Title

Pedoclimatic factors and management determine soil organic carbon and aggregation in farmer fields at a regional scale

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Abstract

The degradation of soil from agricultural land is a major threat to food security and a driver of global changes. Soil conservation systems are thus being promoted and/or adopted worldwide. In this on-farm study conducted in Switzerland, we compared the effect of three cropping systems – conventional with tillage, conventional without tillage (i.e. no-till) and organic farming with tillage – on soil quality. Samples from 60 winter wheat fields belonging to these three systems were analysed for soil carbon concentration, soil aggregate distribution and soil biological properties (microbial carbon and mycorrhizal biomarkers), at three different depths (0-5 cm, 5-20 cm and 20-50 cm). Information about cropping practices was collected through surveys. The main differences in soil properties between systems occurred for the surface layer (0-5 cm depth), with increased soil organic carbon concentration and stock under no-till compared to the conventionally tilled fields. No-till and organic fields showed a higher mean aggregate size and proportion of macroaggregates in the surface layer compared to tilled conventional fields, with a greater amount of carbon in the large macroaggregates. However, large within-system variability was also observed, which tended to override differences between systems. Across systems, clay content, microbial carbon, and the mycorrhizal PFLA biomarkers were the major drivers of soil organic carbon concentration, clay to carbon ratio and carbon accumulation in the large macroaggregate fraction. Aggregation at 0-5 cm was mostly related to tillage depth, while climate variables and especially clay content played a major role for deeper layers. Our results demonstrate that within the constraints set by soil texture and climate, organic agriculture and no-till can contribute to improved soil carbon and aggregation properties. Thus, we advocate for the identification of the main drivers of soil quality in order to inform management and improve soil functioning in agricultural fields in the long term.

Keywords

soil organic carbon, soil biological properties, tillage, cropping practices

1. Introduction

The massive increase in crop yield during the last century has come at a cost of degradation of agricultural soils (Tilman et al., 2002; Virto et al., 2015). Soil organic carbon content is strongly related to many other crucial soil properties and is thus often used as a proxy for soil quality and functioning (Johannes et al., 2017; Schjønning et al., 2018; Wiesmeier et al., 2019; Baveye et al., 2020; Or et al, 2021). The loss of soil organic carbon is therefore a threat to current and future soil quality, as well as a major driver of climate change (Lal et al., 2018). So-called conventional farming systems, relying on intensive tillage and external inputs such as mineral fertilisers and pesticides, have particularly impacted the soil quality, including chemical, physical and biological degradation, and loss of soil organic carbon (Virto et al., 2015). Alternatives to conventional farming have been promoted to alleviate soil degradation and the loss of soil organic carbon in arable systems. For example, reduced soil tillage, crop diversification, the use of organic amendments and the optimisation of input use have been shown to increase soil organic carbon (Merante et al., 2017; Williams et al., 2020). Among those, reduction of soil tillage and the increase of organic inputs to the soil are the main factors allowing to maintain or increase soil organic carbon content (Virto et al., 2012; Palm et al., 2014; Mary et al., 2020).

Besides modifying specific practices, some farming systems as a whole have been promoted with the aim of improving soil quality, but until now none has successfully addressed all of the environmental challenges related to agriculture. Conventional no-till systems, while achieving less soil disturbance thanks to the absence of tillage, usually rely more heavily on herbicides. The effect of herbicides on soil life is still debated (Bünemann et al., 2006), and some studies have shown negative effects of herbicides on microbial communities (e.g. Druille et al., 2016; Helander et al., 2018) while some others have not shown any effects (e.g. Kepler et al., 2020). However, herbicides are also known for other adverse effects on the environment, for example to pollute groundwater and impact aquatic life (Schwarzenbach, 2006; Gregorio et al., 2012). On the other side, organic farming, while banning pesticide use and synthetic inputs, usually involves high soil disturbance due to mechanical weeding and tillage. In addition, both systems tend to have lower productivity (Knapp & van der Heijden, 2018). Lower productivity could result in lower biomass inputs to the soil, however, this may also depend on other factors such as crop variety and a direct link between below and above ground biomass could not always be inferred (Hirte et al, 2021). It is thus crucial to study how these alternative systems compare to conventional farming in terms of soil quality.

Soil carbon concentration also depends on site or regional factors that cannot be managed, or not easily, by farmers, such as soil texture or weather conditions. For example, clay concentration is known to influence and constrain soil organic carbon content in a temperate climate, through its ability to form stable complexes with carbon (Johannes et al., 2017). The ratio of clay to carbon has thus been suggested as an indication of the potential of soil to store carbon (Dexter et al., 2008; Merante et al., 2017) and as an indicator of soil structure (Johannes et al., 2017). Furthermore, Dimassi et al (2014) have shown that carbon stocks increase in wet years and decrease in drier years. Other site related soil properties, such as pH and calcium concentration, have an impact on soil quality. For example, it has been shown that calcium and aluminium concentration are drivers of soil organic carbon in tropical soils (von Fromm et al., 2020). Therefore, the intrinsic characteristics of soils need to be taken into account when investigating organic carbon sequestration potential of soils.

To ensure long term carbon storage, soil organic carbon needs to be stabilised. Several factors govern the stabilisation and retention of soil carbon, of which soil aggregation and clay complexation are central (Hassink 1997; Totsche et al., 2018). In soil, macroaggregates are first formed when new organic matter is added to the soil and binding agents are produced by microbes decomposing the newly added organic matter. With time, microaggregates are formed within macroaggregates, leading to a hierarchy of aggregate fractions (Six et al., 2000a). It has been shown that increased soil aggregate size is directly related to organic carbon protection (Six et al., 2000a). The cropping practices reducing soil organic carbon content act mainly by reducing soil aggregation and aggregate size. In particular, soil tillage, even when practised only once a year, has been shown to breakdown macroaggregates and accelerate their turnover, leading to a decrease in mean aggregate size and to the production of unstable fragments instead (Six et al., 2000a; Grandy & Robertson, 2006). Other important factors also play a role in the formation or destruction of soil aggregates (Blanco-Canqui and Lal, 2004; Six et al., 2004), some being manageable and some not. For example, soil biological activity increases aggregation as earthworms, fungi and bacteria excrete substances fostering aggregation, as well as roots through rhizodeposition. Inorganic binding agents such as calcium also promote the formation of aggregates. While weather-related variables such as freezing-thawing and wetting-drying cycles could form or break down aggregates (Denef et al., 2001; Blanco-Canqui and Lal, 2004; Six et al., 2004).

Previous studies have investigated the influence of either cropping systems (mostly organic vs conventional, or no-till vs conventional) or tillage on soil organic carbon and aggregation (see for example in the reviews by Leifeld and Fuhrer, 2010, and by Sun et al., 2020). However, a comprehensive investigation of the relative importance of cropping system vs cropping practices vs pedoclimatic conditions is still lacking. In addition, identifying the main drivers of soil carbon and aggregates in soils from farmer fields, compared to on station experiments, is also important to evaluate the opportunities for improved soil management to enhance soil quality in the long term. The aim of the present study was to investigate the influence of three cropping systems and cropping practices on soil organic carbon, aggregates and their interaction. The study was conducted in a network of 60 farms belonging to conventional with tillage, conventional with no-till and organic cropping with tillage systems in Switzerland. The objectives of this study were: 1) to assess the difference in organic carbon content and stock between cropping systems at different depths; 2) to compare aggregate size distribution and the carbon accumulation in each aggregate fraction between cropping systems; and 3) to investigate the main drivers of soil carbon and aggregate fraction distribution, using quantitative descriptors of cropping practices, weather conditions and soil properties.

2. Materials and Methods

2.1 Field selection

Samples were collected in 2016 from 60 fields (>1 hectare) distributed across the Swiss Plateau (Supplementary Material Figure S1A). All soils were classified as Cambisol, and were derived from Quaternary moraine. All fields were cultivated with winter wheat, sown in autumn 2015. Twenty fields corresponded to conventional farming, with soil tillage (mainly ploughing) and use of pesticides (mainly herbicides and fungicides) (called thereafter ‘conventional’ fields), 20 fields were conventional no-till fields, with continuous no-tillage for more than 5 years (called thereafter ‘no-till’ fields). Finally, 20 fields were organically certified for more than 5 years, with soil tillage (called thereafter ‘organic’ fields). The field selection, characteristics and practices were described in Büchi et al. (2019). Based on this article, one field was moved from the no-till category to the conventional one for all the analyses presented here.

2.2 Soil sampling

The main soil sampling took place between the 20th of April and the 27th of May 2016. In each field, in a sampling zone of 300-400 m^2, 15-20 soil cores were taken with a hand auger for four different depths, 0-5, 5-20, 20-25, 25-50 cm. For each depth, all individual samples were pooled together to form a unique composite sample for each field and stored in a plastic bag. The soil was then cleaned from plant and animal debris and sieved at 8 mm. Part of the sample was then air dried for aggregate fractionation, while another part was sieved at 2 mm and dried at 40°C for 72h for nutrient analyses. The remaining part was sieved at 2 mm and stored in a cold room for microbial analyses.

Bulk density was determined in the same sampling zone in parallel to the core sampling for all fields. At five different places, undisturbed soil cores (100 cm^3) were taken in the centre of each layer, at 0-5, 10-15, 20-25, 35-40 cm, with a soil sample ring kit. Samples were then dried at 105°C for 24h and weighed to determine bulk density. The median value of the five cylinders was used to represent each depth.

An additional sampling for mycorrhiza analysis took place between the 2nd and 23th of June 2016. In each field, ten soil cores were taken for the depth 0-20 cm with a hand auger and pooled to constitute a composite sample. These samples were kept in a cooling box during transportation and then stored in the lab at 4°C before further processing. Soil samples were then sieved at 5 mm, homogenised and 50 mL subsamples, cleaned from plant and animal debris by hand, were stored at -20°C.

2.3 Soil analyses

For each soil sample of the first sampling, texture, soil organic carbon (SOC), pH and total calcium (Ca) were measured according to the Swiss standard methods (Agroscope, 1996). The clay to carbon ratio was obtained by dividing clay content by SOC.

Soil aggregate fractionation was done following Six et al. (1998). A sample of about 80 g of air-dried soil was rehydrated in deionised water, and then successively sieved at 2000 µm, 250 µm and 53 µm. Four different fractions were thus obtained, large macroaggregates (2000 µm - 8000 µm), small macroaggregates (250 µm - 2000 µm), microaggregates (53 µm - 250 µm) and silt and clay (< 53 µm). Each fraction was then dried at 60°C for 72h, then weighted and prepared for nutrient analysis. Total carbon and nitrogen concentration of each fraction were determined by dry combustion (CN-628 Elemental Determinator; LECO Corp., St Joseph, MN).

Microbial biomass carbon estimates by chloroform-fumigation-extraction were carried out according to Vance et al. (1987) on the soil samples of the main soil sampling. Extracted organic C was determined by infrared spectrometry after combustion (DIMA-TOC 100, Dimatec, Essen, Germany), soil microbial biomass was then calculated according Joergensen (1996).

The soil samples from the second sampling were analysed for phospholipid fatty acids (PFLA), according to a modified version of Bligh and Dyer method (Bligh and Dyer, 1959). The PLFA 16:1ω5 was used as a marker for arbuscular mycorrhizal fungi (Olsson et al., 1999), and employed in this study as a potential explanatory variable for soil carbon content and aggregation.

In tilled soil, the plough depth would in general be around 20 cm. The soil properties from the depths 20-25 cm and 25-50 cm were thus averaged, using their respective bulk density as weights, to obtain values for a composite 20-50 cm layer. Results are therefore presented for three depths: 0-5 cm, 5-20 cm and 20-50 cm.

2.4 Data analyses

All analyses were performed using R 3.6.3 (R Core Team, 2020).

Carbon stocks were computed for each layer as the product of carbon content, bulk density and layer thickness. In addition to individual depths, carbon stock for the composite layer 0-20 cm and 0-50 cm were calculated, using the maximal equivalent soil mass (ESM) method for the plough layer (0-20 cm) and using the minimal ESM method for the whole depth (0-50 cm) (Lee et al., 2009).

To estimate the global level of aggregation of each layer, mean weight diameter (MWD) was computed as the weighted mean of each aggregate size class average size and their respective relative weight proportion. C accumulation in each aggregate size class was obtained by multiplying their relative weight by their respective C concentration.

Differences in soil properties (bulk density, SOC, C stocks and MWD) between cropping systems were tested using analyses of covariance, using clay content as a quantitative covariate and cropping system (conventional, no-till, organic) as a fixed factor. Clay concentration and clay-carbon ratio were tested with one way ANOVA. Tests showing a significant ($p<0.05$) effect of cropping systems were followed by least-squares mean test ('lsmeans' R package; Lenth, 2016) to differentiate the individual cropping systems. The analyses were performed independently for each depth (0-5 cm, 5-20 cm, 20-50 cm).

Differences between layers within each cropping systems were tested using the same methods (ANOVA followed by least-squares mean test).

Differences in aggregate related variables (relative weight and C accumulation) were tested using two-factors analyses of variance with cropping systems and fractions (four levels: large and small macroaggregates, microaggregates, silt and clay) as fixed factors. In case of significant interactions (i.e., different value for each fraction, depending on cropping system) ($p<0.05$), pairwise post-hoc Tukey tests were performed separately for each fraction. The analyses were performed independently for each depth.

2.5 Linear regressions and R^2 decomposition

To investigate the main drivers of soil properties beyond a priori system definitions, additional analyses were performed across the three cropping systems. For each depth, the influence of several explanatory variables (see description below) on soil organic carbon concentration 'SOC', clay to carbon ratio 'CCR', mean weight diameter 'MWD' and carbon accumulation in the large macroaggregate fraction 'CAM' was tested using multiple linear regressions. These linear regressions were followed by a R^2 decomposition, according to 'lmg' method from 'rlaimpo' R package (Grömping, 2006), to assess the importance of each explanatory variable. The explanatory variables were chosen for their known links to soil organic carbon and aggregate formation and persistence.

The explanatory variables that were initially considered were clay concentration (‘clay’), sand concentration, total calcium (‘calc’), pH, number of freezing-thawing days (period: from 01.10.2015 to the date of soil sampling in April-May 2016, definition: number of days where the minimum temperature is below 0°C and the maximum temperature above 0°C), mean air temperature (‘temp’, from 01.07.2015 to the date of soil sampling in April-May 2016), total precipitation (‘rain’, period: from 01.07.2015 to the date of soil sampling in April-May 2016), soil tillage intensity (sum of the STIR ratings (USDA, 2012) of each tillage or weeding implement used, period: harvest of the previous crop to soil sampling), mean number of tillage and weeding interventions (‘nbTW’, period: five-year crop rotation), usual maximum tillage depth (‘depthT’), crop rotation diversity (‘cropDiv’, calculated as the number of different crops (main and cover) during the five-year rotation), presence of rotational leys (‘nbLeys’), organic matter input from crop residues (‘cropOrg’), amendments, and both (‘totOrg’, period: five-year crop rotation), nitrogen inputs (mineral and total ‘totN’), microbial carbon (‘microb’, at soil sampling) and mycorrhizal AMF biomarker (‘amf’, measured one month after soil sampling). The weather data were retrieved from the nearest local weather station. Detailed explanations about how the variables linked to cropping practices were calculated are given in Büchi et al. (2019).

First, univariate regressions between the four response variables (soil organic carbon ‘SOC’, clay to carbon ratio ‘CCR', mean weight diameter ‘MWD’ and carbon accumulation in the large macroaggregate fraction ‘CAM’) and each explanatory variable were performed and only variables showing at least one significant correlation (at $p<0.1$) with at least one of the response variable and depth were included in the model. Correlations between explanatory variables was also checked (Supplementary Material Table S1) and highly redundant variables (>0.7 or <0-.7) were removed when related to the same category. Thus, the variables sand concentration (correlated with clay), number of freezing-thawing days (not significant and correlated with temperature), soil tillage intensity (not significant and correlated with number of tillage and weeding interventions and tillage depth), organic inputs from amendments (not significant and correlated with total organic inputs) and mineral nitrogen fertilisation (correlated with total nitrogen inputs) were not included in the multivariate regressions.

These analyses were performed on 59 fields only, as some explanatory variables were missing for one of the fields.

3. Results

3.1 Bulk soil properties

In general, substantial variability of soil properties was observed between fields within cropping systems. Clay concentration varied widely, between 10% and 48% across all fields and depths, with an overall mean of 22%. No differences in clay concentration were observed between systems or between layers within systems (Table 1, Supplementary Material Figure S1B).

Bulk density varied between 0.89 g/cm^3 and 1.66 g/cm^3 across all fields and layers and showed significant differences between systems only for the 5-20 cm layer (p=0.003), with a higher mean value in no-till (1.36 g/cm^3) compared to conventional (1.26 g/cm^3) and organic (1.22 g/cm^3) systems (Table 1). An increase in bulk density with depth was found for all three systems (on average, from 1.21 g/cm^3 at the surface to 1.46 g/cm^3 at 20-50 cm) (Table 1).

Soil organic carbon concentration SOC varied between 2.9 g/kg and 56.3 g/kg across all fields and depths. The three cropping systems showed significant differences in terms of SOC for the 0-5 cm layer (p=0.012) but not for the 5-20 cm (p=0.231) and 25-50 cm layers (p=0.129) (Table 1). In the uppermost layer (0-5 cm depth), SOC was significantly higher for the no-till system compared to the conventional system, with the organic system intermediate and not different from the other two systems (Table 1). Different depth-distribution patterns of SOC were observed for the different systems. No-till system showed decreasing concentration with depth, in contrast to conventional and organic systems that had more homogeneous SOC concentrations in the two first layers (0-5 and 5-20 cm) (Table 1).

The clay to organic carbon ratio differed between systems for the 0-5 cm layer, with lower values for the no-till (clay/SOC = 10) compared to conventional system (clay/SOC = 14), with organic having intermediate value with a clay/SOC ratio of 12 (Table 1, Figure 1). In addition, the clay to carbon ratio increased with depth.

The mean carbon stock across all systems was 47.8 t/ha for 0-20 cm (equivalent soil mass used for the calculation of carbon stock: 2961 t/ha) and 72.2 t/ha for 0-50 cm (minimal equivalent soil mass: 5387 t/ha), with high variability within systems (Figure 2). In the uppermost layer (0-5 cm depth), differences in SOC stock between systems were observed with higher values in no-till fields and lower in conventional fields (Figure 2, Table 1). No significant differences were observed for the other depths and for topsoil (0-20 cm depth) and total depth (0-50 cm) (Table 1).

3.2 Aggregate size distribution and C and N accumulation in aggregates

Overall, macroaggregates (large: 2000 µm - 8000 µm and small: 250 µm - 2000 µm) were the dominating fraction (compared to microaggregates: 530 µm - 250 µm, and silt and clay: < 53 µm), representing 77% of the total, across all systems and layers (Figure 3). Significant difference in aggregate size distribution between systems was observed only in the 0-5 cm layer. In this layer, conventional system had fewer large macroaggregates than the no-till and organic systems (Figure 3). As a consequence, the conventional system had a higher proportion of small macroaggregates than the other two systems, and higher proportion of microaggregates than no-till. No significant differences were observed for the ‘silt and clay’ fractions. In all the other layers, the three systems showed a similar aggregate size distribution (Figure 3). Following a similar pattern, mean weight diameter (MWD) was significantly different between systems for the 0-5 cm layer ($p<0.001$), with a higher value for no-till and organic systems compared to the conventional system (Table 1). MWD was markedly lower in the subsoil layer (20-50 cm) for all three systems (Table 1). However, as with carbon, MWD showed high within system variability at all depths (Figure 4).

The concentration of carbon in each aggregate fraction showed a tendency to lower concentration in the micro aggregate fractions in all management by depth combinations (Supplementary Material Figure S2). The amount of soil organic carbon accumulated in each aggregate fraction (i.e., equivalent of carbon stock in each fraction) was different between systems for the top layer (0-5 cm depth), in which the amount of carbon accumulated in the large macroaggregate fraction was higher in no-till and organic systems compared to conventional (Figure 5). No significant differences were observed for the other fractions or layers.

3.3 Drivers of soil organic carbon and aggregate properties

Multiple linear regressions were performed to investigate the main drivers explaining the soil carbon and aggregate results, via four response variables: soil organic carbon ‘SOC’, clay to carbon ratio ‘CCR', mean weight diameter ‘MWD’ and carbon accumulation in the large macroaggregate fraction ‘CAM’ (Figure 6 and Supplementary Material Table S2). Fourteen explanatory variables were retained to build the models and assess their contribution in terms of R^2. Figure 6 shows how the partial R^2 decomposed across the 14 variables, grouped into four main categories: 1. site-related, unmanageable pedoclimatic variables: clay content, temperature and rainfall; 2. site-related, partially manageable variables: pH and calcium concentration; 3. site-related, partially indirectly manageable variables: soil biological properties, microbial carbon and mycorrhizal marker, and 4. directly manageable variables: cropping practices.

For SOC, total R^2 was high for all depths (>80%). The variance decomposition of the R^2 showed, for all depths, that, along with clay (28-37%), the biological variables microbial carbon (‘microb’) and mycorrhizal marker (‘amf’) accounted together for the highest part of R^2 (32-38%) (Figure 6 and Supplementary Material Table S2), both with a positive impact on SOC. However, the contribution of ‘amf’ decreased with depth and was significant only at the 0-5 cm depth, while that of ‘microb’ increased with depth (Figure 6). Other variables had negligible contributions in terms of R^2, but pH showed a significant negative slope in the multiple regression for 0-5 cm and 5-20 cm.

For CCR, total R^2 was between 61% and 71%. Clay played a minor role in terms of R^2, but was significant in the model at the three depths. As for SOC, biological variables ‘microb’ and ‘amf’ accounted for the highest part of R^2 (28%-38% in total), with ‘amf’ significant only for 0-5 cm. Effect of cropping practices accounted for 19% of R^2 at 0-5 cm, but only for 13% at 5-20 cm and 8% at 20-50 cm, while effect of weather variables increased from 8% at 0-5 cm to 19% at 20-50 cm.

For MWD, total R^2 was lower than for SOC but increased with depth (59% at 0-5 cm, 66% at 5-20 cm, 78% at 20-50 cm). The decomposition of R^2 showed a clear contrast between the uppermost layer (0-5 cm) and the deeper ones (5-20 cm and 20-50 cm). Clay explained only 9% at 0-5 cm, but 45% at 5-20 cm and 64% at 20-50 cm. In contrast, the R^2 associated to the other explanatory variables was 50% at 0-5 cm, but only 22% at 5-20 cm and 14% at 20-50 cm. For the 0-5 cm layer, cropping practices explained the largest part of the variance, with tillage depth ‘depthT’ being the most important variable (16%, negative slope), followed by nitrogen inputs ‘totN’ (7%, negative slope) (Figure 6). At 5-20 cm, after clay, weather variables were the most important, with temperature (8%, negative slope) and rainfall (6%, positive slope) accounting for the highest partial R^2. At 20-50 cm, except from clay, the other variables in the model explained only 14% of the variability, with significant slopes for temperature (3%, negative) and 'microb' (3%, positive).

For CAM, total R^2 was high for all depths (>80%). The part explained by clay increased from 30% at 0-5 cm to 56% at 5-20 cm and 48% at 20-50 cm. After clay, 'microb' accounted for the highest part of R^2, for all depths (17%, 12%, 18%, positive slopes) (Figure 6). At 0-5 cm, 'amf' also showed high contribution (14%, positive slope), followed by tillage depth 'depthT' (7%, negative slope), calcium concentration (4%, positive slope) and pH (4%, negative slope). At 5-20 cm, temperature (5%, negative slope) and calcium (4%, positive slope) were also significant. At 20-50 cm, beside clay and 'microb', the only other almost significant variable was calcium (2%, positive slope, p=0.09).

4. Discussion

4.1 Influence of cropping systems on soil carbon and aggregation

Overall, this study showed little differences between cropping systems in terms of soil carbon and aggregation, except for the surface soil layer (0-5 cm depth). This may be due to a large within-system variability, which is common in on-farm studies compared to on-station field experiments. However, it might also be due to the soil protection guidelines followed in Swiss agriculture, which incentivise the use of diversified crop rotations and cover crops, and thus help maintaining a reasonably good soil quality in conventional systems (Dupla et al., 2021). Clay content was a strong driver for carbon and aggregate properties, and variability in clay content within systems could partly explain the lack of observed differences between systems. This shows that soil organic carbon related variables should always be interpreted together with clay content to avoid any spurious conclusions. Clay mineralogy also plays an important role for the stabilisation of soil organic carbon (Singh et al., 2018), but this was not assessed in this study, as no differences in clay mineralogy between cropping systems was expected.

This should however be the focus of future studies aimed at disentangling the effect of management from that of site-related factors. This also reinforces clay content as a major driver of soil organic carbon content, as shown by many studies (Hassink, 1997; Merante et al., 2017; Li et al., 2020a,b), due to its ability to stabilize organic carbon (Dexter et al., 2008). However, other variables such as exchangeable calcium and iron or aluminium oxyhydroxides could better reflect the potential of soil carbon stabilisation in certain soils (Rasmussen et al., 2018; Pihlap et al., 2021). A recent study has also shown that calcium and aluminium were stronger drivers of soil organic carbon than clay in tropical soils in sub-Saharan Africa (von Fromm et al., 2020). These studies together, thus, suggest that for each pedoclimatic context, several soil properties need to be considered to assess the potential of carbon sequestration in soils.

The differences between cropping systems observed in the uppermost soil layer (0-5 cm depth) is in accordance with other studies, showing that topsoil is more sensitive than subsoil to management (e.g., Novelli et al., 2017). The superficial layer of the soil is expected to be more affected by cropping practices, especially in no-till systems, where the absence of tillage induces a stratification of most soil properties with depth (Franzluebbers 2002), whereas tilled systems tend to have more homogenous properties within the tilled layer. This strong stratification of soil properties was also observed here for the no-till fields. Despite being a thin layer, the surface layer is at the interface with the atmosphere and plays a major role in soil quality through soil stabilisation, water infiltration ability and potential role in the reduction of erosion (Franzluebbers 2002). Since the topsoil is more prone to erosion, accumulation of carbon in the surface of no-till fields, while improving soil quality, can also put soil carbon at higher risk of loss during major disturbance events.

In this study, no-till systems had higher soil organic carbon concentrations and stocks in the topsoil (0-5 cm depth) compared to conventional systems, while organic systems had intermediate values. However, no difference in carbon stocks was observed for the topsoil (0-

20 cm) and total soil profile (0-50 cm). This shows, in accordance with other studies (e.g. Virto et al., 2012; Mary et al., 2020), that the reduction of tillage alone does not necessarily lead to an increase in carbon stocks across the profile. These studies have shown that the amount of organic inputs to the soil is the main driver explaining differences in carbon stocks between systems (Virto et al., 2012; Mary et al., 2020). In our study, the organic fields did not show any significant increase in carbon stocks compared to conventional fields. This could be explained by the absence of difference in external organic matter inputs between the cropping systems, along with reduced biomass production and yield in the organic fields studied here (Büchi et al., 2019). In contrast, the aggregate mean weight diameter of organic fields was similar to no-till fields, and higher than conventional fields in the uppermost soil layer (0-5 cm). This indicates that some practices may offset the negative effect of tillage on soil aggregate (see section 4.2 below).

The measured organic carbon stocks and clay to carbon ratios highlight a potential for increasing soil organic carbon in the studied fields. At 0-5 cm, 23 fields out of 60 achieved a clay/carbon ratio <10, indicating good soil quality and the potential complexion of all available clay with carbon (Johannes et al., 2017; Merante et al., 2017; Schjønning et al., 2018). These fields with ‘good’ soil quality according to Johannes et al. (2017), while mainly observed in no-till (14 fields), also appeared in the organic (5 fields) and conventional systems (4 fields). This shows that good soil quality can be achieved in all cropping systems. However, most fields presented clay/carbon values >10, meaning the likely presence of non-complexed clay and thus the potential to increase organic carbon storage. The average value for clay/SOC ratios for the conventional fields (0-5 cm) was 14, which is above the threshold limit of 13 defined by Johannes et al. (2017) corresponding to degraded soil structural quality. The clay/carbon ratio increased with depth, showing an even higher potential for carbon increase in subsoils.

An average of 47.7 t C/ha for 0-20 cm and 72.1 t C/ha for 0-50 cm is currently stored in the 60 fields analysed here. An increase in carbon concentration allowing to reach a clay/carbon ratio of 10 for all fields would roughly increase this quantity to 66.7 t C/ha for 0-20 cm and 122.7 t C/ha for 0-50 cm. This would represent a significant potential to store large amounts of carbon in arable fields in the lowlands of Switzerland. Achieving such an increase in carbon storage would contribute to improving soil quality and to the global effort towards mitigation of climate change through carbon sequestration in agricultural soils (Smith et al., 2008; Lal et al., 2018). However, the strategies to practically increase soil organic carbon at depth to such a degree remain unclear.

In addition, climate also plays an important role in determining the maximum potential of carbon sequestration, as mineralisation rate is directly influenced by soil moisture and temperature (Jobbagy and Jackson, 2000; Curtin et al., 2012). A clay to carbon ratio of 10 may thus not be achievable under all climates, but previous studies indicates that this should be the case in Switzerland (Johannes et al., 2017). Furthermore, changing the focus from sole carbon storage to the overall improvement of soil quality and functions might be a more promising approach as advocated in recent studies (Poulton et al., 2017; Baveye et al., 2020).

4.2 Main drivers of soil organic carbon and aggregation

Our results indicated that some fields had potentially a better long-term protection of soil organic carbon compared to others, as a large mean weight diameter of aggregates, proportion of large macroaggregates and accumulation of carbon in these large macroaggregates are known to improve carbon protection and thus reduce its potential loss (Six et al., 2000b). As our results showed that the type of cropping system was not the sole driver of differences in soil carbon and aggregates, we assessed the main drivers among a set of continuous variables across all fields without considering their cropping system ‘label’. Six main factors have been shown to influence soil aggregation (Blanco-Canqui and Lal, 2004; Six et al., 2004): 1.

environmental variables, 2. inorganic binding agents, 3. soil microorganisms, 4. cropping practices such as tillage, 5. soil fauna, and 6. roots. In this on-farm study, we tested the relative importance of variables belonging to the first four of these six categories. Rainfall and mean temperature were used as representative environmental variables (freezing-thawing days was highly correlated with temperature and thus discarded). Total calcium concentration is a known binding agent (Six et al., 2004), which was assessed here together with pH. Microbial carbon and mycorrhizal biomarker were used to test the effect of soil microorganisms. We also included several cropping practices variables, related to crop diversity, ley cultivation, tillage intensity, amount of organic inputs and nitrogen inputs. However, earthworm abundance and diversity were not assessed here, although it has been shown to be an important driver of soil aggregation (Fonte et al., 2007; Sheehy et al., 2019; Guhra et al., 2020).

Environmental variables and inorganic binding agents

As previously discussed, clay concentration was a major driver of soil organic carbon concentration in this study. Rainfall tended to be positively associated with aggregate size, perhaps due to washing off or erosion of small aggregates, or indirectly through positive influence on soil biological activity. Nevertheless, dry-wet cycles, which were not investigated here, have been shown to be more relevant to explain aggregation (Denef et al., 2001; Cosentino et al., 2006; Harrison-Kirk et al., 2014). Mean temperature during the previous autumn and winter was negatively associated with aggregation. Previous studies have shown that frost could either decrease or increase aggregation, depending on soil water content, freezing intensity, soil type (Edwards, 1991; Lehrsch et al., 1993; Lehrsch, 1998; Six et al., 2004).

While not accounting for a large part of the variance, pH and sometimes calcium concentration appeared as significant for almost all carbon related variables. Soil pH of arable fields is among the most frequently managed soil properties, and liming is therefore regularly used to correct this and improve soil structure. The impact of these variables on soil carbon and aggregation and how these could be managed to improve soil quality deserves thus further investigations.

Soil microorganisms

Our analyses showed that for the variables linked to organic carbon (i.e., bulk soil organic carbon concentration, clay/carbon ratio and accumulation of carbon in the large macroaggregates), the explanatory variables accounting for the major part of variability, besides clay content, were the biological variables microbial biomass carbon and the abundance of mycorrhizal fungi. This major role of biological variables contrasts with recent findings of Li et al (2020a) in Australia, who found only little impact of biological variables (microbial diversity and enzyme activity) on soil carbon and nitrogen. The interrelation between soil organic carbon and soil biology is well known (McGill et al., 1975; Kögel-Knabner, 2002; Kallenbach et al., 2016; Paul, 2016), but our results did not allow us to identify if it was high microbial biomass and activity that promoted SOC formation or vice versa.

In contrast, these biological variables did not appear as the principal factors explaining the degree of aggregation itself (i.e. mean weight diameter). although bacteria and fungi have been shown to promote aggregate formation and stabilisation (Bossuyt et al., 2001; Six et al., 2004; Costa et al., 2018). Fungi, and particularly mycorrhizal fungi, play an important role in macroaggregate formation as the hyphae allow to stick soil particles together (Bossuyt et al., 2001; Six et al., 2004; Wilson et al., 2009). Bacteria are also involved in microaggregate formation and stabilisation through the secretion of extracellular polymeric substances that aggregate particles (Six et al., 2004; Costa et al., 2018).

Cropping practices

For the mean aggregate size in the surface layer (0-5 cm), it is notable that the partial R^2 of clay was only 9% while it represented most of the R^2 for the deeper layers (see Figure 6). Apart from clay concentration, variables linked to tillage and fertilisation (for the 0-5 cm layer), and to weather (for the 5-20 cm layer) played a significant role in explaining soil aggregation. Aggregation decreased with increasing tillage depth and nitrogen fertilisation, in accordance with previous observations (Six et al., 2000a for tillage, Fonte et al., 2009 for nitrogen fertilisation). However, the influence of tillage was observed only at 0-5 cm, which is in contrast to several studies showing that tillage is one of the major drivers of reduced aggregation down to the plough depth (Mikha & Rice, 2004; Six et al., 2004; Grandy & Robertson, 2006).

Crop diversity and biomass inputs to the soil (either through crop residue or amendment inputs) have previously been demonstrated to play a role in soil aggregation (Mikha & Rice, 2004; Cates et al., 2016; Abiven et al., 2009). ‘Perennialisation’ is also sometimes mentioned as a driver for soil aggregation (Cates et al., 2016; Panettieri et al., 2017; Jensen et al., 2019), and was tested here using the number of years with leys in the rotation in the model. However, none of these variables were major variables explaining the mean weight diameter or carbon accumulation in our study.

Potential additional drivers

Interestingly, the total R^2 for mean aggregate size (weight diameter) for the 0-5 cm layer was low, and lower than for carbon. This indicates that some drivers of aggregation were probably not captured in this study. In addition to earthworms, another important known driver of aggregation that was not studied here is plant roots and their exudates (Baumert et al., 2018). This could also potentially explain the surprising results that organic systems had similar soil organic carbon and aggregation as the no-till systems despite higher tillage intensity and similar organic inputs in organic fields (Büchi et al., 2019). Cates et al. (2016) showed that higher tillage intensity and lower biomass inputs in organic systems could explain lower aggregation and carbon accumulation. Other studies have shown higher aggregation in organic systems but only under reduced tillage (Loaiza Puerta et al., 2018). Some additional analyses done on a subset of fields of this study have shown a tendency to higher root biomass in the organic fields (on a 0-25 cm depth), probably due to several reasons including management, varietal choice and higher weed biomass (Hirte et al., 2020). Another study on the same fields has shown higher root microbial network complexity in organic fields than conventional and no-till (Banerjee et al., 2019), and the role of this diversity and complexity in aggregate formation is a potential lead that would require further investigations. This, together with potentially higher earthworm biomass in organic fields and increased presence of leys in the rotation, could explain the results observed here.

4.3 Potential for management of soil quality

Our analysis showed that unmanageable pedoclimatic factors played a major role in explaining variability in soil organic carbon concentration and related properties across all depths. This shows the key role of on-farm studies, that allow assessing soil quality within coherent farming systems and sets of practices and on a range of pedoclimatic conditions, while on-station experiments usually test individual practices separately in unique or few pedoclimatic conditions for all treatments, sometimes neglecting their vital role in setting boundaries for soil quality. A recent study from Dupla et al. (2021) also demonstrated important discrepancies between soil quality assessment between on-farm and on-station studies. Our results agree with recent findings from Li et al. (2020ab), who also showed an important role of climate and soil type for shaping physico-chemical soil properties in Australia. Indirectly manageable properties such as microbial and mycorrhiza presence also played an important role in our study, while more directly manageable properties such as soil pH and calcium concentration, and cropping practices only played a minor role. Only the mean weight diameter at the 0-5 cm layer was related to cropping practices and is thus directly manageable by farmers. Subsoil properties were primarily explained by clay content and weather and were little influenced by soil management and cropping systems. Altogether, these results show that when comparing fields with different pedoclimatic conditions, the potential of cropping system classification to explain differences in soil quality is only low. In contrast, according to the local pedoclimatic conditions, the use of practices promoting soil biological properties may benefit soil quality as a whole, while no strong direct link between specific cropping practices and soil aggregate could be demonstrated here.

5. Conclusions

Based on a network of 60 farmer fields in Switzerland, this study demonstrated that traditional cropping system classification (conventional, no-till, organic) only explained differences in soil organic carbon concentration and aggregation size distribution in the surface soil layer, but not in the deeper layers. Clay content was a one of the main driver of almost all assessed soil properties, and thus the potential to increase soil organic carbon storage was primarily determined by soil texture, and climate sometimes. However, many fields had proportionally more clay than carbon, indicating a potential for increasing carbon sequestration regardless of the cropping system. Our results suggest that the specificities of each field in terms of location, climate, soil type and management are more important in determining soil properties than cropping systems labels. This advocates for the identification and consideration of the main drivers of soil quality beyond a priori classification to inform management decision and improve soil functionality in agricultural fields.

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Table and figure legends

Table 1 Mean values and standard error of bulk density (g/cm3), clay concentration, soil organic carbon (SOC, g/kg), clay/carbon ratio, carbon stock (t/ha) and mean weight diameter (MWD, mm) for the three cropping systems. The ‘p-value’ column gives the p-values of the effect of cropping systems for the analyses of variance, or covariance with clay content as covariate. Lowercase letters indicate pairwise differences between cropping systems, for a given layer. Uppercase letters indicate pairwise differences between layers, for a given cropping system (p-values not shown for these analyses). Pairwise comparisons were assessed with a Tukey HSD test, at $p=0.05$. $n=20$ for each cropping system.

Figure 1 Clay to (soil organic) carbon ratio for the three depths 0-5 cm (A.), 5-20 cm (B.) and 20-50 cm (C.), for the three cropping systems. Each ‘bean’ represents the density distribution of the values, with the large black line showing the median of each group. In each panel, the horizontal line represents the threshold value = 10 for the clay to carbon ratio. The lower the ratio is, the better in terms of soil structural quality. Note that the y-axis scale is different for each panel.

Figure 2 Carbon stocks for the three depths 0-5 cm (A.), 5-20 cm (B.) and 20-50 cm (C.), for the three cropping systems. Each ‘bean’ represents the density distribution of the values, with the large black line showing the median of each group.

Figure 3 Aggregate fraction distribution (mean ± 1 standard error, g aggregate/kg dry soil) for each depth and cropping systems. 'conv': conventional systems, 'nt': no-till systems, 'org': organic systems. Lowercase letters indicate pairwise differences between cropping systems, for a given aggregate fraction. From bottom to top of each bar: large macroaggregates (2000 µm - 8000 µm), small macroaggregates (250 µm - 2000 µm), microaggregates (53 µm - 250 µm), silt and clay (< 53 µm). The dashed lines represent a visual aid to compare the size of the bar fractions.

Figure 4 Mean weight diameter for the three depths 0-5 cm (A.), 5-20 cm (B.) and 20-50 cm (C.), for the three cropping systems. Each ‘bean’ represents the density distribution of the values, with the large black line showing the median of each group.

Figure 5 Accumulation of carbon in the aggregate fractions (mean ± 1 standard error, g C/kg dry soil) for each depth and cropping systems. 'conv': conventional systems, 'nt': no-till systems, 'org': organic systems. Lowercase letters indicate pairwise differences between cropping systems, for a given aggregate fraction. From bottom to top of each bar: large macroaggregates (2000 µm - 8000 µm), small macroaggregates (250 µm - 2000 µm), microaggregates (53 µm - 250 µm), silt and clay (< 53 µm). The dashed lines represent a visual aid to compare the size of the bar fractions.

Figure 6 Total R^2 decomposition by variable type, for the multivariate regressions of soil organic carbon content (SOC), clay to carbon ratio (clay/carbon, CCR), mean weight diameter (MWD), and accumulation of carbon in large macroaggregate (CAM) across cropping systems. Variable types: 1. site-related, unmanageable pedoclimatic variables: clay content, temperature and rainfall, 2. site-related, partially manageable variables: soil chemical properties pH and calcium concentration, site-related, partially indirectly manageable variables: soil biology variables properties, microbial carbon and mycorrhiza marker, and 4. directly manageable variables: cropping practices.

Table S1 Pearson correlation coefficients (lower triangle) and p-values (upper triangle) between explanatory variables, for the three depths. Coefficients higher than 0.7 or lower than -0.7 are highlighted in colour, with their respective p-values (colours according to variable categories, as in Figure 6). Note that weather and cropping practices variables are not depth-specific and thus the values are the same for each depth

Table S2 Total R^2 decomposition for the multivariate regressions of soil organic carbon content (SOC), clay to carbon ratio (CCR), mean weight diameter (MWD), and accumulation of carbon in large macroaggregate (CAM) across cropping systems and depths. R2 are given first per categories and then for each individual variable. Significant slopes at $p<0.05$ in the multivariate regressions are indicated with a *, p-values between 0.05 and 0.1 are indicated with a °.

Figure S1 A. Geographic distribution of the fields studied and B. Texture of the field topsoil (0-20 cm) in the ISSS texture triangle. Blue points correspond to conventional systems, red points to no till systems and green points to organic systems. This figure is adapted from Büchi et al., 2019.

Figure S2 Carbon concentration in the aggregate fractions (mean ± 1 standard error, g C/kg aggregate) for each depth and cropping systems. 'conv': conventional systems, 'nt': no-till systems, 'org': organic systems. From bottom to top of each bar: large macroaggregates (2000 µm - 8000 µm), small macroaggregates (250 µm - 2000 µm), microaggregates (53 µm - 250 µm), silt and clay (< 53 µm).

Table 1

		Conventional			No till			Organic			
		mean		se	mean		se	mean		se	p-value
***Bulk density [g/cm3]**	**0-5 cm**	1.24	**B**	0.03	1.22	**C**	0.03	1.18	**B**	0.03	0.624
	5-20 cm	**1.26 b**	**B**	0.03	**1.36 a**	**B**	0.02	**1.22 b**	**B**	0.04	0.003
	20-50 cm	1.49	**A**	0.02	1.47	**A**	0.02	1.43	**A**	0.03	0.391
clay [%]	**0-5 cm**	20.4		1.4	21.3		1.5	22.7		2.0	0.600
	5-20 cm	20.3		1.4	21.0		1.6	23.3		2.0	0.428
	20-50 cm	22.0		1.4	22.6		1.8	23.9		1.9	0.718
***Corg concentration [g/kg]**	**0-5 cm**	**15.2 b**	**A**	1.23	**23.2 a**	**A**	2.47	**20.5 ab**	**A**	2.42	0.012
	5-20 cm	14.4	**A**	1.17	15.7	**B**	1.69	19.8	**A**	2.42	0.231
	20-50 cm	9.1	**B**	0.92	8.4	**C**	0.94	12.5	**B**	2.12	0.129
clay/Corg	**0-5 cm**	**14 a**	**B**	1.0	**10 b**	**B**	0.8	**12 ab**	**B**	0.7	0.004
	5-20 cm	15	**B**	0.9	15	**B**	1.5	13	**B**	0.7	0.235
	20-50 cm	28	**A**	2.5	34	**A**	5.2	25	**A**	2.9	0.232
***C stock [t/ha]**	**0-5 cm**	**6.5 b**	-	0.5	**9.9 a**	-	1.1	**8.8 ab**	-	1.0	0.012
	5-20 cm	19.3	-	1.6	21.0	-	2.3	26.6	-	3.2	0.231
	20-50 cm	30.0	-	3.0	27.8	-	3.1	41.3	-	7.0	0.129
***cumulated C stock [t/ha]**	**0-20 cm**	40.6	-	3.1	48.1	-	4.5	54.8	-	6.3	0.225
	0-50 cm	62.6	-	5.3	68.5	-	6.4	85.5	-	11.7	0.213
***MWD [mm]**	**0-5 cm**	**2.08 b**	**AB**	0.13	**3.20 a**	**A**	0.11	**3.04 a**	**A**	0.16	0.000
	5-20 cm	2.28	**A**	0.16	2.55	**B**	0.20	2.68	**A**	0.17	0.441
	20-50 cm	1.83	**B**	0.16	1.85	**C**	0.23	2.06	**B**	0.23	0.899

* tested with clay as a covariate

Figure 1

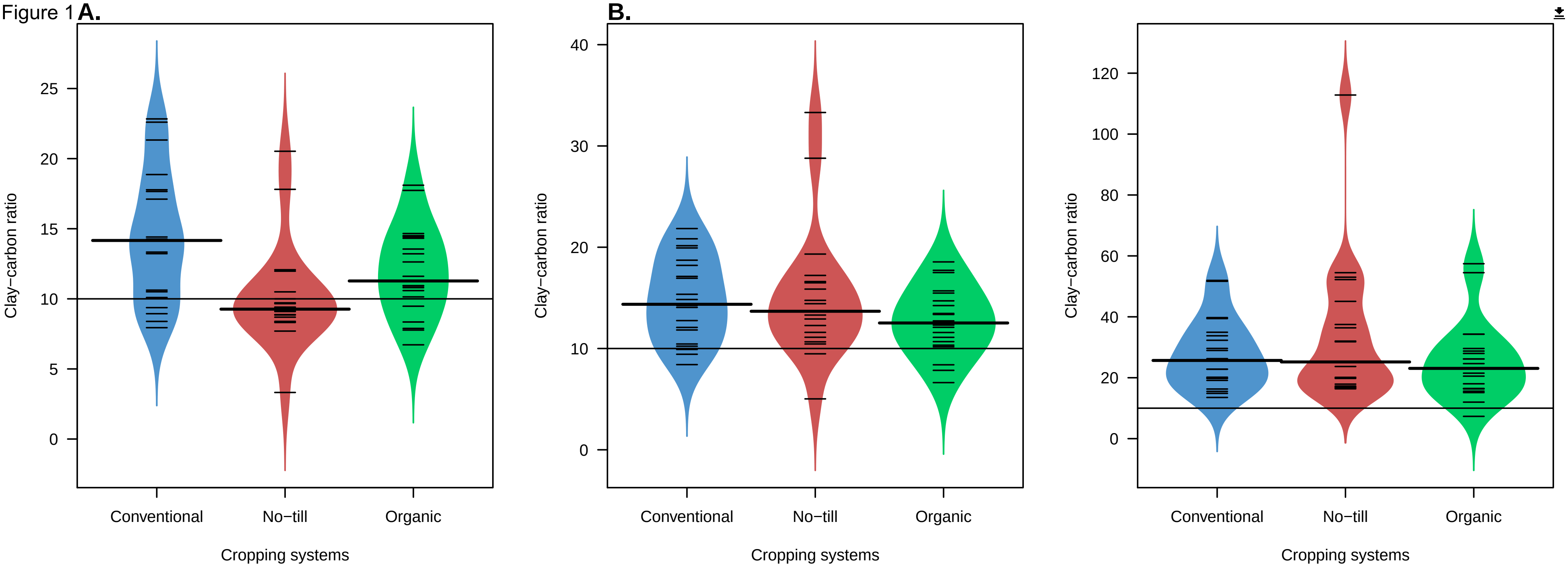

A.
B.
Clay−carbon ratio
0
5
10
15
20
25
30
40
60
80
100
120
Conventional
No−till
Organic
Cropping systems

Figure 2

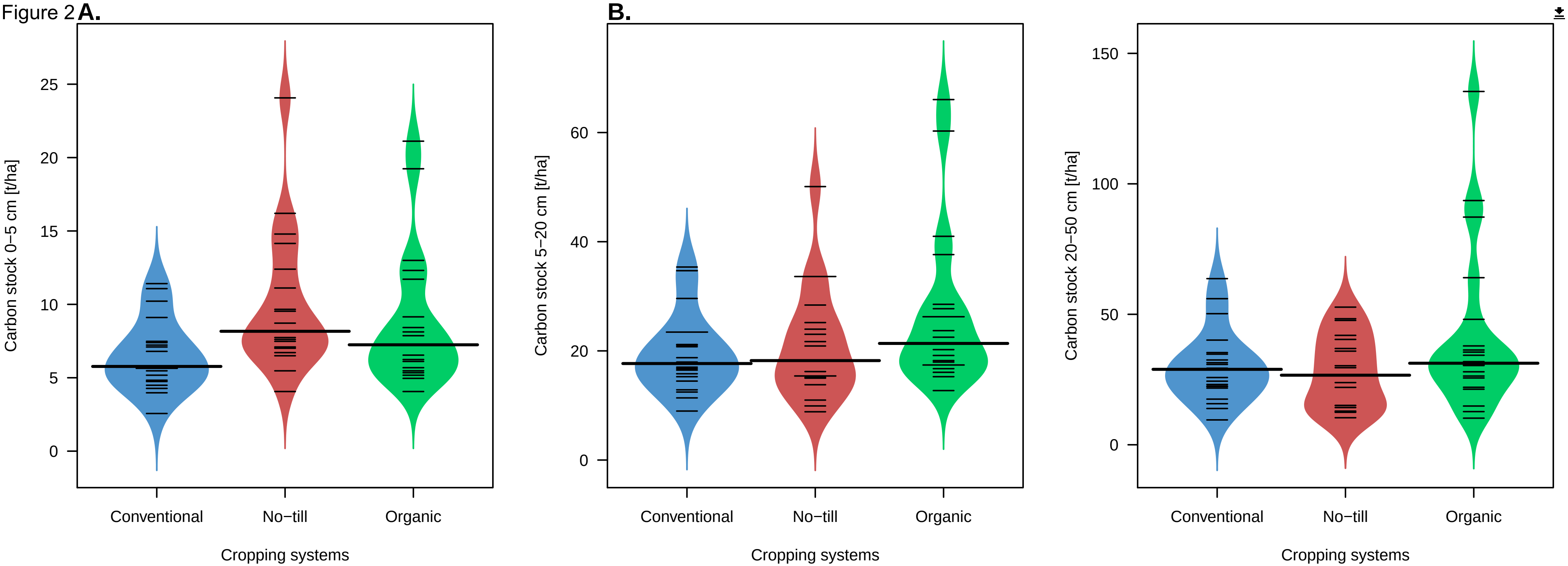

A.
B.
Carbon stock 0−5 cm [t/ha]
0
5
10
15
20
25
Carbon stock 5−20 cm [t/ha]
0
20
40
60
Carbon stock 20−50 cm [t/ha]
0
50
100
150
Conventional
No−till
Organic
Cropping systems

Figure 3

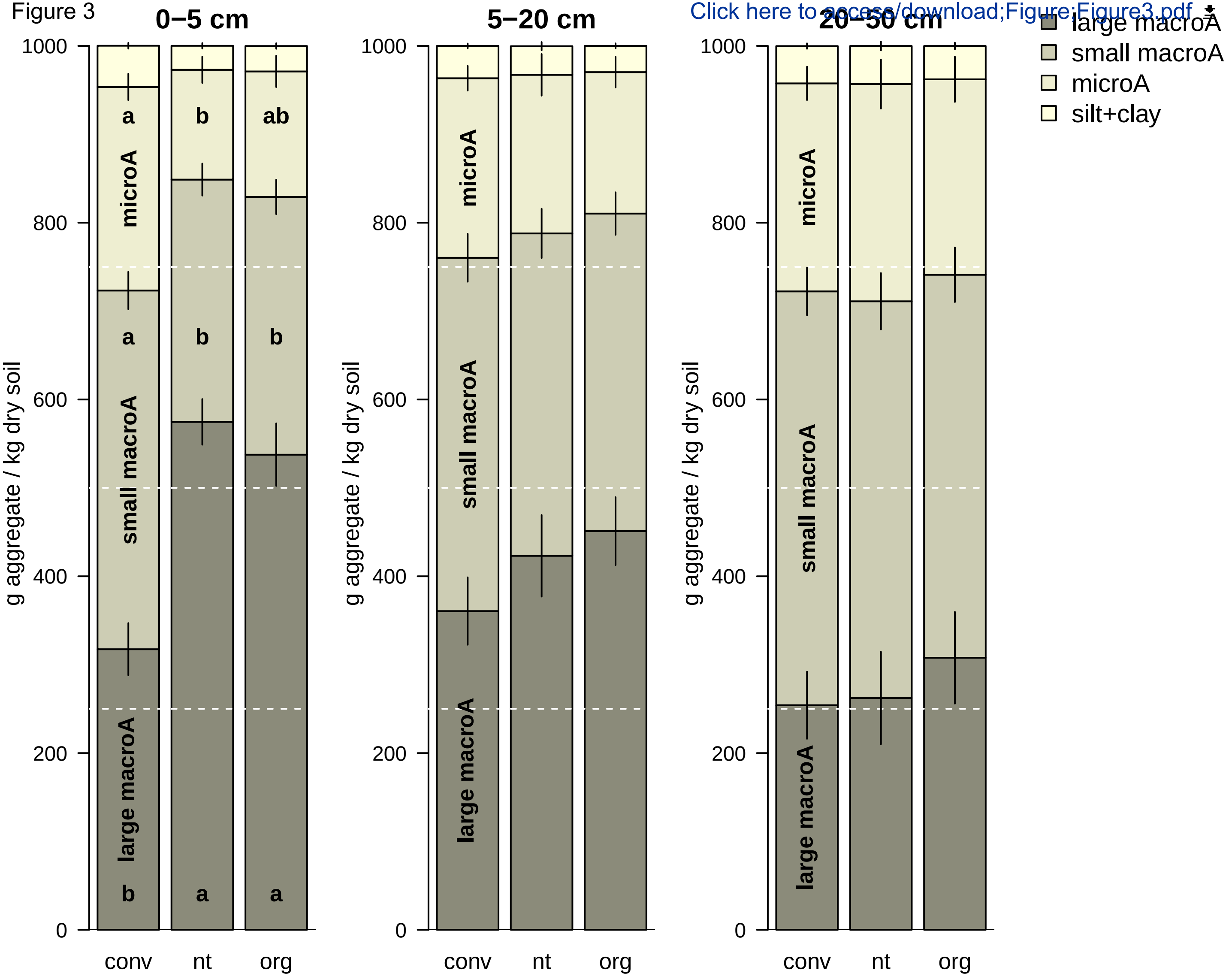

0−5 cm
5−20 cm
20−50 cm
g aggregate / kg dry soil
1000
800
600
400
200
0
conv
nt
org
large macroA
small macroA
microA
silt+clay
a
b
ab
a
b
b
b
a
a

Figure 4

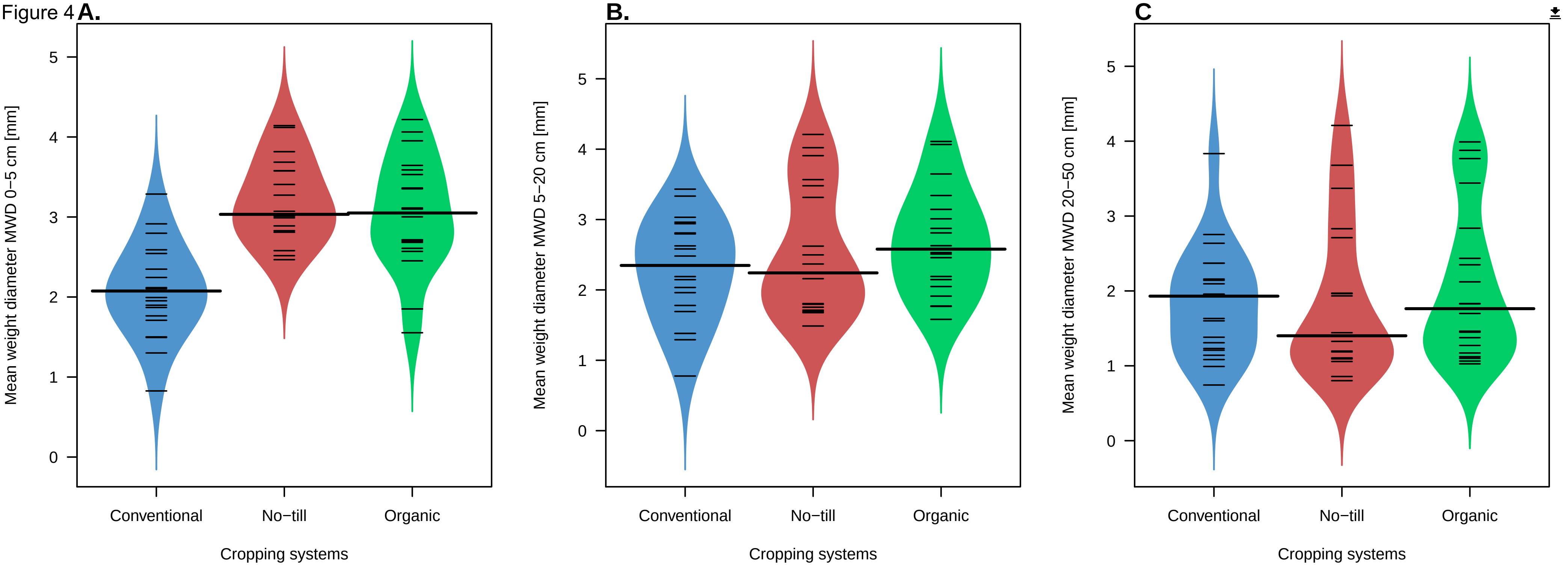

A.
B.
C
Mean weight diameter MWD 0−5 cm [mm]
Mean weight diameter MWD 5−20 cm [mm]
Mean weight diameter MWD 20−50 cm [mm]
0
1
2
3
4
5
Conventional
No−till
Organic
Cropping systems

Figure 5

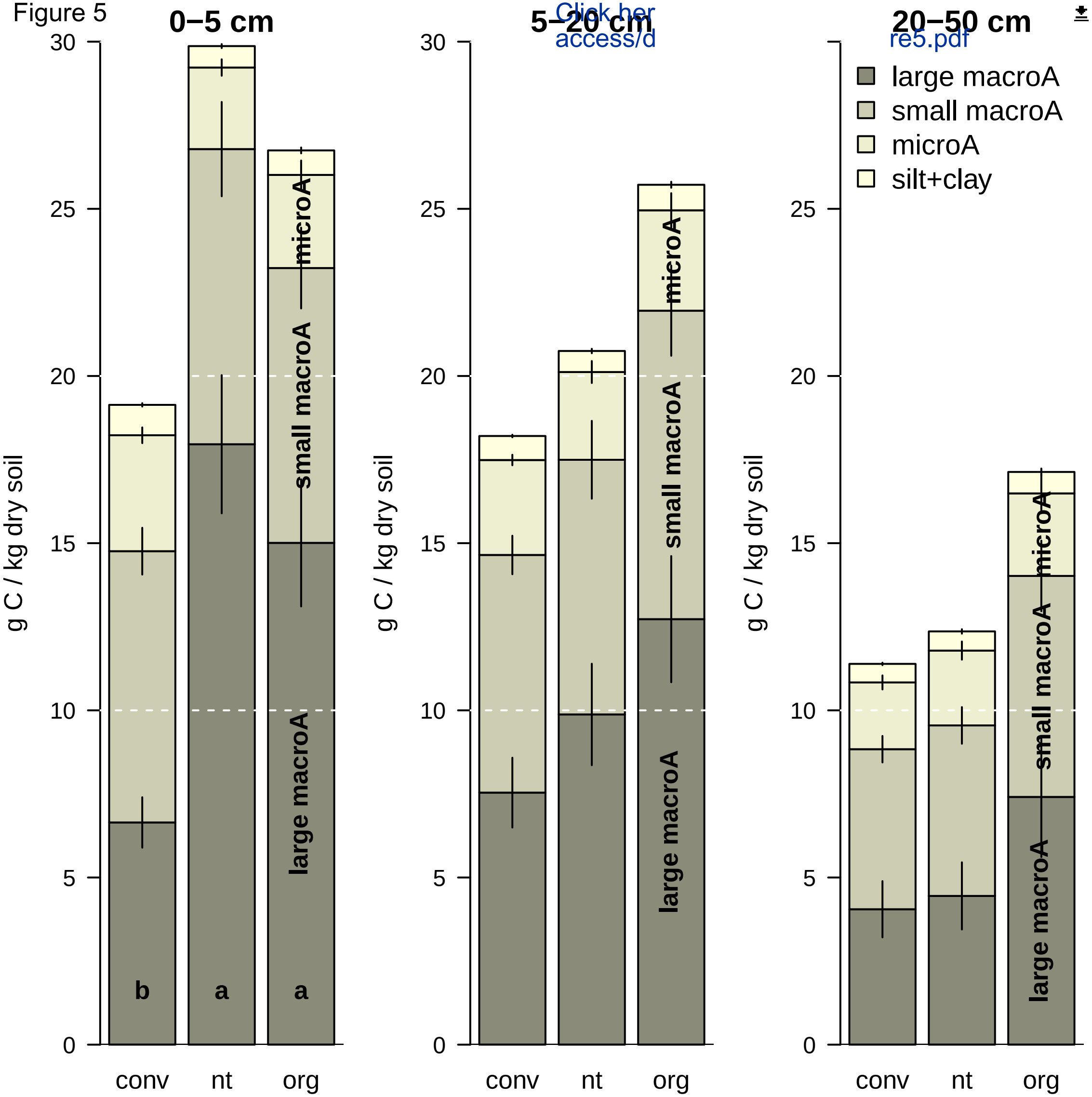
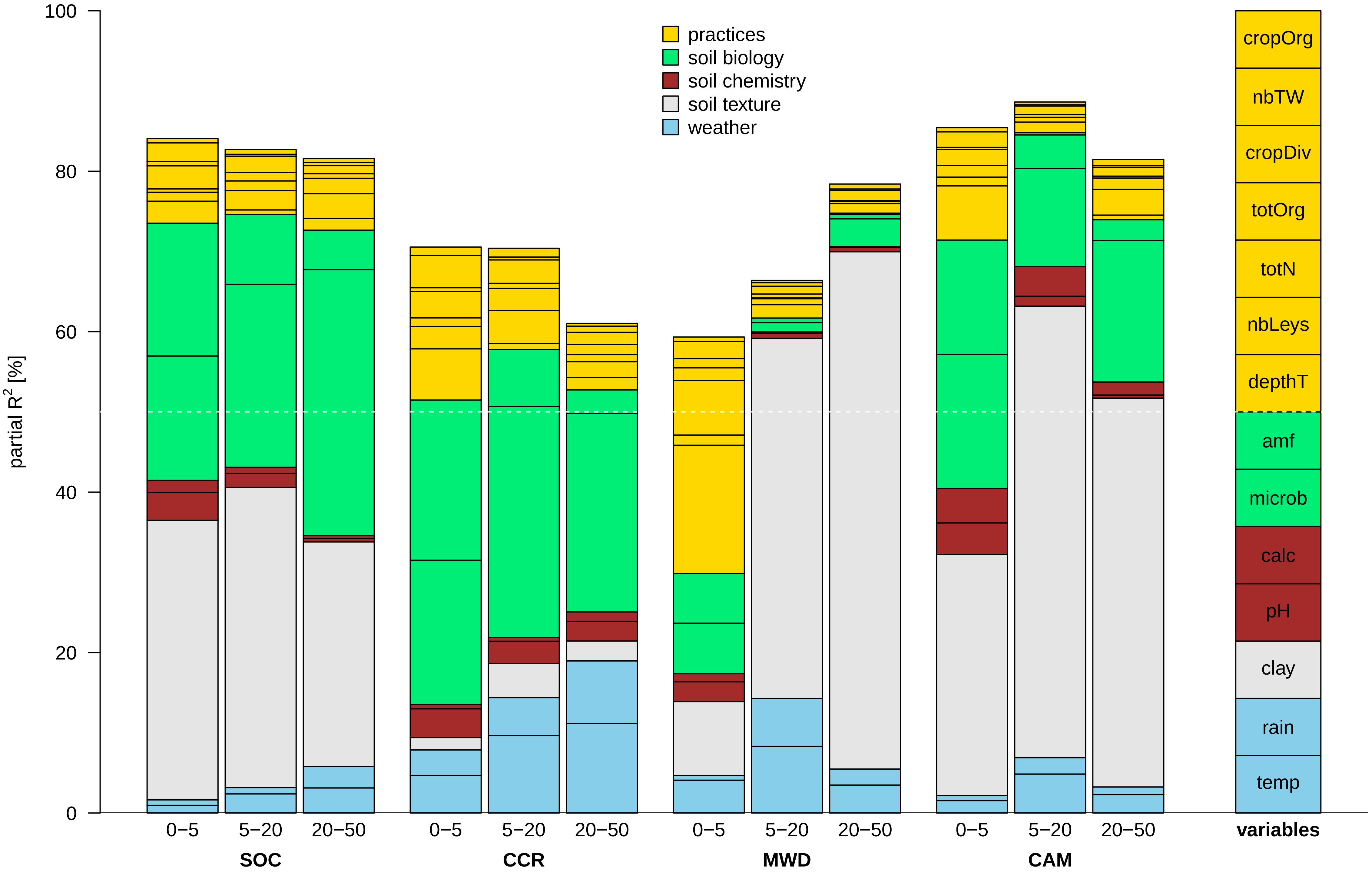

0–5 cm
5–20 cm
20–50 cm
g C / kg dry soil
0
5
10
15
20
25
30
conv
nt
org
b
a
a
large macroA
small macroA
microA
silt+clay

Figure 6


100
80
60
40
20
0
partial R^2 [%]
practices
soil biology
soil chemistry
soil texture
weather
0−5
5−20
20−50
SOC
0−5
5−20
20−50
CCR
0−5
5−20
20−50
MWD
0−5
5−20
20−50
CAM
cropOrg
nbTW
cropDiv
totOrg
totN
nbLeys
depthT
amf
microb
calc
pH
clay
rain
temp
variables