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Review

Reframing the Debate Surrounding the Yield Gap between Organic and Conventional Farming

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Received: 28 December 2018; Accepted: 11 February 2019; Published: 13 February 2019

Abstract: In this article, we review the literature regarding the yield gap between organic and conventional agriculture and then reflect on the corresponding debate on whether or not organic farming can feed the world. We analyze the current framework and highlight the need to reframe the yield gap debate away from "Can organic feed the world?" towards the more pragmatic question, "How can organic agriculture contribute to feeding the world?". Furthermore, we challenge the benchmarks that are used in present yield comparison studies, as they are based on fundamentally distinct paradigms of the respective farming methods, and then come up with a novel model to better understand the nature of yield gaps and the benchmarks that they are premised on. We thus conclude that, by establishing appropriate benchmarks, re-prioritizing research needs, and focusing on transforming natural resources rather than inputs, organic systems can raise their yields and play an ever-greater role in global sustainable agriculture and food production in the future.

Keywords: yield gap; cropping systems; yield-limiting factor; yield ratio; organic agriculture; feeding the world

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1. Introduction

Whether organic agriculture can feed the world is a controversial topic and it is the subject of much debate in recent literature. A number of studies have sought to answer this question by quantifying yield gaps between organic and conventional agriculture, with the recent estimates of reductions in yield for organic systems ranging from 9% to 25%. Diverse meta-analytical approaches have been employed to arrive at these values, in some cases presenting global averages and in others by separating the analysis by crop type, geographical region, or other moderating variables. Recent meta-analyses are reviewed here in Section 1, with a brief discussion of the individual categories of cereals, legumes, oil crops, and tubers.

The meta-analytical design is useful in understanding the average value and range of yield gaps, and in many cases meta-analyses consider moderating variables, such as climate, fertilization rates, or rotational diversity, which allow for a more detailed discussion of how yield gaps might vary under certain conditions. However, even statistically rigorous and nuanced meta-analyses rely on the assumption that organic and conventional yields can be compared directly. Section 2 describes why conventional agriculture is not always a suitable benchmark by which to measure organic agriculture and then argues for an alternative approach to viewing the complex differences between conventional and organic systems.

Modeling approaches complement meta-analytical studies and allow for further exploration of how moderating variables affect yield. Multiple models of agricultural systems have been proposed, from input/output models to more complicated equations (Section 3). We present a novel model describing cropping systems as processes that transform natural resources and inputs into yield (Section 3). Each cropping system is viewed as a unique case in which inputs and their relative importance differ in comparison to alternative cropping systems. This model can be used to explain some of the observed variation in yield gaps between organic and conventional agriculture among crop types and environments (Section 3). In addition, the model provides important insights into how to direct organic agriculture research priorities in the future.

2. Meta-Analytic Approaches

Recent Meta-Analyses

Stanhill [1] was one of the first to approach the yield gap concept from a meta-analytical perspective, using 205 comparisons of 26 crop types and two animal products to arrive at an average organic/conventional yield ratio of 0.91. Data was obtained from three categories: commercial farms, short- and long-term experimental studies, and a 25-year comparison of three agroecosystems. One yield ratio was calculated for each study from all of the included plots and years. Diverse starting conditions could be observed even within the first category, where the farms ranged from biodynamic systems in Western Europe to corn-dominated systems in the American Midwest, but the data were obtained primarily from developed countries with temperate climates. The standard deviation of 0.24 for this dataset reflects the wide variation in yield resulting from the diverse starting conditions. The author acknowledged the difficulty of comparing closed and open systems, although not explicitly, linking yield gaps to non-renewable external inputs, such as fossil fuel energy.

Subsequent meta-analyses have broadened the geographic region under consideration. In an extensive review of organic agriculture, Lotter [2] cites an average yield gap of 10–15% (Table 1), noting that the gap was higher in regions that are characterized by intensive agriculture, such as parts of Central Europe and Japan, and lower under extensive conditions, such as those in the American Midwest. However, the methodology behind the reported value is unclear and it does not distinguish between crop types.

Table 1. Yield gaps by category and crop. Yield gaps (representing all plots and years of the respective study) vary by category of crop under consideration. * denotes a meta-analysis.

Study	Category	Crop	Yield Gap
		All/major	
[2]	All	All	−10 to −15% *
[3]	All	All	−25% *
[1]	All	All	−9% *
[4]	All	All (global)	−19% *
[5]	All	All	−20% *
[6]	All	All (developed countries)	−9% *
[7]	Major crops	Potato, peas, leek, barley, sugar beet, maize (Netherlands)	−13%
		Cereals	
[8]	Cereals	Barley, oats, wheat	−30%
[9]	Cereals	Barley, oats, wheat	−35%
[10]	Cereals	Buckwheat	NS
[11]	Cereals	Cereals	−54%
[12]	Cereals	Cereals	−25%
[3]	Cereals	Cereals	−26%*
[6]	Cereals	Cereals (developed countries)	−7% *
[5]	Cereals	Cereals (global average)	−21% *
[13]	Cereals	Corn	−24 to −41%

Table 1. *Cont.*

Study	Category	Crop	Yield Gap
[14]	Cereals	Corn	−0%
[15]	Cereals	Corn	NS
[16]	Cereals	Corn	−13 to −33%
[17]	Cereals	Corn (legume rotation)	−62%
[17]	Cereals	Corn (manure-fertilized)	+37%
[16]	Cereals	Sorghum	−16 to −27%
[13]	Cereals	Wheat	NS
[18]	Cereals	Wheat	−17 to −84%
[16]	Cereals	Wheat	−10 to +10%
[19]	Cereals	Winter wheat	−42%
[20]	Cereals	Winter wheat	−39%
[21]	Cereals	Winter wheat	−38%
[22]	Cereals	Winter wheat	−10%
[23]	Cereals	Winter wheat	−14%
[24]	Cereals	Winter wheat	−36%
[25]	Cereals, Legumes	Corn, soybean, wheat	−10%
Fruits			
[3]	Fruits	Fruits	NS *
[6]	Fruits	Fruits (developed countries)	−4% *
[5]	Fruits	Fruits (global average)	−28% *
Legumes			
[3]	Legumes	Legumes	NS *
[6]	Legumes	Legumes (developed countries)	−18% *
[5]	Legumes	Legumes (global average)	−12% *
[13]	Legumes	Soybean	−19%
[16]	Legumes	Soybean	−17%
[2]	Legumes	Soybean (legume rotation)	+96%
[2]	Legumes	Soybean (manure-fertilized)	+52%
Oil crops			
[3]	Oil crops	Oil crops	NS *
[6]	Oil crops	Oil crops (developed countries)	−1% *
[5]	Oil crops	Oil crops (global average)	−26% *
Tubers			
[9]	Tubers	Potato	−15%
[22]	Tubers	Potato	−36 to −42%
[6]	Tubers	Starchy roots (developed countries)	−11% *
[5]	Tubers	Roots/tubers (global average)	−26%*
Vegetables			
[26]	Vegetables	Sweet corn, tomato	NS
[27]	Vegetables	Tomato	−4 to −9%
[15]	Vegetables	Tomato	NS
[3]	Vegetables	Vegetables	−33% *
[6]	Vegetables	Vegetables (developed countries)	−12% *
[5]	Vegetables	Vegetables (global average)	−20% *

Badgley et al. [6] calculated two separate organic/conventional yield ratios for developed and developing countries in order to account for substantial differences in agricultural methods. Whereas, the developed world yield ratio was 0.914 for plant foods and the ratio in developing countries was 1.736. Nitrogen availability was cited as the predominant yield-limiting factor for organic agriculture under most conditions. The yield gaps were calculated for separate crop categories as well, ranging in developed countries from 1% for oil crops to 18% for legumes. This study was criticized for failing to define organic systems and for applying single-study yield ratios to national agricultural data [28,29].

More recent studies have calculated larger yield gaps, ranging from 19–25% [3,5]. In a meta-analysis of 362 conventional-organic comparisons, de Ponti et al. [5] arrived at a global average of 20% reduction under organic conditions, with a standard deviation of 21%. The authors hypothesized a higher yield gap under conditions where the observed yields approach the theoretical maximum due to intensive management and lack of water limitation, such as northern Europe, but found only weak support for this hypothesis.

Seufert et al. [3] found the largest yield gap (25%) among the meta-analyses, with wide variation depending on crop type and management practices. Legumes had the smallest yield gap (5%) of the crop categories reviewed, and best-practice organic management reduced the yield gap to 13% across crop types. In contrast to Badgley et al. [6], only certified-organic or non-certified systems in compliance with organic regulations were considered under the organic category, and conventional-organic comparisons were required to have similar temporal and spatial scales. The authors noted that nitrogen availability limited the yields in organic, but not conventional, systems, as evidenced by increased organic yields when additional nitrogen was provided.

Using a larger dataset of 1071 conventional-organic comparisons and a novel meta-analytical method, Ponisio et al. [4] calculated a yield gap of 19%. No difference was found between yield gaps in developed and developing countries, in contrast to Badgley et al. [6].

A more recent study analyzed publicly available state-level crop yield statistics from the United States Department of Agriculture (USDA), which were collected under the organic and agricultural producer surveys in 2014 [30]. In that study, Kniss et al. arrived at an organic yield average of 80% of conventional yield for the United States. However, even within one country and one year of production, the authors state that the organic to conventional yield ratio varied widely among crops and that several crops showed no significant yield gap between organic and conventional production.

The meta-analytical framework that was used in these studies is clearly valuable and it has allowed for yield gaps to be quantified across a broader range of conditions than can be achieved with any single study. Despite progress towards greater nuance by calculating multiple yield gaps according to geographic region, crop type, or nitrogen management, meta-analyses nonetheless lose some of the detail that is visible in a single study. Using a meta-analytical approach to investigate how yield gaps change due to complex factors, such as agrobiodiversity, rotational complexity, or integrated crop-livestock systems requires a statistically rigorous number of published studies in each subcategory, and these studies are not always available.

3. Reframing the Yield Gap Debate

Meta-analytical studies are a valuable technique to summarize yield comparison studies, but we suggest that it is time to reconsider the question that they address and the benchmarks they use.

Meta-analytical approaches comparing conventional and organic yields worldwide often seek to contribute to the debate of whether organic agriculture can feed the world. However, that is the wrong question, or perhaps it is the right question at the wrong time. Today, when organic agriculture accounts for 1.2% of worldwide agricultural land [31], it does not make sense to question whether it can feed the world. Perhaps in thirty or forty years, in a world where organic agriculture accounts for 40–50% of arable land, this question may gain renewed meaning. However, at present, the focus must be on questions relevant to the current state of affairs: how, and how much, can organic methods contribute to feeding the world? The "Can organic feed the world?" debate has thus far led to lively controversy, but few satisfying answers; reframing the question can move the debate toward concrete examples, as presented in Section 3.

Using conventional agriculture as the benchmark against which organic agriculture must be compared falsely assumes that the systems have the same goals and values. When comparing a conventional wheat farmer's yields in Germany of 7–10 Mg/ha, achieved using all available synthetic fertilizers and plant protection agents, with the 3.5–6.5 Mg/ha achieved by his neighbor with organic practices assumes that the two systems are essentially the same, except that organic agriculture uses non-synthetic inputs. In reality, however, the farmers are operating under distinct paradigms. Conventional and organic agriculture have different values, even when low-input practices are employed in conventional systems and the conventional-organic comparison becomes less of a dichotomy than a continuum. The conventional approach assumes that the production of food, fiber, and fuel must be maximized to satisfy the demands of a growing human population. Organic agriculture seeks to balance yield with other values, such as biodiversity and conservation of natural resources, as, for instance, required by Reg. (EC) 834/2007. The maximum yield achievable in the organic paradigm must necessarily lie somewhere below the conventional level if it is to leave room for other creatures to exist and to avoid exploitation of the natural environment. The abundance of many insect and plant species is negatively correlated with yield [11] and a more recent study even suggested pesticide usage, increased application of fertilizers, and year-round tillage in intensive farming as plausible reasons for a 75% decline of flying insect biomass over 27 years [32]. Organic agriculture must be judged not by the production-driven values system of conventional agriculture, but instead by standards that are consistent with its own values. The model that is presented in Section 3 shows how the distinct values of organic and conventional agriculture cause a divergence in inputs that accounts for a large proportion of yield gaps, as calculated by previous methods.

Furthermore, the geographical bias of the conventional benchmark used in many meta-analyses distorts the reader's perspective on the debate over feeding the world. While some meta-analyses discriminate between geographical regions, others fail to do so, and thus often use the artificially high benchmark of intensive agriculture in the developed world. In Central Europe, yields that were achieved under the optimized intensive cultivation approach the theoretical maximum that was established by climatic conditions. Nonetheless, their direct contribution to eradicating world hunger is small, as many of the crops are commodities produced for the global commodity markets. Discussion about feeding the world based on these systems is misleading. Feeding the world primarily requires raising yields in subsistence agriculture, not incremental gains in the production of low-value commodities, and the conversion to organic agriculture in developing regions is predicted to make a greater contribution to global food security than conversion in Europe and North America [33]. Farmers in Central Europe who produce commodities for the world market desire optimizing yields by all available means and will do so as long as it is affordable. Farmers in developing countries produce food to fill the needs of the local community, not global markets, and must do so on soil that is often more vulnerable than that in the global North. Section 3 describes how focusing on the transformation of natural resources rather than transformation of high inputs can greatly contribute to fighting world hunger by addressing yield gaps where they are most critical for food security.

4. A Novel Model for Cropping Systems as Applied to Yield Gaps

4.1. Previous Models of Agricultural Yields

While meta-analyses provide a useful tool for estimating organic and conventional yield gaps, they lack predictive value. Knowing that organic cereal yields are 7–26% lower than conventional as a global average, the range calculated by the meta-analyses cited here cannot provide information about yields that could be expected under individual conditions. Individual studies have reported yield gaps of up to 84% for wheat, for example, but minor or nonexistent yield gaps for maize and buckwheat [10,15,18]. These differences are due not only to crop type, but also to a variety of factors that contribute to yield. In the meta-analyses presented here, the authors attribute yield responses in organic farming to factors, such as limited nitrogen availability, weed pressure, pests, and disease, when sufficient relevant studies are available for analysis. We do not challenge these findings, but rather frame them in the context of crop type and prevailing cropping conditions in order to gain greater explanatory power (see Section 4.3).

Over the past thirty years, many models describing yield as the product of multiple factors have been proposed. Bouman et al. [34] present an overview of crop growth simulation models, starting with early research by C. T. de Wit at the Wageningen Agricultural University. De Wit and Penning de Vries [35] proposed four production situations with corresponding differences in yield: potential (limited only by temperature and radiation), water-limited, nitrogen-limited, and nutrient-limited (cited in [34]). Pests, weeds, and disease could reduce yields to below the maximum theoretical value in each of these instances.

Rabbinge [36] expanded on previous work by dividing factors that contribute to yield into those that establish potential yield (crop characteristics, temperature, sunlight), reduce potential to attainable yield (nutrient and water limitation), and reduce attainable to actual yield (pests, diseases, and weeds). The author notes that the latter category, the growth-reducing factors, "should be controlled mainly by biological measures" in sustainable agricultural systems, but does not discuss the relative magnitude of these factors under organic and conventional conditions.

Van Ittersum and Rabbinge [37] proposed that differences in the relative importance of input factors could be used to explain the actual yields and resource use efficiencies. Biophysical factors are viewed as distinct from socio-economic factors, which were often neglected in previous models. The model also extends to three spatial scales: field, farm, and region.

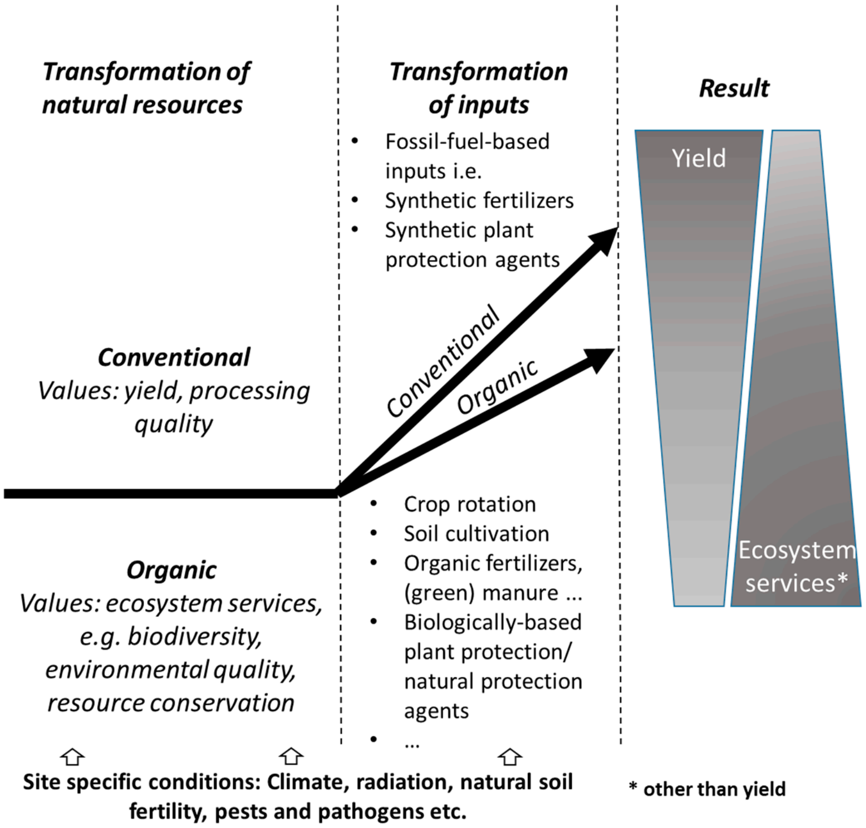

Figure 1. Simplified model to describe a cropping system as a process of transformation.

Over time, relatively simple conceptual models of crop yields have evolved into increasingly complex software programs that are based on systems analysis and mathematical modeling approaches [34,38]. The simplified model that is presented in Figure 1 differs in two important ways. First, this model is conceptual rather than strictly quantitative, as quantitative models are already available. Second, it is focused not on predicting yields, but rather on explaining the relative magnitude of yield gaps between the organic and conventional systems. It thus builds on previous agricultural models by applying them in a novel context, contributing to a more nuanced understanding of the concept of yield gaps in the process. This simplified model should not be viewed as an attempt to make quantitative predictions, but as a theoretical tool to re-frame the yield gap debate and set new research priorities.

4.2. Transformation of Natural Resources

As can be seen from the model, both conventional and organic systems are fundamentally based in site-specific natural resources: light availability, the inherent fertility of the soil, and local climatic conditions. Because these resources are unaffected by agricultural management practices, they are identical between conventional and organic systems at a certain location, and thus the yields that are formed from the transformation of these resources are also similar. However, conventional and organic systems may respond differently to a given set of starting conditions. For example, the higher microbial diversity and activity found under organic management may increase the bioavailability of nutrients and organic carbon stored in the soil to crops managed under these conditions, even when the initial soil was identical [22,39]. Organic management also provides an advantage under dry conditions, as higher levels of soil organic matter increase the soil water capacity [40]. In a drought year, Lotter et al. [2] found that a manure-based organic corn system out-yielded the conventional treatment by 37% and the organic soybean yields were 52–96% higher than conventional. Organic agriculture provides a more attractive alternative under changing climate conditions, as it increases carbon sequestration, has higher energy use efficiency and resiliency to climate change, and reduces global warming potential as compared to conventional [40,41].

While the transformation of natural resources is comparable between organic and conventional systems, organic methods can be superior when it comes to providing ecosystem services and preserving the quality of resources, such as soil and groundwater. Biodiversity, especially of insects, is higher on organic farms, which leads to the increased provision of ecosystem services, such as pollination and biological control [41–46]. Soil quality parameters are improved under organic management, including reduced losses by erosion and runoff, increased organic matter, higher microbial biomass and diversity, and more rapid nitrogen mineralization [14,22,41,47–50]. Both nitrate and phosphorus leaching are reduced under organic management, even when scaled by yield or production area [9,43,51,52]. Part of this may be due to the fact that nutrient losses in the runoff from organic material, such as compost, are much smaller than from synthetic fertilizer [53]. It is important to acknowledge that conventional farms in certain regions and production systems often do implement practices that are intended to remedy these issues, for example, increasing agrobiodiversity by introducing more complex crop rotations or mitigating greenhouse gas emissions through climate smart agriculture (CSA) [54].

4.3. Transformation of Inputs

The gap between conventional and organic yields primarily comes from the transformation of inputs, not from the transformation of natural resources. Conventional management uses a variety of inputs eschewed by organic agriculture, which primarily relies on renewable resources and seeks to replenish rather than mine the soil. Consequently, nutrient limitation is a primary cause of suboptimal yields under organic conditions, particularly when it comes to the amount and timing of nitrogen availability [27,55]. Early-season nitrogen limitation is a common problem, as mineralization from organic matter in the soil releases nitrogen later in the season [17,56]. Synthetic soil fertilizers increase and plant protection agents secure yield, but this artificial increase formed from fossil fuels should not be compared with yield that formed from predominantly natural soil fertility. The observation that these inputs contribute greatly to the perceived yield gaps [57] reinforces the need for a new benchmark for organic agriculture. Yields were artificially inflated through resource mining; the unsustainable depletion of fossil fuels or minerals, such as phosphorus, cannot serve as the point of comparison for a system of agriculture that seeks to operate within ecologically sustainable limits.

If the yield gap is primarily explained by the transformation of inputs, differences in inputs should predict the size of the yield gap, and this is indeed the case. In his critique of Badgley et al. [6], Cassman [28] highlighted the fact that nutrient inputs were not standardized in system comparisons. This is less a particular weakness of the study in question, however, than a failure of yield calculations in general to account for the distinction between yield that formed from predominantly natural soil fertility and yield created through the addition of non-renewable inputs. By separating studies based on nitrogen inputs, Ponisio et al. [4] were able to determine that the yield gaps are much lower (9%) when nitrogen inputs are similar between organic and conventional treatments than when they differ (17–30%). However, the differences in phosphorus input did not significantly affect the organic/conventional yield ratios.

4.4. Predicting the Yield Gap: Explanatory Power of the Novel Model

Applying the model to cereals, grain and fodder legumes, oilseeds, and tubers helps to explain why yield gaps that were reported in meta-analytical studies differ for these crop categories. As mentioned above, differences in inputs account for conventional-organic yield gaps, but each crop category is unique in terms of which inputs are the most significant. Sprengel's and Liebig's concept of the most limiting factor applies here: gaps are determined not by the average of yield losses imposed by individual factors affecting crop growth, but by the factor with the greatest influence on yield. For cereals, which have high growth rates early in the season, and tubers, like potato, which have high nutrient demand in a short period, nutrient availability is the primary growth-limiting factor, whereas weeds and disease play a greater role for legumes and insect pests may severely limit the yields of oil crops, such as rapeseed.

4.4.1. Cereals

Yield gaps for cereals calculated in meta-analyses range from 7–26% (Table 1). Badgley et al. [6] calculated a yield gap of only 7% for cereals in developed countries, the smallest difference of any of the meta-analyses, whereas Seufert et al. [3] calculated the highest value, with 26%. De Ponti et al. [5] found that the gap was smallest for maize (11%) and highest for barley (31%). Seufert et al. [3] likewise found that maize had a smaller yield gap than the mean for all crop types (25%), whereas barley and wheat had larger yield gaps. The yield gap for cereals as a whole is generally lower than for vegetables (Table 1), but higher than for legumes.

Nitrogen availability is the primary factor limiting cereal productivity [58], and differences in nitrogen inputs account for the majority of the yield gap here. Natural nitrogen mineralization processes are poorly matched with the timing of the greatest nitrogen uptake in wheat [59], such that nitrogen availability from natural sources plays a lesser role than inputs in forming crop yield. Because high inputs of synthetic N fertilizers can be applied at crucial periods in conventional systems, the cereal yields may be higher in these systems. However, nitrogen availability can be increased by organic best practices rather than by relying on synthetic fertilizers. Oleson et al. [60,61] showed that supplementation of 50 kg/ha farmyard manure raised the organic cereal yields by 0.4–1.3 Mg/ha in a nitrogen-limited system. Other supplements, such as biogas slurry or green manure, could likewise contribute, as could management strategies that better match the timing of nitrogen availability to crop requirements.

Protein content is often considered to be an important indicator of quality in cereals, as it contributes to baking properties, and it has been the subject of many conventional-organic comparisons. Studies have found 3–23% lower protein content in organic wheat as compared to conventional [19–21]; this gap is primarily ascribed to nitrogen limitation [62]. However, discussions of grain protein content have little to contribute to the debate regarding the feeding of the world, and testing the quality of protein rather than the quantity gives a better indication of the baking properties of organic wheat [63]. Furthermore, the late fertilization that is often employed by conventional farmers to boost grain protein is frequently not taken up, instead leaching into groundwater and contributing to nitrate pollution.

Worthy of note is that the yield gap is generally smaller for maize than other cereals in temperate zones with sufficient water availability. Weed pressure, accounting for 23% of the yield gap by one estimate, is major limiting factor for maize [13,14,17]. However, the yield gap disappears when organic weed management is effective. Posner et al. [25] showed that, in years where mechanical weed cultivation was successful, the yield gap was only 1%, as compared to 26% in years when it was unsuccessful. Crop rotation significantly affects maize productivity, as organic maize that is grown in rotation with multiple cover crop species yields over 100% more than organic maize that is grown in monocultures, attaining yields that are not statistically different from the county average for conventional maize [64].

4.4.2. Legumes

Yield gaps are generally much smaller for legumes than other crop categories, e.g., 5%, as calculated by Seufert et al. [3] (Table 1). This can be explained partially by the greater reliance of these crops on natural sources of fertility rather than inputs. Legumes obtain nitrogen primarily through the symbiosis with diazotrophic bacteria as well as available soil nitrogen, and additional synthetic nitrogen fertilizer has little effect.

The yield gap for fodder legumes, which are rarely cultivated in conventional agriculture, is extremely small. This can be explained by the fact that these crops require negligible inputs: there is no need for synthetic N fertilizer, other nutrients are not usually limiting, except in low-fertility soils, and plant protection agents are generally not frequently used.

Grain legumes have a slightly higher yield gap than forage legumes, but the gap is still much smaller than for other crop categories, and the yields are higher under organic conditions in some cases. In Stanhill's meta-analysis, beans were the only crop observed to have significantly higher yields under organic conditions [1]. Badgley et al. [6] found a higher yield gap for legumes (18%) than cereals (7%) in developed countries, but legume yields were 52% higher under organic conditions when considered globally. De Ponti et al. [5] calculated organic soybean yields in the United States (U.S.) to be 92% of conventional. This yield gap was smaller than for any other legume that was considered. Soybean also had a smaller-than-average yield gap in the meta-analysis by Seufert et al. [3]. In contrast to that analysis, Ponisio et al. [4] found no yield gap differences between the leguminous and non-leguminous crops; legumes were not considered as a separate category from vegetables and oil crops. Yield gaps can arise, however, when the inputs differ significantly. Weeds and diseases can limit organic yields if no mechanically- or biologically-based strategies for weed and pest management are available. De Ponti et al. [5] calculated the largest yield gaps for soybean between the intensively managed conventional and organic conditions, ascribing the magnitude of the gap to pests, disease, and phosphorus limitation. Cavigelli et al. [13] noted that the 19% soybean yield gap in a long-term study was entirely due to weeds. Here, the differences in plant protection inputs explain the relative magnitude of the yield gap, even within the category of legumes.

4.4.3. Oil Crops

Oil crops, as a whole, often have a small yield gap, but some oil crops, such as oilseed rape, are practically impossible to grow under organic conditions in regions where insect pests are present. In contrast, sunflower is a commonly grown oilseed crop for which organic yields can often equal conventional levels, contributing to the small yield gaps that were reported for oilseeds. Badgley et al. [6] found the smallest yield gap for oil crops of any category considered, being 1% in developed countries. As crops in this category were not listed, however, it is difficult to determine whether this included oilseed rape. Similarly, oilseed crops had the smallest yield gap of any category, except for fruits in the analyses by Seufert et al. [3] and Ponisio et al. [4]. In contrast to the minor yield gaps that were found by the aforementioned meta-analyses, de Ponti et al. [5] found organic oilseed yields to be 26% lower than the conventional. Oilseed rape, however, represents a special case, where almost all production in Central Europe is conventional. Insect herbivory is the limiting factor in this case, and there are no effective organic methods of pest control available, especially with regards to the pollen beetle (*Meligethes aeneus*). Weed pressure at sensitive developmental stages also affects yields [65], but the yield gap is primarily explained by the differences in plant protection agents. Here, it would make little sense to first try to increase nutrient availability to make organic oilseed rape cultivation more feasible; research into organic pest control methods must be prioritized.

4.4.4. Tubers

The yield gap for tubers is often greater than for cereals, but they were also more variable [66]. Starchy roots had the second-highest yield gap of the categories considered, 11% in the developed world, as calculated by Badgley et al. [6]. In 21 organic-conventional comparisons, all from Europe, de Ponti et al. [5] found that organic potato yields were only 70% of the conventional. In contrast, organic sugar beet and sweet potato yields were 105% of the conventional, raising the tuber average to 74% of the conventional. Tubers were considered under the vegetable category by Seufert et al. [3], where the yield gap amounted to 33%. This is similar to the yield gap of nearly 30% that was presented by Ponisio et al. In potato, the primary yield-limiting factor is nutrient availability, followed by pathogens, such as *Phytophthora infestans* [66,67]. Möller et al. [68] found that 48% of the yield gap in organic potato could be attributed to N limitation, whereas 25% was explained by disease for which no organic management was possible. Inputs of synthetic fertilizers and plant protection thus primarily account for the yield gap in potato.

5. Conclusions and Future Directions

Here, we have called for a reframing of the yield gap debate, changing the question under consideration from “Can organic agriculture feed the world?” to “How can organic agriculture contribute to feeding the world?” The model that is outlined in Figure 1 represents a novel approach in that it seeks not to quantify yield gaps with absolute values, but to explain and predict their magnitude under diverse starting conditions. This model does not conclusively establish the future role of organic agriculture, but it rather provides an indication as to how its research priorities should be directed in the future.

First, we need a new benchmark (Figure 2). For any meaningful discussion of yield gaps between organic and conventional farming to take place, it needs to be clear where the upper boundary lies without violating the values of organic farming. It is clear that there are limits that we cannot exceed if the other goals of organic agriculture are to be pursued. However, the threshold of an ecologically sustainable yield may differ depending on the respective agroecosystem, contemporary technological capabilities, and the presiding social values. For instance, in a highly sensitive agroecosystem, a sustainable balance of the tradeoffs between crop yield and ecological impacts will presumably result in lower yields than in an agroecosystem with high environmental buffering capacity, where crop production may be managed more intensively without excessive negative ecological impacts. Alternatively, if society places a higher value on clean groundwater, for example, maximizing yields becomes less important than minimizing soluble nitrate emissions and the yield benchmark may be lowered. Currently, societal values allow for production to exceed the ecologically sustainable limits in the quest to maximize yields. However, those high yields must not be mistaken for an appropriate benchmark for yield comparisons of conventional and organic farming, as the latter system already integrates societal values, such as contributing to biological diversity and minimizing the use of non-renewable resources.

New ecologically sustainable benchmarks are not a fixed target, and as such they cannot be defined by an absolute value, but rather they must be established through consensus over the balance of tradeoffs that are considered to be acceptable by the respective society. Debate over this approach and the alternative paradigms has begun, for example, with the concept of ecological intensification, in which ecosystem services partially replace reliance on anthropogenic inputs as a source of crop productivity [69]. Recent metrics that were developed for sustainable intensification are particularly useful when they go beyond the original efficiency-focused framework and emphasize various aspects of sustainability. Other useful frameworks include measuring environmental impacts on a yield-scaled basis [70] and assorted "eco-efficiency metrics" [71] that integrate multiple criteria that are related to sustainability and productivity [72,73]. However, the strengthening of this debate must continue. Where is the acceptable upper limit, or phrased alternatively, how large of a potential yield gap are we willing to accept in order to avoid the negative environmental tradeoffs that are associated with high conventional yields?

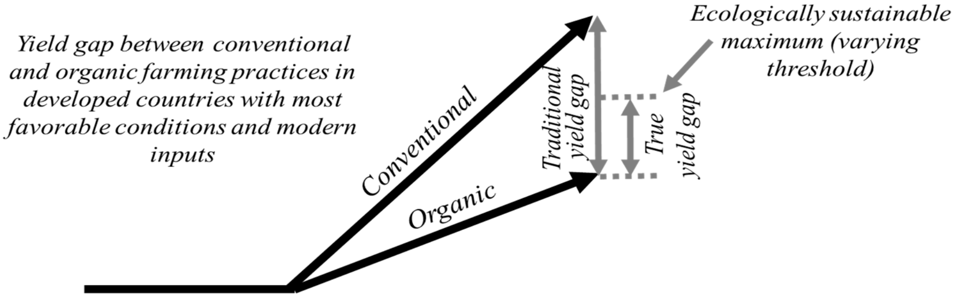

Figure 2. The true yield gap between organic and intensive conventional management shrinks when an ecologically sustainable threshold is set as benchmark.

Second, we need to set new priorities for developing agriculture to focus on raising the lowest yields rather than the higher ones, especially in organic systems. Best-practices organic agriculture is already highly refined. Seufert et al. [3] found that the yield gap is lower when the comparison is between the organic and conventional systems that both use the best respective management practices. Ponisio et al. [4] likewise found that multi-cropping and crop rotation in organic systems reduced the yield gap to 9% and 8%, respectively, as compared to 14% when the organic systems did not use these best-practice techniques. In organic systems that use best-practice methods, yields might already approach the current ecologically sustainable maximum. Rather than investing resources here, where they would bring only incremental gains, the organic branch should prioritize cases in which the yield gap is largest, which is an example of sustainable intensification [74]. Technologies developed and adopted in organic farming systems are already highly attractive in developing countries: they require little capital investment or technological know-how, conserve resources, such as soil and groundwater where they are especially vulnerable, and reduce risks as compared to less-diverse systems [33] (Figure 3). The transfer of best-practice knowledge can help to raise yields under these conditions and in underperforming organic systems in developed countries as well.

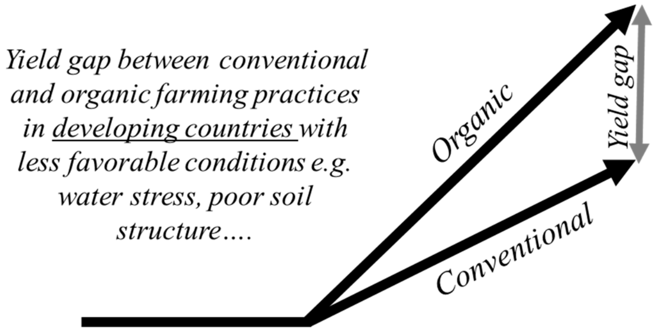

Figure 3. The gap between conventional and organic yield may go into reverse under less favorable conditions.

To do this, we must make a third change: redirecting the agricultural research focus from maximizing yield due to transformation of inputs towards maximizing yield due to the transformation of natural resources. Breeding for rhizosphere traits can play an important role here [75]. Root system architecture and interactions with beneficial rhizosphere microorganisms strongly influence nutrient uptake, and the breeding for these traits can create cultivars that are able to make full use of inherent soil fertility [76]. Breeding for high nutrient use efficiency, encompassing utilization efficiency as well as acquisition efficiency and translocation efficiency, can help in transforming a greater proportion of this natural fertility into yield, especially if agroecosystem-specific characteristics are taken into account [77]. At present, today's conventional breeding is often focused on developing cultivars that transform synthetic inputs into yield under intensive management practices. Hildermann et al. [21] showed that conventionally bred wheat cultivars out-yielded organically bred cultivars under conventional management, but that there was no yield difference under organic conditions. Organic plant breeding can present an attractive alternative to the conventional model by developing cultivars that are suited to low-input conditions for use in developing countries, and developing cultivars that maximize rhizosphere interactions that transform the natural capital of the soil into yield should be a focus for conventional and organic systems alike.

The Green Revolution worked best where industrial techniques could be implemented, such as in parts of India and China, but it was less successful in parts of the African continent where these methods were impractical [33]. Pretty and Hine [78] point out that expanding sustainable agriculture in areas with low food security will do more to combat world hunger than in attempting to increase total food supply through industrialization of agriculture. Organic methods can thus substantially contribute to feeding the world, as they can increase yields where those increases lead to food security and self-sufficiency for the farmers and local communities. As organic agriculture seeks to set its research priorities for the future, however, the focus should also be on raising below-average yields in developed countries, by addressing the factors that most limit yields. Nitrogen availability in cereals and tubers, weeds in grain legumes, and insect pests in oilseed rape are a few examples of research needs that will help in substantially increasing organic yields. By establishing appropriate benchmarks, re-prioritizing research needs, and focusing on transforming natural resources rather than inputs, organic systems can raise yields and thus play an ever-greater role in global sustainable agriculture and food production in the future.

Author Contributions: Conceptualization: K.-P.W.; methodology: K.-P.W., J.E.S.; writing—original draft preparation: J.E.S. and K.-P.W.; writing—review & editing: J.E.S. and K.-P.W.; visualization: J.E.S. and K.-P.W.; supervision: K.-P.W.; funding acquisition: K.-P.W.

Funding: Parts of the content of this article originate from an extensive literature survey carried out in the "OK-Net Arable" project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 689687.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study, in the collection, analyses, or interpretation of data, in the writing of the manuscript and in the decision to publish the results.

References

1. Stanhill, G. The comparative productivity of organic agriculture. *Agric. Ecosyst. Environ.* **1990**, *30*, 1–26. [CrossRef]
2. Lotter, D.W.; Seidel, R.; Liebhardt, W. The performance of organic and conventional cropping systems in an extreme climate year. *Am. J. Altern. Agric.* **2003**, *18*, 146–154. [CrossRef]
3. Seufert, V.; Ramankutty, N.; Foley, J.A. Comparing the yields of organic and conventional agriculture. *Nature* **2012**, *485*, 229–232. [CrossRef] [PubMed]
4. Ponisio, L.C.; M'Gonigle, L.K.; Mace, K.C.; Palomino, J.; de Valpine, P.; Kremen, C. Diversification practices reduce organic to conventional yield gap. *Proc. R. Soc. B Biol. Sci.* **2015**, *282*, 20141396. [CrossRef] [PubMed]
5. de Ponti, T.; Rijk, B.; van Ittersum, M.K. The crop yield gap between organic and conventional agriculture. *Agric. Syst.* **2012**, *108*, 1–9. [CrossRef]
6. Badgley, C.; Moghtader, J.; Quintero, E.; Zakem, E.; Jahi Chappell, M.; Avilés-Vázquez, K.; Samulon, A.; Perfecto, I. Organic agriculture and the global food supply. *Renew. Agric. Food Syst.* **2007**, *22*, 86–108. [CrossRef]

7. Schrama, M.; de Haan, J.J.; Kroonen, M.; Verstegen, H.; van der Putten, W.H. Crop yield gap and stability in organic and conventional farming systems. *Agric. Ecosyst. Environ.* **2018**, *256*, 123–130. [CrossRef]
8. Eltun, R. The Apelsvoll cropping system experiment III. Yield and grain quality of cereals. *Nor. J. Agric. Sci.* **1996**, *10*, 7–22.
9. Eltun, R.; Korsaeth, A.; Nordheim, O. A comparison of environmental, soil fertility, yield, and economical effects in six cropping systems based on an 8-year experiment in Norway. *Agric. Ecosyst. Environ.* **2002**, *90*, 155–168. [CrossRef]
10. Kalinova, J.; Vrchotova, N. The influence of organic and conventional crop management, variety and year on the yield and flavonoid level in common buckwheat groats. *Food Chem.* **2011**, *127*, 602–608. [CrossRef]
11. Gabriel, D.; Sait, S.M.; Kunin, W.E.; Benton, T.G.; Steffan-Dewenter, I. Food production vs. biodiversity: Comparing organic and conventional agriculture. *J. Appl. Ecol.* **2013**, *50*, 355–364. [CrossRef]
12. Poutala, R.; Kuoppamaki, O.; Korva, J.; Varis, E. The Performance of Ecological, Integrated and Conventional Nutrient Management-Systems in Cereal Cropping in Finland. *Field Crops Res.* **1994**, *37*, 3–10. [CrossRef]
13. Cavigelli, M.A.; Teasdale, J.R.; Conklin, A.E. Long-term agronomic performance of organic and conventional field crops in the mid-Atlantic region. *Agron. J.* **2008**, *100*, 785–794. [CrossRef]
14. Larsen, E.; Grossman, J.; Edgell, J.; Hoyt, G.; Osmond, D.; Hu, S. Soil biological properties, soil losses and corn yield in long-term organic and conventional farming systems. *Soil Tillage Res.* **2014**, *139*, 37–45. [CrossRef]
15. Poudel, D.D.; Horwath, W.R.; Lanini, W.T.; Temple, S.R.; van Bruggen, A.H.C. Comparison of soil N availability and leaching potential, crop yields and weeds in organic, low-input and conventional farming systems in northern California. *Agric. Ecosyst. Environ.* **2002**, *90*, 125–137. [CrossRef]
16. Wortman, S.E.; Galusha, T.D.; Mason, S.C.; Francis, C.A. Soil fertility and crop yields in long-term organic and conventional cropping systems in Eastern Nebraska. *Renew. Agric. Food Syst.* **2012**, *27*, 200–216. [CrossRef]
17. Lotter, D.W. Organic agriculture. *J. Sustain. Agric.* **2003**, *21*, 59–128. [CrossRef]
18. Ryan, M.H.; Derrick, J.W.; Dann, P.R. Grain mineral concentrations and yield of wheat grown under organic and conventional management. *J. Sci. Food Agric.* **2004**, *84*, 207–216. [CrossRef]
19. Arncken, C.M.; Maeder, P.; Mayer, J.; Weibel, F.P. Sensory, yield and quality differences between organically and conventionally grown winter wheat. *J. Sci. Food Agric.* **2012**, *92*, 2819–2825. [CrossRef]
20. Bilsborrow, P.; Cooper, J.; Tetard-Jones, C.; Srednicka-Tober, D.; Baraniski, M.; Eyre, M.; Schmidt, C.; Shotton, P.; Volakakis, N.; Cakmak, I.; et al. The effect of organic and conventional management on the yield and quality of wheat grown in a long-term field trial. *Eur. J. Agron.* **2013**, *51*, 71–80. [CrossRef]
21. Hildermann, I.; Thommen, A.; Dubois, D.; Boller, T.; Wiemken, A.; Maeder, P. Yield and baking quality of winter wheat cultivars in different farming systems of the DOK long-term trials. *J. Sci. Food Agric.* **2009**, *89*, 2477–2491. [CrossRef]
22. Maeder, P.; Fliessbach, A.; Dubois, D.; Gunst, L.; Fried, P.; Niggli, U. Soil Fertility and Biodiversity in Organic Farming. *Science* **2002**, *296*, 1694–1697. [CrossRef]
23. Maeder, P.; Hahn, D.; Dubois, D.; Gunst, L.; Alfoeldi, T.; Bergmann, H.; Oehme, M.; Amado, R.; Schneider, H.; Graf, U.; et al. Wheat quality in organic and conventional farming: Results of a 21 year field experiment. *J. Sci. Food Agric.* **2007**, *87*, 1826–1835. [CrossRef]
24. Mayer, J.; Gunst, L.; Mäder, P.; Samson, M.; Carcea, M.; Narducci, V.; Thomsen, I.K.; Dubois, D. Productivity, quality and sustainability of winter wheat under long-term conventional and organic management in Switzerland. *Eur. J. Agron.* **2015**, *65*, 27–39. [CrossRef]
25. Posner, J.L.; Baldock, J.O.; Hedtcke, J.L. Organic and Conventional Production Systems in the Wisconsin Integrated Cropping Systems Trials: I. Productivity 1990–2002. *Agron. J.* **2008**, *100*, 253–260. [CrossRef]
26. Bulluck, L.R.; Brosius, M.; Evanylo, G.K.; Ristaino, J.B. Organic and synthetic fertility amendments influence soil microbial, physical and chemical properties on organic and conventional farms. *Appl. Soil Ecol.* **2002**, *19*, 147–160. [CrossRef]
27. Clark, M.S.; Horwath, W.R.; Shennan, C.; Scow, K.M.; Lantni, W.T.; Ferris, H. Nitrogen, weeds and water as yield-limiting factors in conventional, low-input, and organic tomato systems. *Agric. Ecosyst. Environ.* **1999**, *73*, 257–270. [CrossRef]
28. Cassman, K. Editorial response by Kenneth Cassman: Can organic agriculture feed the world—Science to the rescue? *Renew. Agric. Food Syst.* **2007**, *22*, 83–84.
29. Connor, D.J. Organic agriculture cannot feed the world. *Field Crops Res.* **2008**, *106*, 187–190. [CrossRef]

30. Kniss, A.R.; Savage, S.D.; Jabbour, R. Commercial Crop Yields Reveal Strengths and Weaknesses for Organic Agriculture in the United States. *PLoS ONE* **2016**, *11*, e0161673. [CrossRef]
31. Willer, H.; Lernoud, J. *The World of Organic Agriculture: Statistics and Emerging Trends 2018*; FiBL: Frick, Switzerland, 2018.
32. Hallmann, C.A.; Sorg, M.; Jongejans, E.; Siepel, H.; Hofland, N.; Schwan, H.; Stenmans, W.; Müller, A.; Sumser, H.; Hörren, T.; et al. More than 75 percent decline over 27 years in total flying insect biomass in protected areas. *PLoS ONE* **2017**, *12*, e0185809. [CrossRef] [PubMed]
33. Halberg, N.; Alroe, H.F.; Knudsen, M.T. *Global Development of Organic Agriculture: Challenges and Prospects*; CABI: Wallingford, UK, 2006.
34. Bouman, B.A.M.; van Keulen, H.; van Laar, H.H.; Rabbinge, R. The 'School of de Wit' crop growth simulation models: A pedigree and historical overview. *Agric. Syst.* **1996**, *52*, 171–198. [CrossRef]
35. de Wit, C.T. Resource use efficiency in agriculture. *Agric. Syst.* **1992**, *40*, 125–151. [CrossRef]
36. Rabbinge, R. The Ecological Background of Food-Production. *Ciba Found. Symp.* **1993**, *177*, 2–29. [PubMed]
37. van Ittersum, M.K.; Rabbinge, R. Concepts in production ecology for analysis and quantification of agricultural input-output combinations. *Field Crops Res.* **1997**, *52*, 197–208. [CrossRef]
38. van Ittersum, M.K.; Leffelaar, P.A.; van Keulen, H.; Kropff, M.J.; Bastiaans, L.; Goudriaan, J. Developments in modelling crop growth, cropping systems and production systems in the Wageningen School. *Neth. J. Agric. Sci.* **2002**, *50*, 239–247. [CrossRef]
39. Breland, T.A.; Eltun, R. Soil microbial biomass and mineralization of carbon and nitrogen in ecological, integrated and conventional forage and arable cropping systems. *Biol. Fertil. Soils* **1999**, *30*, 193–201. [CrossRef]
40. Gomiero, T.; Pimentel, D.; Paoletti, M.G. Environmental Impact of Different Agricultural Management Practices: Conventional vs. Organic Agriculture. *Crit. Rev. Plant Sci.* **2011**, *30*, 95–124. [CrossRef]
41. Kremen, C.; Miles, A. Ecosystem Services in Biologically Diversified versus Conventional Farming Systems: Benefits, Externalities, and Trade-Offs. *Ecol. Soc.* **2012**, *17*, 40. [CrossRef]
42. Gomiero, T.; Paoletti, M.G.; Pimentel, D. Energy and environmental issues in organic and conventional agriculture. *Crit. Rev. Plant Sci.* **2008**, *27*, 239–254. [CrossRef]
43. Mondelaers, K.; Aertsens, J.; van Huylenbroeck, G. A meta-analysis of the differences in environmental impacts between organic and conventional farming. *Br. Food J.* **2009**, *111*, 1098–1119. [CrossRef]
44. Rahmann, G. Biodiversity and Organic farming: What do we know? *Landbauforsch. Völkenrode* **2011**, *61*, 189–208.
45. Winqvist, C.; Bengtsson, J.; Aavik, T.; Berendse, F.; Clement, L.W.; Eggers, S.; Fischer, C.; Flohre, A.; Geiger, F.; Liira, J.; et al. Mixed effects of organic farming and landscape complexity on farmland biodiversity and biological control potential across Europe. *J. Appl. Ecol.* **2011**, *48*, 570–579. [CrossRef]
46. Tuck, S.L.; Winqvist, C.; Mota, F.; Ahnström, J.; Turnbull, L.A.; Bengtsson, J. Land-use intensity and the effects of organic farming on biodiversity: A hierarchical meta-analysis. *J. Appl. Ecol.* **2014**, *51*, 746–755. [CrossRef] [PubMed]
47. Thiele-Bruhn, S.; Bloem, J.; de Vries, F.T.; Kalbitz, K.; Wagg, C. Linking soil biodiversity and agricultural soil management. *Curr. Opin. Environ. Sustain.* **2012**, *4*, 523–528. [CrossRef]
48. Wang, S.; Li, Z.; Fan, G. Soil quality and microbes in organic and conventional farming systems. *Afr. J. Microbiol. Res.* **2012**, *6*, 5077–5085.
49. Cavigelli, M.A.; Mirsky, S.B.; Teasdale, J.R.; Spargo, J.T.; Doran, J. Organic grain cropping systems to enhance ecosystem services. *Renew. Agric. Food Syst.* **2013**, *28*, 145–159. [CrossRef]
50. Williams, A.; Hedlund, K. Indicators of soil ecosystem services in conventional and organic arable fields along a gradient of landscape heterogeneity in southern Sweden. *Appl. Soil Ecol.* **2013**, *65*, 1–7. [CrossRef]
51. Kirchmann, H.; Bergstrom, L. Do organic farming practices reduce nitrate leaching? *Commun. Soil Sci. Plant Anal.* **2001**, *32*, 997–1028. [CrossRef]
52. Benoit, M.; Garnier, J.; Anglade, J.; Billen, G. Nitrate leaching from organic and conventional arable crop farms in the Seine Basin (France). *Nutr. Cycl. Agroecosyst.* **2014**, *100*, 285–299. [CrossRef]
53. Evanylo, G.; Sherony, C.; Spargo, J.; Starner, D.; Brosius, M.; Haering, K. Soil and water environmental effects of fertilizer-, manure-, and compost-based fertility practices in an organic vegetable cropping system. *Agric. Ecosyst. Environ.* **2008**, *127*, 50–58. [CrossRef]

54. Paustian, K.; Lehmann, J.; Ogle, S.; Reay, D.; Robertson, G.P.; Smith, P. Climate-smart soils. *Nature* **2016**, *532*, 49–57. [CrossRef] [PubMed]
55. Berry, P.M.; Sylvester-Bradley, R.; Philipps, L.; Hatch, D.J.; Cuttle, S.P.; Rayns, F.W.; Gosling, P. Is the productivity of organic farms restricted by the supply of available nitrogen? *Soil Use Manag.* **2002**, *18*, 248–255. [CrossRef]
56. McNeill, A.M.; Eriksen, J.; Bergstrom, L.; Smith, K.A.; Marstorp, H.; Kirchmann, H.; Nilsson, I. Nitrogen and sulphur management: Challenges for organic sources in temperate agricultural systems. *Soil Use Manag.* **2005**, *21*, 82–93. [CrossRef]
57. Godfray, H.C.; Beddington, J.R.; Crute, I.R.; Haddad, L.; Lawrence, D.; Muir, J.F.; Pretty, J.; Robinson, S.; Thomas, S.M.; Toulmin, C. Food Security: The Challenge of Feeding 9 Billion People. *Science* **2010**, *327*, 812–818. [CrossRef] [PubMed]
58. Gunst, L.; Richner, W.; Maeder, P.; Mayer, J. DOC trial: Nutrient supply in winter wheat—Where is the deficit? *Agrarforschung Schweiz* **2013**, *4*, 74–81.
59. Pang, X.P.; Letey, J. Organic farming: Challenge of timing nitrogen availability to crop nitrogen requirements. *Soil Sci. Soc. Am. J.* **2000**, *64*, 247–253. [CrossRef]
60. Olesen, J.E.; Hansen, E.M.; Askegaard, M.; Rasmussen, I.A. The value of catch crops and organic manures for spring barley in organic arable farming. *Field Crops Res.* **2007**, *100*, 168–178. [CrossRef]
61. Olesen, J.E.; Askegaard, M.; Rasmussen, I.A. Winter cereal yields as affected by animal manure and green manure in organic arable farming. *Eur. J. Agron.* **2009**, *30*, 119–128. [CrossRef]
62. L-Baeckstrom, G.; Hanell, U.; Svensson, G. Baking quality of winter wheat grown in different cultivating systems, 1992-2001: A holistic approach. *J. Sustain. Agric.* **2004**, *24*, 53–79. [CrossRef]
63. Linnemann, L. *Abschlussbericht: Entwicklung einer prozessnahen Diagnostik der Mehlqualität und Teigbereitung zur Optimierten Herstellung von Backwaren aus Öko-Weizensorten*; BÖLN Project 06OE296; BÖLN: Darmstadt, Germany, 2010.
64. Smith, R.G.; Gross, K.L.; Robertson, G.P. Effects of crop diversity on agroecosystem function: Crop yield response. *Ecosystems* **2008**, *11*, 355–366. [CrossRef]
65. Valantin-Morison, M.; Meynard, J.M. Diagnosis of limiting factors of organic oilseed rape yield. A survey of farmers' fields. *Agron. Sustain. Dev.* **2008**, *28*, 527–539. [CrossRef]
66. Palmer, M.W.; Cooper, J.; Tétard-Jones, C.; Średnicka-Tober, D.; Barański, M.; Eyre, M.; Shotton, P.N.; Volakakis, N.; Cakmak, I.; Ozturk, L.; et al. 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. *Eur. J. Agron.* **2013**, *49*, 83–92. [CrossRef]
67. Finckh, M.R.; Schulte-Geldermann, E.; Bruns, C. Challenges to Organic Potato Farming: Disease and Nutrient Management. *Potato Res.* **2006**, *49*, 27–42. [CrossRef]
68. Möller, K.; Habermeyer, J.; Zinkernagel, V.; Reents, H. Impact and Interaction of Nitrogen and Phytophthora infestans as Yield-limiting and Yield-reducing Factors in Organic Potato (*Solanum tuberosum* L.) Crops. *Potato Res.* **2007**, *49*, 281–301. [CrossRef]
69. Bommarco, R.; Kleijn, D.; Potts, S.G. Ecological intensification: Harnessing ecosystem services for food security. *Trends Ecol. Evol.* **2013**, *28*, 230–238. [CrossRef] [PubMed]
70. Zhao, X.; Christianson, L.E.; Harmel, D.; Pittelkow, C.M. Assessment of drainage nitrogen losses on a yield-scaled basis. *Field Crops Res.* **2016**, *199*, 156–166. [CrossRef]
71. Gustafson, D.I.; Collins, M.; Fry, J.; Smith, S.; Matlock, M.; Zilberman, D.; Shryock, J.; Doane, M.; Ramsey, N. Climate adaptation imperatives: Global sustainability trends and eco-efficiency metrics in four major crops—Canola, cotton, maize, and soybeans. *Int. J. Agric. Sustain.* **2014**, *12*, 146–163. [CrossRef]
72. Firbank, L.G.; Elliott, J.; Field, R.H.; Lynch, J.M.; Peach, W.J.; Ramsden, S.; Turner, C. Assessing the performance of commercial farms in England and Wales: Lessons for supporting the sustainable intensification of agriculture. *Food Energy Secur.* **2018**, *7*, e00150.
73. Giuliano, S.; Ryan, M.R.; Véricel, G.; Rametti, G.; Perdrieux, F.; Justes, E.; Alletto, L. Low-input cropping systems to reduce input dependency and environmental impacts in maize production: A multi-criteria assessment. *Eur. J. Agron.* **2016**, *76*, 160–175. [CrossRef]
74. The Royal Society. *Reaping the Benefits: Science and the Sustainable Intensification of Global Agriculture*; RS Policy Document 11/09; The Royal Society: London, UK, 2009.

75. Wissuwa, M.; Mazzola, M.; Picard, C. Novel approaches in plant breeding for rhizosphere-related traits. *Plant Soil* **2009**, *321*, 409–430. [CrossRef]
76. Trivedi, P.; Schenk, P.M.; Wallenstein, M.D.; Singh, B.K. Tiny Microbes, Big Yields: Enhancing food crop production with biological solutions. *Microb. Biotechnol.* **2017**, *10*, 999–1003. [CrossRef] [PubMed]
77. Kubota, H.; Iqbal, M.; Quideau, S.; Dyck, M.; Spaner, D. Agronomic and physiological aspects of nitrogen use efficiency in conventional and organic cereal-based production systems. *Renew. Agric. Food Syst.* **2018**, *33*, 443–466. [CrossRef]
78. Pretty, J.; Hine, R. *Reducing Food Poverty with Sustainable Agriculture: A Summary of New Evidence*; University of Essex: Colchester, UK, 2001.