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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