17% from Seufert et al. (2012) and 12% from de Ponti et al. (2012) - be higher than under conventional management (Fig. 2).

While scientific consensus on the size of the average organic-conventional yield gap is thus emerging, it is important to consider the geographical bias inherent in these studies. The data synthesized in meta-analyses is mostly from North America or Europe (Fig. 1), while countries in Latin America or Asia, which have a lot of organic area or organic producers (Willer and Lernoud, 2017), are strongly underrepresented in scientific studies of organic yields (Seufert and Ramankutty, 2017). To date, not enough well-controlled and well-designed studies comparing organic and conventional yields have been conducted in countries of the Global South to be able to make robust conclusions on the size of the average yield difference between organically and conventionally managed farms in these contexts. Some evidence suggests that yields under organic management can either be higher or lower than conventional systems, depending on whether the conventional systems are low-input or high-input systems (Lyngbaek et al., 2001; Bettiol et al., 2004; Eyhorn et al., 2007; Jimenez et al., 2007; Valkila, 2009; Panneerselvam et al., 2011; Panneerselvam et al., 2012; Forster et al., 2013; Riar et al., 2017). It has also to be kept in mind that organic agriculture in developing countries typically represents an export-oriented farming system (as 96% of organic food is consumed in high-income countries, Willer and Lernoud, 2017), and research on organic crop yields has typically focused on cash crops like cotton (Eyhorn et al., 2007; Panneerselvam et al., 2011; Panneerselvam et al., 2012; Forster et al., 2013; Riar et al., 2017), coffee (Lyngbaek et al., 2001; Valkila, 2009; Haggar et al., 2011), cocoa (Jacobi et al., 2015; Schneider et al., 2017) or bananas (Jimenez et al., 2007).

Context-Dependency of the Organic-Conventional Yield Gap

While studies generally agree about the magnitude of the overall yield gap between organic and conventional agriculture, as well as about the fact that this yield gap varies in different studies and different sites (Fig. 2), there is no scientific consensus to date on what factors are responsible for this variability in the organic-conventional yield gap (Fig. 3; Table 1).

While Seufert et al. (2012), for example, observed a smaller yield gap under best management, higher nitrogen inputs, rainfed conditions, for legumes and perennials, Ponisio et al. (2015) – using a more conservative estimation method – did not observe these same effects (Table 1). Instead, Ponisio et al. (2015) observed that when crop diversification practices were used under organic management but not under conventional management this resulted in lower yield gaps.

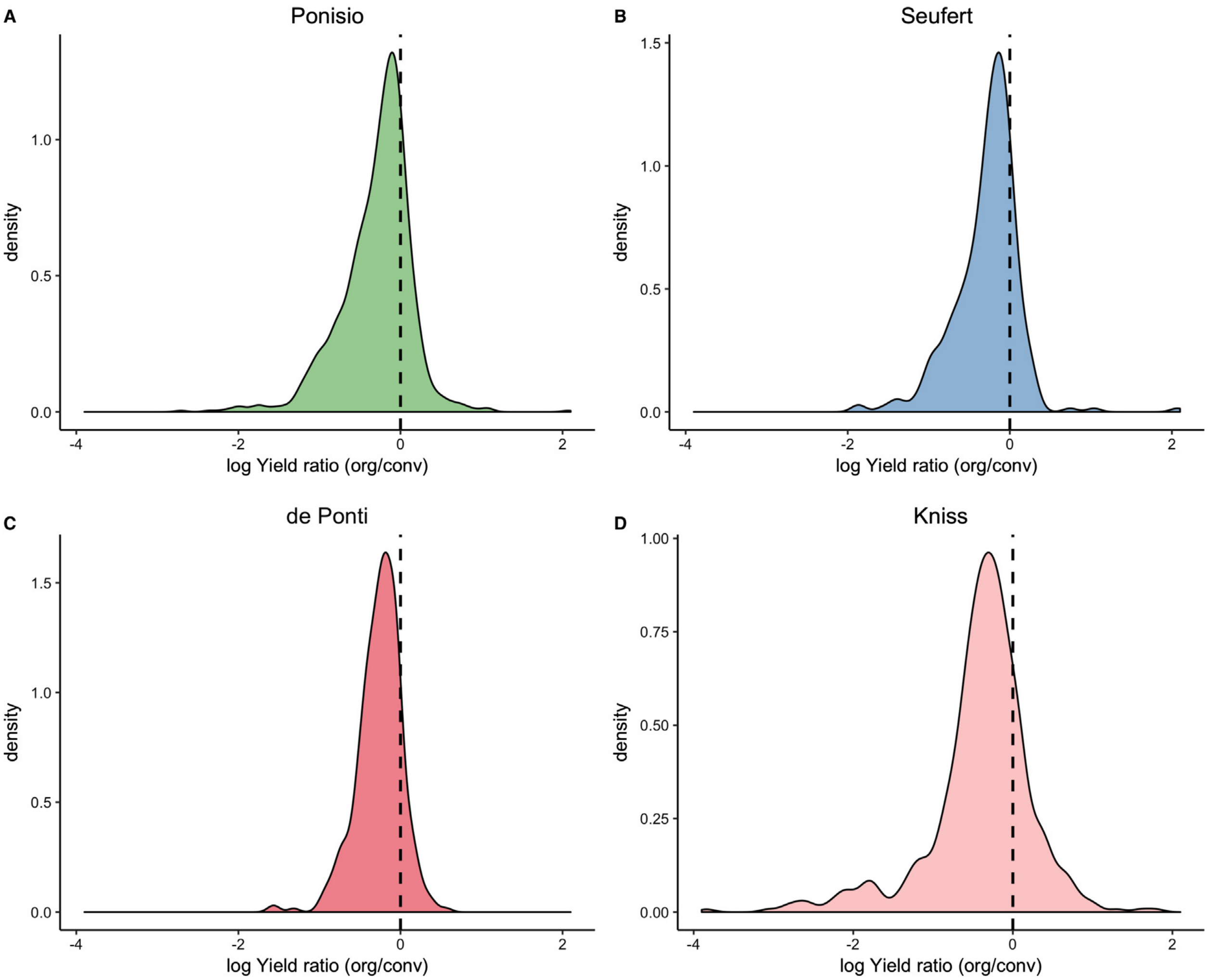

Figure 2 Distribution of yield gap ($\log_e$ $\text{Yields}_{org}/\text{Yields}_{conv}$) across different studies, sites and experiments, as observed by four large-scale studies, including Ponisio et al. (2015), panel (**a**), Seufert et al. (2012), panel (**b**), de Ponti et al. (2012), panel (**c**) and Kniss et al. (2016a), panel (**d**). Dotted line represents no difference.

Similarly, different meta-analyses and analyses of agricultural census data differ in their conclusions on the size of the yield gap between organic and conventional management for different crop types (**Fig. 3**a) or crop species (**Fig. 3**b). But even though the variability between different studies – particularly for some categories like vegetables and fruits – is high, there are still some patterns that remain consistent: Cereals tend to have high yield gaps ranging from −21% to −53% (**Fig. 3**a), particularly wheat and barley (**Fig. 3**b). Soybean, instead, shows a lower yield gap in all studies except the census data analysis from the US (**Fig. 3**b), and potato has a very high yield gap of −30% to −60% across all studies.

The often inconsistent results on explanatory variables influencing the organic-conventional yield gap between different synthesizing studies are probably caused by multiple factors: **(1) Differences in statistical methods used**. For example, while some results between Seufert et al. (2012) and Ponisio et al. (2015) were qualitatively similar (e.g. for perennials/annuals, legumes/non-legumes, irrigated/rainfed, soil pH or some crop types), Ponisio et al. (2015) concluded these were not statistically significant due to more conservative statistical methods. These discrepancies could thus be addressed by increased sample sizes, as well as by more consistent use of best meta-analysis practices (Philibert et al., 2012). **(2) Low sample size**. For example, Seufert et al. (2012) included only 13 and de Ponti et al. (2012) only 25 observations on fruits. **(3) Differences in crop species included in the crop group comparisons**. For example, Ponisio et al. (2015) included tomato in the 'fruit' category, while de Ponti et al. (2012), Seufert et al. (2012) and Kniss et al. (2016a) included tomato in the 'vegetable' category. **(4) Differences in the conventional system organic yields are compared to**. For example, Kniss et al. (2016a) observe much higher yield gaps for maize and soybean than other studies (**Fig. 3**b), which could be due to yields under conventional agriculture for these crops in the US being amongst the highest in the world (Licker et al., 2010). **(5) Differences in management in the organic system**. Numerous primary studies have shown that organic crop yields depend on the type of management practices – e.g. tillage, fertilization, pest control, crop rotation or crop varieties used (Brennan et al., 2009; Bedoussac and Justes, 2010; Mikó et al., 2014; Chen et al., 2018). While

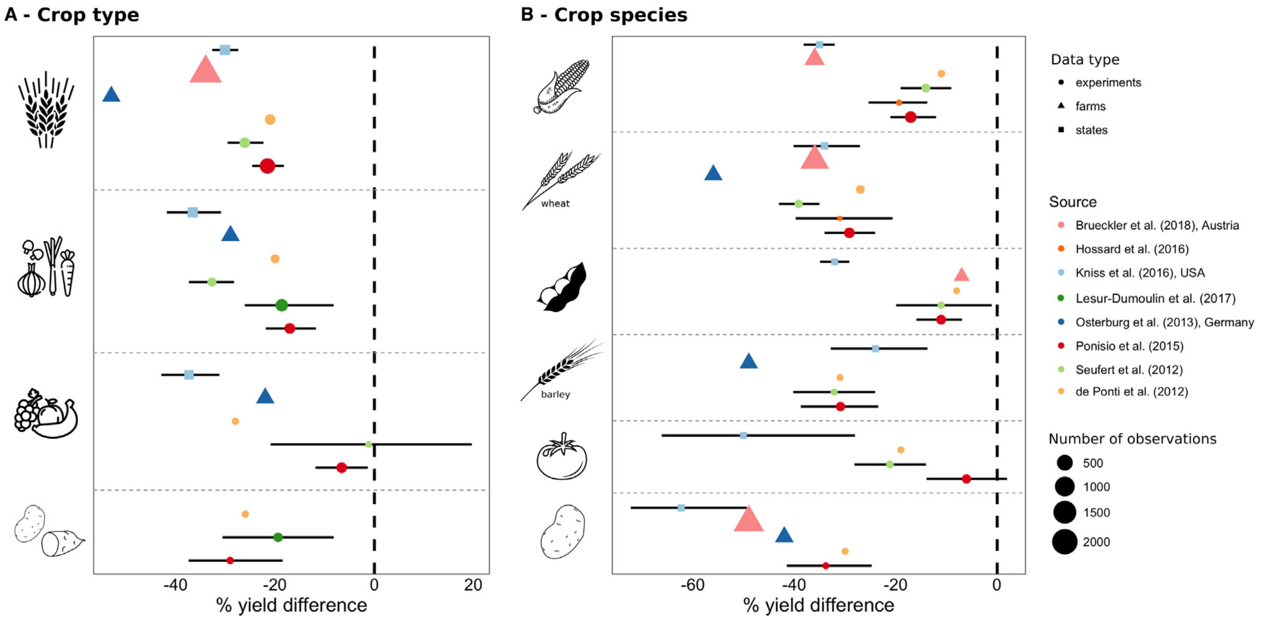

Figure 3 Average yield difference (%) between organic and conventional agriculture for different crop types (panel **a**; i.e. cereals, vegetables, fruits and tubers) and crop species (panel **b**; i.e. maize, wheat, soybean, barley, tomato and potato), as observed by six large-scale studies (de Ponti et al., 2012; Seufert et al., 2012; Osterburg et al., 2013; Ponisio et al., 2015; Hossard et al., 2016; Kniss, Savage and Jabbour, 2016a; Brückler et al., 2017; Lesur-Dumoulin et al., 2017). Most studies included in this comparison represent global quantitative reviews or meta-analyses of the scientific literature, but Kniss et al. (2016a) is a summary of census data from the US, while Brückler et al. (2017) and Osterburg et al. (2013) represent summaries of farm surveys (the European farm accountancy data, FADN) for Austria and Germany, respectively. Note that Hossard et al. (2016) compares organic systems to conventional low-input systems. The size of the dot shows the number of yield comparisons (i.e. nr. of experiments, nr. of farms or nr. of US states) included in each study and crop group. Error bars represent 95% confidence intervals (CIs), where they were available or could be calculated. Data sources: Brückler – Table 1; Hossard – Table 2; Kniss – own calculations based on data provided in S1 Data (for crop groups) and Figs. 1 and 2 (for crop species); Lesur-Dumoulin – Fig. 3; Osterburg – Table A1-1; Ponisio – Fig. 1 (for crop groups) and Fig. S3 (for crop species); Seufert – Fig. 1; de Ponti – Table 1.

some meta-analyses have attempted to examine the influence of some of these practices (Seufert et al., 2012; Ponisio et al., 2015), they were not able to test some other potentially relevant management practices (e.g. pest control, weed control, crop residue or tillage) due to insufficient information reported in primary studies or inconsistent categories. These meta-analyses might thus not have been able to capture the actually important management practices or they might not have been able to analyze the complex interactions between different practices due to small sample sizes. **(6) Differences between sites with different agro-ecological conditions**. The same management practices applied in different locations can lead to very different yield outcomes (Posner et al., 2008a; Doltra et al., 2010). Again, several meta-analyses tried to examine the influence of such site-specific factors (like climate or soil conditions) on the organic-conventional yield gap, but came to differing conclusions (Seufert et al., 2012; Ponisio et al., 2015; Lesur-Dumoulin et al., 2017). This might again be caused either by too small sample sizes, that do not allow the analysis of multiple important factors simultaneously, or by not capturing the actually relevant variables.

There is also some suggestion that data from real-world farm surveys tend to show a higher yield gap than data from meta-analyses (for which the majority of data comes from experimental trials), as seen, for example, for cereals and vegetables (Fig. 3a), as well as for maize, tomato and potato (Fig. 3b). This suggests that farming system trials might not necessarily reflect situations on real world farms, and that commercial organic farmers might have lower yields, or that commercial conventional farmers might have higher yields than on plots in experimental trials managed by scientists. A recent study comparing small-plot experiments with larger-scale field experiments supports the former hypothesis, as it showed that field-scale experiments on commercial fields could not replicate the higher organic yields from small experimental plots, due to the difficulty of applying organic management practices (like mechanical weed control) at larger scales (Kravchenko et al., 2017).

In summary, more scientific evidence needs to be collected to allow generalizable conclusions on factors influencing the size of the organic-conventional yield gap. The challenge here is to isolate important variables amongst a whole range of potential drivers that are often correlated and/or interact with each other. In addition, data from experimental trials should be complemented by census data or farm surveys to examine whether patterns observed in scientific studies are transferrable to real-world farms.

Yield-Limiting Factors

Nutrient Availability

Nitrogen (N) availability is often reported as one of the most important yield-limiting factors in organic systems (Scow et al., 1994; Cavero et al., 1996; Clark et al., 1999a,b; Fortune et al., 2006; Olesen et al., 2007; Forster et al., 2013; Palmer et al.,

Table 1 Variables influencing the organic-conventional yield gap according to different meta-analyses (i.e. de Ponti et al., 2012; Seufert et al., 2012; Ponisio et al., 2015; Lesur-Dumoulin et al., 2017) and large-scale census data analyses (Kniss et al., 2016a)

Variable	*Category*	*Seufert*	*Ponisio*	*Lesur-D*	*de Ponti*	*Kniss*
Plant types						
Plant type	legumes	↑	→	→	/	↑
	non-legumes	→	→	→	/	↓
	perennials	↑	→	→	/	↑
	annuals	→	→	→	/	↓
Management practices						
N input amount	higher org N inputs	↑	↑	/	/	/
	similar N inputs	→	↑	/	/	/
	higher conv N inputs	→	↓	/	/	/
BMP	BMP used	↑	→	/	/	/
Irrigation	rainfed	↑	→	/	/	/
Crop rotation	longer organic rotation	→	↑	/	/	/
/	similar rotation	→	→	/	/	/
	no rotation	↓	→	/	/	/
Multicropping	organic polyculture	→	↑	/	/	/
	both monoculture	→	→	/	/	/
	both polyculture	→	→	/	/	/
Study site characteristics						
Study type	experimental stations	→	→	/	↓	/
Time conversion	>3 years	↑	→	/	/	/
Soil pH	neutral soils	↑	↑	/	/	/
	strong acidic or alkaline	↓	↓	/	/	/
Region	developing	↓	→	/	→	/
	Asia	↓	/	/	↑	/
	Europe	↓	/	/	↓	/

Arrows indicate direction of effect relative to average yield gap (e.g. yield gap for fruits is found to be lower than average yield gap in Seufert et al.). A green arrow indicates a better and an orange arrow a worse performance than the average yield gap, while a blue arrow indicates that the category was not different from the mean effect, or that the variable was found to be not significant. A slash indicates that this category was not assessed. BMP = best management practices.

2013). Nitrogen can either be limiting due to lower N application in organic systems (Clark et al., 1999b), and/or due to lower availability of applied organic N (Scow et al., 1994; Nguyen et al., 1995; Cavero et al., 1996; Palmer et al., 2013). Only a very small portion of the N in organic nutrient inputs like animal manure or crop residues is directly available to crops as mineral N. Most of the N in organic input is in organic form and thus dependent on microbial mineralization to be available for crop growth. Given the dependence of N mineralization on the microbial community, as well as on climate and soil properties, release of N from organic matter is often slow and there is often a time lag between the time when crop nutrient demand is highest, and the time when crop N availability is highest (Pang and Letey, 2000; Berry et al., 2002). Given that the majority of organic farms show an N surplus in farm nutrient budgets (Watson et al., 2002), N limitation of organic crops is in most cases most likely due to asynchrony between crop N demand and crop N availability rather than due to insufficient N inputs (Pang and Letey, 2000; Berry et al., 2002). Some of this asynchrony can be addressed, for example, by increasing N inputs in earlier years to build up the organic pool, and reducing it in subsequent years (Pang and Letey, 2000), by combining slow-release organic inputs like composts or animal manures with high N amendments like fishmeal, blood meal or guano that have higher N availability, or by breeding crop varieties that, for example, have a longer growing period, are better at exploiting limited soil nutrient resources or have improved photosynthetic N use efficiency (Dawson et al., 2008). It is important to point out, though, that at least a part of the N limitation of organic yields can probably still be attributed to overall low N inputs, given, for example, that in 45% of the yield comparisons in the meta-analysis by Ponisio et al. (2015) the organic system received lower N inputs than the conventional system.

Due to an often strong focus on N as a limiting nutrient, organic farms often show imbalances of other nutrients like phosphorus (P), potassium (K) and sulfur (S), resulting both in surpluses as well as deficits of these nutrients at the farm scale (Oehl et al., 2002; Watson et al., 2002; Zikeli et al., 2017). For P, the use of animal manures and composts as N source typically results in P surpluses due to their low N:P ratios, while the use of green manures can result in P deficits (Nelson and Janke, 2007). But P deficits in the farm budget do not necessarily lead to P limitations of yields in the short-term, given the often high soil reserves of P in temperate regions (Oehl et al., 2002; Torstensson et al., 2006; Welsh et al., 2009). It has also been shown that P inputs through organic matter can result in equivalent or even higher P availability than conventional management, as it stimulates soil microbial activity and thus results in higher release of P from soil organic matter (Bhat et al., 2017). A few studies do, however, also show limitations of organic yields by P availability, for example in organic systems with limited use of organic matter inputs in regions with low soil P concentrations like southern Australia (Ryan et al., 2004; Evans et al., 2006), or for high-yielding systems that include crops with high P requirements (Welsh et al., 2009). Similarly, while K budgets on organic farms are sometimes negative (Watson et al., 2002), K only rarely becomes limiting to organic yields, for example on sandy soils with high K leaching rates (Askegaard and Eriksen, 2006; Torstensson et al., 2006).

Overall, N availability still seems to be the primarily limiting nutrient on organic farms. But other nutrients should not be forgotten, especially on farms with negative nutrient budgets that will deplete soil nutrient resources in the long-term.

Weed Control

Weed infestation is often reported as another important (Clark et al., 1999b; Ryan et al., 2004) or even the most important contributor (Penfold et al., 1995; Cavigelli et al., 2008; Posner, Baldock and Hedtcke, 2008b; Delmotte et al., 2011; Schipanski et al., 2014; Teasdale and Cavigelli, 2017) to the organic-conventional yield gap. Meta-analyses of biodiversity in organic versus conventional farms also confirm that plants are the organism group that benefits most from organic farming in arable fields (Tuck et al., 2014) and that densities of weeds are considerably higher in organic compared to conventional agriculture (Bengtsson et al., 2005). But some studies have also shown that nutrient availability might still often be the primarily limiting factor in organic systems, despite higher weed densities under organic management (Benaragama et al., 2016a,b).

High weed pressure can sometimes be addressed through mechanical weed control and tillage (Stonehouse et al., 1996; Schipanski et al., 2014), but cultural and preventative practices, like crop rotations, cover crops, crop choice and managed plant diversity, are essential for sustainable weed management to manage the soil seed bank (Bond and Grundy, 2001; Bàrberi, 2002). It is also important to point out that weeds can have both a positive and a negative role in agroecological systems. While weed competition for nutrient resources can reduce growth of the main crop and weeds can sometimes provide habitat for crop pests, more abundant and diverse weed communities can also contribute to pest control or pollination (Altieri and Letourneau, 1982; Marshall et al., 2003; Capinera, 2005). Higher weed densities do thus not only have negative impacts on yields.

Pest Control

Pest outbreaks (including arthropod and nematode pests, as well as pathogens) are also important yield-limiting factors in some organic systems (Östman et al., 2003), particularly for crops that experience pests for which no adequate organic pest control methods have been developed (e.g. the lack of appropriate fungicides for potato blight, Finckh et al., 2006; Torstensson et al., 2006; Musyoka et al., 2017; Schrama et al., 2018). Meta-analyses have shown that biological pest control and natural enemy abundances are enhanced on organic compared to conventional farms (Crowder et al., 2010; Garratt et al., 2011). But organic pest management practices still seem to be less efficient than conventional pesticides, as pest populations appear to be, on average, higher under organic management, but with high variability (Garratt et al., 2011). But there are also many studies that show similar or lower pest pressures on organic compared to conventional farms (Drinkwater et al., 1995; Phelan et al., 1995; Clark et al., 1998; Gosme et al., 2012; Shrestha et al., 2014; Aviron et al., 2016).

Many studies do, however, suggest pests to only be of secondary importance for organic yields and that nutrient availability or weed abundance are more limiting (Clark et al., 1998; Finckh et al., 2006; Möller et al., 2007; Bouws and Finckh, 2008; Palmer et al., 2013). A review on pest control under organic management has concluded that diseases are generally considered to be more limiting to crop yields than arthropod pests (Zehnder et al., 2007), while a review on disease management under organic agriculture concluded that nutrient availability or weeds might typically be more limiting to organic yields than diseases (van Bruggen and Finckh, 2016). Overall, it thus seems that while pests do contribute to yield reductions on organic fields, other yield-limiting factors are often more important.

Critiques of organic agriculture argue that pests would further limit organic yields if organic was to be scaled up, as organic farms currently benefit from pest suppression of surrounding conventional farms (Avery, 2001). A modelling study supported this hypothesis, but was based on the assumption that organic farms do not carry out any pest control (Adl et al., 2011). But in fact, organic management allows many forms of pest control, including the use of some pesticides (Zehnder et al., 2007) and pest pressures can sometimes be similar or even lower on organic farms (see discussion above). A landscape-scale study in France even suggests that an increased density of organic farms reduces pest pressure on both organic and conventional fields (Gosme et al., 2012), while a meta-analysis on pest populations in organic agriculture has observed that studies carried out at the farm-scale show reduced pest pressure on organic fields compared to field-scale studies (Garratt et al., 2011).

Cultivar Choice

Some estimates suggest that up to 95% of cultivars used in organic management were bred for conventional systems (van Bueren et al., 2011). But conventional cultivars were typically bred under high-input conditions, and aimed at maximizing the use of high N resources under generally non-limiting environmental conditions (Dawson et al., 2008; van Bueren et al., 2011). Conventional cultivars are thus typically not well-adapted to low-input or organic systems. An analysis of the performance of wheat varieties of different release dates showed, for example, that older cultivars performed relatively better under organic management than more modern cultivars (Jones et al., 2010). This suggests that modern breeding results in varieties that are not well-adapted to organic systems, as they have improved ability of utilizing mineral N resources, but are less good at utilizing soil N resources (Foulkes et al., 1998). While comparisons of organic and conventional wheat varieties have shown that varieties bred under organic management performed substantially better under organic agriculture (Murphy et al., 2007; Mikó et al., 2014).

It is difficult to quantify the impact of cultivar choice on the yield gap between organic and conventional farming systems. Long-term farming system comparisons typically use modern conventional crop cultivars and do not include cultivar choice in an analysis of yield-limiting factors. But it is quite likely that the yield potential in organic systems is limited substantially by the lack of targeted breeding programs for organic cropping systems (Murphy et al., 2007; Dawson et al., 2008; Wolfe et al., 2008; van Bueren et al., 2011).

Water Limitation

While conventional yields are often limited by water availability, as they receive sufficient nutrient inputs, pest and weed control in high-input systems (Kravchenko et al., 2005; Teasdale and Cavigelli, 2017), organic yields are typically limited by other factors than water, and thus do not respond as much to additional irrigation or precipitation (Kravchenko et al., 2017).

Yield Stability

Evidence on the average organic yield gap has grown substantially in recent years, but there are still very few analyses of organic versus conventional temporal yield variability or stability (Seufert and Ramankutty, 2017). A recent meta-analysis examined temporal yield stability in horticultural crops, and found no difference between organic and conventional management (Lesur-Dumoulin et al., 2017). A (non-exhaustive) overview of studies that have quantified yield stability in organic versus conventional systems shows that yield stability typically does not differ, or is lower under organic management (**Table 2**). There are only few studies that report higher yield stability for some organic crops like maize and spelt (Smith and Gross, 2006; Brückler et al., 2017; Schrama et al., 2018). Even fewer studies have examined spatial variability within organic versus conventional fields, but the ones who did, found that organically managed fields showed higher spatial variability than conventional ones, due to higher variability in N and water availability within fields (Kravchenko et al., 2005).

An important shortcoming of most of the studies that have examined yield stability is that they use potentially problematic measures for yield stability. The only meta-analysis that has quantified yield variability to date (Lesur-Dumoulin et al., 2017), concluded that temporal yield stability between organic and conventional management did not differ in horticultural crops, based on an analysis of standard deviation (SD) and variance. But given that according to the Taylor-Power Law (TPL) the mean is linearly correlated with variance or SD and given that yields often follow the TPL (Döring et al., 2015), this lack of difference between variances of organic and conventional yields, might mean that organic crops – which have lower mean yields - have still higher variability (and thus lower stability) relative to their means. Other studies use the Coefficient of Variation (CV) to quantify yield variability (**Table 2**). And while the CV is a better measure than SD or variance, it can still be misleading, as it often changes non-linearly with mean yields and is typically smaller at high yield levels and thus overcompensates the scaling of the mean (Döring et al., 2015). As a consequence, the stability of high conventional yields might be over-estimated when using the CV.

While some evidence suggests that organic yields are – on average – less stable than conventional yields, the final verdict on this question is still out. More studies are needed that systematically compare temporal and spatial yield variability in organic versus conventional systems using more appropriate measures of yield stability.

Cropping System Yields

There are two arguments that support the need for examining cropping system yields at farm or even larger regional and global scales when comparing organic and conventional agriculture – one favoring the productivity of organic agriculture, the other disfavoring organic agriculture: On the one hand, organic farming systems often rely on principles of cropping system diversification and thus often include a larger variety of different crop or food outputs, which might reduce productivity of a single crop species, but can lead to overall higher cropping system yields (Davis et al., 2012; Schneider et al., 2017). On the other hand, organic farming systems often depend on leguminous crops to fix N, and thus often have longer crop rotation time shares with leguminous crops that do not directly contribute to food production (Barbieri et al., 2017), or they include longer fallow periods or break crops to reduce pest or weed pressure and restore soil fertility (Robson et al., 2002). In addition, organic systems currently often rely on nutrient inputs from conventional systems (Nowak et al., 2013), and it is thus important to consider the additional land area required for N fixation if organic agriculture was to be scaled up (Connor, 2008, 2013; de Ponti et al., 2012). While the inclusion of multiple types of crops could thus increase organic cropping system productivity per unit area time, the inclusion of non-food crops in the rotation for N fixation or other purposes could decrease organic cropping system productivity per unit area time relative to conventional agriculture.

To date, almost no studies have examined the question of the productivity of organic versus conventional systems at the cropping system level. Regarding the productivity of multicropping systems like agroforestry, Schneider et al. (2017) has shown that yields of individual agroforestry crops, like cocoa, are lower under organic management, but that total system yields in these systems (including e.g. the production of plantain, banana, diverse fruits and tubers) is equivalent or even higher than under

Table 2 Overview of studies that quantified temporal yield variability in organic versus conventional farming systems, showing whether the study concluded higher yield stability (green arrow), lower yield stability (orange arrow) or similar yield stability (blue arrow) between organic and conventional yields, as well as the type of yield stability measure used (CV is coefficient of variation; SD is standard deviation or variance)

	Study location	*Crop*	*Stability*	*Measure*	*Study type*
Schrama et al. (2018)	Netherlands	barley	→	CV	experiment
Brückler et al. (2017)[a]	Austria	barley	↓	CV	farm survey
Schrama et al. (2018)	Netherlands	maize	↑	CV	experiment
Smith and Gross (2006)	Michigan, US	maize	↑	CV	experiment
Smith et al. (2007)	Michigan, US	maize	→	CV	experiment
Clark et al. (1999a,b)	California, US	maize	↓	CV	experiment
Posner et al. (2005)	Wisconsin, US	maize	→	SD; CV	experiment
Brückler et al. (2017)[a]	Austria	maize	↓	CV	farm survey
Smith et al. (2007)	Michigan, US	wheat	↓	CV	experiment
Jones et al. (2010)	UK	wheat	→	variance component analysis	experiment
Posner et al. (2005)	Wisconsin, US	wheat	→	SD; CV	experiment
Brückler et al. (2017)[a]	Austria	wheat	↓	CV	farm survey
Brückler et al. (2017)[a]	Austria	spelt	↑	CV	farm survey
Brückler et al. (2017)[a]	Austria	triticale	↓	CV	farm survey
Brückler et al. (2017)[a]	Austria	rye	↓	CV	farm survey
Brückler et al. (2017)[a]	Austria	oat	↓	CV	farm survey
Delmotte et al. (2011)	France	rice	↓	regression tree analysis	farm survey
Smith et al. (2007)	Michigan, US	soybean	↓	CV	experiment
Posner et al. (2005)	Wisconsin, US	soybean	→	SD; CV	experiment
Brückler et al. (2017)[a]	Austria	soybean	↓	CV	farm survey
Clark et al. (1999a,b)	California, US	common bean	→	CV	experiment
Brückler et al. (2017)[a]	Austria	faba beans	↓	CV	farm survey
Brückler et al. (2017)[a]	Austria	field peas	↓	CV	farm survey
Schrama et al. (2018)	Netherlands	peas	→	CV	experiment
Schrama et al. (2018)	Netherlands	potato	→	CV	experiment
Brückler et al. (2017)[a]	Austria	potato	→	CV	farm survey
Posner et al. (2005)	Wisconsin, US	alfalfa	↓	SD; CV	experiment
Clark et al. (1999a,b)	California, US	safflower	→	CV	experiment
Lesur-Dumoulin et al. (2017)	global	horticulture	→	SD	meta-analysis
Schrama et al. (2018)	Netherlands	leek	→	CV	experiment
Brückler et al. (2017)[a]	Austria	pumpkin	→	CV	farm survey
Clark et al. (1999a,b)	California, US	tomato	→	CV	experiment

[a]Brückler et al. (2017) did not assess temporal yield variability in a single farm/field, but quantified yield variability across farms and years across administrative units.

conventional monoculture. But few other studies have compared long-term cropping system yields across crop species and across entire crop rotations between organic and conventional systems (Seufert and Ramankutty, 2017). Regarding the additional need for N-fixation in organic crop rotations, Badgley et al. (2007) provided an estimate of the additional N-fixing capacity through leguminous cover crops on existing agricultural land and concluded that leguminous cover crops (which would not require additional land area as they are grown between two cash crops) could fix enough N to replace synthetic fertilizers. But their estimate was criticized as a gross over-estimate as it did not account for already existing cover crops nor for climatic limitations to cover crop cultivation (Connor, 2008). Muller et al. (2017) estimated global crop production under a scenario of full conversion to organic agriculture, while accounting for questions of N availability, and concluded that – without accounting for the impact of climate change on crop yields - a fully organic world would require 33% more land area to grow the same amount of food but this would still result in an N deficit of 3 kg/ha. It is, however, important to note that the study by Muller et al. (2017) did not provide a full estimate of all potential N sources for organic management, as it only included additional N inputs from additional biological N fixation in organic crop rotations in a very simplified manner, but it did not account for potential N inputs from additional leguminous cover crops, additional use of animal manure or food waste and composts. This study thus also did not fully answer the question of N availability for large-scale organic management and we thus do not yet know how much additional land area would be required to provide adequate N inputs for organic management at the cropping system level.

Future Development of Organic Yields

While organic yields on individual farms often increase with time due to improvements in soil fertility and farmer knowledge (Martini et al., 2004; Schrama et al., 2018), some evidence suggests that the organic-conventional yield gap has grown over time, as conventional yields increased faster than organic yields in the last 20–40 years (Kirchmann et al., 2008; Mayer and Mäder, 2016). This increase in the organic yield gap over time observed in long-term farming system trials (i.e. in three Swedish long-term experiments, Kirchmann et al., 2008; as well as the DOK trial in Switzerland, the WICTS in Wisconsin, US and the LTRAS trial in California, US, Mayer and Mäder, 2016) suggests that conventional agriculture benefitted more from agricultural research and extension than organic agriculture and that even researchers on experimental farms were not able to address yield-limiting problems under organic management as well as they did under conventional management. This would not be surprising, given that organic agriculture has to date only received a small fraction of the research investment received by conventional agriculture. In many countries, the share of agricultural research invested in organic research has been even less than the share of agricultural land managed with organic methods: In the US, for example, research on organic agriculture made up less than 0.1% of the US Department of Agriculture (USDA) research budget in 1995 (Lipson, 1997), and only 0.02% of all research done through the land grant system in 2000–1 (Sooby, 2001), while its market share had reached 1% by 2000 (Willer and Yussefi, 2000). In Europe, instead, research on organic agriculture made up, for example, 0.05% of the budget of all research on agriculture, fisheries and forestry in Framework Programme 5 between 1998–2002 (Schmid et al., 2008), while the market share of organic agriculture was ca. 1.5% in 1997 (Willer and Yussefi, 2000). It is thus safe to state that organic yield management still has huge potential for improvement if organic research is expanded and key knowledge gaps are addressed (Seufert and Ramankutty, 2017).

To improve organic yields there are three priority research needs: (1) address N availability challenges under organic management, (2) develop sustainable weed management practices for organic agriculture, and (3) develop crop varieties that are better adapted to organic management systems. While trying to improve organic yields, it is, however, very important to not only focus on the single dimension of yield but to also consider how practices aimed at yield improvement influence other ecosystem services like water quality and pollination and to aim for yield-improving methods that have minimal trade-offs with other farming system outcomes (Röös et al., 2018). In addition, yield assessments should go beyond the often simplistic measurement of yield in terms of dry products produced per unit area per year, but also consider yield stability and also quantify cropping system productivity in terms of calories or food energy produced across longer time periods and across the entire cropping system (including land area required to produce nutrient inputs). Finally, when doing research on organic yields it is essential to work closely with organic farmers, to identify factors that are limiting yields on real-world organic farms and to ensure that results from experimental research stations are relevant to the practice of organic farmers.

References

Adl, S., Iron, D., Kolokolnikov, T., 2011. A threshold area ratio of organic to conventional agriculture causes recurrent pathogen outbreaks in organic agriculture. Elsevier Sci. Total Environ. 409 (11), 2192–2197. https://doi.org/10.1016/J.SCITOTENV.2011.02.026.

Alexandratos, N., Bruinsma, J., 2012. World Agriculture towards 2030/2050: The 2012 Revision, ESA Working Paper. FAO.

Altieri, M.A., Letourneau, D.K., 1982. Vegetation management and biological control in agroecosystems. Elsevier Crop Prot. 1 (4), 405–430. https://doi.org/10.1016/0261-2194(82)90023-0.

Askegaard, M., Eriksen, J., 2006. Potassium retention and leaching in an organic crop rotation on loamy sand as affected by contrasting potassium budgets. Wiley/Blackwell (10.1111). Soil Use Manag. 16 (3), 200–205. https://doi.org/10.1111/j.1475-2743.2000.tb00193.x.

Avery, A.A., 2001. Nature's Toxic Tools: The Organic Myth of Pesticide-free Farming. Center for Global Food Issues, Churchville.

Aviron, S., et al., 2016. Local landscape heterogeneity affects crop colonization by natural enemies of pests in protected horticultural cropping systems. Elsevier Agric. Ecosyst. Environ. 227, 1–10. https://doi.org/10.1016/J.AGEE.2016.04.013.

Badgley, C., Moghtader, J., Quintero, E., Zakem, E., Chappell, M.J., et al., 2007. Organic agriculture and the global food supply. Renew. Agric. Food Syst. 22 (2), 86–108. https://doi.org/10.1017/s1742170507001640.

Badgley, C., Perfecto, I., 2007. Can organic agriculture feed the world? Renew. Agric. Food Syst. 22 (2), 80–82. https://doi.org/10.1017/s1742170507001871.

Bàrberi, P., 2002. Weed management in organic agriculture: are we addressing the right issues? Weed Res. 42 (3), 177–193.

Barbieri, P., Pellerin, S., Nesme, T., 2017. Comparing crop rotations between organic and conventional farming. Nature Publishing Group Sci. Rep. 7 (1), 13761. https://doi.org/10.1038/s41598-017-14271-6.

Bedoussac, L., Justes, E., 2010. The efficiency of a durum wheat-winter pea intercrop to improve yield and wheat grain protein concentration depends on N availability during early growth. Springer Netherlands Plant Soil 330 (1–2), 19–35. https://doi.org/10.1007/s11104-009-0082-2.

Benaragama, D., Shirtliffe, S.J., et al., 2016a. Does yield loss due to weed competition differ between organic and conventional cropping systems? Edited by H. Albrecht. Wiley/Blackwell (10.1111). Weed Res. 56 (4), 274–283. https://doi.org/10.1111/wre.12213.

Benaragama, D., Shirtliffe, S.J., et al., 2016b. Long-term weed dynamics and crop yields under diverse crop rotations in organic and conventional cropping systems in the Canadian prairies. Elsevier Field Crops Res. 196, 357–367. https://doi.org/10.1016/J.FCR.2016.07.010.

Bengtsson, J., Ahnström, J., Weibull, A.-C., 2005. The effects of organic agriculture on biodiversity and abundance: a meta-analysis. J. Appl. Ecol. 42 (2), 261–269. https://doi.org/10.1111/j.1365-2664.2005.01005.x.

Berry, P.M., et al., 2002. Is the productivity of organic farms restricted by the supply of available nitrogen? Soil Use Manag. 18, 248–255.

Best, H., 2009. Organic farming as a rational choice empirical investigations in environmental decision making. Ration. Soc. 21 (2), 197–224.

Bettiol, W., et al., 2004. Organic and conventional tomato cropping systems. Sci. Agric. 61 (3), 253–259.

Bhat, N.A., et al., 2017. Soil biological activity contributing to phosphorus availability in vertisols under long-term organic and conventional agricultural management. Frontiers Front. Plant Sci. 8, 1523. https://doi.org/10.3389/fpls.2017.01523.

Bond, W., Grundy, A.C., 2001. Non-chemical weed management in organic farming systems. Wiley/Blackwell (10.1111). Weed Res. 383–405. https://doi.org/10.1046/j.1365-3180.2001.00246.x.

Bouws, H., Finckh, M.R., 2008. Effects of strip intercropping of potatoes with non-hosts on late blight severity and tuber yield in organic production. Wiley/Blackwell (10.1111). Plant Pathol. 57 (5), 916–927. https://doi.org/10.1111/j.1365-3059.2008.01860.x.
Brennan, E.B., et al., 2009. Seeding rate and planting arrangement effects on growth and weed suppression of a legume-oat cover crop for organic vegetable systems. Agron. J. 101 (4), 979–988.
Brückler, M., Resl, T., Reindl, A., 2017. Comparison of organic and conventional crop yields in Austria. Die Bodenkultur J. Land Manag. Food Environ. 68 (4), 223–236. https://doi.org/10.1515/boku-2017-0018.
van Bruggen, A.H.C., Finckh, M.R., 2016. Plant diseases and management approaches in organic farming systems. Annu. Rev. Phytopathology 54 (1), 25–54. https://doi.org/10.1146/annurev-phyto-080615-100123.
van Bueren, E.T.L., et al., 2011. The need to breed crop varieties suitable for organic farming, using wheat, tomato and broccoli as examples: a review. NJAS-Wageningen J. Life Sci. 58 (3), 193–205.
Capinera, J.L., 2005. Relationships between insect pests and weeds: an evolutionary perspective. Weed Sci. 53 (6), 892–901. https://doi.org/10.1614/WS-04-049R.1.
Cassidy, E.S., et al., 2013. Redefining agricultural yields: from tonnes to people nourished per hectare. Environ. Res. Lett. 8 (3), 34015.
Cavero, J., et al., 1996. The effect of nitrogen source and crop rotation on the growth and yield of processing tomatoes. Nutrient Cycl. Agroecosyst. 47 (3), 271–282.
Cavigelli, M.A., Teasdale, J.R., Conklin, A.E., 2008. Long-term agronomic performance of organic and conventional field crops in the mid-atlantic region. Agron. J. 100 (3), 785. https://doi.org/10.2134/agronj2006.0373.
Chappell, M.J., et al., 2009. Wildlife-friendly farming vs land sparing. Front. Ecol. Environ. 7 (4), 183–184.
Chappell, M.J., LaValle, L.A., 2011. Food security and biodiversity: can we have both? An agroecological analysis. Springer Netherlands Agric. Hum. Values 28 (1), 3–26. https://doi.org/10.1007/s10460-009-9251-4.
Chen, G., et al., 2018. Can conservation tillage reduce N_2O emissions on cropland transitioning to organic vegetable production? Elsevier Sci. Total Environ. 618, 927–940. https://doi.org/10.1016/J.SCITOTENV.2017.08.296.
Clark, M.S., et al., 1998. Agronomic, economic, and environmental comparison of pest management in conventional and alternative tomato and corn systems in northern California. Agric. Ecosyst. Environ. 68 (1), 51–71.
Clark, S., Klonsky, K., et al., 1999b. Crop-yield and economic comparisons of organic, low-input, and conventional farming systems in Californias Sacramento Valley. Am. J. Altern. Agric. 14 (3), 109–121.
Clark, S., Horwath, W.R., et al., 1999a. Nitrogen, weeds and water as yield-limiting factors in conventional, low-input, and organic tomato systems. Agric. Ecosyst. Environ. 73 (3), 257–270.
Connor, D., 2008. Organic agriculture cannot feed the world. Field Crops Res. 106 (2), 187–190. https://doi.org/10.1016/j.fcr.2007.11.010.
Connor, D.J., 2013. Organically grown crops do not a cropping system make and nor can organic agriculture nearly feed the world. Field Crops Res. 144, 145–147.
Connor, D.J., Mínguez, M.I., 2012. Evolution not revolution of farming systems will best feed and green the world. Glob. Food Secur. 1 (2), 106–113.
Crowder, D.W., et al., 2010. Organic agriculture promotes evenness and natural pest control. Nature Publishing Group Nature 466 (7302), 109–112. https://doi.org/10.1038/nature09183.
Davis, A.S., et al., 2012. Increasing cropping system diversity balances productivity, profitability and environmental health. Edited by J. P. Hart. Public Library of Science PLoS One 7 (10), e47149. https://doi.org/10.1371/journal.pone.0047149.
Dawson, J.C., Huggins, D.R., Jones, S.S., 2008. Characterizing nitrogen use efficiency in natural and agricultural ecosystems to improve the performance of cereal crops in low-input and organic agricultural systems. Elsevier Field Crops Res. 107 (2), 89–101. https://doi.org/10.1016/J.FCR.2008.01.001.
Delmotte, S., et al., 2011. On farm assessment of rice yield variability and productivity gaps between organic and conventional cropping systems under Mediterranean climate. Eur. J. Agron. 35 (4), 223–236.
Doltra, J., Lægdsmand, M., Olesen, J.E., 2010. Cereal yield and quality as affected by nitrogen availability in organic and conventional arable crop rotations: a combined modeling and experimental approach. Eur. J. Agron. 34, 83–95.
Döring, T.F., Knapp, S., Cohen, J.E., 2015. Taylors power law and the stability of crop yields. Elsevier Field Crops Res. 183, 294–302. https://doi.org/10.1016/J.FCR.2015.08.005.
Drinkwater, L.E., et al., 1995. Fundamental differences between conventional and organic tomato agroecosystems in California. Ecol. Appl. 5 (4), 1098–1112.
Evans, J., McDonald, L., Price, A., 2006. Application of reactive phosphate rock and sulphur fertilisers to enhance the availability of soil phosphate in organic farming. Kluwer Academic Publishers Nutrient Cycl. Agroecosyst. 75 (1–3), 233–246. https://doi.org/10.1007/s10705-006-9030-1.
Eyhorn, F., Ramakrishnan, M., Mäder, P., 2007. The viability of cotton-based organic farming systems in India. Int. J. Agric. Sustain. 5 (1), 25–38.
Finckh, M.R., Schulte-Geldermann, E., Bruns, C., 2006. Challenges to organic potato farming: disease and nutrient management. Springer Netherlands Potato Res. 49 (1), 27–42. https://doi.org/10.1007/s11540-006-9004-3.
Foley, J.A., et al., 2005. Global consequences of land use. American Association for the Advancement of Science Science 309 (5734), 570. https://doi.org/10.1126/science.1111772.
Foley, J.A., et al., 2011. Solutions for a cultivated planet. Nature 478 (7369), 337–342.
Forster, D., et al., 2013. Yield and economic performance of organic and conventional cotton-based farming systems–results from a field trial in India. PLoS One 8 (12), e81039.
Fortune, S., Hollies, J., Stockdale, E.A., 2006. Effects of different potassium fertilizers suitable for use in organic farming systems on grass/clover yields and nutrient offtakes and interactions with nitrogen supply. Wiley/Blackwell (10.1111). Soil Use Manag. 20 (4), 403–409. https://doi.org/10.1111/j.1475-2743.2004.tb00389.x.
Foulkes, M.J., Sylvester-Bradley, R., Scott, R.K., 1998. Evidence for differences between winter wheat cultivars in acquisition of soil mineral nitrogen and uptake and utilization of applied fertilizer nitrogen. Cambridge University Press J. Agric. Sci. 130 (1), 29–44.
Garibaldi, L.A., et al., 2017. Farming approaches for greater biodiversity, livelihoods, and food security. Elsevier Current Trends Trends Ecol. Evol. 32 (1), 68–80. https://doi.org/10.1016/J.TREE.2016.10.001.
Garratt, M.P.D., Wright, D.J., Leather, S.R., 2011. The effects of farming system and fertilisers on pests and natural enemies: a synthesis of current research. Elsevier Agric. Ecosyst. Environ. 141 (3–4), 261–270. https://doi.org/10.1016/J.AGEE.2011.03.014.
Gosme, M., et al., 2012. Local and neighbourhood effects of organic and conventional wheat management on aphids, weeds, and foliar diseases. Agric. Ecosyst. Environ. 161, 121–129.
Green, R.E., et al., 2005. Farming and the fate of wild nature. Science 307 (5709), 550–555. https://doi.org/10.1126/science.1106049.
Haggar, J., et al., 2011. Coffee agroecosystem performance under full sun, shade, conventional and organic management regimes in Central America. Springer Netherlands Agrofor. Syst. 82 (3), 285–301. https://doi.org/10.1007/s10457-011-9392-5.
Holt-Giménez, E., et al., 2012. We already grow enough food for 10 billion people… and still cant end hunger. J. Sustain. Agric. 36 (6), 595–598.
Hossard, L., et al., 2016. A meta-analysis of maize and wheat yields in low-input vs. Conventional and organic systems. The American Society of Agronomy, Inc. Agron. J. 108 (3), 1155. https://doi.org/10.2134/agronj2015.0512.
Hughner, R.S., et al., 2007. Who are organic food consumers? A compilation and review of why people purchase organic food. J. Consumer Behav. 6 (2,Äê3), 94–110.
Van Ittersum, M.K., et al., 2013. Yield gap analysis with local to global relevance—a review. Elsevier Field Crops Res. 143, 4–17. https://doi.org/10.1016/J.FCR.2012.09.009.
Jacobi, J., et al., 2015. Farm resilience in organic and non-organic cocoa farming systems in Alto Beni, Bolivia. Agroecol. Sustain. Food Syst. 39 (7), 798–823.
Jimenez, M., et al., 2007. Organic banana production in Ecuador: its implications on black Sigatoka development and plant–soil nutritional status. Renew. Agric. Food Syst. 22 (4) https://doi.org/10.1017/s1742170507001895.
Jones, H., et al., 2010. The effect of the year of wheat variety release on productivity and stability of performance on two organic and two non-organic farms. J. Agric. Sci. 148 (3), 303–317.

Kearney, J., 2010. Food consumption trends and drivers. Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci. 365 (1554), 2793–2807. https://doi.org/10.1098/rstb.2010.0149.
Kirchmann, H., et al., 2008. Can organic crop production feed the world? In: Kirchmann, H., Bergström, L. (Eds.), Organic Crop Production - Ambitions and Limitations. Springer, Dordrecht, pp. 39–72.
Kniss, A.R., Savage, S.D., Jabbour, R., 2016a. Commercial crop yields reveal strengths and weaknesses for organic agriculture in the United States. PLoS One 11 (8), e0161673.
Kniss, A.R., Savage, S.D., Jabbour, R., 2016b. Correction: commercial crop yields reveal strengths and weaknesses for organic agriculture in the United States. PLoS One 11 (11), e0165851. https://doi.org/10.1371/journal.pone.0161673.
Kravchenko, A.N., et al., 2005. Management, topographical, and weather effects on spatial variability of crop grain yields. Agron. J. 97 (2), 514–523.
Kravchenko, A.N., Snapp, S.S., Robertson, G.P., 2017. Field-scale experiments reveal persistent yield gaps in low-input and organic cropping systems. National Academy of Sciences Proc. Natl. Acad. Sci. U. S. A. 114 (5), 926–931. https://doi.org/10.1073/pnas.1612311114.
Lesur-Dumoulin, C., et al., 2017. Lower average yields but similar yield variability in organic versus conventional horticulture. A meta-analysis. Springer Paris Agron. Sustain. Dev. 37 (5), 45. https://doi.org/10.1007/s13593-017-0455-5.
Licker, R., et al., 2010. Mind the gap: how do climate and agricultural management explain the "yield gap" of croplands around the world? Glob. Ecol. Biogeogr. https://doi.org/10.1111/j.1466-8238.2010.00563.x.
Lipson, M., 1997. Searching for the' O-word': Analyzing the USDA Current Research Information System for Pertinence to Organic Farming. Organic Farming Research Foundation, Santa Cruz, CA.
Loos, J., et al., 2014. Putting meaning back into "sustainable intensification". Front. Ecol. Environ. 12 (6), 356–361.
Lyngbaek, A.E., Muschler, R.G., Sinclair, F.L., 2001. Productivity and profitability of multistrata organic versus conventional coffee farms in Costa Rica. Agrofor. Syst. 53 (2), 205–213.
Marshall, E.J.P., et al., 2003. The role of weeds in supporting biological diversity within crop fields. Weed Res. 44 (June 2002), 77–89. https://doi.org/10.1046/j.1365-3180.2003.00326.x.
Martini, E., et al., 2004. Yield increases during the organic transition: improving soil quality or increasing experience? Field Crops Res. 86 (2–3), 255–266. https://doi.org/10.1016/j.fcr.2003.09.002.
Mayer, J., Mäder, P., 2016. Langzeitversuche – eine Analyse der Ertragsentwicklung. In: Freyer, B. (Ed.), Ökologischer Landbau: Grundlagen, Wissensstand und Herausforderungen. UTB, pp. 421–443.
McGuire, A.M., 2017. Agricultural science and organic farming: time to change our trajectory. The American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, Inc. Agric. Environ. Lett. 2 (1), 170024. https://doi.org/10.2134/ael2017.08.0024.
Mikó, P., et al., 2014. Comparison of bread wheat varieties with different breeding origin under organic and low input management. Euphytica 199 (1–2), 69–80.
Möller, K., et al., 2007. Impact and interaction of nitrogen and phytophthora infestans as yield-limiting and yield-reducing factors in organic potato (*Solanum tuberosum* L.) crops,. Springer Netherlands Potato Res. 49 (4), 281–301. https://doi.org/10.1007/s11540-007-9024-7.
Muller, A., et al., 2017. Strategies for feeding the world more sustainably with organic agriculture. Nature Publishing Group Nat. Commun. 8 (1), 1290. https://doi.org/10.1038/s41467-017-01410-w.
Murphy, K.M., et al., 2007. Evidence of varietal adaptation to organic farming systems. Field Crops Res. 102 (3), 172–177.
Musyoka, M.W., et al., 2017. Effect of organic and conventional farming systems on nitrogen use efficiency of potato, maize and vegetables in the Central highlands of Kenya. Elsevier Eur. J. Agron. 86, 24–36. https://doi.org/10.1016/J.EJA.2017.02.005.
Nelson, N.O., Janke, R.R., 2007. Phosphorus sources and management in organic production systems. HortTechnology 17 (4), 442–454.
Nguyen, M.L., Haynes, R.J., Goh, K.M., 1995. Nutrient budgets and status in three pairs of conventional and alternative mixed cropping farms in Canterbury, New Zealand. Elsevier Agric. Ecosyst. Environ. 52 (2–3), 149–162. https://doi.org/10.1016/0167-8809(94)00544-O.
Nowak, B., et al., 2013. To what extent does organic farming rely on nutrient inflows from conventional farming? Environ. Res. Lett. 8 (4), 44045.
Oehl, F., et al., 2002. Phosphorus budget and phosphorus availability in soils under organic and conventional farming. Nutrient Cycl. Agroecosyst. 62 (1), 25–35.
Olesen, J.E., et al., 2007. The value of catch crops and organic manures for spring barley in organic arable farming. Elsevier Field Crops Res. 100 (2–3), 168–178. https://doi.org/10.1016/J.FCR.2006.07.001.
Osterburg, B., Kätsch, S., Wolff, A., 2013. Szenarioanalysen zur Minderung von Treibhausgasemissionen der deutschen Landwirtschaft im Jahr 2050, Thünen Report. Johann Heinrich von Thünen-Institut, Braunschweig. https://doi.org/10.3220/REP.
Östman, Ö., Ekbom, B., Bengtsson, J., 2003. Yield increase attributable to aphid predation by ground-living polyphagous natural enemies in spring barley in Sweden. Ecol. Econ. 45 (1), 149–158.
Palmer, M.W., et al., 2013. The influence of organic and conventional fertilisation and crop protection practices, preceding crop, harvest year and weather conditions on yield and quality of potato (*Solanum tuberosum*) in a long-term management trial. Elsevier Eur. J. Agron. 49, 83–92. https://doi.org/10.1016/J.EJA.2013.03.004.
Pang, X.P., Letey, J., 2000. Organic farming: challenge of timing nitrogen availability to crop nitrogen requirements. Soil Sci. Soc. Am. J. 64 (1), 247–253.
Panneerselvam, P., et al., 2012. Indian farmers experience with and perceptions of organic farming. Renew. Agric. Food Syst. 27 (2), 157–169.
Panneerselvam, P., Hermansen, J.E., Halberg, N., 2011. Food security of small holding farmers: comparing organic and conventional systems in India. J. Sustain. Agric. 35 (1), 48–68. https://doi.org/10.1080/10440046.2011.530506.
Penfold, C.M., et al., 1995. Biological farming for sustainable agricultural production. Animal Prod. Sci. 35 (7), 849–856.
Phelan, P.L., Mason, J.F., Stinner, B.R., 1995. Soil-fertility management and host preference by European corn borer, *Ostrinia nubilalis* (Hübner), on *Zea mays* L.: a comparison of organic and conventional chemical farming. Elsevier Agric. Ecosyst. Environ. 56 (1), 1–8. https://doi.org/10.1016/0167-8809(95)00640-0.
Philibert, A., Loyce, C., Makowski, D., 2012. Assessment of the quality of meta-analysis in agronomy. Elsevier Agric. Ecosyst. Environ. 148, 72–82. https://doi.org/10.1016/J.AGEE.2011.12.003.
Ponisio, L.C., et al., 2015. Diversification practices reduce organic to conventional yield gap. Proc. R. Soc. Lond. B Biol. Sci. 282 (1799), 20141396.
de Ponti, T., Rijk, B., Van Ittersum, M.K., 2012. The crop yield gap between organic and conventional agriculture. Agric. Syst. 108, 1–9.
Posner, J., Baldock, J., Hedtcke, J., 2005. The Wisconsin Integrated Cropping Systems Trials: Yields, Yield Variability, and Yield Trends 1990-2002, Wisconsin Integrated Cropping Systems Trial 10th Report. University of Wisconsin-Madison. Available at: http://wicst.wisc.edu/wp-content/uploads/wicst-yields-yield-variability-and-yield-trends-1990-20021.pdf.
Posner, J.L., Baldock, J.O., Hedtcke, J.L., 2008a. Organic and conventional production systems in the Wisconsin integrated cropping systems trials: I. Productivity 1990–2002. Agron. J. 100 (2), 253–260.
Posner, J.L., Baldock, J.O., Hedtcke, J.L., 2008b. Organic and conventional production systems in the Wisconsin integrated cropping systems trials: I. Productivity 1990–2002. Agron. J. 253–260. https://doi.org/10.2134/agronj2007.0058.
Ray, D.K., et al., 2015. Climate variation explains a third of global crop yield variability. Nat. Commun. 6.
Riar, A., et al., 2017. A diagnosis of biophysical and socio-economic factors influencing farmers choice to adopt organic or conventional farming systems for cotton production. Frontiers Front. Plant Sci. 8, 1289. https://doi.org/10.3389/fpls.2017.01289.
Robson, M.C., et al., 2002. The agronomic and economic potential of break crops for Ley/arable rotations in temperate organic agriculture. Academic Press Adv. Agron. 77, 369–427. https://doi.org/10.1016/S0065-2113(02)77018-1.
Röös, E., et al., 2018. Risks and opportunities of increasing yields in organic farming. A review. Springer Paris Agron. Sustain. Dev. 38 (2), 14. https://doi.org/10.1007/s13593-018-0489-3.

Ryan, M.H., Derrick, J.W., Dann, P.R., 2004. Grain mineral concentrations and yield of wheat grown under organic and conventional management. J. Sci. Food Agric. 84 (3), 207–216. https://doi.org/10.1002/jsfa.1634.

Schipanski, M.E., et al., 2014. Multivariate relationships influencing crop yields during the transition to organic management. Elsevier Agric. Ecosyst. Environ. 189, 119–126. https://doi.org/10.1016/J.AGEE.2014.03.037.

Schmid, O., et al., 2008. Organic Action Plans: Development, Implementation and Evaluation. A Resource Manual for the Organic Food and Farming Sector. Frick, Switzerland. Available at: http://orgprints.org/13481/1/manual.pdf.

Schneeberger, W., Darnhofer, I., Eder, M., 2002. Barriers to the adoption of organic farming by cash-crop producers in Austria. Am. J. Altern. Agric. 17 (1), 24–31.

Schneider, M., et al., 2017. Cocoa and total system yields of organic and conventional agroforestry vs. monoculture systems in a long-term field trail in Bolivia. Cambridge University Press Exp. Agric. 53 (3), 351–374. https://doi.org/10.1017/S0014479716000417.

Schrama, M., et al., 2018. Crop yield gap and stability in organic and conventional farming systems. Agric. Ecosyst. Environ. 256, 123–130. https://doi.org/10.1016/j.agee.2017.12.023.

Scott, J.C., 1977. The Moral Economy of the Peasant: Rebellion and Subsistence in Southeast Asia. Yale University Press.

Scow, K., et al., 1994. Transition from conventional to low-input agriculture changes soil fertility and biology. Calif. Agric. 48 (5), 20–26.

Seufert, V., Ramankutty, N., 2017. Many shades of gray—the context-dependent performance of organic agriculture. Sci. Adv. 3 (3), e1602638.

Seufert, V., Ramankutty, N., Foley, J., 2012. Comparing the yields of organic and conventional agriculture. Nature 485, 229–232. https://doi.org/10.1038/nature11069.

Seufert, V., Ramankutty, N., Mayerhofer, T., 2017. What is this thing called organic?–How organic farming is codified in regulations. Food Policy 68, 10–20.

Shrestha, G., Prajapati, S., Mahato, B.N., 2014. Plant diseases and their management practices in commercial organic and conventional vegetable farms in Kathmandu valley. Himalayan College of Agricultural Sciences & Technology Nepal. J. Agric. Sci. 12, 129–141.

Smith, P., 2013. Delivering food security without increasing pressure on land. Glob. Food Secur. 2 (1), 18–23.

Smith, R.G., Gross, K.L., 2006. Weed community and corn yield variability in diverse management systems. JSTOR Weed Sci. 54 (1), 106–113.

Smith, R.G., Menalled, F.D., Robertson, G.P., 2007. Temporal yield variability under conventional and alternative management systems. Agron. J. 99 (6), 1629. https://doi.org/10.2134/agronj2007.0096.

Sooby, J., 2001. State of the States: Organic Farming Systems Research at Land Grant Institutions 2000-2001. Organic Farming Research Foundation, Santa Cruz. Available at: https://www.cabdirect.org/cabdirect/abstract/20013037834.

Stonehouse, D.P., et al., 1996. A case study approach to comparing weed management strategies under alternative farming systems in Ontario. Can. J. Agric. Economics/Revue Canadienne D'agroeconomie 44 (1), 81–99.

Teasdale, J.R., Cavigelli, M.A., 2017. Meteorological fluctuations define long-term crop yield patterns in conventional and organic production systems. Nature Publishing Group Sci. Rep. 7 (1), 688. https://doi.org/10.1038/s41598-017-00775-8.

Tilman, D., et al., 2011. Global food demand and the sustainable intensification of agriculture. Proc. Natl. Acad. Sci. 108 (50), 20260–20264.

Torstensson, G., Aronsson, H., Bergström, L., 2006. Nutrient use efficiencies and leaching of organic and conventional cropping systems in Sweden. Agron. J. 98 (3), 603. https://doi.org/10.2134/agronj2005.0224.

Trewavas, A., 2001. Urban myths of organic farming. Nature 410, 409–410.

Tuck, S.L., et al., 2014. Land-use intensity and the effects of organic farming on biodiversity: a hierarchical meta-analysis. J. Appl. Ecol. 51 (3), 746–755.

Tuomisto, H.L., et al., 2012. Does organic farming reduce environmental impacts?–A meta-analysis of European research. J. Environ. Manag. 112, 309–320.

Valkila, J., 2009. Fair trade organic coffee production in Nicaragua–Sustainable development or a poverty trap? Ecol. Econ. 68 (12), 3018–3025.

Wandel, J., Smithers, J., 2000. Factors affecting the adoption of conservation tillage on clay soils in southwestern Ontario, Canada. Cambridge University Press Am. J. Altern. Agric. 15 (4), 181. https://doi.org/10.1017/S0889189300008754.

Watson, C.A., et al., 2002. A review of farm-scale nutrient budgets for organic farms as a tool for management of soil fertility. Soil Use Manag. 18 (s1), 264–273.

Welsh, C., et al., 2009. High yielding organic crop management decreases plant-available but not recalcitrant soil phosphorus. Agron. J. 1027–1035. https://doi.org/10.2134/agronj2009.0043.

Willer, H., Lernoud, J., 2017. The World of Organic Agriculture - Statistics and Emerging Trends 2017. Frick & Bonn.

Willer, H., Yussefi, M., 2000. Ökologische Agrarkultur weltweit - Organic Agriculture World-Wide. Statistiken und Perspektiven - Statistics and Perspectives. DE, Bad Dürkheim.

Wolfe, M.S., et al., 2008. Developments in breeding cereals for organic agriculture. Euphytica 163 (3), 323–346.

Yiridoe, E.K., Bonti-Ankomah, S., Martin, R.C., 2005. Comparison of consumer perceptions and preference toward organic versus conventionally produced foods: a review and update of the literature. Renew. Agric. Food Syst. 20 (4), 193–205.

Zehnder, G., et al., 2007. Arthropod pest management in organic crops. Annu. Rev. Entomology 52, 57–80.

Zikeli, S., Deil, L., Möller, K., 2017. The challenge of imbalanced nutrient flows in organic farming systems: a study of organic greenhouses in Southern Germany. Elsevier Agric. Ecosyst. Environ. 244, 1–13. https://doi.org/10.1016/J.AGEE.2017.04.017.