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The crop yield gap between organic and conventional agriculture

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ABSTRACT

A key issue in the debate on the contribution of organic agriculture to the future of world agriculture is whether organic agriculture can produce sufficient food to feed the world. Comparisons of organic and conventional yields play a central role in this debate. We therefore compiled and analyzed a meta-dataset of 362 published organic–conventional comparative crop yields. Our results show that organic yields of individual crops are on average 80% of conventional yields, but variation is substantial (standard deviation 21%). In our dataset, the organic yield gap significantly differed between crop groups and regions. The analysis gave some support to our hypothesis that the organic–conventional yield gap increases as conventional yields increase, but this relationship was only rather weak. The rationale behind this hypothesis is that when conventional yields are high and relatively close to the potential or water-limited level, nutrient stress must, as per definition of the potential or water-limited yield levels, be low and pests and diseases well controlled, which are conditions more difficult to attain in organic agriculture.

We discuss our findings in the context of the literature on this subject and address the issue of upscaling our results to higher system levels. Our analysis was at field and crop level. We hypothesize that due to challenges in the maintenance of nutrient availability in organic systems at crop rotation, farm and regional level, the average yield gap between conventional and organic systems may be larger than 20% at higher system levels. This relates in particular to the role of legumes in the rotation and the farming system, and to the availability of (organic) manure at the farm and regional levels. Future research should therefore focus on assessing the relative performance of both types of agriculture at higher system levels, i.e. the farm, regional and global system levels, and should in that context pay particular attention to nutrient availability in both organic and conventional agriculture.

1. Introduction

During the past 15 years organic agriculture has been on the rise in many parts of the world. However, despite this growth and the increased research, policy, media, and public attention, only a small share of the total agricultural land is under organic agriculture (e.g. 4% in Europe; Eurostat, 2007). The small market shares in industrialized countries may, from the consumer's perspective, be attributed to the price premiums at which organic food is marketed (Offermann and Nieberg, 2001), and from the producer's perspective to lower and more variable yields, limited demand for organic products, and the challenges of converting to organic production. The question is what the future can and should be for organic agriculture. Some argue it could become the conventional production system of the future, while others think it will remain by and large a fringe activity. Of the many issues that will determine its future role and position, those listed below, in random order, are in our opinion key issues.

First, organic agriculture's role will be determined by whether it can be or become economically competitive with conventional agriculture. This depends on productivity of organic agriculture, demand for its products, and on the extent to which consumer prices reflect costs of externalities associated with both production orientations, including costs of environmental and health externalities. This factor therefore also has a strong policy component. Second, competing claims on land and competition over other resources needed for food, feed, the bio-based economy and nature conservation play an essential role. Third, the relationship between the type of agriculture and biodiversity is relevant. Feeding the world with organic agriculture may require more land than with conventional agriculture and hence the area of natural and semi-natural ecosystems may be lower, whereas the quality of biodiversity on and around agricultural land may be higher. Fourth, as global food security has become a primary concern (Godfray et al., 2010), the productivity of organic agriculture and thus the contribution that it can make to feeding the world is an important factor. Moreover, productivity also significantly influences the

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other issues listed above. Finally, it is important to what degree non-organic production systems may evolve that can also meet objectives of our society currently being met by organic agriculture, for instance through 'ecologizing' conventional agriculture. Important factors in this respect are that some practices in conventional agriculture cause environmental damage, and that the scarcity of natural resources will also increasingly become a limitation in conventional systems.

Organic agriculture's productivity and potential contribution to feeding 9 billion people is not only a crucial question, but also one of its most contentious issues (Padel and Lampkin, 1994). Statements on the feasibility of feeding the world with organic agriculture are often directly or indirectly based on comparisons of organic and conventional yields. Stanhill (1990), using mostly data from before 1985, was probably the first to conduct an extensive literature review of organic–conventional comparative yield data. Penning de Vries et al. (1997) used crop growth simulations to conclude that organic agriculture can only produce enough food to feed 9 billion people at a global level (but not in every region) assuming diets with modest amounts or no animal proteins. On the basis of a review of comparisons of organic and conventional empirical yield data and simulations Lotter (2003) argues that, if meat consumption is reduced, large-scale conversion to organic agriculture is feasible without resulting in food shortages. More recently, Badgley et al. (2007) also used comparative yield data to argue that organic production can 'contribute substantially' to feeding the current and future world population, and that it may even be possible to reduce the agricultural land base. A result that was heavily disputed by Cassman (2007), Connor (2008), and Goulding et al. (2009), as they argued that the yield data used by Badgley et al. and the assumptions made on nutrient availability in organic systems, particularly nitrogen, were too optimistic.

Considering the central role that organic agriculture's productivity plays in the on-going debate on its future, and taking into account the criticism on previous research, the aim of our work was to undertake an extensive meta-analysis of the comparative performance of organic agriculture at the crop or field level. Animal production was not included directly, but indirectly through the inclusion of fodder crops. We attempted to obtain all published data to prevent any bias against or in favor of organic agriculture. But at the same time, we also critically assessed the quality of each data entry before including it into our analysis. We postulated the following hypothesis to add explanatory power to the comparative analysis: The closer conventional agriculture gets to the potential or water-limited yield level, the larger the yield gap will be between organic and conventional systems. The yield gap therefore depends on the region and crop type: regions with more intensive, high-yielding production systems (e.g. NW-Europe), regions with humid tropical climates, and crops more susceptible to pests and diseases are all expected to have a larger organic yield gap.

Central to this hypothesis is that yield potentials or potential yields of crops are defined as the maximum yield of a given cultivar under defined climatic conditions, while avoiding water and nutrient limitations and yield reductions due to pests and diseases (Lobell et al., 2009; Van Ittersum and Rabbinge, 1997). Yield limiting factors, in particular nutrient limitations, and pests and diseases generally play a larger role in organic agriculture; so the better these are lifted or controlled in conventional agriculture the larger the gap between organic and conventional yields may be. In this paper we refer to the relative yield of a crop grown with organic vs. conventional practices as the organic–conventional comparative yield; the smaller this relative yield the larger the yield gap of organic agriculture.

We finally discuss to what extent our findings are representative of the potential of both organic and conventional agriculture, which factors are important in upscaling organic production from the crop level to the cropping system, farm and global level, and to what extent there is scope for improving both organic and conventional yields. In our conclusions we briefly touch upon the implications of our findings for feeding the world.

2. Materials and methods

2.1. The literature search

A literature review of organic–conventional comparative yield data was undertaken in 2004 and updated in 2010. In 2004 WebSpirs was used as a portal to search the following literature databases: CAB Abstracts for 1984 through April 2004, AGRIS for 1986 through March 2004, AGRICOLA for 1984 through March 2004, and TROPAG & RURAL for 1975 through December 2003. The search term used was a complex Boolean search containing exactly or approximately (1) the term 'organic,' 'bio-organic,' 'ecological,' 'biological,' or 'bio-dynamic' adjacent to (2) the term 'agriculture,' 'farming,' 'husbandry,' 'system,' 'production,' or 'cropping' in combination with (3) terms equal or similar to the terms 'yield' and 'compare.' Publications had to contain yield data both on organic and on conventional agriculture. Although some publications containing comparative data on organic and conventional yields might have been missed, it was considered the best way of searching the more than 13,000 records that exactly or approximately contained the term 'yield' in combination with 'organic' and 'agriculture'. In 2010 OvidSP was used to search the following literature databases: CAB Abstracts for 2004 through 2010 week 41, AGRICOLA for 2004 through September 2010 and TROPAG & RURAL for 2004 through June 2010. The original search term used in 2004 in WebSpirs could not be repeated satisfactorily in OvidSP due to changes in the configuration of the software. Therefore, a new search term was used containing the thesaurus terms 'organic farming' (for CAB Abstracts and TROPAG & RURAL), or 'organic production' (for AGRICOLA), and 'crop yield', and the search term 'conventional'.

Since farming systems that adhere to organic standards are referred to in many different ways across the world, searching for 'organic agriculture' alone would not yield all relevant entries. Whereas the search term for organic was widened to account for this plurality, data were only included in further analysis if production practices appeared to be in line with the definition of organic agriculture used by the International Federation of Organic Agriculture Movements (IFOAM). In the *IFOAM Basic Standards for Organic Production and Processing* (IFOAM, 2005) the term 'organic' is defined as 'the farming systems and products described in the IFOAM Basic Standards.' These basic standards not only exclude artificial fertilizers, artificial pesticides and herbicides, and genetic engineering, but also include the maintenance of long-term soil fertility, compatibility with natural cycles, maintenance of agricultural and natural biodiversity, provision for animals to express their innate behavior, and promotion of local and regional production and distribution. This paper adheres to *this* definition, though we were often not able to verify every single item of the definition, for instance, items related to biodiversity and local and regional production and distribution. Sometimes it was also hard to verify the one related to the maintenance of long-term soil fertility. In this paper 'conventional agriculture' generally refers to any agricultural system in which chemical inputs are used. Conventional agriculture may at present have high external inputs in industrialized countries and low external inputs in developing countries, but it does not rule out any external inputs that may be beneficial for its productivity.

2.2. Screening of publications

The 2004 literature search yielded 641 records and the 2010 search, after deduplication, 381 records, bringing the total to 1022. After screening these abstracts, 314 records were kept (130 and 184, respectively). Of these, the full text versions were obtained from major libraries, on-line journals, and through email correspondence with the authors and organizations concerned. If certain records contained valuable information in the abstract given in the literature database, but were impossible to acquire or translate, comparative yields were directly taken from the abstracts (less than 5% of the references).

Both during screening of the abstracts and in the process of studying the full text versions, publications were discarded for one or more of the following reasons: data pertaining to non-food and non-fodder crops, the absence of comparative yield data even though the record contained the search terms of the query; duplication of the same publication in multiple databases; multiple publications reporting on the same trials/datasets; yield data being outdated; unrepresentative yield levels; insufficient information on treatments and/or yield data; measurements on individual plants rather than plots of given areas; and overall data quality. Since both conventional and organic systems continuously evolve, data from before 1985 were considered outdated and not included, with the exception of long-term trials extending significantly beyond that year. Yield data for industrialized countries were considered unrepresentative if conventional yields appeared to be far below the regional average, unless this was caused by factors that can also occur in real farming situations, such as pests, diseases or droughts. For developing countries 'unrepresentative' implied conventional yield levels that seemed to be far below yields achieved under best farmers' management. Overall data quality refers to any other aspect of the data that makes the data unrepresentative of the potential of one or both systems, such as certain experimental treatments (e.g. drastically reducing the availability of a certain plant nutrient) or in case the organic and conventional yield data in a data entry were from very different soils or climates. The screening resulted in ca. 135 useful publications (ca. 45 from the 2004 literature search, and ca. 90 from the 2010 search) of which data were inserted into our database.

2.3. Other sources

Comparative yield data that were analyzed by Badgley et al. (2007) and Goulding et al. (2009) were added to our database if they met our data quality criteria and if they had not been selected already, which was only the case for four publications cited by Goulding et al. and none of those used by Badgley et al. Of the total of 293 yield data entries used by Badgley et al. (2007) only 42 entries (14%) met our data quality criteria. Of the 13 references containing yield data proposed by Goulding et al. (2009) about half met our data quality criteria. Of our data, about 85% were new data, i.e. not yet analyzed by either Badgley et al. or Goulding et al. The majority of the developing countries data in Badgley et al. either concerned rice data from the System of Rice Intensification (SRI) production systems or data from Pretty et al. (2003). As SRI is heavily debated (e.g. Dobermann, 2004; Uphoff et al., 2008) we only included SRI data from peer-reviewed journals. Although the data from Pretty et al. are valuable in their own right, their data were excluded as the aim of their research was to develop improved low external input systems (the use of chemical inputs was minimized but not fully abandoned); their aim was not to compare organic and conventional systems. In some publications more than one conventional system is compared with organic agriculture, e.g. a 'regular' conventional system and an Integrated Crop Management (ICM) or 'reduced input' conventional system. Here we sometimes deviated from other publications (e.g. Badgley et al., 2007) on comparative yields in that we have taken the conventional system with the highest yield, irrespective of whether this concerned 'regular' conventional or ICM conventional. Likewise, some publications compare multiple organic systems (e.g. 'regular' organic and biodynamic organic). In these cases we also took the organic system with the highest yield for comparison with the conventional system.

The development of organic agriculture has, probably more so than conventional agriculture, been driven by practitioners and grassroots organizations that are less embedded in established international agricultural research and development circles. In order to capture data unpublished in the peer-reviewed publications included in the literature databases, and data from recent research and ongoing long-term trials, more than 300 individuals and organizations involved in research and development for organic agriculture across the world were contacted by email in 2004 with a request for comparative organic–conventional yields. Some 60 responses were received. While these contained valuable information and links to publications, only 10 contained additional yield data not yet retrieved from the literature databases. For this reason this procedure was not repeated in 2010. The literature searches and the survey together generated ca. 150 useful publications, many of which contained data for multiple crops, locations, and/or experiments. The yield dataset is available upon request.

2.4. Statistical analyses

We tested differences between crop groups and regions using an analysis of variance and the non-parametric method Kruskal–Wallis, respectively. To test the hypothesis that the organic yield gap increases with the yield level of the conventional system, we analyzed data of five crops, being four crops for which we had most data entries: wheat, corn, barley and potatoes; and the leguminous crop with the highest number of entries: soybean. The number of entries for wheat was sufficiently large for a more detailed analysis, i.e. we analyzed not only all wheat data, but also a subset of wheat data from experimental farms only. For each crop we plotted the relative yield as a function of the conventional yield and computed linear regression lines. We also performed an exponential regression analysis between the organic yield level (y) and the conventional yield level (x): $y = a + b * x^c$ and tested whether c is significantly smaller than 1 (note that if $c = 1$ the exponential model is similar to the linear model). We finally compared for each crop the mean relative yield associated to the n lowest conventional yield entries with the mean relative yield associated to the n highest conventional yield entries, using the student t-test. To this end we sorted the data for each crop by the conventional yield level, and roughly divided the data in three subsets: high, medium, and low conventional yields. We then compared the mean relative yield belonging to the high conventional yield subset with the mean relative yield belonging to the low conventional yield subset. The total number of data entries per crop used in this analysis slightly differed from that used elsewhere in the paper, as some yield data were given in units that could not be converted to t/ha (e.g. yield per harvested row length).

3. Results

3.1. Overview of the data set

The meta-analysis resulted in the inclusion of 362 paired sets of organic–conventional yield data in our database. The data cover 43 countries worldwide, with the majority of data (85%) coming from Europe and North-America: Europe (180 sets), North-America

Table 1
Number of data entries, averages and ranges of the organic–conventional relative yields of selected crop groups and crops. Averages of crop groups followed by at least one common letter were not significantly different according to the test for multiple comparisons of Bonferroni ($P < 0.05$). Within each crop group crops are listed in order of relative yield.

Crop	n[a]	Relative yield		Remarks
		Average (%)	Range (%)	
Cereals	156	79 ab	40–145	
Rice (*Oryza sativa* L.)	7	94	86–105	
Corn (*Zea mays* L.)	34	89	60–141	Almost all in North-America (26); some other countries (8)
Oats (*Avena sativa* L.)	14	85	40–145	–
Other cereals	8	81	45–111	Triticale (3), unspecified cereals (3), buckwheat (1), sorghum (1)
Rye (*Secale cereale* L.)	7	76	63–104	Data comprise spring, fall, and winter rye
Wheat (*Triticum* spp. L.)	66	73	40–130	Data comprise spring, summer, winter, and durum wheat
Barley (*Hordeum vulgare* L.)	20	69	46–105	Data comprise spring, summer, and winter barley
Root and tuber crops	24	74 a	37–114	
Potato (*Solanum tuberosum* L.)	21	70	37–114	All from European countries
Other root and tuber crops	3	105	89–114	Sweet potato (2), sugar beets (1)
Pulses	39	88 b	48–126	
Soybean (*Glycine max* L.)	16	92	74–126	Virtually all from USA (14)
Other pulses	12	91	67–121	Green beans (4), and other pulses.
Pea (*Pisum sativum* L.)	9	85	67–100	
Oilseed crops	11	74 ab	41–114	High variation
Other oilseed crops	4	82	50–110	Rapeseed (2), canola (1), safflower (1)
Sunflower (*Helianthus annuus* L.)	3	77	54–114	Almost all from North-America
Flax seed (*Linum usitatissimum* L.)	4	65	41–86	All from Canada
Vegetables	74	80 ab	21–140	
Carrots (*Daucus carota* L.)	7	89	75–106	Includes winter carrots (2x). Europe (6), Canada (1)
Lettuce (*Lactuca sativa* L.)	8	86	71–101	Argentina (3), USA (2), Turkey (1), Spain (1), Netherlands (1)
Tomato (*Lycopersicon esculentum* Miller)	20	81	21–140	USA/Canada (7), Europe (5), Latin America (3), Asia (2), Tunisia (2), Turkey (1)
Other vegetables	40	77	27–122	18 different crops among which cabbage (5), onions (5), bell pepper (4), pac choi (4). Mostly from Europe and North-America
Fruits	25	72 a	20–94	
Other fruits	14	78	50–94	Grapes, melons, apricot, blackcurrant, cherry, kiwi, peach, pear from Europe (9), Turkey (2), USA (2), New Zealand (1)
Apple (*Malus* spp. Miller)	6	69	44–92	44–46% in Netherlands (2); 70–92% Germany (1), Switzerland (1), and USA (2)
Strawberries (*Fragaria* spp. L.)	5	59	20–92	20–72% USA (4), 92% Jordan (1)
Other food crops	2	92	78–106	Coffee, ginger
Fodder crops	33	86 ab	42–177	
Grass-clover	8	89	77–108	All data from Europe
Other fodder crops	25	85	42–177	Includes mixed grain-legumes, alfalfa, fodder beets, silage and others. Most from Europe
Total	362	80	20–177	–

[a] n = the number of yield data entries; other food crops had too few entries for a statistical analysis.

(126), Asia (22), Middle-East & North-Africa (14), Australia and New Zealand (12), and Latin-America (8). A total of 67 crops is represented (Table 1). Cereals comprise 43% of all data with 156 entries, followed by vegetables, pulses, fodder crops, fruits, root and tuber crops, oilseed crops, and other food crops. Only 9% of the data are from developing countries. Roughly two-thirds of the data are from experimental farms and one-third from commercial farms. Ca. 18% of all data were from long-term data collection (>5 years). Ca. 16% of the data were from on-farm statistics. The criterion for identification as ‘on-farm statistics’ was that several/many organic farms in a geographical area are compared to several/many conventional farms in the same/similar geographical area or to known averages in that geographical area. We distinguished between on-farm statistics (several/many farms in the sample) and on-farm data (a few selected farms in the sample, often paired farms). If data from few farms were given, but the data are statistical (i.e. not a selection of farms, but all farms in an area known to the institution are included in the data) we have included these under on-farm statistics. The data entries also varied greatly in the size of the area from which individual data were collected for a given data entry (in case of data entries that are an average of multiple data points in a given area), acreage per entry, and the number of farms, fields, or plots per entry. Also, not all crops are equally important in terms of their contribution to human nutrition and energy intake. For all of the above reasons it may be argued that certain data should be given more weight in the calculations, but given the difficulty of establishing unambiguous criteria for doing so, we gave all entries the same weight.

3.2. Relative yields

The relative yield of organic agriculture was determined separately for each data entry by dividing the (average) organic yield for that entry by the (average) conventional yield for that entry. It was expressed as a percentage. The resulting percentages were averaged for each crop or crop group and for all data (Table 1). On average, organic yields are 80% of those obtained under conventional agriculture; the standard deviation was 21%. When excluding relative yields higher than 120% ($n = 13$), which affect the average disproportionally in favor of organic agriculture because conventional agriculture is in the denominator, the average relative yield is 79% (standard deviation 21%). The average relative yield of the pre-2004 data (data not shown) is the same as that for all data including the 2004–2010 update. This indicates that the relative performance of organic agriculture has, on average, not substantially changed in the past years.

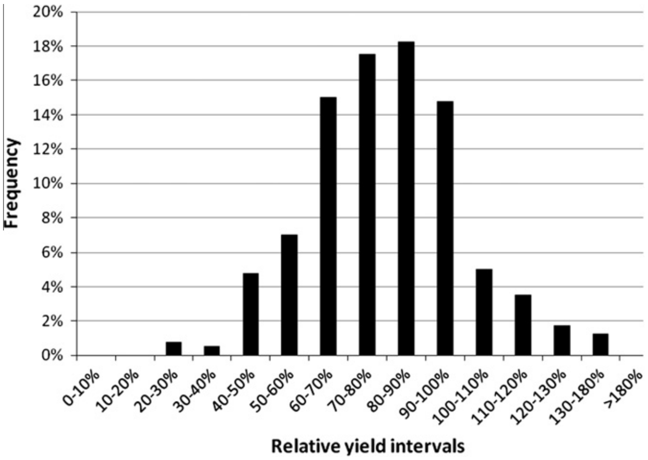

Fig. 1. Frequency of occurrence of relative yields of organic vs. conventional agriculture, grouped in 10% intervals.

The relative yield data were grouped in 10% intervals (Fig. 1). Apart from a few outliers >150%, the relative yields are roughly normally distributed with a peak for the 70–80% and 80–90% intervals. Thirty-six percent of all data had a relative yield between 70% and 90%. Sixty-six percent of all data had a relative yield between 60% and 100%.

3.3. Differences between regions, crops, and type of data

The relative yield differs ($P < 0.001$) across regions of the world; the relative yield was lowest in Northern Europe (70%) and highest in Asia (89%) (Table 2). When analyzing data from the Netherlands and Denmark, countries with high external input agriculture, which brings actual yields relatively close to the genetic yield potential, we found a small but statistically significant difference in the relative yield for these countries vs. the rest of the data. Under tropical conditions and in developing countries relative yields tended to be higher when compared to the rest of the data, but the difference was not statistically significant. Relative yields at individual commercial farms are significantly higher than those in trials (88% vs. 81%). Relative yields for on-farm statistics were lower than those from both trials and individual commercial farms.

Differences between crop groups were statistically significant ($P = 0.01$). Cereals and vegetables have the same relative yield as the overall average (Table 1). Pulses and fodder crops have slightly higher values (88% and 86%, respectively). Root and tuber crops, oilseed crops (both 74%) and fruits (72%) have relative yields lower than the average. Testing multiple comparisons (Bonferroni correction) resulted in a statistically significant difference between fruits (72%) and pulses (88%) only. At the individual crop level rice, soybeans, the category ‘other pulses’, corn, carrots, and grass-clover (in order of decreasing relative yield) perform considerably better than the average in terms of relative yields (Table 1). The categories ‘other root and tuber crops’ and ‘other food crops’ also have a high relative yield, but these values are based on only few data entries. Barley, apple, the category ‘other fodder crops’, flax seed, and strawberries are among the crops that perform considerably below average. Some of these have relatively small sample sizes.

3.4. Is the yield gap of organic agriculture positively correlated with the conventional yield?

Our hypothesis was that the closer conventional agriculture gets to the potential or water-limited yield, the larger the yield gap between organic and conventional systems will be. For all crops and the wheat subset the regression line pointed at decreasing relative yields as conventional yields increase (Fig. 2). In other words, the yield gap between organic and conventional agriculture tended to increase as conventional yields increase. However, these trends are only statistically significant for wheat (all data) and soybeans; for the same crops the mean relative yield associated to the n lowest conventional yield entries was significantly higher than the mean relative yield associated to the n highest conventional yield entries ($P < 0.001$; and $P < 0.025$ respectively – Table 3). The exponential component of the regression was non-significant for all crops/subsets.

Table 2
Average relative yields of organic practices vs. conventional for different regions and types of data. Averages of regions followed by at least one common letter did not differ significantly according to the Kruskal–Wallis test for multiple comparisons corrected with the Bonferroni factor ($P < 0.05$).

Category of differentiation	n[a]	Relative yield (%)	Remarks
Overall	362	80	
Asia	22	89 a	Many from India, rest from five other countries
Central Europe	16	88 ac	Switzerland, Austria
Middle-East & North-Africa	14	85 ac	Incl. Turkey (7) and four other countries
North-America	126	84 ad	USA, Canada
Southern Europe	34	81 ab	European Mediterranean countries
Eastern Europe	18	80 ab	Post-communist economies, excl. Albania, Croatia
NW-Europe	78	73 bc	Germany, Denmark, Netherlands, GBR
Latin-America	8	73 ab	Vegetables (7), coffee (1)
Australia & New Zealand	12	73 bcd	
Northern Europe	34	70 b	Finland, Sweden, Norway
Netherlands & Denmark vs. rest	50 vs. 312	74 vs. 81	High external input countries. $P = 0.019$
Developing vs. developed countries	33 vs. 296	84 vs. 79	$P = 0.13$ (ns)
Tropical vs. non-tropical countries	29 vs. 327	86 vs. 80	$P = 0.12$ (ns)
Long-term vs. Short-term	66 vs. 249	84 vs. 80	Long = > 5 years. Short = 1–5 years. $P = 0.17$ (ns)
On-farm vs. trial	42 vs. 226	88 vs. 81	$P = 0.038$
On-farm statistics	59	76	

[a] Categories do not always add up to the total number of entries, as for some data it was uncertain to which category they belong. There may also be partial overlap of categories.

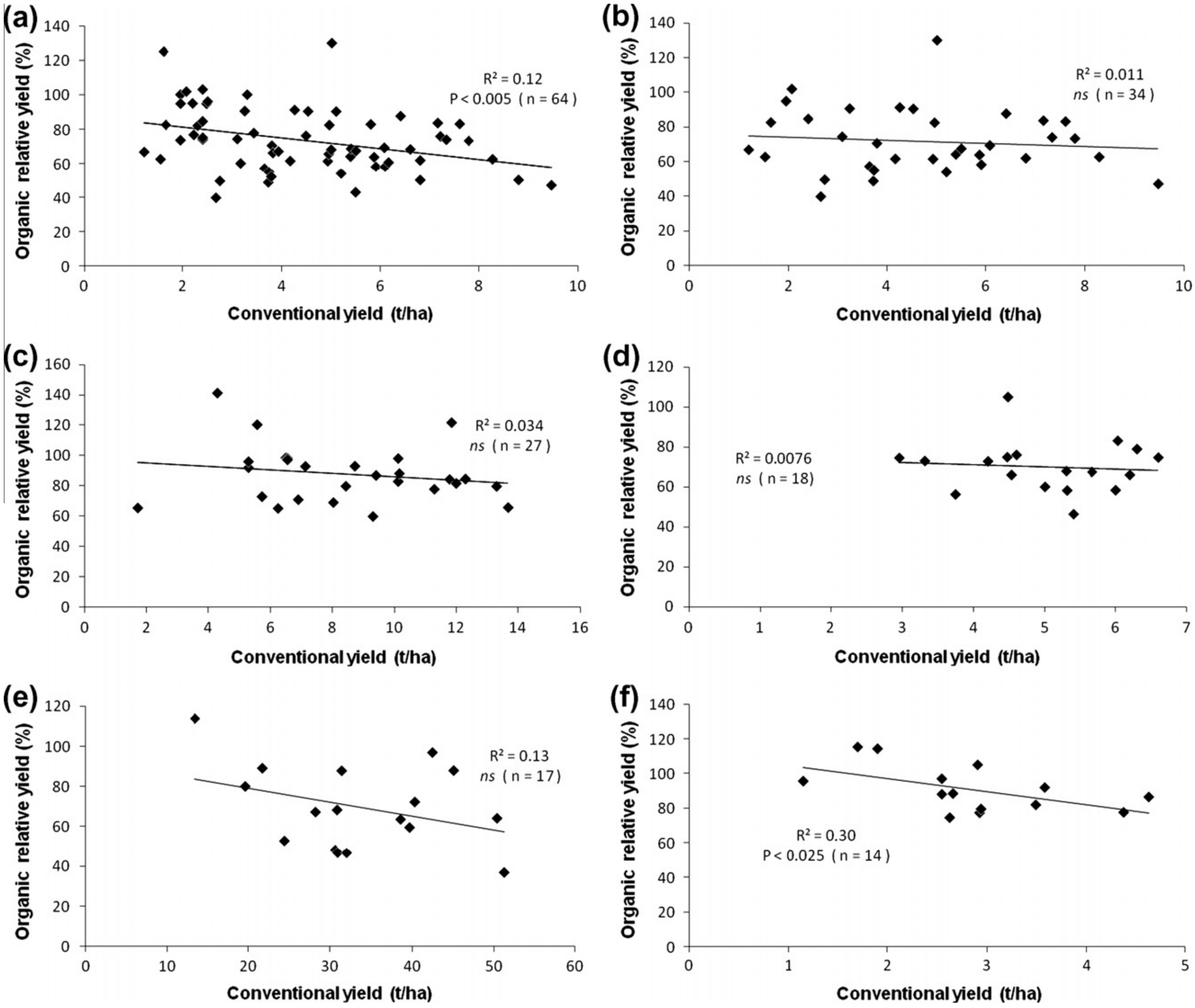

Fig. 2. The relative yield of organic agriculture as a function of the absolute conventional yield, including linear regression line, R^2-value and its P-value, and number of data points for (a) all wheat data, (b) wheat data from experiments, (c) corn, (d) barley, (e) potatoes, and (f) soybeans.

4. Discussion

4.1. Relative yield of organic vs. conventional practices

The average organic–conventional relative yield that we found (80%) takes an intermediate position between empirical data presented by other authors. Stanhill (1990) found a value of 91%. Most of his data were from the 1970s and some were as old as from the 1930s. Badgley et al. (2007) found a value of 130%. This value, however, was distorted. Many of their data for developing countries had relative yields far greater than 100%. As the conventional yields were far below best practice, these data do not give a fair representation of the potential relative performance of organic and conventional agriculture. On the basis of 25 data entries for wheat, Goulding et al. (2009) found a value of 65%. However, relatively many of their entries were from before 1985.

Yield gaps of organic agriculture differed between crops and between regions (Tables 1 and 2). However, it is difficult to provide explanations for the differences. For instance, contrary to what may be expected on the basis of the higher disease and pest incidence in the (humid) tropics, the yield gap is comparatively small for Asia and for developing countries and tropical conditions in general. The comparatively low organic yield gap for soybeans, the category 'other pulses' and for grass-clover may in part be explained by their ability to fix nitrogen. Since most of our corn data are from North-America where corn is grown in rotation with soybeans, this may also in part explain the comparatively good performance of corn. We must, however, be cautious in drawing conclusions on causal relationships between the factors mentioned and the yield gap. Factors were sometimes confounded in our data, as for instance some crops are only grown in certain regions and it is not possible to determine which of the factors are the explanatory variables.

Our finding that there is on average hardly any difference in the relative yield between long-term and short-term experiments is in line with the mixed results of others, reporting both organic yield increases with time (Gliessman et al., 1996; Neera et al., 1999; Mäder et al., 2002; Petersen et al., 1999; Tamaki et al., 2002) as well as some decreases (e.g. Mäder et al., 2002) before a stabilization of yields occurred (Petersen et al., 1999).

Our results indeed pointed, to some extent, at an increase in the yield gap between organic and conventional agriculture as conventional yields increase. Stanhill (1990) also found this relation in long-term field plot experiments, although he did not formulate the hypothesis. However, the trend in our data was only statistically significant for two out of five of the crops that we tested: wheat (all data) and soybeans (Fig. 2, Table 3). The fact that organic yield gaps were on average 8% higher in The Netherlands and Den-

Table 3

Results of the Student *t*-test to estimate whether the yield gap increases as the conventional yield level increases. A low *P*-value indicates a statistically significant result of increasing yield gap with increasing conventional yields. *n* (total) = the total number of entries per crop used in this analysis; *n* (subset) = the number of entries in the subsets of highest/lowest conventional yields; *n* lowest, respectively, *n* highest = the mean relative yield belonging to the *n* lowest and *n* highest conventional yield entries for the given crop, respectively. *P* denotes the probability of the observed difference under the assumption of no difference in relative yields between the *n* lowest and *n* highest observations.

Crop	*n*		Mean relative yield		Difference (%)	*P*
	Total	Subset	*n* Lowest (%)	*n* Highest (%)		
Wheat – All data	64	15	86	67	−19	*P* = 0.0006
Wheat – research data	34	10	75	70	−5	*P* = 0.27 (ns)
Corn	27	8	94	85	−9	*P* = 0.23 (ns)
Barley	18	6	76	71	−5	*P* = 0.28 (ns)
Potatoes	17	6	75	70	−5	*P* = 0.34 (ns)
Soybeans	14	4	105	84	−21	*P* = 0.010

mark (with relatively high conventional yields) than in the other countries may also give some support to the hypothesis. However, contrary to what might be expected under our hypothesis, crops which showed the largest yield gap were not always among those that are most susceptible to pests and diseases (e.g. barley and flax seed). Interestingly, the crop which showed the clearest and statistically most significant relationship between the yield gap and the conventional yield level was soybean, even though this crop does not depend on fertilizer nitrogen. This increasing yield gap with higher conventional yields may be due to relatively high yield losses as a result of pests and diseases and/or to P limitations in organic systems. However, further research would be needed to draw firm conclusions in relation to this hypothesis; such research should aim at quantifying yield potentials for different crops and regions to allow a more profound testing of the hypothesis.

4.2. Factors important in upscaling organic production

Our analysis of yield gaps was at crop and field level. The results cannot readily be upscaled to higher system levels. Organic agriculture relies for its crop nutrients on natural soil fertility, legume crops, compost and manure. When legumes are grown as a green manure crop instead of a food or fodder crop to add nitrogen to the system, the average yield of food and fodder crops over the entire rotation is reduced. Yield data of the entire cropping or farming system should in those cases be adjusted accordingly, as was done for instance by Korsaeth (2008) and Taube et al. (2005). Quite often, however, legumes serve as food or fodder crop, in which case nitrogen fixation is not at the cost of overall food production and part of the fixed nitrogen is made available to other crops in the rotation (e.g. Wander et al., 2007; Welsh et al. 2009). In those cases, still additional nitrogen (and other nutrients) must be added to the cropping or farming system through other sources to make it possible to attain relatively high yields for the non-legume crops in the rotation. We did not perform an in-depth analysis of this issue for our data, but it may be assumed that at crop rotation or farm level at least some organic yields in our database would have to be reduced to account for non-productive green manure crops.

Another important source of nutrients in organic farming is manure. Some of the successful organic production systems are dependent on relatively large manure applications imported from outside the farming system (e.g. Clark et al., 1999; Jaim and Al Kader, 1998). If these systems were to be adopted more widely in a given region, manure may become a limiting resource, thus reducing overall organic food crop yields (e.g. Jaim and Al Kader, 1998). By applying manure to food crops, rather than returning manure to fodder-producing areas, fodder yields may also decrease due to soil nutrient depletion.

Conventional systems rely on external inputs to maintain soil fertility. Some of these external sources are finite (e.g. phosphorus and some micro nutrients) which may become a threat to this type of agriculture in the long run. Also, future energy scarcity may influence farmers' access to fertilizer nitrogen through increases in prices. Phosphorus depletion may affect conventional *and* organic agriculture. In conclusion, a thorough analysis of the productivity of organic and conventional agriculture at crop rotation, farm and regional level is needed that accounts for the availability of crop nutrients. Since maintaining soil fertility is generally a greater challenge for organic systems (e.g. Nguyen and Haynes, 1995), we hypothesize that at higher system levels yield gaps of organic agriculture may be larger than 20%.

Another issue in the upscaling of our results is that data from developing countries are highly underrepresented in our dataset. Often current conventional yield levels from developing countries are well below the potential or water-limited level for that system (Lobell et al., 2009). Yield reductions due to pests and diseases are greater and more difficult to prevent in the humid tropics, and nutrients are limiting in for instance Africa (e.g. Giller et al., 2011; Tittonell et al., 2008). It remains to be investigated how this will affect the overall yield gap of organic agriculture.

4.3. Scope for improvement: can we increase organic and conventional yields?

The publications and other sources we reviewed, compared organic and conventional yields both from experimental and commercial farms. A key question in relation to these data, and hence to our findings, is whether the average relative yield of organic agriculture compared to conventional agriculture that we found (80%) is an underestimation or an overestimation of the potential of organic agriculture. In line with our data quality requirements, we discarded data from industrialized countries if conventional yields were far below the regional average, and data from developing countries if conventional yields appeared to be far below yields achieved under best farmers' management. However, often regional averages and best farmers' management are below the production potential for given locations. From experiments, crop models and other regions we know that yields could be significantly higher if management were optimized (Lobell et al., 2009; Penning de Vries et al., 1997). Therefore, the conventional yield levels that we have analyzed are often an underestimation and offer scope for improvement. Yet, one may also argue that environmental restrictions and legislation (such as in the European Union) will reduce acceptable input levels and hence eventually affect future yield levels in conventional systems.

Likewise, it may be argued that there is scope for improving yields in organic agriculture. Proper farming system design is crucial in optimizing organic agriculture. Organic system design is more than omitting chemical inputs and plugging in some organic practices. One has to rethink rotational designs, crop compositions, varieties, inclusion or exclusion of livestock, livestock species and breeds, and many other system elements. Murphy et al. (2007) showed that varieties used in conventional agriculture are not always the highest yielding varieties in organic systems, something also proposed by Wolfe et al. (2008). A key element in system design is the inclusion of leguminous crops in the rotation without reducing the number of productive crops. Examples are the inclusion of grass-clover pastures into rotations, undersowing, and for Europe the (re)introduction of fodder peas. In these cases an adequate P supply through other sources is essential. The nutrient supply to organic crops relies more than conventional crops on better closing of nutrient cycles. Newly developed and hygienic modern technologies make it possible to bring nutrients contained in human urine and feces back into the nutrient cycle (e.g. Adam et al., 2009; Johnston and Richards, 2003), or to re-use nutrients through compost from household waste and residues from biogas production. As organic farmers have fewer means (no mineral fertilization, herbicides and pesticides) to manage their system, organic agriculture requires greater expertise (Clark et al., 1999; Mühlebach and Mühlebach, 1994) and more time to optimize farm management (Martini et al., 2004). Organic agriculture is also more so than conventional agriculture dependent on system properties that take many years to develop (e.g. equilibria between pests and diseases and their natural antagonists). One may argue that further research into organic agriculture and organic practices, which has so far only been a fraction of that on conventional agriculture (Lotter, 2003), will increase yields (Lampkin, 1994; Mäder et al., 2002) and their sustainability. Such research may, however, also point at inherent limitations in terms of nutrient availability in organic systems as argued in Section 4.2.

5. Conclusions

Our review and meta-analysis of yield data comparing organic and conventional agriculture showed that currently organic yields of individual crops are on average 80% of conventional yields. The analysis of 362 datasets also showed a high variation of the yield gap of organic agriculture (standard deviation 21%). Some of this variation seems systematic. Relative yields differed between crops with e.g. soybean, some other pulses, rice and corn scoring higher than 80% and wheat, barley and potato scoring lower than 80%. Most regions have relative yields fairly close to the overall average, but Asia and Central Europe had comparatively higher and Northern Europe lower relative yields. In Denmark and The Netherlands, countries with very intensive agricultural systems, the organic–conventional yield gap was somewhat larger. As the different factors were sometimes confounded in our meta-analysis, these findings should be seen as an indication of possible causes rather than firm causal relationships.

Our findings gave some support to our hypothesis that the organic–conventional yield gap is higher when conventional yields are high, but the relationship and hence the evidence underpinning our hypothesis was not strong. Further research is needed that quantifies potential and water-limited yields of conventional farming for locations from which empirical data were obtained. This allows for examining the rationale behind this hypothesis, i.e. when in a specific case conventional yields are high (relative to the potential or water-limited level), nutrient stress must, as per definition of the potential or water-limited yield levels, be low and pests and diseases well controlled, which are conditions more difficult to attain in organic agriculture.

Several factors have been discussed in relation to how representative these data are of the potential of both systems, and whether 80% is an underestimation or overestimation of the potential of organic systems. When upscaling our results at the field and crop level to the crop rotation, farm and regional level, a critical issue will be to which extent sufficient nutrients can be supplied in organic systems to maintain the yield levels, as reported in our database for the crop level, at higher system levels. This relates in particular to the role of legumes in the rotation and the farming system, and to the availability of (organic) manure at higher system levels. We hypothesize that at higher system levels average yield gaps of organic agriculture may be larger than 20%. The above issues, as well as the underrepresentation of data from developing countries, call for more quantitative and empirical research at higher system levels.

For a fair comparison of the potential of organic and conventional agriculture we propose that data must be used from well-documented, mature and optimally designed farming systems from across the world, that take into account soil fertility maintenance, the inclusion of legumes in rotations and the availability of manure at the system level, and that make use of the best available knowledge and technologies to reduce the impact of water and nutrient stress and of pests and diseases in both organic and conventional systems. The systems must be compared at rotation level using a unit (e.g. grain equivalents) that allows for comparing farming systems with different crop compositions.

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