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Crop yield gap and stability in organic and conventional farming systems

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ABSTRACT

A key challenge for sustainable intensification of agriculture is to produce increasing amounts of food and feed with minimal biodiversity loss, nutrient leaching, and greenhouse gas emissions. Organic farming is considered more sustainable, however, less productive than conventional farming. We analysed results from an experiment started under identical soil conditions comparing one organic and two conventional farming systems. Initially, yields in the organic farming system were lower, but approached those of both conventional systems after 10–13 years, while requiring lower nitrogen inputs. Unexpectedly, organic farming resulted in lower coefficient of variation, indicating enhanced spatial stability, of pH, nutrient mineralization, nutrient availability, and abundance of soil biota. Organic farming also resulted in improved soil structure with higher organic matter concentrations and higher soil aggregation, a profound reduction in groundwater nitrate concentrations, and fewer plant-parasitic nematodes. Temporal stability between the three farming systems was similar, but when excluding years of *Phytophthora* outbreaks in potato, temporal stability was higher in the organic farming system. There are two non-mutually exclusive mechanistic explanations for these results. First, the enhanced spatial stability in the organic farming system could result from changes in resource-based (i.e. bottom-up) processes, which coincides with the observed higher nutrient provisioning throughout the season in soils with more organic matter. Second, enhanced resource inputs may also affect stability via increased predator-based (i.e. top-down) control. According to this explanation, predators stabilize population dynamics of soil organisms, which is supported by the observed higher soil food web biomass in the organic farming system.We conclude that closure of the yield gap between organic and conventional farming can be a matter of time and that organic farming may result in greater spatial stability of soil biotic and abiotic properties and soil processes. This is likely due to the time required to fundamentally alter soil properties.

1. Introduction

During the second half of the 20th century, agricultural yields have increased through improved crop varieties, use of pesticides, and mineral fertilizers (Robertson et al., 2014; Vitousek et al., 2009; FAO, 2013; Zhang et al., 2013). However, land use intensification has also led to loss of soil organic matter and soil biodiversity (FAO, 2013). With ongoing intensification, these processes are expected to continue in most parts of the world (Lal, 2004; Foley et al., 2005), which may reduce the buffering capacity of soils against adverse conditions (Bot and Benites, 2005; De Vries et al., 2013), resulting in enhanced sensitivity to extreme weather effects, pest and pathogen outbreaks, as well as to losses of nutrients to ground and surface water and greenhouse gasses emissions. Organic farming based on increasing organic matter supply to soils has been proposed as a solution to revert this trend and a recent meta-analysis showed that soil carbon levels indeed increase under organic farming, mostly as a result of substantial additions of organic matter (Gattinger et al., 2012). Although organic agriculture holds the promise of counteracting loss of soil organic matter, soil biodiversity (Mäder et al., 2002; Tsiafouli et al., 2014) and associated ecosystem services (Robertson et al., 2014), yields are usually reported to be lower than in conventional agriculture (De Ponti et al., 2012; Seufert et al., 2012; Ponisio et al., 2015). This yield gap, coined "the structural difference between the yields of various farming systems" (*sensu* Seufert et al., 2012), has raised concerns about the potential of organic agriculture as a sustainable solution to meet the increasing food, animal feed, and biomass production requirements necessary to sustain the growing world population (Trewavas, 2001).

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Most comparisons between organic and conventional agriculture have focussed on relatively short-term experiments (De Ponti et al., 2012; Seufert et al., 2012). Particularly for a period longer than 10 years, there are only very few realistic, well documented long-term comparisons between conventional and organic farming systems, see Robertson et al. (2014). These suggest that the yield gap between organic and conventional farming may decline over time, however, little is known about the time needed for closure of the yield gap and which are the underlying ecosystem processes. Comparisons have almost exclusively focussed on average yields (Mäder et al., 2002; Seufert et al., 2012), whereas relatively little attention has been paid to temporal and spatial variability (Mallory and Porter, 2007), which can be used to calculate the degree of stability (Collins, 2000; Tilman et al., 2006; Fraterrigo and Rusak, 2008). Stability analysis may reveal additional differences in sustainability between farming practices and increasing stability may also underlie closure of the yield gap. For example in homogeneously managed fields, the soil community can be highly variable over space (Robertson et al., 1993), which could have an impact on average yield. However, relatively little is known about differences in spatial and temporal variability of soil properties within and between differently managed soils and their functional consequences (Robertson and Wall-Freckman, 1995; Berg and Bengtsson, 2007; Wall et al., 2013).

Here, we tested the following hypothesis: yields in conventional and organic farming gradually when time since the start of organic farming proceeds. We tested this hypothesis by analysing annual yields in a 13-year-old field experiment including one organic and two conventional farming systems that were established under identical soil conditions. The organic farming system was based on farmyard manure (ORG-BIO), and one conventional system was based on applying pig slurry as fertilizer supply (CON-SLU), whereas the other used mineral fertilizer (CON-MIN) (Fig. S2). The farming systems experiment was carried out between 2001 and 2013 at the Wageningen University Research experimental farm in Vredepeel, the Netherlands, which is situated on sandy loam soil with 93.3% sand, 4.5% silt, and 2.2% clay (Langeveld et al., 2005).

Our first analyses showed that yields in the different farming systems indeed converged, thus supporting our hypothesis. We then proceeded by analysing how yield changes in the different farming systems were associated with changes in key soil properties, signs of inefficiency in the local nutrient economy such as leaching of nitrate, and changes in temporal and spatial stability of key soil properties. We determined yields, nitrate leaching, as well as physical, chemical and biological soil parameters. Using the coefficient of variation, we calculated long-term temporal stability in yield. In the same way, we analysed short-term temporal and spatial stability in soil parameters in the final year (Mallory and Porter, 2007; Smith et al., 2007).

2. Materials and methods

2.1. General setup

The Vredepeel farming systems experiment (N 51° 32′ 36″, E 5° 51′ 13″) in the Netherlands is based on a 6-year crop rotation system with the following major crops: potato, peas, leek, barley, sugar beet and maize, which were present each year and were followed by a cover crop (Table S1). The Vredepeel farm has been taken into production in the 1950's and has been an experimental farm since 1989. The original organic top layer was ploughed into the first 50 cm of soil. The soil contains 93.3% sand, 4.5% silt, and 2.2% clay[1], has ~3.8% organic matter content and is characterised by high to very high phosphorus content (~2.2 mg kg^{-1}). The soil can be classified as a Hortic Podzol according to the international soil classification scheme and an Arenic Alaquod according to the USDA soil classification scheme. The field experiment in its current design with three farming systems was set up in 2001 and is also described in Langeveld et al. (2005) and Quist et al. (2016). Each farming system had six fields of 180 m x 15 m or 180 m x 18 m (Fig. S2). Each field was treated as a replicate but had a different crop each year. The organic farming system (ORG-BIO) is based on no pesticides/herbicides/fungicides and on high organic matter inputs, 3050 kg effective organic matter (EOM) ha^{-1} yr^{-1}, which is defined as the organic matter that is still available one year after incorporation in the soil (Sukkel et al., 2008). The other two farming systems were subject to routine pesticide applications. Regarding fertilization, one system used pig slurry (CON-SLU: 1950 kg EOM ha^{-1} yr^{-1}) and the other system used mineral fertilizer only (CON-MIN: 1250 kg EOM ha^{-1} yr^{-1}); for details on crop-specific fertilization levels, see Table S3. EOM was calculated using the compound-specific humification coefficient for the different organic matter types (see Table S3) that were applied in the different farming systems. Yield and nitrate estimations were collected at four sampling points placed along a diagonal line in each field (Fig. S2). Nitrate concentrations (mg/l) in groundwater at 2 m depth were taken from collection tubes, measured in February of each year between 2000 and 2014 (Fig. S4, S5). This is the time of the year when the amount of water leaching to the ground water is highest. Physical, chemical and biological soil properties were collected at five sampling points in each field that were situated along a diagonal (Fig. S2). Each farming system had a total size of ~4 ha. Farming systems were irrigated during periods of insufficient rainfall. The decision to irrigate was based on farming-system and crop-specific soil moisture assessment, which resulted in generally higher irrigation intensity in the conventional systems than in the organic system (27.5 l/m2 in the conventional systems vs 0 l/m2 in BIO-ORG in 2011; 78.3 l/m2 in the conventional systems vs 27.5 l/m2 in BIO-ORG in 2012). Because ORG-BIO and the two conventional systems could not be completely randomized due to regulations on organic farming, they were positioned next to each other (Fig. S2). In order to establish that there were no site differences at the start of the current experiment between ORG-BIO and CON-MIN/CON-SLU, we have analysed data from a previous experiment that was carried out from 1993 to 2000 on the entire experimental area (see Supplementary information and Figs. S5&S6). For more information on the research site, see Electronic Appendix S6 and Table S7.

2.2. Yield estimation

Annual yield estimation at all three farming systems was done on a fresh weight basis. To take possible intra-crop variation into account, we used the mean of four plots of 1 m^2 within each field in the following five crops: potato, maize, peas, barley and leek. To be able to compare yields between farming systems, we used a yield index, which was calculated by relating yields of each of the three farming systems to a crop-specific long-term average yield, which was calculated by averaging the average yield of a crop for all three farming systems. To calculate a crop-independent index of the annual yield of a farming system, we first rescaled the annual yields of each crop by dividing them by their crop-specific long-term mean yields (over all three farming systems). The yield index is the annual mean of these rescaled crop yields, multiplied by 100 (for a more complete overview of the index, see Electronic Appendix S6). To avoid bias, we only included those crops that were present in all three cropping systems. Not all crops were present in all years and varieties of maize differed between organic and conventional systems in the early years of the experiment (see Table S1). Sugar beet was excluded from this calculation as it was replaced by carrot in the organic farming system.

2.3. Groundwater nitrate concentrations

Between 2000 and 2014, nitrate concentrations were determined in the groundwater at a depth of 2 m underneath the soil surface, below the rooting zones of the crops, using a cylinder of Ø 4 cm with a permeable bottom (Fig. S5). The groundwater table at the experimental farm fluctuates between a depth of 0.8 and 1.2 m. Each year, the cylinders were placed in the soil after harvest (November of year x) and removed at the start of the growing season (March of year x + 1). Four cylinders were placed along a diagonal line in a subset of the fields in each of the farming systems (Fig. S2, S8). Prior to sampling, each cylinder was completely emptied and groundwater samples were taken 24 h later when the cylinders had filled again with the surrounding pore water. Sampling was always carried out during the last week of February or the first week of March. Extracted pore water was kept cool at 5 °C. Analyses were carried out at the Chemical Biological Soil Laboratory (CLBL) in Wageningen, where nitrate (NO_3^-) was measured in the solution using ultra-violet spectrophotometry. Nitrate was measured in February because excess nitrate from the last growing season enters the ground water in winter, especially in that month. Theoretically, when the ground water level is at 1 m below the soil surface and there is a precipitation excess of 300 mm (in that part of the Netherlands), it takes about 9 months – 1 year before fertilization can be measured in the ground water at 1 m depth (Fraters et al., 2012).

2.4. Sampling design for physical, chemical, and biological properties

To detect spatial and temporal changes in physical, chemical and biological soil properties, soil samples were collected from five sampling points in each field at three times during the growing season: May, July and October 2013. Four crops (potato, maize, peas and barley) were examined in each farming system as these crops were similar throughout the season. Distance between two individual sampling points was 30 m and at each sampling point, 3 sub-samples were taken and pooled. Each sub-sample was 3 cm x 3 cm x 10 cm deep. From these pooled sub-samples, we determined soil moisture, soil organic matter fraction, soil pH_{H2O}, N availability and N mineralization. To detect whether farming practices affected organic matter in the deeper soil layers, also samples of the 0–30 cm layer were taken. Nematode community composition and microbial community composition were determined from the samples collected in May. Prior to analyses, pooled samples were refrigerated at 4 °C, homogenized and sieved through a 2 mm grid to remove coarse roots, stones and coarse litter.

2.5. Soil physical parameters

At each sampling time, soil moisture was determined from 10 ± 1 g of field soil that had been air-dried for 48 h at 70 °C. The soil organic matter (SOM) content was measured in soil samples after been oven-drying at 70 °C, and dry combustion at 550 °C. Differences in soil aggregation between the crops in the three farming systems were determined from the soil samples collected in October 2013. Soil aggregates were assessed using wet sieving (mesh sizes 2 mm, 0.5 mm, 0.25 mm), according to Six et al. (1998). The smallest mesh size (53 μm) was not used because the grain size of the large sand fraction was larger than the mesh width.

2.6. Soil chemical parameters

Total net nitrogen (N) mineralization was determined using a subsample of 25 ± 0.1 g of soil. This soil sample was split into two halves. One half (12.5 ± 0.05 g) was used to determine immediate availability of NO_3^+-N and NH_4^--N by KCl extraction within 24 h after collecting the samples. After adding 25 ml of demineralized water, the sample was incubated on a flatbed shaker at 250 rpm for 2 h and pH_{H2O} was determined. To each sample, 25 ml of 2 M KCl was added, followed by incubation in the flatbed shaker for 2 h at 250 rpm, after which availability of NO_3^+ and NH_4^- were determined using an autoanalyser (SEAL QuAAtro SFA system, Beun- de Ronde B.V. Abcoude, the Netherlands). The other half of each soil sample was incubated at 20 °C in the dark for 20 days under 14% soil moisture, after which NO_3^- and NH_{4+} availability were determined using the same procedure. The difference between the total mineral N in both measurements was considered the potential available mineralized N.

2.7. Biota

Nematodes were extracted from 100 g of soil, according to the protocol of Oostenbrink (1960). An estimation of the total numbers of nematodes was done by microscopic counts of nematodes in 1/10 of the sample. Dauer larvae were excluded from this count as they do not contribute to the active soil food web (Hohberg, 2003). Differences in fungal and bacterial biomass and fungal/bacterial ratios among the different farming systems and crop species were assessed using PLFA analysis, which allows for a comparative study of broad community shifts in soil microbes between treatments. A sub-sample of 6 g of soil was used to extract PLFA according to the protocol of Moeskops et al. (2010). The fatty acids i-15:0, a-15:0, 15:0, i-16:0, 17:0, cyclo-17:0, 18:1v7 and cyclo-19:0 were chosen as bacterial PLFAs and PLFA 18:2v6 was used as an indicator of fungal biomass (Frostegård and Bååth, 1996). The ratio of fungal to bacterial biomass was used as an indicator of shifts in the relative abundance of these groups (Bardgett et al., 1996). Another dataset on biomass of nematodes, bacteria and fungi was collected in 2011 from a subset of the fields that are described in the present study, following the same nematode extraction protocol as explained above. In this analysis, fungal biomass was assessed using microscopic counts (De Vries et al., 2006), biomass of bacteria was estimated using microscopic counts of fluorescent-stained bacteria (Bloem, 1995), and nematodes numbers were assessed as described above. Some of the methods are perhaps less accurate than more recently developed methods (e.g. qPCR methods for bacteria, fungal biomass estimation but also for nematodes, see Quist et al., 2016).

2.8. Statistical analysis

The effect of farming system and crop species on average yields, groundwater nitrate concentrations and physical, chemical and biological soil factors were analysed using a linear mixed model in Statistica 7.0, where farming system was considered a fixed effect. Differences between individual farming systems were assessed with Tukey's HSD Test at $\alpha < 0.05$. The coefficient of variation (CV) was used to assess spatial and temporal variability of the soil parameters and yield, using the method of Smith and Gross (2006). For each farming system and each crop species, CV was calculated as the standard deviation of yield (over all the years that a crop was present in the rotation)/average yield (for the same time period). A similar procedure was followed to calculate the CV for all physical, chemical and biological soil factors. We used the F-max-test, which allows for assessing differences in variability between treatments (e.g. Murphy, 1986), to compare the variability between farming systems, using a pairwise testing approach.

3. Results

3.1. Yield comparison

Across all years, the results of the three farming systems were remarkably similar; the only difference was that ORG-BIO had significantly lower yields for potato than both conventional farming systems (Fig. 1A). Our results show that the mean yield difference (13% when averaged over 13 years) in our long-term experiment is lower than the mean difference (21%) between organic and conventional farming in published studies (De Ponti et al., 2012; Seufert et al., 2012). Between 2001 and 2013, ORG-BIO experienced marked declines in yield in years with *Phytophthora* outbreaks, which were chemically controlled only in the conventional farming systems (Fig. 1A). When including these years, as shown by the hatched bar in Fig. 1A, there was no significant difference in yields between farming systems (Fig. 1A). Temporal stability did not differ between conventional and organic

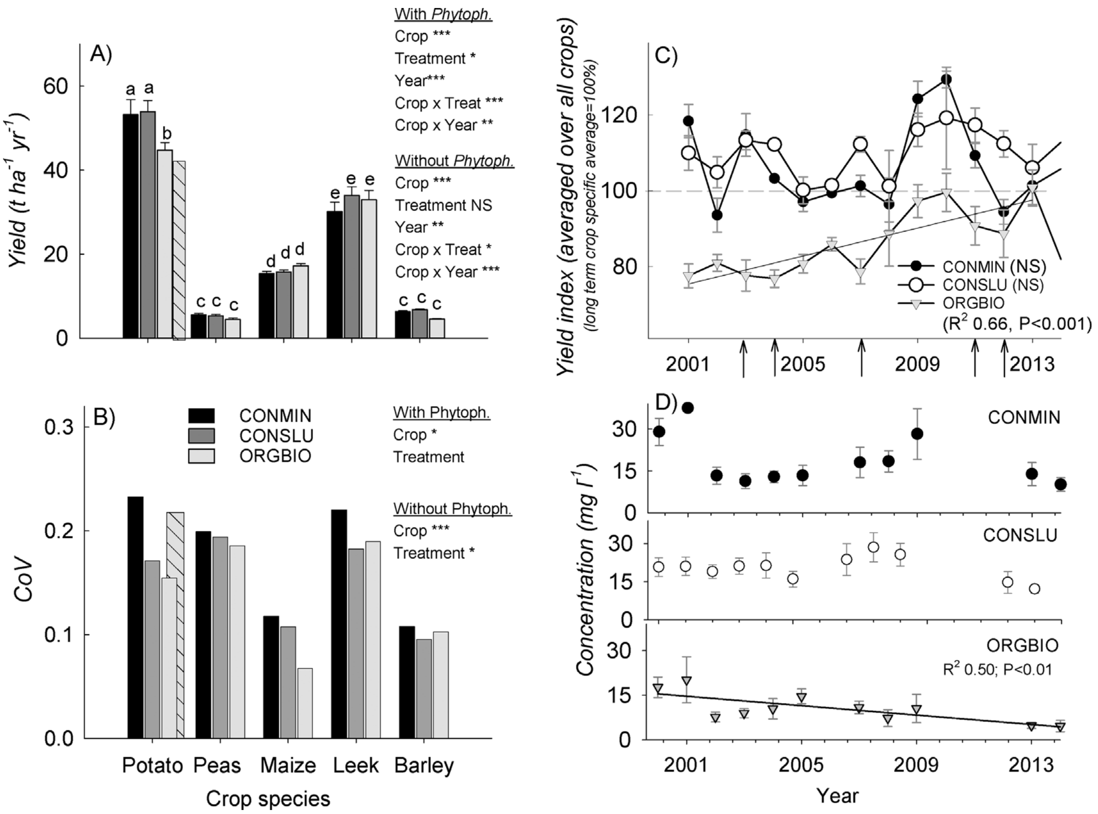

Fig. 1. A: Long-term crop-independent yield indexes (mean ± SE) over period 2001–2013; striped light grey bar for potato indicates yield when *Phytophthora* years were included. B: Temporal coefficient of variation in yield (CoV) between 2001 and 2013. C: Changes in the relative yield index (2001–2013). *Phytophthora* years are indicated by arrows along x-axis. D: Nitrate concentrations in groundwater (mean ± SE) between 2000 and 2014 (including *Phytophthora*-outbreak years). symbols are similar to those in panel C. Different letters indicate statistically significant differences at $\alpha < 0.05$.

farming systems, as indicated by similar coefficients of variation (Fig. 1B). However, when excluding the years with *Phytopthora* outbreaks in potato, as shown by the light grey bar in Fig. 1B, there was a difference in temporal stability between farming systems ($F_{(2,120)} = 3.6$; P = 0.03), where ORG-BIO had a lower coefficient of variation than CON-MIN (0.14 ± SE 0.02 vs 0.18 ± SE 0.03; P = 0.03). CON-SLU was intermediate (0.15 ± SE 0.02) and not significantly different from the other two systems. After starting the experiment, yields of ORG-BIO continued to increase, eventually approaching the levels of both conventional farming systems (Fig. 1C). These differences were larger in the early years of the experiment, which is why the yield index starts lower and increases throughout the study period. This increase in the yield index between 2001 and 2013 was significant only for ORG-BIO (R^2 0.66; $P < 0.001$; Fig. 1C), despite low yields in *Phytophthora* years (as indicated small arrows in Fig. 1C). During that same period, nitrate concentrations in groundwater declined in ORG-BIO, but not in the two conventional farming systems (Fig. 1D).

3.2. Averages of soil properties

Detailed analyses of the three farming systems in 2013 show that all soil physical parameters, soil organic matter, soil aggregate stability, and soil moisture content had higher values in ORG-BIO than in both conventional systems (Fig. 2A–C). For some properties our results show marked differences between the three farming systems. For example, soil organic matter levels were lowest in CON-MIN, intermediate in CON-SLU, and highest in ORG-BIO, whereas soil aggregates and soil moisture were higher in ORG-BIO than in both conventional farming systems (Fig. 2A–C). Soil organic matter was also sampled to greater depth (0–30 cm) which revealed slightly lower levels at greater depth, nevertheless, qualitatively patterns were similar among farming systems (Fig. 3). Chemical soil properties showed mixed patterns (Fig. 2D–F): in all seasons pH was lowest and plant-available nitrogen was highest in both conventional systems (Fig. 2E), indicating that these systems had higher potential leaching of nitrate. Potential nutrient mineralization and pH in summer and autumn were higher in ORG-BIO than in either conventional farming system, indicating a substantially higher provisioning of nutrients from decomposing organic matter in the organic farming system (Fig. 2D & F). Soil pH in CON-SLU was higher than in CON-MIN, and there was a trend towards higher soil N mineralization in CON-SLU in summer, which points at higher nutrient provisioning in CON-SLU than CON-MIN (Figs. 2D & 2F). Soil biological properties also showed a mixed pattern: in 2013, there were no differences in total nematode numbers among the farming systems (Fig. 2G), whereas ORG-BIO had the highest numbers of nematodes in the 2011 sampling (Fig. S11A). Several genera of plant-feeding nematodes formed an exception to this, as they were significantly more numerous in the conventional systems than in ORG-BIO in the 2011 sampling (Figs. S10, S11). Bacterial and fungal biomass in 2013 were higher in ORG-BIO than in either conventional system, indicating a larger heterotroph biomass in the organic farming system (Fig. 2H–I). Data from 2011, however, which was based on fungal and bacterial counts showed no differences in microbial biomass among farming systems (Fig. S9).

3.3. Variability in soil properties

In 2013, in spite of the fact that spatial variability (CV) in physical soil properties did not differ among farming systems (Fig. 2J–L), all chemical properties (pH, inorganic N availability, N mineralization) had a significantly lower coefficient of variation in ORG-BIO than in either conventional farming system (Fig. 2M–O), thus indicating lower

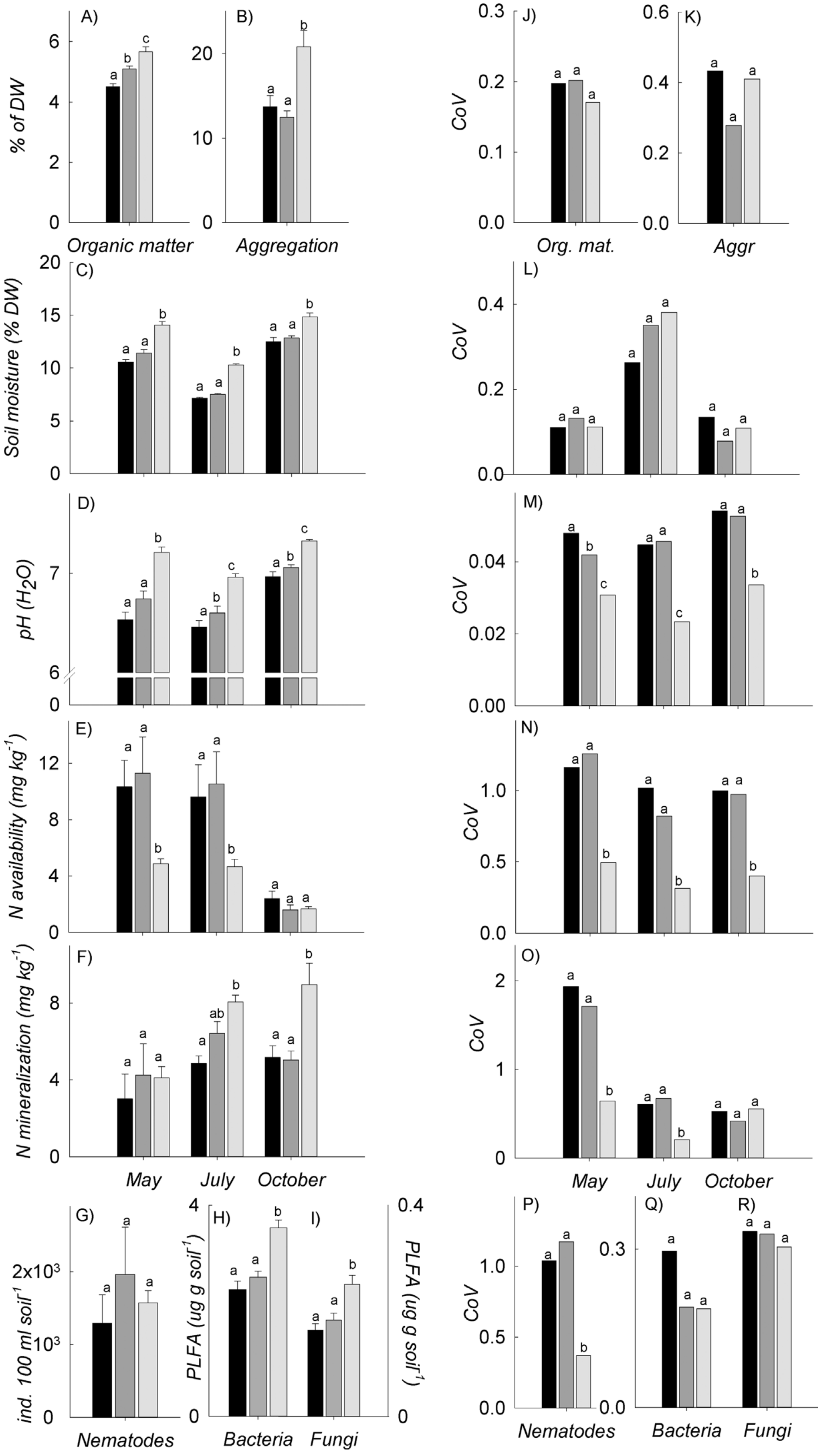

Fig. 2. Means (left panels) and spatial variation (right panels) in physical, chemical and biological soil properties in organic and conventional farming systems: physical (A & J show organic matter; B & K show soil macro-aggregate fraction; C & L show soil moisture), chemical (D & M show $pH_{(H2O)}$; E & N show nitrogen availability; F & O show potential N mineralization) and biological (G & P show nematodes; H & Q show bacteria; I & R show fungi). Spatial variation in soil properties is expressed by the coefficient of variation (CoV). Different letters indicate statistically significant differences at $\alpha < 0.05$. Error bars depict standard errors.

spatial variability in ORG-BIO. In 2013, nematode numbers had a significantly lower CV in ORG-BIO than in either conventional farming system (Fig. 2P), which was consistent with the pattern in 2011 (Fig. S9). This same pattern appeared for the temporal variability (CV) between 2005 and 2013, both for all nematodes pooled together, as well as for plant parasitic nematodes alone (Fig. S10, S11). In 2013, spatial variability in bacterial and fungal biomass, was not significantly different among farming systems (Fig. 2Q–R), as indicated by the

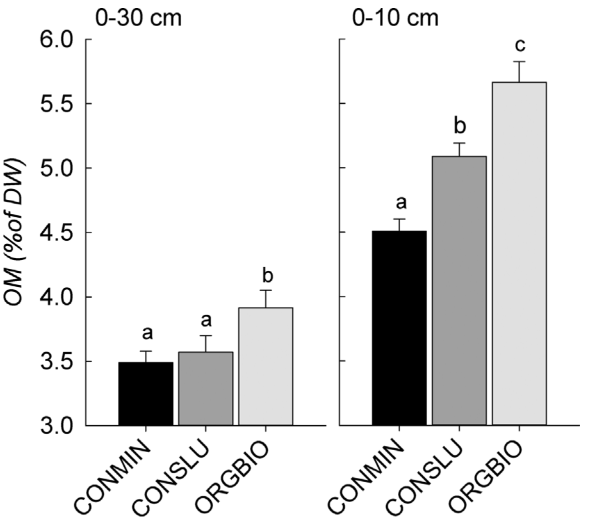

Fig. 3. Soil organic matter percentage in the 0–30 layer (left panel) and the 0–10 cm layer (right panel) for 2013. Different letters indicate significant differences at α < 0.05. Error bars depict standard errors.

similar coefficients of variation in different farming systems. A slightly different pattern appeared from the data collected in 2011, which were based on bacterial and fungal counts. These counts revealed a higher coefficient of variation only for CON-MIN, indicating lower spatial stability in CON-MIN than in CON-SLU and ORG-BIO.

The coefficient of variation for the available nitrogen was higher for all measured crops in both conventional farming systems than in similar crops in ORG-BIO, although there was substantial variation between crops and sampling points within crops (Fig. 4). At 2 m depth, winter time groundwater nitrate levels in ORG-BIO were more than 50% lower than in both conventional systems (Fig. 4). These differences remained when nitrate concentrations in groundwater were corrected for differences in the total nitrogen that was applied to the different farming systems.

4. Discussion

At the start of the farming systems experiment, there was a 'yield gap' between the organic and the two conventional farming systems. Nevertheless, this yield gap largely declined during the next 13 years. Interestingly, this reduction of the yield gap was achieved while using at least 23% less N input in the organic system (Electronic Appendix, Table 1). When corrected for total N inputs, the ground water at 2 m depth under the organic farming system contained 50% less nitrate than groundwater under conventional systems, which is in line with previous observations in other farming systems comparisons (Robertson et al., 2014). This difference and relative amount of N loss (60 kg N leaching per hectare in both conventional systems compared to 30 kg N per hectare for ORG BIO) is substantially higher than losses through NH_3 emissions, which have been assessed as 2 kg Nha for CON-SLU and 1 kg N ha for CON-MIN versus 3 kg Nha for ORG-BIO (unpublished data H. Verstegen), which is in line with values that were measured previously (Smits et al., 2005). Therefore, our results show a declining yield gap between organic and conventional farming with progressing time since conversion, coinciding with enhanced N-input efficiency of the organic compared to the other farming systems.

One possible caveat is that yields and yield indexes have been based on fresh weights. Percentage dry matter may be expected to vary among years and possibly also between farming systems. Therefore, our use of fresh yield data most likely will have increased the variation in our data. However, the observed long-term trends of ORG-BIO yields converging with those of CON-MIN and CON-SLU are considerably greater than may be due to systematic trends in percentage dry matter of the crops. Moreover, variations within year are less likely due to variations in percentage dry matter, as crops have been grown under comparable climatic conditions. Therefore, we think that our results are valid with respect to the long-term patterns, and that the variation within years may have made our tests even more conservative, as increased variability decreases statistical power. Additionally, differences in crops species and varieties used may also have contributed to the declining yield gap. That would point at a 'learning effect' of the farmers contributing to increased efficiency of organic farming practices. Nevertheless, our results are broadly in line with the results from the Kellogg Biological Station (Robertson et al., 2014), and seems to support that: 1) nitrate losses decrease in organic farming systems but this takes time, 2) yield gap between conventional and organic agriculture diminishes and takes a considerable amount of time.

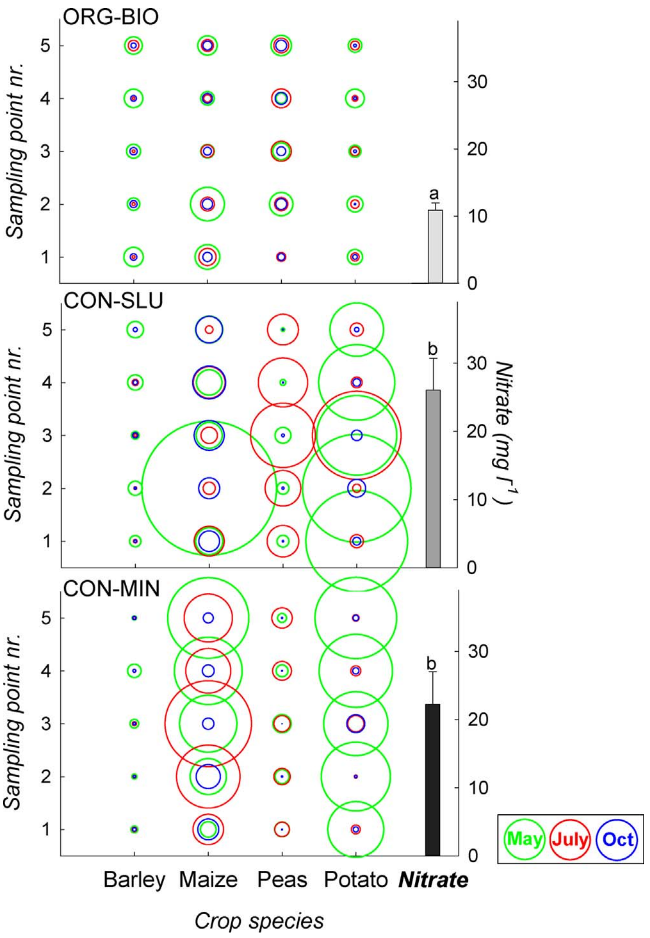

Fig. 4. Spatial variation in total soil mineral N availability and groundwater nitrate concentrations in conventional and organic farming systems. Circles depict total soil mineral N availability ($NO_3^- + NH_4^+$) during the different seasons for each crop in each of the different farming systems. Leek was not included in the sampling scheme because it had not been planted in 2013. Circle diameter corresponds with N availability (see inset legend for scale). Because of large differences in scale, N availability in May was divided by five, N availability in July was divided by two, and data from October were unaltered. The bar at the far right of each panel shows mean levels of nitrate in the groundwater (February–October < 0.05.

Unexpectedly, organic farming resulted in a lower coefficient of variation for many chemical and biological soil variables, thus indicating greater spatial stability in chemical and biological soil properties and processes. Information on spatial stability is not available for the entire experimental period, so that it cannot be established to what extent spatial stability may have contributed to the enhanced efficiency of the organic farming system, or to what extent it is a side effect. Nevertheless, the results from 2013 and the temporal data that are available (nitrate levels of the ground water and nematode data) suggest that the time necessary to convert conventional into organic farming systems is related to fundamental changes in abiotic and biotic soil properties leading to a more efficient, spatially and temporarily stable farming system with a fundamental role for the soil food web in nutrient provisioning to the crops. Hence, our results suggest the observed changes in yield and nitrate leaching may be related to changes in spatial and temporal stability of soil processes.

Analysis of spatial and temporal stability reveals that differences in the performance of farming systems may not always become expressed in the means, but that differences may show much stronger in the spatial and temporal variability of the systems. As the vast majority of studies focuses on comparison between average performances (Seufert et al., 2012; Mäder et al., 2002), differences in variation are not always considered. Therefore, although average performance is not always statistically different between farming systems, variation may be different with possibly far reaching consequences for a future that may promote this variation rather than decrease it.

There are several possible explanations for the link between organic matter inputs and spatial stability. First, mechanisms responsible for the enhanced spatial stability in the organic farming system could result from changes in resource-based (i.e. bottom-up) processes (Moore et al., 2004). In the organic farming system, organic matter content was increased by supply of farmyard manure and other organic compounds. The decomposition rate of farmyard manure can be up to four times slower (Levi-Minzi et al., 1990), thus presenting a more effective resource-based driver of stability than the easily degradable organic matter present in pig slurry. Second, enhanced resource inputs may also affect stability via increased predator-based (i.e. top-down) control (Moore et al., 2004), such as when predators stabilize population dynamics of soil organisms and thereby reduce spatial and temporal variation in soil processes, such as also observed at the Kellogg Biological Station (Robertson et al., 2014). Both changes in bottom-up and top down processes may subsequently result in enhanced soil food web stability (Stamou et al., 2011). Third, more stable abiotic conditions to support the soil food web may result from higher organic matter content, soil moisture, and soil aggregation (Van Bruggen and Semenov, 2000).

Temporal stability did not differ between the organic and conventional farming systems. However, the stability analysis revealed an interesting phenomenon: if outbreak years of *Phytophthora infestans* (an oomycete pathogen that is only suppressed by chemicals, which are used in the conventional systems, but not in the organic system) were excluded from the analysis, organic farming turned out to have higher temporal stability than conventional farming. Whereas emergence of aboveground pathogens on a single crop species may enhance the temporal instability in the organic system, such as in the case of *P. infestans*, this was not the case in the conventional farming systems. We have not systematically examined candidate properties, as there are many of them. For example, our results show higher abundance and higher variability in numbers of plant-parasitic nematodes in the conventional system than in the organic system (Figs. S9, S11). Such patterns have previously been linked to differences in organic matter levels and microbial activity (Van Bruggen and Semenov, 2000) and plant-parasitic nematodes can cause serious yield depression. It may also be that the increased organic matter levels renders the organic farming system less susceptible to extreme drought events, which might be supported by the lower number of irrigation events in the organic system. Analysing the contributions of these and other properties to temporal stability differences between the farming systems would require further studies.

It is possible that the observed changes in yield are partly a result of the observed changes in spatial stability through a reduction in ‘leaky points’ (localities where the soil loses large amounts of nitrate during heavy rain) in the organic system. Leaky points could be indicators of a less efficient local soil food web, for example resulting from reduced food web size or less dense interaction webs (Van der Heijden and Hartmann, 2016), which could lead to major loss of nutrient retention capacity. Although the observed lower spatial variation in the organic farming system seems to point towards enhanced food web functioning, more spatially explicit sampling including a higher density of sampling points and spatially explicit food web reconstruction in combination with process flux measurements and yield are needed to further understand the mechanisms underlying the observed spatial stability and its relation to productivity (Bradford et al., 2014). Such future approaches should focuses both on in-depth studies on presently available research locations, where the spatial patterns can be explored in currently running long-term experiments, and validation of the observed spatial patterns across a wide array of farmers’ fields varying in soil type, climatic conditions and farming systems.

Our results indicate that reduction in soil organic matter levels, which is happening in many conventional farming systems around the world (Lal, 2004), may not only decrease soil fertility but also reduce spatial stability in soil properties and ecosystem processes. This in turn may negatively influence sustainable delivery of food, animal feed, and biomass production and of other ecosystem services supplied by soils (Robertson et al., 2014). As our study has been carried out on one soil type under temperate climate conditions, these results should be considered as proof of principle that need to be verified under a wider array of environmental conditions. Nevertheless: the yield gap between organic and conventional agriculture may eventually close, but that takes a significant amount of time. Comparisons between farming systems should therefore at least include more than ten years following transition. Furthermore, we show that the organic farming system had greater spatial stability and it will be interesting to examine what is the role of enhanced spatial stability in closing of the yield gap.

Organic farming depends on large amounts of external inputs of organic matter. This makes it highly dependent on a scarce resource: the availability of slow decomposing organic matter. It requires novel solutions, such as integration of organic matter-fixing bioenergy crops (Schrama et al., 2015) a wide-spread implementation of cover crops, integration of organic matter-fixing crops in crop rotation systems, return of organic matter to soils, and a better integration of arable farming and livestock farming (Lal, 2004; Robertson et al., 2014; Zhang et al., 2013; Wall et al., 2013). A pivotal question will be to what extent the stabilizing role of soil organic matter in farming systems is based on quantity or on quality of the organic matter. As the quantity of organic matter available for organic farming can be a major constraint in many regions of the world, solving this scarcity should be a top priority for further enhancing the sustainability of farming systems practices.

Author contributions

All authors designed research; JJdH, MK, HV, MS and SC performed research; JJdH, HV and MK initiated the long-term farming systems experiment; MS analyzed data with input from WvdP and SC; MS and WHvdP wrote paper with inputs from JJdH and SC.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.agee.2017.12.023.

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