FFECTS OF ORGANIC VERSUS CONVENTIONAL FARMING METHODS ON PHYSICAL AND CHEMICAL SOIL QUALITY INDICATORS

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Abstract

A comparative study of organic and conventional arable farming systems was conducted in The Netherlands to determine the effect of management practices on chemical and biological soil properties and soil health. Soils from thirteen accredited organic farms and conventionally managed neighbouring farms were analysed using a polyphasic approach combining traditional soil analysis, culture-dependent and independent microbiological analyses, a nematode community analysis and an enquiry about different management practices among the farmers. Organic management, known primarily for the abstinence of artificial fertilizers and pesticides, resulted in significantly lower levels of both nitrate and total soluble nitrogen in the soil, higher numbers of bacteria of different trophic groups, as well as larger species richness in both bacteria and nematode communities and more resilience to a drying– rewetting disturbance in the soil. The organic farmers plough their fields less deeply and tend to apply more organic carbon to their fields, but this did not result in a significantly higher organic carbon content in their soils. The levels of ammonium, organic nitrogen, phosphate and total phosphorus did not differ, significantly between the soils under different management. Fifty percent of the conventional Dutch farmers also used organic fertilizers and the numbers of farmers using a green crop fertilizer did not differ between the two management types. Soil type – clayey or sandy soil – in general had a much stronger effect on the soil characteristics than management type. The soil type influenced pH, nitrate, ammonium, phosphate and organic carbon levels as well as numbers of oligotrophic bacteria and of different groups of nematodes, and different diversity indices. With the collected data set certain soil characteristics could also be attributed to the use of different management practices like plow depth, crop or cover crop type or to the management history of the soil.

Keywords: Bacterial population structure; Biodiversity; Organic farming; Physi- chemical soil characteristics; Soil health

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Introduction

The recent use of policy by the European Union to develop more environmentally sensitive farming practices and the importance of surplus reduction has led to a widespread interest in organic farming. The ambition of the Dutch government is to have 10% of the agricultural land under organic management by 2010 (Anonymous, 2004). Under organic management, traditional conservation-minded farming methods are combined with modern farming techniques but conventional inputs such as synthetic pesticides and fertilizers are excluded.

Instead of synthetic inputs, compost and animal and green manures are used to build up soil fertility; pests are controlled naturally, crops are rotated, and both crops and livestock diversified (Reganold et al., 2001). Varying results with respect to chemical and biological soil parameters were obtained in recent years with studies comparing conventional farms – often only one or a few – with organic or reduced-input farming systems. Most data on nutrient levels in organic and conventional soils were derived from short and longterm trial systems.

Clark et al. (1998) found that the inputs to soil of C, P, K, Ca, and Mg were higher in organic and low-input systems as a result of manure applications and cover crop incorporations. However, Ma¨der et al. (2002) reported lower inputs of N, P, and K in their organic systems than in the conventional system. Nutrient levels in the soil varied accordingly. Higher levels of total and organic C, total N, and soluble P were reported for organic soils (Cavero et al., 1997; Clark et al., 1998; Poudel et al., 2002), whereas Ma¨der et al. (2002) reported small differences for soil chemical parameters like organic C and P.

Soil mineral N levels during the cropping season varied by crop, farming system and the amount and source of N fertilization (Poudel et al., 2002), while N availability was most important in limiting the yield in organic systems (Clark et al., 1999). Soil pH was slightly higher in the organically managed soils (Clark et al., 1998; Ma¨der et al., 2002). In a biological sense, healthy, thriving ecosystems are generally considered to be highly diverse with numerous taxa, which form a complex food web with many trophic levels (Metting and Blaine, 1993).

Therefore, taxonomic and functional diversity indices are often used as an index for the health status of soils (e.g. Brussaard et al., 2004; Van Bruggen and Semenov, 2000). Cultivated soils often have lower microbial diversities than they had as a natural habitat (e.g. Buckley and Schmidt, 2001). But, organically managed soils had a higher diversity of bacteria (Drinkwater et al., 1995; Ma¨der et al., 2002), arbuscular mycorrhizal fungi (Oehl et al., 2003), nematodes (Mulder et al., 2003), earthworms (Ma¨der et al., 2002) and insects and arthropods (Asteraki et al., 2004; Drinkwater et al., 1995; Ma¨der et al., 2002) than conventionally managed soils. Also a higher microbial activity (Ma¨der et al., 2002; Workneh et al., 1993) and microbial biomass (Ma¨der et al., 2002; Mulder et al., 2003) were found in organic soils.

However, some authors found no differences in bacterial biodiversity (Lawlor et al., 2000) or in fungal communities (Franke-Snyder et al., 2001) between organically or conventionally managed soils. A healthy soil is defined as a stable system with resilience to stress, high biological diversity, and high levels of internal nutrient cycling (Van Bruggen and Semenov, 2000). In this study, we searched for the effects long-term organic management under Dutch conditions has on soil health determined by physical, chemical, and especially biological parameters of the soil. In most of the above-mentioned studies different treatments were studied on one experimental farm. We chose a polyphasic approach to study many soils combining chemical and physical analysis, culture dependent and independent microbiological analyses, nematode community analysis, and enquiries among the farmers for the management practices used. Also the effects of soil type, different (cover) crops, separate management practices like plow depth, and the management history of the soils were studied.

Research Methods & Methodology

Data - All arable organic farms were SKAL-accredited and, thus used no chemical fertilizer, pesticides or genetically modified organisms for at least the last 2 years. All farmers filled in a questionnaire about the farm practices in the last 3 years regarding (cover) crops, amount and types of animal and green manure and/or fertilizer used, pesticides, disinfectants, mechanical weeding, soil improvements, and plowing depth.

Amounts of added organic C, N, and P/ha were calculated based on average (organic) fertilizer contents (Anonymous, 1997). The farmers further gave their opinions on their soil’s quality (including nutrient balances and yields), structure (including tillage, compactness, aeration, homogeneity), and moisture content (including water holding capacity and drainage status) on a 0–3 scale, these scores were used to calculate an average qualification by the farmer on their soils overall quality.

Physical and chemical analyses – Fractions of clay particles silt particles (2–50 mm) and sand particles (50–2000 mm) were determined in the soils. Sandy soils contained more than 60% sandy particles, in clayey/loamy soils the fraction of sandy particles was less. The dried soil samples were ground and analyzed: NO3, NH4, total soluble N content, and PO4 were CaCl2-extracted and total P and total N content were digested in H2SO4 before spectrophotometrically analyses with a Segmented Flow Analyzer (Skalar Analytical BV, Breda, The Netherlands). Organic-N was calculated as Norg = Ntotal soluble (NO3 + NH4). Total N and organic C contents were with a CHN1110 Element Analyzer (CEInstruments, Milan, Italy). The pH was determined in water and the sizes of the different fractions of soil particle sizes were determined. The moisture content of the fresh soils was determined in duplicate with 5 g samples on a Mettler LJ16 moisture content analyzer (Mettler Toledo International Inc., Ohio, USA).

Soil respiration – Basal respiration at 20 8C was determined in duplicate in 50 g of fresh soil sample. A continuous airflow of 65 ml/min was passed over the soil sample in glass tubes (length 24 cm, diameter 3.5 cm) incubated at 20 8C for 168 h to determine the basal respiration. The CO2-concentration in this air stream was measured by means of a computer- controlled switching device and an infrared CO2-analyser (ADC 7000, Analytical Development Corporation, Hoddesdon, UK), which allowed two-hourly measurements. The basal respiration was expressed as mg CO2/g dw/ h. The recovery of the soil microflora after a disturbance, the response amplitude a measure for the soil's resilience, was determined in duplicate measuring the response in CO2 production in 50 g of rewetted dried soil (to the original field amounts).

Copiotrophic and oligotrophic bacteria enumeration – Two subsamples of 10 g of fresh soil per sample were suspended in 90 ml of sterile deionized water. These bacterial suspensions were mixed in an orbital shaker at 300 rpm for 15 min, sonicated in an ultrasonic cleaner (Bransonic 12, Branson Cleaning Equipment Co., Shelton, CT) for 5 min and again mixed in the orbital shaker for 2 min. After 1 min of sedimentation, samples were taken for further 10-fold serial dilutions. Fifty microliters of suitable dilutions were plated in triplicate on high and low carbon media for isolation of copiotrophic and oligotrophic bacteria, respectively (Semenov et al., 1999). The high nutrient medium contained 0.5 g MgSO47H2O, 0.5 g KNO3, 1.3 g K2HPO43H20, 0.06 g CaNO34H2O, 2.5 g glucose, 0.2 g enzymatic casein hydrolysate (Sigma– Aldrich Chemie Gmbh, Steinheim, Germany), and 15.0 g Bacto Agar (Difco Laboratories, Detroit, MI, USA) per liter and 100 ppm sterile cycloheximide (Sigma–Aldrich). The total amount of carbon was estimated at 1000 mg/l of medium. The low nutrient medium was similar to the high carbon medium but 100-fold diluted and contained Agar Noble (Sigma– Aldrich)instead of Bacto agar. After incubation for 60 h (copiotrophs) or 4 weeks (oligotrophs) at 25 8C in the dark, bacterial colonies were counted and colony forming units (CFUs) were calculated per g dry soil.

DNA isolation and eubacterial DGGE – DNA was extracted from 0.5 g (fresh weight) soil samples, and the Bio101 FastDNA1 SPIN Kit for soil according to the manufacturer's specifications (Bio101, Carlsbad, CA, USA) except that bead beating (three times 90 s) was used instead of the FastPrep1 Instrument. The V6–V8 region of the 16S rRNA gene was amplified from soil DNA with the primers 968f-GC and 1401r (Heuer and Smalla, 1997) using a touchdown scheme (Rosado et al., 1998) for 30 thermal cycles. The PCR products were examined by standard 1% (w/v) agarose-0.5 Tris-borate-EDTA (TBE) gel electrophoresis with ethidium bromide staining, to confirm product integrity and estimate yield. DGGE was performed using the Dcode system (BIOrad Laboratories, Hercules, CA, USA). We used 6% acrylamide gels (37.5 acrylamide:1 bisacrylamide) with a 45–60% denaturing gradient as defined by Muyzer et al. (1993) to separate the generated amplicons (100% denaturant is 7 M urea and 40% formamide) and an 8% acrylamide stack without denaturing agents. The gels were poured from the top in the Dcode template, prepared with Gelbond PAG film (Amersham Pharmacia Biotech AG, Uppsala, Sweden) to one side, using a gradient maker and a Heidolph Pumpdrive (Heidolph, Schwabach, Germany) set at 4 ml/min. Electrophoresis was performed in 0.5 TAE buffer for 16 h at 100 V at a constant temperature of 60 8C. Gels were stained with BIOrad's Silver Stain (BIOrad Laboratories, Hercules, CA, USA) according to the manufacturer's protocol, but using the protocol for gels >1 mm thick instead of 0.5–1 mm to compensate for the barrier formed by the Gelbond. After staining the gels were preserved for at least 1 h in Cairn's preservation solution of 25% ethanol (v/v) and 10% glycerol (v/v), covered by a permeable cellophane sheet (Amersham Pharmacia Biotech Ag, Uppsala, Sweden) and dried overnight at 60 8C. Scanned images of the DGGE gels were analysed with Phoretix 1D (NonLinear Dynamics Ltd., Newcastle upon Tyne, UK) and the intensity and mobility of the bands were calculated. Data of different DGGE gels were standardized by referring to the synthetic marker. 16S rDNA fragments detected by DGGE were considered to represent dominant bacterial groups, making up at least 0.1–1% of the total community (Muyzer et al., 1993; Heuer and Smalla, 1997). The bacterial diversity in the samples was estimated in three ways: as species richness S, the shannon index of bacterial diversity, H0 , and the evenness of equitability E. Species richness S is equal to the number of DGGE fragments detected disregarding their relative intensities. The Shannon index was calculated as H0 = Pi log Pi based on the relative band intensities, as formulated by Eichner et al. (1999). Pi was defined as ni/N, where ni is the area of a peak in intensity and N the sum of all peak areas in the lane profiles. And finally, the evenness was calculated as E = (1/Pi) 2 (1/S).

Statistical analyses – One-sided paired t-tests were used for the comparisons between organic and conventional soils for all chemical, physical and biological numerical variables, both for sandy and clayey soils separately as for the combined soil types. Nominal and ordinal data were compared by Chi-square tests on frequencies. All variables were tested for correlations among them. The data were divided in three data sets; a bacteriological data set with eubacterial DGGE data (DGGE; 114 amplicons), a nematode data set (NEMA; 88 species), and a chemical, physical and biological data set (CPB). The CPB data set included data on clay, silt and sand fractions, pH, moisture content, estimated amounts of organic C, N and P added as (organic) fertilizer, levels of NO3, NH4, total soluble N (Nts), organic N (Norg), PO4, total P (Ptot), and Corg, basal respiration and response amplitude, bacterial species richness (Sbact), shannon–weaver (Hbact), and evenness (Ebact), nematode, total numbers of copiotrophic and oligotrophic bacteria, nematode species richness (Snema), shannon–weaver (Hnema), and evenness (Enema), total numbers of nematodes and numbers per trophic group, enrichment index (EI), basal index (BI), structure index (SI) and channel index (CI), data on plow depth, weeding strategy, crop type and cover crop use. Each set with normalized and standardized quantitative variables was analyzed with three kinds of discriminant analyses. The data were first split in smaller data sets with less than 20 variables and the most significant variables were then combined in new data sets and analyzed again. Analyses were done with the DISCRIM, CANDISC and STEPDICS procedures in SAS 8.02 (SAS Institute Inc., Cary, NC, USA). Discriminant analyses were done with four classes based on both soil and management type (organicclay, conventional-clay, organic-sand and conventional-sand), five classes based on plowing depth and mechanical weeding (no plowing, 0–25 cm with or without mechanical weeding and more than 25 cm plow depth with or without mechanical weeding), five classes according to crop (grass, wheat, onion, potato or sugar beet), four classes according to cover crop (none, leguminosae, graminae or cruciferae) and three classes based on management history (conventional, 0–5 or over 5 years of organic management).

Comparison organically and conventionally management - All characteristics of the pairs of soils were tested for differences between management types, first for clay and sandy soils separately, then regardless of soil type. The farmers did not significantly differ in their opinions about the quality of their soil, describing their soils as 'adequate' to 'good' (2–3), this value based on answers given in the questionnaire about soil quality, structure and moisture (Table 1). The organic farmers tend to add more organic carbon to their soils via organic fertilizers. The total amounts of N and P applied as synthetic or organic fertilizer did not differ between the two groups of farmers. Therefore, the N/C ratio of the applied fertilizers did differ. Fifty percent of the conventional farmers also used fertilizers of animal origin and about 40% also used mechanical weeding. Similar numbers of organic and conventional farmers used green manure crops, but they were used more often on clayey soils than on sandy soils. Thus, many management practices were shared between the two management types. Organic farms on clayey soils did not differ in the number of years of organic management from those on sandy soils.

We searched for the effects long-term organic management has on soil health as determined by physical, chemical and especially biological parameters of the soil. In contrast to previous studies on often only one pair or a few more soils – often from one experimental farm station – we looked at 13 accredited organic arable farms and 14 conventionally managed neighboring farms. We made no further distinction between conventional farms and low-input or integrated farms. Non-organic just meant conventional. A polyphasic approach was chosen to study the soils combining chemical and physical analysis, culture dependent and independent microbiological analyses, nematode community analysis and enquiries among the farmers for the management practices used. Often management practices were shared among both management types and many of the measured or calculated soil characteristics were not significantly differing between the two management types, emphasizing that the differences between organic and conventional are more gradual than black-and-white. Successful practices in organic farming are readily adopted in conventional farming and of course, where possible also the conventional farmer will reduce his input of energy and pesticides. Many conventional farmers in The Netherlands also use the abundantly available animal manures. With so many different crops and growth stages in our study we did not take into account the yield or yield reductions obtained by the farmers in the field. All farmers qualified their soils as rather good and they reported few problems in the previous years. The major differences we found between organic and conventional management were the lower nitrate and total soluble nitrogen levels in the soil under the first type, but ammonium and organic nitrogen did not differ significantly. Nitrate is more prone to leaching. Nitrate leaching levels in organic and conventional farms under similar cropping were similar or slightly higher in conventional farms, unless high conventional gifts of nitrogen were given in conventional farming, than also leaching was much higher (Stopes et al., 2002). We did not look at the rates of processes of nutrient transformation in the different soils, just at the nutrient availability at the sampling time. Poudel et al. (2002) found higher N mineralization rates in conventional soils and a lower potential risk of N leaching in the organic soils. Like Mäder et al. (2002) we found a trend, though not a significant difference, in higher organic carbon contents in the organic soils. The phosphate content in our organic soils was only lower in the clay soils, not in the sandy soils and we did not find a significant difference in the pH of organic soils like Mäder et al. (2002) and Clark et al. (1998) found. In comparison to e.g. Californian soils, the Dutch soils contained high amounts of organic carbon and other nutrients. These amounts and the quality of the organic matter returned to soil are important in promoting better physiological conditions in the soil, even more than the farming systems per se (Shepherd et al., 2002). Yearly atmospheric deposition rates of nitrogen in The Netherlands are currently approximately 40 kg/ha: all Dutch arable soils are therefore relatively high in nutrients, despite management type. But, despite the equally high nutrient levels observed in both, there are significant differences in bacterial and nematode species diversity and bacterial numbers between organic and conventional management.

Van Bruggen and Semenov (2000) defined a healthy soil as a stable system with resilience to stress, high biological diversity and high levels of internal nutrient cycling. The organic soils in our study did have a smaller response amplitude after drying–rewetting stress than the conventional soils. Furthermore, the organic soils also had a higher biological diversity in both nematodes and eubacteria and a higher biological activity in the soil. The organic farmers applied more organic carbon to their fields to maintain the organic matter in their soils and nitrate levels – the nitrogen source more prone to leaching – were lower in the organic soils at the sampling time. Thus, one can conclude that organically managed soils on average are more stable systems with a larger soil health as defined by Van Bruggen and Semenov (2000).

Organic farming, basically known for the absence of artificial fertilizer and pesticides use, and conventional farming, with the possibility of using both, do share a lot of management practices and soil characteristics under the rather intensive Dutch conditions. The main differences between the two management types are the significantly lower levels of both nitrate and total soluble nitrogen and the larger species richness in both bacteria and nematodes and higher numbers of bacteria in organic soils. The organic farmers plow less deeply and tend to apply more organic carbon with their fertilization to their soils. But, also a large proportion of the conventional farmers use fertilizers of organic origin or use cover crops to enrich their soils. The soil type, clayey or sandy, has a more pronounced effect on most of the determined soil characteristics than its management types. With the use of discriminant analyses certain observed differences in chemical, biological and management practices could be connected to soil type, but also to the crop type, the use of cover crops and the management history of the farm. The main reasons for the higher biodiversity in the organic soil – and thus supposedly a higher soil health – seem to be the lower plow depth and especially the use of the organic amendments and the absence of artificial fertilizer, which results in lower nitrate levels and a higher biodiversity in nematodes and bacteria.

Changing from conventional to organic farming leads to a gradual increase in biodiversity. Some nematode species and eubacterial amplicons do temporary increase in the younger organic farms, which agrees to the fact that during a transition period of about 5 years organic farmers may face problems with pest and (root) diseases, but that afterwards they generally are less severe in organically managed soils than in conventionally managed soils (Van Bruggen and Termorshuizen, 2003).

Selection of soil quality indicators and agricultural management practices

Based on an earlier review by Bünemann et al. (2018) in the iSQAPER project framework, and work by Spiegel et al. (2015), we have initially chosen six soil quality indicators. Main considerations in making this selection were:

Changes in soil quality and fertility are gradual and significant effects of land use and management generally cannot be measured within at least five years after their introduction;

hence, long-term experiments (LTEs) are of critical importance. Focus will be on “dynamic” over “static” indicators as only the former can reflect changes within a reasonable time span.

Most indicators are soil and site specific (e.g. soil organic matter content and pH), so it is essential that experiments have been done under comparable conditions (e.g. LTEs with split-plot design, or at least with neighbouring parcels) under identical soil and climate conditions.

It is necessary to distinguish between short-term effects and long-term changes in soil quality indicators.

Indicators can be related to potential changes in soil functions and soil threats.

It is important not only to identify the most appropriate bio-physical indicators, but also to ensure that farmers and land managers can easily understand and relate to these indicators so that they may be used to support on-farm management decisions.

The selected soil quality indicators were: soil organic matter (SOM) content, pH, aggregate stability, water-holding capacity and (number of) earthworms. Yield, although not a soil property, is also considered here as it is a good measure for soil quality and a primary concern to farmers.

Five agricultural management practices were chosen as “promising”: organic matter addition, no-tillage, crop rotation, irrigation, and—at the system level—organic agriculture. For each LTE, we compared results with respect to the corresponding “standard practice” (reference): no organic matter input, conventional tillage, monoculture, non-irrigation, and conventional farming.

Conclusions and recommendations

Our study has confirmed that land management practices influence soil quality indicators in various ways. There are clear trends and relative changes in the five indicators as determined by the four-paired practices. However, the magnitude of the trends and direction of the indicator changes vary with the different management practices.

Several management practices had negative effects on soil quality indicators. For example, yield levels were lower under organic farming as compared to conventional farming and, to a lesser extent, no-tillage compared to conventional tillage. However, the yield reduction could be marginal, if other principles of conservation agriculture such as proper residue management and crop rotation are applied.

Conversely, there are also positive aspects under organic farming such as higher marketing price and reduced environmental damages. Therefore, to evaluate whether it is judicious to convert conventional farming to organic farming, socio-economic aspects will have to be considered in combination with soil quality impacts.

Under the framework chosen, earthworm numbers appear to be the most sensitive indicator for the four paired management practices and positively affected by all the promising practices in comparison to the corresponding standard practices. SOM content responds positively to all the promising practices in comparison to the references. Aggregate stability and yield are less sensitive to the practices, and soil pH appears to be the least sensitive indicator.

The agricultural practices chosen (e.g. organic matter input) represent categories rather than specific treatments (e.g. addition of farmyard manure, compost, green manure, crop residue, or slurry). Although details on the various different treatments under those categories were documented in the literature review database (Table S2), a full-blown meta-analysis was beyond the intention and scope of research performed for the iSQAPER project and current manuscript.

LTE's are an invaluable source of information and at the basis of understanding the mechanisms and magnitude of soil change. Given the ever increasing pressures on agricultural land, every effort possible should be undertaken to maintain, enhance, and connect existing LTE's, and where possible invest to extend their network.

Opposite to our hypothesis, the potential for deducing meaningful trends for soil quality indicators from agricultural management practices was restricted by using currently available LTE data as the only source of information. Main reasons are the large study area with its huge range of pedo-climatic conditions, and the heterogeneous setup of LTEs making comparison of data difficult or impossible. Efforts such as the systematic mapping of evidence relating to the impacts of agricultural management on SOC described by Haddaway et al. (2015) are promising and should be extended to collate data about other soil quality relevant indicators.

Finally, it should be noted that farmers often know very well which specific soil parameters are the most relevant for their particular situation. Therefore, the view of land managers should be taken into account when evaluating various sets of indicators for soil quality (Lima et al., 2013; Palm et al., 2014), necessitating a transdisciplinary and participatory approach.

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