Both organic and integrated pest management of apple orchards maintain soil health as compared to a semi-natural reference system.

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Abstract

Growing concerns about the negative environmental impacts of agriculture have resulted in the increasing adoption of farming systems that try to reconcile crop production with environmental sustainability, such as organic farming. As organic farming refrains from using synthetic inputs, it heavenly relies on maintaining soil health. However, it is still poorly understood how organic management performs in terms of maintaining soil health in real commercial and heterogeneous farm settings as compared to conventional management, and especially as compared to a natural reference system. Here, we compared a set of soil health indicators among 24 commercial apple orchards that were either managed organically or conventionally using Integrated Pest Management (IPM) practices. In addition, we quantified the same indicators in 12 semi-natural grasslands as a benchmark to assess to what extent soil processes and functions have been degraded due to agricultural practices. As soil heath indicators, we quantified soil bulk density, organic matter content, organic carbon content, organic carbon stock, total nitrogen (N), potential heterotrophic respiration, potential net N mineralization, litter decomposition and litter stabilization, and we added the diversity of the herbaceous vegetation and the soil microbiome as covariates in our models. We found no differences between organic and IPM orchards, and neither of the farming systems showed evidence of impaired soil health compared to the semi-natural benchmark, with the exception of higher decomposition rates measured in both orchard types. We observed, however, high spatial variation in soil health between drive and crop rows within the orchards. Especially in the IPM orchards, crop rows showed impaired soil health compared to the adjacent drive rows, indicating that there is still opportunity to improve soil management in the IPM system. In addition, our results show that a considerable part of the variation in soil characteristics can be attributed to the study site, suggesting that both natural heterogeneity and personal management preferences by individual farmers are more important than the management system. Overall, and at least in terms of the soil variables measured in this study, our results suggest that perennial crop systems can be managed in a sustainable way, without jeopardizing soil health.

Keywords

Soil health; Organic agriculture; Integrated Pest Management; Semi-natural reference; Apple orchards

1. Introduction

Since the 1950s, agricultural productivity has greatly increased due to the use of agrochemicals and high-yielding crop varieties in combination with increased irrigation and mechanization. At the same time, land use conversions have further expanded agricultural lands, mostly at the expense of natural habitats (Tilman et al., 2017). These practices have allowed agricultural output to keep ahead of the increasing global food demand, but have come at a high cost for biodiversity and the delivery of ecosystem services (ES) (Foley et al., 2011; Tilman et al., 2017). With a projected further increase in food demand of 50 % by 2050 (FAO, 2017), it is crucial to mitigate these negative environmental impacts of agriculture and yet at the same time maintain or even enhance yield levels.

Over the last decades, a variety of solutions has been put forward to achieve this goal, such as sustainably increasing agricultural productivity, reducing food waste or shifting to more sustainable, plant-based diets (Foley et al., 2011; D. R. Williams et al., 2020). At the same time, there has been an increasing interest in the adoption of farming systems that aim at minimizing environmental degradation and improving the efficiency of internal resource use, such as organic farming (Barrios, 2007; Tuomisto et al., 2012). As organic farming refrains from using synthetic fertilizers and pesticides, it relies on natural ecosystem processes such as nutrient cycling and food web dynamics to grow and protect crops (Boone et al., 2019; Reganold and Wachter, 2016). Literature reviews and meta-analysis show that organic farming practices, at least on a per area basis, generally perform better than conventional practices in terms of environmental impacts (Boone et al., 2019; Gomiero et al., 2011; Lynch et al., 2012; Tuomisto et al., 2012, but see Clark & Tilman, 2017). For example, organic farms are often found to sustain a higher floral and faunal diversity, as well as related ecosystem services such as pollination and natural pest control (Crowder et al., 2010; Tuck et al., 2014). Whereas the greatest beneficial impacts of organic farming are likely to be expected in the soil environment, as organic farming practices are frequently reported to lead to higher soil organic matter contents, more efficient nutrient cycling, and better soil quality in general (Bai et al., 2018; Gattinger et al., 2012; Lynch et al., 2012), these impacts often highly depend on the specific farming practices, the crop type and soil texture (Bai et al., 2018).

Awareness of the importance of soil multifunctionality has recently increased, both in the scientific and the farming community (Bünemann et al., 2018; Hou et al., 2020). In this context, the concept of soil health is commonly used, not only in terms of agricultural production and the delivery of ecosystem services, but also as an essential component of meeting the United Nations' Sustainable Development Goals (SDGs) (Hou et al., 2020; Lehmann et al., 2020). Yet much remains to be learned about how soil health is influenced by different agricultural practices. Most research so far has used controlled field plot experiments to assess how soil health metrics are impacted by specific soil management practices, such as (no-)tillage or the application of certain amendments (e.g. Keel et al., 2019; Montanaro et al., 2017; Nazaries et al., 2021). Although providing useful insights in the functioning of agroecological processes, the highly controlled and simplified nature of these experiments makes it difficult to extrapolate results to real and intrinsically heterogeneous farm settings. An alternative approach is the use of on-farm studies, which are more realistic in terms of scale and heterogeneity, and which are generally conducted in well-established and stabilized systems (Drinkwater, 2002). Furthermore, farming systems can consist of a multitude of different practices within the boundaries that are set by (inter)national legislation. As a result, farming systems are often very heterogeneous, making on-farm studies in commercial farms much needed to assess the effectiveness of these systems in meeting agricultural and environmental goals. Finally, few studies so far have included natural references when comparing soil health among farming systems (but see H. Williams et al., 2020). Such a natural reference system can be used as a benchmark to assess to what extent soil processes and functions have been degraded due to agricultural practices, thus providing an additional perspective to the comparison between farming systems. Including a reference allows to assess the potential soil health that can be reached on agricultural soils, if the impact of agricultural practices is minimized. A natural reference system should preferentially consist of unmanaged land or land that is managed with the purpose of ecosystem conservation.

Much of the current research on the impact of conventional and organic farming practices on soil health is centered around annual cropping systems (Bai et al., 2018; Lee et al., 2015). Perennial crops, such as fruit trees, have received less attention, most likely because of their relatively low share in the total global area under organic farming (FAO, 2017; Montanaro et al., 2017b). However, policy support and the increasing consumer demand for organic fruits have led to a rapid increase in organic fruit production in recent years (Willer and Lernoud, 2019). In the European Union, 3.4 million hectares are dedicated to fruit cultivation of which approximately 25 % is being managed organically (Eurostat, 2021). With an increase in the total area under organic management of approximately 7 % each year, fruit crops are the third fastest growing organic crop after dry pulses and oilseeds (Eurostat, 2021). In this context, it is important to know how organic fruit cultivation impacts soils, not only compared to conventional cultivation, but also compared to natural reference systems. Most relevant research to date has focused on soil carbon sequestration, for which fruit crops hold great potential due to low soil disturbance and the presence of ground cover vegetation (Midwood et al., 2020; Montanaro et al., 2017a; Zanotelli et al., 2015). Several studies have shown that carbon stocks are generally greater in organic systems compared to conventional systems (Canali et al., 2009; Montanaro et al., 2017a). This difference is mostly attributed to the higher input of organic fertilizers and higher retention of pruning debris, leaf litter and understory vegetation in organic fruit systems compared to conventional systems (Montanaro et al., 2017a). For other soil health metrics, differences among organic and conventional fruit cultivation systems remain less clear and seem to be highly context dependent. Several studies report that organic practices are associated with improved levels of soil organic matter, lower soil bulk densities, higher availability of N and P and improved biological soil properties in general (Carey et al., 2009; Di Prima et al., 2018; Reganold et al., 2001; Sanchez et al., 2003). However, other studies have found no significant difference between organic and conventional fruit farms (Glover et al., 2000; Orpet et al., 2020).

Here, we aimed to compare soil health among commercial apple orchards that are either managed organically or that use Integrated Pest Management (IPM). We also aimed to quantify to what extent soil health has been degraded due to agricultural practices, and therefore included a semi-natural reference system as benchmark in our sampling. More specifically, during our sampling in March 2020 we covered 12 organic orchards, 12 IPM orchards and 12 reference semi-natural grasslands in the main fruit cultivation region in Flanders, Belgium. In the orchards, we separately sampled the drive rows and the crop rows. Since the interpretation of a “healthy” soil is highly context-specific (Baveye, 2021; Fierer et al., 2021; Lehmann et al., 2020), we refrained from using an overall soil health index but instead selected a set of physical, chemical and biological soil characteristics that were relevant for our specific study system.

2. Materials and methods

2.1 Study sites and sampling

The study sites were located in the Hageland-Haspengouw region in Flanders, Belgium (from 50°45’38’’N to 50°56’47’’N and from 4°31’08’’E to 5°24’27’’E) (Fig. 1). The region has a temperate oceanic climate with an average annual temperature of 9.8 °C and an average annual precipitation of 925 mm (data obtained from the Royal Meteorological Institute of Belgium, KMI). Soil samples were taken in 24 orchards and 12 semi-natural grasslands, further referred to as “study sites”. The average surface area of the 36 study sites was 1.4 ha, average distance to the closest neighboring study site was 2.5 km, with a minimum of 0.4 km and a maximum of 14.6 km. All orchards were planted with the apple variety Jonagold (*Malus* *domestica 'Jonagold'*) and were managed either following organic or IPM principles as determined by European and Flemish legislation. More specifically, no chemical-synthetic fertilizers or pesticides were used in the 12 organic orchards, whereas in the 12 IPM orchards, principles concerning the sustainable use of pesticides were applied. As a natural reference system, semi-natural grasslands with similar soil texture, hydrology and slope as the orchards were selected. These grasslands were managed extensively either by mowing or grazing, and no fertilizers of pesticides were used. Across all 36 sites, soil samples were collected in March 2020, right before the start of the growing season. Six 2 m^2 sampling plots were established in each orchard at a distance of at least 10 m from the borders; three in the drive rows and three in the adjacent crop rows. We distinguished between drive and crop rows because they are managed differently, possibly affecting soil properties such as organic carbon an total nitrogen content (Carey et al., 2009; Midwood et al., 2020). Drive rows have a vegetation cover mainly consisting of grasses and are left unmanaged, except for mowing and the disposal of pruning debris, whereas in the crop rows all herbaceous vegetation is removed and fertilizers are applied. In the reference semi-natural grasslands, only three plots were established because there were no drive and crop rows. In each plot, five different soil cores were taken with a 2-cm diameter auger at three different depths (0-10 cm, 10-30 cm and 30-50 cm) and the cores were pooled into one aggregate sample per depth per plot. In total, 540 soil samples from 180 plots were obtained across all study sites. Samples were stored at 4 °C until further analysis.

2.2 Soil physical analysis

From each sample (n=540), 10 g of fresh soil was oven-dried at 105 °C to obtain the soil gravimetric water content (% moisture). Bulk density was measured in a subset of 60 plots; one drive row plot and one crop row plot in each orchard, and one plot in each semi-natural grassland. In each depth layer (0-10 cm, 10-30 cm and 30-50 cm), an undisturbed sample was obtained using Kopecky rings, totaling 180 samples for bulk density measurement.

Samples were first air-dried for two weeks, then crushed and oven-dried for 24 h at 105 °C before weighing. Bulk density (Mg m^{-3}) was calculated using the volume of the ring and the sample weight, correcting for the presence of stones when necessary.

2.3 Soil chemical analysis

For chemical analysis, aliquot samples (n=540) were air dried and sieved through a 2-mm sieve before further processing. Weight loss of dry soil after combustion at 650 °C was used to determine soil organic matter (SOM) content. Soil organic carbon (SOC) and total nitrogen (N) concentrations were determined using an EA1108 Elemental Analyzer (CARLO ERBA Reagents, Milan, Italy) after powdering the dried soil and removal of carbonates by 2 M HCl. Soil organic carbon stocks (Mg ha^{-1}) were calculated for each depth layer in both the crop and drive rows (n=180), based on SOC concentrations, bulk densities and the thickness of the respective soil layer. We accounted for differences in soil mass using the equivalent soil mass approach described by Poeplau and Don (2013). This was necessary because in the organic orchards, weeds in the crop row are controlled mechanically by tillage of the topsoil, possibly affecting soil bulk density. Soil pH was quantified for all samples from the top layer (n=180) using a pH probe in a 1:10 soil/distilled water solution.

2.4 Soil biological analysis

Potential heterotrophic respiration rate, a measure of the metabolic activity of the soil microbiota, was determined with an *ex situ* respiration experiment following the protocol of Aerts et al. (2017). Soil samples from the top layer (0-10 cm) were combined across plots, resulting in two samples per orchard (crop row and drive row) and one sample for each semi-natural grassland. From each sample (n=60), 40 g air-dried soil was transferred into air-tight glass jars (287 mL), compacted to a bulk density of 1.5 g cm^{-3} and set to 60 % of water filled pore space by adding demineralized water. The jars were placed at 25 °C in a dark incubation room and, after an incubation period of 8 days, sealed air-tight. CO_2-concentrations in the headspace of the jars were measured periodically using a LI-820 CO_2 infrared gas analyzer (LI-COR Biosciences, Lincoln, Nebraska USA). Three blank jars ware included to correct for atmospheric background concentrations of CO_2. In total, 11 measurements spread over a period of 24 days were used to calculate an average respiration rate (mg CO_2 kg^{-1} h^{-1}) for each sample, using the method described by Aerts et. al. (2017). Simultaneously, aliquot samples (n=60) were used to determine potential net nitrogen (N) mineralization rates. Two 10-g dry soil weight equivalent duplicates per sample were weighed into 50 mL Falcon tubes and brought to 60 % of water filled pore space. One sample was analyzed immediately for NO_3^- and NH_4^+ concentrations using an automated colorimetric analysis system, while the other sample was incubated at 22 °C in a dark room for 25 days before analysis. Potential net N mineralization rate (mg kg^{-1} d^{-1}) was calculated as the difference in N content before and after incubation, divided by the number of incubation days.

In addition, we quantified *in situ* litter decomposition using the standardized 'Tea Bag Index' (TBI) developed by Keuskamp et al. (2013). At each sampling plot, 3 pairs of Lipton green tea and Lipton rooibos tea bags were buried at a depth of 8 cm, totaling 36 tea bags per orchard and 18 tea bags per semi-natural grassland site. The tea bags were retrieved after approximately 80 days and mass loss was calculated after drying the bags for 48 h at 70 °C. Due to their different composition, the labile fraction of the green tea is completely decomposed after the incubation period but part of the labile fraction of the rooibos tea remains. This difference in decomposition rate allows for the simultaneous calculation of the decomposition rate constant k and the stabilization factor S, following the guidelines by Keuskamp et al. (2013). Both parameters play an important role in carbon cycling, k relating to short-term carbon dynamics and S being indicative for long-term carbon storage (Górecki et al., 2021; Keuskamp et al., 2013). A total of 897 tea bags (83 %) was retrieved undamaged, resulting in litter decomposition data for 33 out of 36 study sites. For two semi-natural grasslands and one organic orchard, no data could be calculated due to lost and damaged bags.

2.5 Data analysis and statistics

To assess the effect of soil management on the different soil health indicators, linear mixed-effects models (LMMs) were used with management type (organic vs. IPM vs. semi-natural), location (drive row vs. crop row) and sampling depth as fixed factors. Separate models were constructed for soil organic matter, bulk density, total N, soil organic carbon, soil organic carbon stock, soil respiration, N mineralization, litter decomposition rate k and litter stabilization factor S. Whenever sampling depth was a significant factor in the full model, additional models were constructed for each depth layer separately. Because of different depth layer thickness, also SOC stocks were analyzed using separate models for each depth layer, as well as a model for the summed SOC stock up to a depth of 50 cm. Depending on the response variable, several fixed covariates were included in the models. Diversity indices for the plant species from the vegetation cover and for the soil microbiome were calculated based on data from a parallel project (see Supplementary material, Methods S1 for details and methodology). Diversity indices included plant species richness (S_Plant), Shannon diversity (H_Plant) and Inverse Simpson index (IS_Plant). For the biological soil characteristics, several covariates relating to the soil microbiome were included: OTU richness fungi (S_Fun), OTU richness bacteria (S_Bac), Shannon diversity fungi (H_Fun), Shannon diversity bacteria (H_Bac), Inverse Simpson index fungi (IS_Fun) and Inverse Simpson index bacteria (IS_Bac) (see Supplementary material, Methods S2). In addition, a set of spatial predictors (distance-based Moran's eigenvector maps, dbMEMs) were added as explanatory variables to the models to account for trends resulting from the spatial structure of the study system (Dray et al., 2006). dbMEMs were calculated based on the geographical coordinates of the study sites using the function 'dbmem' from R package adespatial (Dray et al., 2021). First-order interaction terms between management, location and depth and all other relevant fixed factors and covariates were also included. Before inclusion in the models, variance inflation factors (VIF) were calculated for all predictor variables to test for multicollinearity. Variables with a VIF higher than 3 were dropped.

All LMMs were simplified using a backwards-stepwise selection based on Akaike's Information Criterion (AIC) using the 'buildlme' function from the R package buildmer (Voeten, 2021). Location nested in sampling plot nested in study site was fitted as a random effects term to account for the non-independent spatial structure of the study design. If samples were pooled, as was for instance the case for the biological soil characteristics, the random effect structure was adjusted accordingly. F- and p-values were calculated using ANOVA tables and marginal and conditional R^2-values were obtained for all models, representing respectively the variance explained by the fixed factors and the variance explained by the fixed and random factors combined, using the function 'r.squaredGLMM' in R package MuMIn (Bartoń, 2020). Semi-partial R^2_β coefficients were calculated using the method of Edwards et al. (2008) to assess the percentage of variation in the response variable that can be explained by the respective explanatory variables (function 'r2beta' from R package r2glmm; Jaeger, 2017). When necessary, variables were transformed to meet the assumptions of normal distribution and independence of residuals.

3. Results

3.1 Soil physical variables

Overall, soil bulk density was not significantly different between the three management systems (Table 1). Most of the variation in bulk density was explained by sampling location (drive row vs. crop row) and sampling depth, with bulk density increasing with depth and generally being lower in the crop rows compared to the drive rows (Table 2, Fig. 2). Multiple comparison tests, however, showed that lower bulk density in the crop rows, compared to the drive rows, was only significant in the organic orchards, and only in the two uppermost soil layers (1.21 ± 0.05 g cm^{-3} vs. 1.35 ± 0.04 g cm^{-3} for the 0-10 cm layer and 1.37 ± 0.02 g cm^{-3} vs. 1.50 ± 0.03 g cm^{-3} for the 10-30 cm layer, respectively). Compared to the semi-natural reference system, no differences in bulk density were found except for the 10-30 cm depth layer under the crop rows from both orchard types, which had lower bulk densities than the semi-natural grasslands (1.37 ± 0.02 g cm^{-3} for organic and 1.43 ± 0.02 g cm^{-3} for IPM, compared to 1.52 ± 0.03 g cm^{-3} for semi-natural grasslands). As expected, soil bulk density decreased with increasing soil organic matter content, this relationship was present in all management systems and all depth layers (Table 1, Fig. S3).

3.1 Soil chemical variables

Soil organic matter content varied with sampling depth, with higher concentrations closer to the soil surface (Table 1, Table 2, Fig. 2). Sampling location had a significant effect in the full model, and this effect differed between management systems as indicated by the significant interaction term (management x location). However, separate models for each depth layer revealed that there was a location effect only in the top layer of the IPM orchards. For the 0-10 cm depth layer, soil organic matter content was higher in the drive rows of the IPM orchards compared to the crop rows (6.80 ± 0.39 % vs. 4.79 ± 0.15 %, respectively) (Table 2, Fig. 2). Furthermore, no differences in soil organic matter content were found between IPM orchards, organic orchards or semi-natural grasslands.

Both soil organic C and total N as measured by elemental analysis were most strongly effected by sampling depth, with higher concentrations closer to the soil surface (Table 1, Table 2, Fig. 2). In the models for the 0-10 cm depth layer, also location had a significant effect on both organic C and total N, with concentrations generally being lower in the crop rows relative to the drive rows. However, pairwise comparison tests revealed that lower values in the crop rows compared to the drive rows were only significant in the IPM orchards (0.13 ± 0.01 % vs.

0.21 ± 0.02 % for total N and 1.37 ± 0.09 % vs. 2.19 ± 0.18 % for organic C, respectively). For total N, lower concentrations in the drive rows of the IPM orchards were also found in the 30-50 cm layer (0.06 ± 0.01 % for the drive rows vs. 0.07 ± 0.01 % for the crop rows).

SOC stocks were highest in the semi-natural grasslands and lowest in the crop rows of the IPM orchards. This applied to all depth layers, as well as to the summed SOC stock up to a depth of 50 cm (Table 2, Fig. 3). However, differences in SOC stock between management types and locations were not significant, except for the higher SOC stock in the drive rows compared to the crop rows of the IPM orchards in the 0-10 cm layer (3.29 ± 0.26 Mg ha^{-1} vs. 2.20 ± 0.14 Mg ha^{-1}, respectively). None of the other fixed factors were significant, and all had very low explanatory power as reflected by the low semi-partial R^2_β coefficients and low marginal R^2-values (Table 1). Conditional R^2-values, however, were very high, indicating that most of the variation in SOC stock is explained at the random factor level, more specific by study site ID (> 90 % of random effect variance).

3.3 Soil biological variables

Potential heterotrophic respiration rate differed significantly between management systems, with lowest average respiration rates measured for soils from the IPM orchards (1.11 ± 0.11 mg CO_2 kg^{-1} h^{-1}), intermediate respiration rates for soils from the organic orchards (1.28 ± 0.07 mg CO_2 kg^{-1} h^{-1}) and highest respiration rates for soils from the semi-natural grasslands (1.78 ± 0.17 mg CO_2 kg^{-1} h^{-1}). In both orchard types, heterotrophic respiration was higher for samples taken from the drive rows compared to the crop rows (Table 2, Fig. 4a). However, this difference was only significant for IPM orchards (1.54 ± 0.10 mg CO_2 kg^{-1} h^{-1} for the drive rows vs. 0.69 ± 0.07 mg CO_2 kg^{-1} h^{-1} for the crop rows). Soils samples from the semi-natural grasslands showed significantly higher respiration rates than samples from the crop rows in both orchard types, but were not different from respiration rates measured on samples from the drive rows. In addition, respiration rates significantly increased with species richness of the fungal microbiome and decreased with the soil C:N ratio (Table 3, Fig. S4). When potential respiration rates were calculated relative to the organic carbon content of the soils, management system and fungal microbiome richness did not longer have a significant effect in the linear mixed effects model, and most of the variation was explained by the C:N ratio (Table S5, Fig. S6).

Potential net N mineralization rates were significantly higher in soil samples taken from the crop rows of the organic orchards compared to the drive rows (0.63 ± 0.20 mg kg^{-1} d^{-1} vs. 0.37 ± 0.18 mg kg^{-1} d^{-1}, respectively). For the IPM orchards a similar trend was found, though not significant (Table 2, Fig. 4b). Soil samples from the semi-natural grasslands showed similar net N mineralization rates as samples from the orchards, only being lower than those from the crop rows of the organic orchards (which were highest overall, Fig. 4b). In addition, potential net N mineralization rates and soil organic carbon content were positively correlated in the crop rows, but negatively correlated in the drive rows (Fig. S7).

The decomposition rate constants (k) that were obtained with the tea bag technique were significantly lower in the semi-natural grasslands (0.01 ± 0.01) compared to the organic and IPM orchards (0.02 ± 0.01 and 0.02 ± 0.01, respectively). Also the location within the orchards had a significant effect, with higher decomposition rates in the crop rows of the IMP orchards compared to the drive rows. In the organic orchards, this effect was opposite but not significant (Fig. 4c). Decomposition rates also increased with increasing soil C:N ratio (Table 3, Fig. S8). Litter stabilization factor (S) did not differ between any of the management systems or locations (Fig. 4d), but was strongly positively correlated with pH (Table 3, Fig. S9).

4. Discussion

4.1 Soil health indicators

In this study, we compared a set of physical, chemical and biological soil health indicators among commercial apple orchards that were either managed organically or conventionally using IPM practices, both in relation to a semi-natural reference system. Our results show that none of the physical or chemical soil health indicators were significantly different between any of the three systems, not in the full models nor in the separate models for each depth layer. For the biological indicators, we did find differences in potential heterotrophic respiration and decomposition rate among management systems. Potential respiration rates were lowest in the IPM orchards and highest in the semi-natural grasslands. However, this is most likely caused by similar patterns of variation in SOC content between the management systems. Since SOC plays an key role in supplying carbon and energy to the microbial community, higher SOC content is expected to increase microbial activity, resulting in higher respiration rates (Awale et al., 2017; Luján Soto et al., 2021; Montanaro et al., 2017b). Indeed, when respiration rates were calculated relative to the soil organic carbon content, differences between management systems were no longer present. For the decomposition rates calculated by the tea bag method, differences between management systems only existed between the both orchard types on the one hand, and the semi-natural reference on the other hand. However, the lower decomposition rates in the semi-natural grasslands were most likely caused by extremely warm and dry weather during the final weeks of field incubation. Although all tea bags were buried in soils with similar temperature and moisture content, lack of shade trees made the soils in the semi-natural grasslands dry out before the end of the incubation period, possibly interrupting litter decomposition (Parton et al., 2007). In summary, we can conclude that none of the soil health indicators differed between the organic and the IPM system, and only the decomposition rates slightly deviated from those measured in the semi-natural reference system.

4.2 Comparison between organic and IPM apple cultivation systems

The lack of contrast in soil health between organic and IPM apple cultivation systems is in line with results from other studies (Glover et al., 2000; Orpet et al., 2020; Reganold et al., 2001). This might be due to the fact that those studies, like ours, were designed to evaluate the management systems in their entirety, rather than evaluating specific management practices. Although specific organic practices, such as the application of certain organic amendments, are often associated with increased soil health (Nazaries et al., 2021; Nunes et al., 2018; Sanchez et al., 2003), this does not always imply similar results for real organic farm settings, where a variety of soil management practices can be used within the boundaries of organic certification (Orpet et al., 2020). While some organic farmers, for instance, choose to maximize the reliance on natural ecosystem processes, other might lean more towards adopting the features of conventional farming systems in a process that is often referred to as organic "conventionalization" (Goldberger, 2011; Rover et al., 2020). Examples of this conventionalization are an increased prevalence of large-scale monocultures, increased mechanization, and the replacement of synthetic pesticides and fertilizers with certified organic alternatives (Best, 2008; Buck et al., 1997; Goldberger, 2011). At the same time, conventional farms in Europe are obliged to apply IPM practices following the 2009/128/EC directive on the sustainable use of pesticides (EU, 2009), causing them to shift towards practices with a lower environmental impact. Both factors may have contributed to a convergence in management practices between management systems in our study, resulting in the absence of large differences in soil characteristics. At the same time, we observed that a considerable part of the variation in soil health can be attributed to the study site, suggesting that both natural heterogeneity and personal management preferences by individual farmers are more important than management system.

4.3 Comparison with a semi-natural reference system

Importantly, and with the exception of small differences in decomposition rate, our results show no differences in soil health indicators between both farming systems on the one side and the semi-natural reference system on the other side. This is in contrast to the few other studies that used a reference to quantify potential soil health, which reported lower soil health under agricultural management (Wander and Bollero, 1999; H. Williams et al., 2020). However, these two studies considered annual crops and used unmanaged field margins as a benchmark, whereas our study focused on a perennial crop and a reference system that is managed for biodiversity and ecosystem conservation. Consequently, and at least for the soil variables measured in this study, our results suggest that agricultural practices in both organic and IPM orchards do not cause strongly impaired soil properties and that both systems seem close to having their potential soil health. It could be argued that even the semi-natural grasslands are to a certain extent degraded regarding soil properties and functions, since they do not represent real pristine habitats. However, primary, non-managed grasslands do not occur in Flanders. An alternative would have been to use forest as a reference system, which could possibly have indicated that both organic and IPM agricultural systems are, in fact, not reaching full soil health potential. This was for instance the case in Gonzaga et al. (2016) and Ortiz et al. (2017), where soils under perennial sugarcane crops and coconut orchards in Brazil were found to be of less quality compared to soils under native Atlantic forest.

4.4 Spatial variability within the orchards

Unlike management system, location (drive row vs. crop row) did have an effect on most soil health indicators. This impact often differed between the organic and IPM systems, as indicated by the presence of a significant interaction between management system and location in most of the linear mixed models. For the IPM orchards, the drive rows had higher levels of SOM, total N, SOC, SOC stock, potential RH and potential net N_{min} than the adjacent crop rows. Only decomposition rates were higher in the crop rows. For the organic orchards, only bulk density and potential net N_{min} differed between the drive and crop rows, with both indicators showing lower average values in the crop rows. Differences between drive and crop rows were exclusively present in the top soil layer (0-10 cm), with exception of bulk density for which the effect of location was also present in the 10-30 cm layer. These findings indicate that there is a high level of spatial variability within the orchards, and that this variability is more pronounced in the IPM orchards. Higher soil health in the drive rows of the IPM orchards compared to the adjacent crop rows is probably the result of a combination of management factors. In the drive rows, the permanent vegetation cover together with the regular addition of mulched prunings and leaf litter all contribute to higher organic inputs, which are known to increase soil organic carbon content, total N and mineralisable N content (Carey et al., 2009; Marquez-Garcia et al., 2013; Midwood et al., 2020; Palese et al., 2014). Similar organic inputs are likely absent in the crop rows of the IPM orchards, where herbicides prevent the development of a vegetation cover. For organic orchards, where herbicides are replaced with mechanical weeding, we expected similar results since tillage is also associated with lower organic inputs and generally impaired soil properties (Di Prima et al., 2018; Houben et al., 2018; Nunes et al., 2018). However, only minor differences were found between the drive and crop rows of the organic orchards, possibly due to the addition of organic amendments in the crop rows, or the fact that some farmers only apply mechanical weeding when weeds are growing too tall, allowing for the temporal development of a vegetation cover in the crop rows. Finally, pairwise comparison revealed that only the crop rows of the IPM orchards slightly differed from our semi-natural reference system, with lower bulk density in the 10-30 cm soil layer and lower potential heterotrophic respiration. This result, together with the high discrepancy between crop and drive rows in the IPM orchards, suggests that some improvement concerning sustainable soil management is still possible in the crop rows of the IPM orchards.

4.5 Implications and future prospects

The results from our on-farm study show that, with the exception of slightly higher decomposition rates measured in the orchards, both organic and IPM farming systems can maintain soil health as compared to a semi-natural reference system. Because of the high variety of applied practices within both farming systems, these results suggest that there is no single best solution to maintain soil health in apple cultivation, but rather a variety of different practices can be used to achieve this result. Future research should address whether the IPM and organic systems, as applied in our study region, are also effective in maintaining soil health in other regions. For example in the dryland regions in China, where fruit cultivation typically depends on conventional methods with high input of synthetic fertilizers and pesticides, and is often associated with severe soil degradation (Gao et al. 2021). On-farm studies that investigate the potential of IPM or organic management practices in these regions can be set up to develop farming systems that can better meet environmental standards. Finally, comparing soil health with a local (semi-)natural benchmark can allow the quantification of the degree of soil degradation and the assessment of the potential soil health that can be reached under local conditions.

5. Conclusions

Overall, and at least in terms of the soil variables measured in this particular study, our results suggest that perennial crop systems can be managed in a sustainable way, without jeopardizing soil health. Although there was some spatial variability in soil characteristics between the drive and crop rows within the orchards, both the IPM and organic farming system in our study were generally able to maintain soil health as compared to our semi-natural benchmark. Exploring the potential of both farming systems for the maintenance or improvement of soil quality can be of great interest in other regions where fruit cultivation heavily depends on conventional farming methods, and where agricultural intensification is associated with severe soil degradation. Finally, as some perennial crops have recently been suggested to be a worthy alternative to annual staples in terms of their contribution to global food supply (Kreitzman et al., 2020), this study further highlights the potential of perennial crops to accomplish food production while at the same time minimizing soil degradation.

List of figures and tables

Table 1. Results of the final linear mixed-effects models for all physical and chemical soil health indicators, showing marginal (R^2_m) and conditional (R^2_c) R²-values for all models. For each indicator, a full model as well as separate models for each depth layer are shown. Test statistic (F) and semi-partial R^2_β are given for each retained explanatory variable after model reduction. *P < 0.05, **P < 0.01, ***P < 0.001.

Bulk density (BD)	Full model R^2_m= 0.526 ; R^2_c = 0.636		Depth 0-10 cm R^2_m= 0.248 ; R^2_c = 0.641		Depth 10-30 cm R^2_m= 0.418 ; R^2_c = 0.630		Depth 30-50 cm R^2_m= 0.151 ; R^2_c = 0.554	
	F	R^2_β	*F*	R^2_β	*F*	R^2_β	*F*	R^2_β
Management	2.0	0.029	1.8	0.096	2.4	0.118	0.8	0.042
Location	23.2***	0.339	11.7**	0.297	16.6***	0.401	2.4	0.086
Depth	13.6***	0.251	-	-	-	-	-	-
SOM	23.8***	0.119	8.1**	0.129	12.6***	0.183	7.2**	0.118
Management x Location	9.5**	0.240	6.1*	0.121	7.2*	0.222	2.8	0.102
Management x SOM	5.8**	0.063	-	-	-	-	-	-
Soil organic matter (SOM)	Full model R^2_m= 0.366 ; R^2_c = 0.782		Depth 0-10 cm R^2_m= 0.144 ; R^2_c = 0.662		Depth 10-30 cm R^2_m= 0.024 ; R^2_c = 0.779		Depth 30-50 cm R^2_m= 0.058 ; R^2_c = 0.850	
	F	R^2_β	*F*	R^2_β	*F*	R^2_β	*F*	R^2_β
Management	1.3	0.031	1.1	0.024	0.4	0.010	2.1	0.040
Location	5.0*	0.059	6.5*	0.071	0.4	0.006	4.1	0.043
Depth	230.7***	0.609	-	-	-	-	-	-
IS_Plant	3.0	0.026	3.4	0.026	0.3	0.000	1.8	0.004
Open	0.2	0.001	2.1	0.016	-	-	-	-
MEM10	1.6	0.014	3.9	0.031	0.7	0.005	0.1	0.001
Management x Location	7.2**	0.083	16.8***	0.184	5.7	0.071	2.2	0.034
Management x IS_Plant	1.7	0.027	1.3	0.019	0.6	0.010	1.2	0.022
Management x Open	1.3	0.011	-	-	-	-	-	-
Soil organic carbon (SOC)	Full model R^2_m= 0.543 ; R^2_c = 0.764		Depth 0-10 cm R^2_m= 0.162; R^2_c = 0.505		Depth 10-30 cm R^2_m= 0.453 ; R^2_c = 0.944		Depth 30-50 cm R^2_m= 0.137 ; R^2_c = 0.940	
	F	R^2_β	*F*	R^2_β	*F*	R^2_β	*F*	R^2_β
Management	2.9	0.145	0.1	0.009	2.7	0.140	0.6	0.032
Location	4.5*	0.162	7.1*	0.199	0.9	0.040	3.5	0.148
Depth	113.7***	0.699	-	-	-	-	-	-
S_Plant	0.4	0.010	-	-	2.2	0.054	2.3	0.065
Open	-	-	0.0	0.000	-	-	-	-
MEM6	5.8*	0.195	-	-	12.7**	0.347	-	-
MEM10	6.0*	0.193	-	-	3.3	0.115	5.1*	0.154
Management x Location	5.6*	0.195	5.5*	0.175	3.1	0.125	2.3	0.094
Management x S_Plant	3.1	0.153	-	-	3.5*	0.202	-	-
Total nitrogen (N)	Full model R^2_m= 0.579 ; R^2_c = 0.824		Depth 0-10 cm R^2_m= 0.174 ; R^2_c = 0.524		Depth 10-30 cm R^2_m= 0.031 ; R^2_c = 0.919		Depth 30-50 cm R^2_m= 0.026 ; R^2_c = 0.937	
	F	R^2_β	*F*	R^2_β	*F*	R^2_β	*F*	R^2_β
Management	3.0	0.143	0.2	0.012	0.4	0.026	0.2	0.013
Location	1.8	0.099	11.0**	0.303	1.0	0.046	2.8	0.120
Depth	189.8***	0.795	-	-	-	-	-	-
S_Plant	0.2	0.005	-	-	-	-	-	-
MEM1	6.2*	0.198	-	-	-	-	-	-
Management x Location	4.0	0.165	7.7*	0.234	3.4	0.131	4.6*	0.173
Management x S_Plant	2.9	0.137	-	-	-	-	-	-
Location x S_Plant	0.4	0.021	-	-	-	-	-	-
SOC stock	Depth 0-50 cm R^2_m= 0.032 ; R^2_c = 0.911		Depth 0-10 cm R^2_m= 0.129 ; R^2_c = 0.650		Depth 10-30 cm R^2_m= 0.034 ; R^2_c = 0.870		Depth 30-50 cm R^2_m= 0.029 ; R^2_c = 0.855	
	F	R^2_β	*F*	R^2_β	*F*	R^2_β	*F*	R^2_β
Management	0.1	0.005	0.3	0.020	0.0	0.001	0.0	0.002
Location	1.2	0.058	8.7**	0.271	0.0	0.000	0.1	0.004
S_Plant	0.1	0.004	-	-	1.2	0.036	0.5	0.015
Open	-	-	0.3	0.007	-	-	-	-
Management x Location	2.6	0.113	4.2*	0.182	0.2	0.011	0.4	0.017

Table 2. Mean values ± 1SE for bulk density (BD), soil organic matter (SOM), total nitrogen (N), soil organic carbon (SOC), soil organic carbon stock, potential heterotrophic respiration (Pot. RH), potential net nitrogen (N) mineralization (Pot. Nmin), litter decomposition constant (k) and litter stabilization factor (S). Separate values by depth layer are shown for the drive and crop rows of both orchard types, as well as for the semi-natural grasslands. Significant differences (*P* < *0.05*) between values within the same row are indicated by letters and were calculated using a Tukey's test for pairwise comparisons.

		Organic orchard		IPM orchard		Semi-nat. grassland
Variable	Depth (cm)	Crop row	Drive row	Crop row	Drive row	Grassland
BD (Mg m^{-3})	0-10	1.209 (0.046)^{a}	1.353 (0.039)^{b}	1.361 (0.031)^{ab}	1.348 (0.042)^{b}	1.282 (0.045)^{ab}
	10-30	1.365 (0.022)^{a}	1.504 (0.034)^{bc}	1.429 (0.022)^{ab}	1.447 (0.020)^{ac}	1.519 (0.029)^{c}
	30-50	1.496 (0.046)	1.554 (0.031)	1.554 (0.019)	1.549 (0.029)	1.551 (0.028)
SOM (%)	0-10	5.851 (0.265)^{ab}	5.707 (0.273)^{ab}	4.792 (0.152)^{a}	6.800 (0.388)^{b}	7.967 (0.729)^{ab}
	10-30	4.476 (0.247)	3.962 (0.146)	3.981 (0.132)	4.092 (0.145)	4.358 (0.337)
	30-50	2.878 (0.135)	2.976 (0.101)	3.215 (0.148)	3.337 (0.144)	3.181 (0.237)
Total N (%)	0-10	0,177 (0.014)^{ab}	0,184 (0.011)^{ab}	0,132 (0.007)^{a}	0,205 (0.015)^{b}	0,192 (0.026)^{ab}
	10-30	0,130 (0.013)	0,115 (0.007)	0,103 (0.007)	0,109 (0.006)	0,123 (0.027)
	30-50	0,063 (0.006)^{ab}	0,062 (0.009)^{ab}	0,056 (0.005)^{a}	0,065 (0.005)^{b}	0,070 (0.012)^{ab}
SOC (%)	0-10	1.794 (0.180)^{ab}	1.916 (0.120)^{ab}	1.373 (0.089)^{a}	2.190 (0.179)^{b}	2.101 (0.274)^{ab}
	10-30	1.382 (0.160)	1.192 (0.096)	1.114 (0.096)	1.175 (0.078)	1.426 (0.417)
	30-50	0.655 (0.076)	0.606 (0.101)	0.546 (0.054)	0.664 (0.073)	0.787 (0.140)
SOC stock (Mg ha^{-1})	0-10	2.872 (0.289)^{ab}	3.068 (0.209)^{ab}	2.199 (0.142)^{a}	3.288 (0.264)^{b}	3.364 (0.438)^{ab}
	10-30	4.657 (0.538)	4.018 (0.303)	3.756 (0.324)	3.959 (0.269)	4.807 (1.406)
	30-50	2.294 (0.266)	2.123 (0.355)	1.914 (0.188)	2.083 (0.248)	2.760 (0.489)
	Sum 0-50	9.823 (0.900)	9.209 (0.785)	7.868 (0.589)	9.330 (0.646)	10.650 (2.113)
Pot. RH (mg kg^{-1} hr^{-1})	0-10	1.144 (0.116)^{ab}	1.421 (0.113)^{bc}	0.687 (0.067)^{a}	1.537 (0.101)^{bc}	1.777 (0.167)^{c}
Pot. RH/SOC	0-10	0.680 (0.075)^{ab}	0.776 (0.079)^{bc}	0.541 (0.077)^{a}	0.751 (0.071)^{bc}	0.911 (0.131)^{c}
Pot. N_{min} (mg kg^{-1} d^{-1})	0-10	0.370 (0.184)^{a}	0.628 (0.196)^{b}	0.161 (0.053)^{a}	0.238 (0.075)^{a}	0.260 (0.096)^{a}
k	0-10	0.017 (0.001)^{bc}	0.020 (0.001)^{bc}	0.020 (0.001)^{b}	0.016 (0.001)^{ac}	0.014 (0.001)^{a}
S	0-10	0.177 (0.005)	0.219 (0.007)	0.187 (0.005)	0.205 (0.004)	0.158 (0.008)

Table 3. Results of the final linear mixed-effects models for all biological soil health indicators, showing marginal (R^2_m) and conditional (R^2_c) R^2-values for all models. Test statistic (F) and semi-partial R^2_β are given for each retained explanatory variable after model reduction.

*P < 0.05, **P < 0.01, ***P < 0.001.

Soil biological indicators	Pot. heterotrophic resp. R^2_m= 0.643 ; R^2_c = 0.729		Pot. net N mineralization R^2_m= 0.249 ; R^2_c = 0.615		Litter decomposition k R^2_m= 0.358 ; R^2_c = 0.512		Litter stabilization S R^2_m= 0.333 ; R^2_c = 0.700	
	F	R^2_β	*F*	R^2_β	*F*	R^2_β	*F*	R^2_β
Management	3.6*	0.178	1.3	0.075	6.2**	0.235	1.3	0.032
Location	15.2***	0.318	10.4*	0.250	10.0**	0.087	4.4	0.062
pH	0.8	0.011	-	-	-	-	14.1***	0.217
SOC	-	-	1.8	0.040	-		-	-
C:N	5.1*	0.156	-	-	6.8*	0.142	2.0	0.035
S_Fun	5.9*	0.142	-	-	-	-	1.8	0.030
IS_Fun	-	-	-	-	-	-	2.3	0.027
IS_Bac	-	-	0.2	0.005	-	-	-	-
IS_Plant	-	-	-	-	0.3	0.003	2.7	0.047
Management x Location	2.2	0.064	5.2*	0.210	6.4*	0.084	3.6	0.058
Management x S_Fun	-	-	-	-	-	-	1.6	0.047
Management x pH	3.3	0.092	-	-	-	-	-	-
Location x C	-	-	6.8*	0.174	-	-	1.6	0.048

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