Received: 28 August 2021 | Revised: 18 January 2022 | Accepted: 22 January 2022

DOI: 10.1002/ldr.4216

RESEARCH ARTICLE

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# Responses of soil organic carbon, aggregate diameters, and hydraulic properties to long-term organic and conventional farming on a Vertisol in India

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**Funding information**
Biovision Foundation for Ecological Development, Coop Sustainability Fund, Swiss Agency for Development and Cooperation (SDC). Foundation fiat panis Liechtenstein Development Service

## Abstract

Organic matter management can improve soil structural properties. This is crucial for agricultural soils in tropical regions threatened by high rainfall intensities. Compared to conventional farming, organic farming is usually deemed to increase organic carbon and improve soil structural properties such as stability and permeability. However, how much, if any, buildup of organic carbon is possible or indeed occurring also depends on soil type and environmental factors. We compared the impact of seven years of organic farming (annually 13.6 t $ha^{-1}$ of composted manure) with that of conventional practices (2 t $ha^{-1}$ of farmyard manure with 150–170 kg N $ha^{-1}$ of mineral fertilizers) on soil structural properties. The study was conducted on a Vertisol in India with a two-year crop rotation of cotton soybean wheat. Despite large differences in organic amendment application, organic carbon was not significantly different at 9.6 mg C $g^{-1}$ on average in the topsoil. However, the size distribution of water-stable aggregates shifted toward more aggregates <137 μm in the organic systems. Cumulative water intake was lower compared to the conventional systems, leading to higher runoff and erosion. These changes might be related to the lower pH and higher exchangeable sodium in the organic systems. Our results indicate that higher application of organic amendments did not lead to higher soil organic carbon and associated improvement in soil structures properties compared to integrated fertilization in this study. Chemical properties may dominate soil aggregation retarding the uptake and integration of organic amendments for sustainable agricultural intensification in tropical, semiarid climates.

**KEYWORDS**
aggregate size distribution, organic farming, soil organic carbon, tropics and subtropics, wet aggregate stability

## 1 | INTRODUCTION

Vertisols in tropical and semiarid regions are one of the most productive soils if managed properly. Their main benefits are associated with good soil fertility due to their high cation exchange capacity (Murthy, 1988) and high water holding capacity which is particularly important in drought prone semiarid or monsoonal regions (Virmani et al., 1982). Despite these beneficial properties, the agricultural potential of Vertisols can be limited by soil structural impediments, like low root penetrability, low hydraulic conductivity, and intensive shrinking and swelling (Atasoy, 2008; Bravo-Garza et al., 2009). Soil compaction, often induced by poor soil management, is a major issue due to the narrow range of soil water content when tillage operations should be carried out (Connolly et al., 2001). Once compacted, Vertisols have very low infiltration rates and suffer from water logging and high soil strength when dry. Sodicity and, in some cases, salinity, can also be inherent problems of these soils particularly in agricultural systems in water-limited regions (Wicke et al., 2011). Moreover, the clayey soil texture of Vertisols bears a high risk of degradation through slaking (Ahmad & Mermut, 1997). In the monsoonal climates of India, high rainfall intensities (Goswami et al., 2006) coupled with soil compaction, surface sealing, and a low infiltration capacity (Foster et al., 1985), may lead to high surface runoff and create massive erosion problems (Gardner & Gerrard, 2003; Singh et al., 1992).

To combat soil structural degradation, maintain adequate aggregate stability, and improve infiltration, high input of biomass is recommended as practiced in organic farming systems for sustainable agricultural intensification. Many studies have shown that large inputs of biomass increased soil organic carbon content (SOC) (Jha et al., 2014; Katkar et al., 2011; Sharma et al., 2011). In many cases, biomass input stabilized larger aggregates (Chakraborty et al., 2010; Saha & Mishra, 2009; Sleutel et al., 2009). This could lead to a more stable macropore structure enabling higher infiltration and reduced surface runoff as shown by a reduction of erosion from 32 to 8 Mg ha$^{-1}$ on a silt loam soil prone to erosion (Reganold et al., 1987). A study on the changes of the soil properties of a Vertisol after incubation with various organic amendments reported increased aggregate diameters (Ghosh et al., 2011). This incubation experiment showed that clay dispersion on a sodic Vertisol decreased, despite a higher exchangeable sodium content after the addition of organic amendments. Hence, the stabilizing effect of soil organic matter outweighed the dispersive effect of sodium (Ghosh et al., 2010). The stabilizing effect of soil organic matter is particularly relevant in tropical and semiarid climates where poor soil structural stability and dispersion is generally associated with sodicity on Vertisols (D'Odorico et al., 2013; Wong et al., 2010). These studies show that the composition of exchangeable cations is important as it could potentially affect soil structural stability. There is considerable ambiguity about the effect of different farming systems and different types of biomass input on the soil structure due to the dynamic interactions between soil properties like SOC, exchangeable cations, and aggregate stability (Amézketa, 1999; Rabot et al., 2018; Schweizer et al., 2017).

One of the most prominent soil properties that are advocated to increase soil health, enhance crop yields, and which could contribute to offsetting $CO_2$ emission is SOC content (Lal, 2004, 2006). Increasing SOC has been a paradigm for many farming systems in recent decades. The SOC storage capacity on Vertisols is considered particularly large due to the high clay content and the associated high total particle surface area (Chevallier et al., 2004; Hua et al., 2014). However, many studies that compared Vertisols to other local soil types found that the SOC contents of Vertisols under agricultural use were generally around 10 mg C g$^{-1}$ in the topsoil and therefore relatively low compared to other soils (Dudal, 1965). Agricultural soils with an SOC content of <10 mg C g$^{-1}$, which are often found in India, were postulated to jeopardize soil health and related ecosystem services (Lal, 2020). Several studies on the addition of organic amendment to Vertisols have found relatively high rates of SOC uptake in comparisons with soils with lower clay contents (Jha et al., 2021; Manna et al., 2005). These studies highlight the potential of Vertisols for SOC sequestration. The incorporation of fresh crop residues has been related to improved soil structural properties in Vertisols (Bravo-Garza et al., 2010; Crook, 1993), whereas the SOC content was deemed to be of little impact on the structural properties of Vertisols in the absence of large biomass inputs (McGarry, 1996). Such contrasting results show the need for further studies about the varying impact of organic agriculture on SOC contents and its relation to structural properties in Vertisols, in order to explore its potential of soil health improvement. The SOC content has been postulated as primary control of aggregate stability in temperate regions (Williams & Petticrew, 2009). Compared to the large body of literature on SOC in agricultural soils in temperate regions, further research on soils in subtropical, semi-arid areas is required to assess the effect of organic amendments in relation to soil chemical properties that may influence soil properties in these climates.

The impact of land use management on soil structure and aggregates is often determined by isolating size fractions by sieving. A cut-off at 250 μm diameter is applied in numerous studies and commonly used to separate microaggregates from macroaggregates according to the concept of a structural hierarchy of soil aggregates (Emerson, 1967; Oades & Waters, 1991; Tisdall & Oades, 1982). A comparison of aggregate isolation methods has shown that Vertisols contain mostly water-stable microaggregates <100 μm (Field et al., 2004). SOC has been postulated to be most important for aggregates 1–50 μm and 50–500 μm (Warkentin, 1982). This indicates that the soil structure of Vertisols is characterized by fine structures of several μm reflecting their high content of clay-sized particles. To measure and evaluate an impact of biomass input on aggregate structures at such fine scale requires a more detailed size distribution analysis than sieving is able to achieve. Automatic imaging-based size analyses methods such as the dynamic image analysis have been recently shown to resolve changes of aggregate size distributions at the scale of several μm (Felde et al., 2020; Kayser et al., 2019; Schweizer et al., 2019). This method has the potential to detect differences in aggregate size distribution rather than only changes in predefined size fractions. It is a novel method to identify and to help explain the impact of farming systems and SOC content on soil structural properties at a scale of several μm.

We analyzed water-stable aggregate size distribution as a measure of soil structural stability in the 7th year of a long-term experiment (Forster et al., 2013). The main purpose of this long-term experiment was to compare and assess the productivity and sustainability of organic and conventional farming in the semi-arid subtropics. The experiment was established in Kasrawad, Madhya Pradesh (India), by the Swiss Research Institute for Organic Agriculture (FiBL) in 2007. The experimental site enables further analyses to better understand long-term effects related to soil health and ecosystem services such as carbon sequestration, soil structural stability, and hydraulic properties. Our hypothesis was that soil management practices, such as different management practices in organic or conventional farming systems, alter the SOC content and soil structural properties, which impact the soil ability to take in water. Our objectives were: (i) to compare whether the organic and conventional farming systems on a Vertisol differ in SOC content and bulk density; (ii) to quantify the effect of these farming systems on the size distribution of water-stable soil aggregates; (iii) to relate aggregate sizes to other soil chemical properties (exchangeable cations); and (iv) to determine whether soil hydraulic properties like infiltration and surface runoff are affected by organic matter management.

## 2 | MATERIAL AND METHODS

### 2.1 | Study site

The experimental site is located at the Narmada River belt in Nimar Valley, Madhya Pradesh (India), at 250 m asl (22°8′30.3"N, 75°37′49″E). The climate at the study site is subtropical, semiarid, 25 °C mean annual temperature, and 800 mm average precipitation with most of the rain falling during the monsoon season from June to September (further details in Forster et al., 2013). The amount of rain in the year prior to sampling in early 2014 was 467 mm. The socio-economic conditions of the region were described in a previous study (Eyhorn et al., 2007).

The soil at the long-term experiment was a Pellic Vertisol (Calcaric) (WRB, 2014) with blocky (sub-) angular aggregates in the topsoil at 0–20 cm and slickensides as well as rhombohedral aggregates with the long axis tilted at 40–175 cm (photo of the soil profile in Figure S1). The soil profile was calcareous throughout with increased size of carbonate concretions that reached up to 4 cm in diameter in the deep subsoil at 205–250 cm depth. The topsoil contained 55% clay-sized particles (<2 μm), 38% silt-sized particles (2–63 μm), and 7% sand-sized particles, and the texture class was 'clay' according to the Guidelines for Soil Description (FAO, 2006).

The long-term experiment was set up in 2007 and is described in detail by Forster et al. (2013). Before the start of the experiment, the land was under conventional management with mineral fertilization, comparable to the conventional management treatment practiced in the experiment. Prior to the setup of the experiment, wheat was grown without fertilization from December 2006 to March 2007. At harvest, the land was divided into 5 × 5 m grids that were harvested separately to evaluate the comparability of the soils. The information on the wheat grain yield of these grids as well as the organic C and pH of the soil were used to optimize the layout of the experiment, that is, the allocation of plots and blocks and ensure the comparability of the farming systems. At the start of the experiment, the pH ($H_2O$) was 8.7 (Forster et al., 2013) and the average SOC content was 5.7 (±SE 0.6) mg C $g^{-1}$ in the top 20 cm of the soil. The Fe and Al contents in 0–20 cm were 15.9 (±SD 0.5) mg Fe $g^{-1}$ and 1.4 (±SD 0.1) mg Al $g^{-1}$ on average across all plots according to dithionite-citrate-bicarbonate extraction (Mehra & Jackson, 1958). The sampled plots of 256 $m^2$ each consisted of a randomized complete block design with four blocks (replicates) and four farming systems. At the time of sampling, the experiment had been cultivated for 7 years with *Gossypium hirsutum-Glycine max-Triticum aestivum* (cotton-soybean-wheat) in a two-year crop rotation according to local farming practices. Four farming systems were distinguished: Two organic systems, biodynamic (BIODYN) and organic (BIOORG), and two conventional systems, conventional without genetically modified *Bt* cotton (CON) and conventional with *Bt* cotton (CONBtC).

The organic systems BIODYN and BIOORG were fertilized with an equivalent of 100 kg N $ha^{-1}$ by applying composted farmyard manure (FYM, 13.6 Mg $ha^{-1}$) incubated for 6 months. Besides the compost, in BIODYN smaller amounts of so-called Cow Pit Pat (CPP) and biodynamic preparations were applied. A dose of 5 kg $ha^{-1}$ of CPP was applied at sowing, which contained FYM mixed with 0.3% egg shells, 0.5% basalt powder, and 0.01%, respectively of the biodynamic preparations 502–507 (Chalker-Scott, 2013; Yadav, 2010), which was incubated for 45 days. In BIODYN, additionally the biodynamic preparations 500 (cow horn filled with cow dung, 71 g $ha^{-1}$) and 501 (cow horn filled with ground quartz crystals, 2.5 g $ha^{-1}$) (Chalker-Scott, 2013) were applied 5 times to the soil during each crop. Since BIODYN and BIOORG received the same amount and type of compost and the proportion of biodynamic preparations was relatively low, we evaluated the joint effect of these organic systems in addition to more detailed comparisons.

The conventional system CON received 150 kg N ha$^{-1}$ as integrated fertilization of urea with 2 Mg ha$^{-1}$ FYM. Conventional CON-BtC received the most N with 170 kg N ha$^{-1}$ and 2 Mg ha$^{-1}$ FYM. Both organic systems included a cover cropping phase with *Vigna mungo*, *Vigna radiata*, *Vigna unguiculata*, *Crotalaria juncea*, and *Pennisetum glaucum*. The cover crops were cut at flowering and then incorporated into the soil. The cover crop was planted after cotton harvest, thus 1 year before the soil sampling for this study. Tillage was uniform across all treatments. It followed local practices and used oxen-drawn ploughs, harrows, and levelers. Drip irrigation was used during the cotton phase, whereas during the noncotton phase, the crops were supplied with water by flood irrigation. Irrigation was applied at sowing and two to three times during the cropping season. The watering regime applied was irrigation to field capacity. Due to the uniformity of the site, all treatments received the same amount of irrigation (further details in Forster et al., 2013).

## 2.2 | Soil sampling and chemical analysis

Bulk density samples were collected using 100 cm$^3$ soil cores with a height of 4 cm. To take samples representative for the ploughed topsoil (0–20 cm) and the subsoil (20–40 cm), we collected the soil cores at 8–12 cm and 28–32 cm depth. To account for swelling and shrinking of these Vertisols, soil water content was also determined at the time of bulk density sampling (McGarry & Daniells, 1987). We collected cores at 1, 15, and 30 days after irrigation from each plot. During this time, the bulk density increased on average from 1.19 to 1.25 and 1.29 g cm$^{-3}$, while the water content decreased from 0.41 to 0.38 and 0.35 (g g$^{-1}$). Assuming equal shrinkage over all treatments, average bulk density over the three sampling times was calculated.

The core samples were ground to pass a 2 mm mesh, and the total carbon content was measured by combustion with an Elementar Vario Max CN (Elementar Analysensysteme GmbH, Hanau, Germany). Inorganic carbon, that is, carbonates, was measured using the Scheibler calcimeter (Loeppert & Suarez, 1996). The content of SOC was calculated as the difference between total and inorganic C. We calculated the SOC stocks by the SOC contents and the bulk density for the topsoil (0–20 cm) and subsoil (20–40 cm).

Topsoil samples (0–20 cm) from each plot were collected prior to the wheat harvest. Three samples were collected per plot and mixed to give one sample per plot. Samples were air-dried and ground to <2 mm. Soil pH and electrical conductivity were both determined in the supernatant of a 1:2.5 soil: water suspension (g g$^{-1}$) (Rhoades, 1996; Sonmez et al., 2008).

To analyze potential differences of the prevalent exchangeable cations in the long-term experiment, we measured the content of exchangeable calcium, magnesium, potassium, and sodium. Exchangeable Fe and Al cations were not investigated since we expected them to remain at very low contents according to the pH of the study site at 8.3 (Bloom et al., 2005). Exchangeable cations were determined using $NH_4Cl$ as the replacing solution and analyzed with inductively coupled plasma optical emission spectrometry (iCAP 6000, Thermo Scientific, Waltham, USA). The effective cation exchange capacity (ECEC) was calculated as the sum of exchangeable calcium, magnesium, potassium, and sodium. The exchangeable sodium percentage (ESP) was calculated as proportion of sodium from the ECEC.

## 2.3 | Aggregate size distribution by dynamic image analysis

The air-dried soil samples from the topsoil (0–20 cm) were gently sieved to pass a 10 mm sieve. Aggregate diameter was determined automatically by dynamic image analysis in a water stream with rear illumination from pulsed laser light (Kayser et al., 2019; Schweizer et al., 2019). Briefly, we used a QICPIC machine in combination with the LIXELL flow cell and SUCELL homogenization unit (Sympatec GmbH, Clausthal-Zellerfeld, Germany). To account for the optical requirements of the size range < 1 mm, 5 g of the soil sample were fractionated by wet sieving into >250 μm, 63–250 μm, and <63 μm. The >250 μm sieve fraction was analyzed with a free fall setup to avoid potential dispersion in the pump unit. A distortion of results by bubbles and root hairs was minimized by definition of specific shape criteria for each sieve fraction using the sphericity (Table 1). The sphericity describes the ratio of the perimeter to the equivalent circle and increases when particles are rounder. We calculated the aggregate size from the minimum Feret diameter (Allen, 1981). The volumetric aggregate size distribution was calculated for 100 aggregate size classes 0–900 μm as volumetric Q3 distribution density, by relation to the chosen density of 2.65 g cm$^{-3}$ to approximate a mass distribution according to the ISO norm (ISO 9276-1:1998, 1998). A high volumetric distribution density of a specific size indicated a large mass proportions of aggregates of this size. We added the size distributions of the <63 μm and the 63–250 μm fraction, weighted on the basis of their mass contributions, to the >250 μm fraction. The aggregate size ranges that showed system differences (Section 3.2) were summarized as two aggregate levels and defined as microaggregates <137 μm and macroaggregates 137–419 μm. Further explanation of this approach is provided in Figure S2.

## 2.4 | Surface crack measurements, double ring infiltration, and surface runoff upon simulated rain

The coverage of the soil surface with cracks was analyzed using image analysis. We took photographs of 0.15 m$^2$ cleaned soil surfaces 20 days after irrigation in between the plant rows with 3 replicates per plot (Figure S3). By thresholding in ImageJ 1.47 (Rasband, 2014), we calculated the proportion of cracks (darker colors) from the whole soil surface. Within each photographed area, the depth of cracks was measured at 5 different positions using a rod.

Double ring infiltrometers with 30 and 50 cm diameter of the inner and outer ring were inserted 10 cm deep into the soil (DIN

**TABLE 1** Size and shape criteria to exclude bubbles and root hairs in the dynamic image analysis of soil aggregates with a QICPIC machine (Sympatec GmbH, Clausthal-Zellerfeld, Germany)

| Sieve fraction | Included range | Included sphericity | Included optical density |
|---|---|---|---|
| <63 μm | 0–100 μm | 0.6–0.93 (of >60 μm particles) | <1.4% |
| 63–250 μm | 0–400 μm | 0.6–0.93 (of >100 μm particles) | <1.4% |
| >250 μm | 0–900 μm | 0.6–0.93 (of >150 μm particles) | <2% |

19682–7:2015–08, n.d.). We recorded the water level 5 times during approximately 20– 25 hr with two replicates per plot 39 days after irrigation. Due to the highly variable infiltration on Vertisols (Deb & Shukla, 2012; Favre et al., 1997; Krantz et al., 1978), we measured duplicates of every plot. We corrected for evaporation using a daily rate of 8 mm (Kawadia & Tiwari, 2017). To compare the treatments, we fitted the Philip's equation (Philip, 1957) to each individual measurement over time and computed the average amounts of water infiltrated after a short time of 3 hr and a longer time of 20 hr.

To measure surface runoff, we simulated a rainfall event of 50 mm rain during 30 min at 39 days after irrigation on the harvested plots. Rain was dripped from 81 drippers at 1 m height above 1 $m^2$ bare ground. A Boyle-Mariotte-flask 1 m above the drippers was used to maintain a uniform pressure head for water flow. The soil surface was bunded using metal walls inserted to a depth of 10 cm into the soil to intercept surface runoff.

### 2.5 | Ploughing time

To assess labor requirement for the soil management practices, that is, ploughing the fields, we recorded the time it took to cultivate the plots. This was done prior to soil sampling. The average ploughing time per plot was calculated across the four ploughing events within the crop rotation, that is, after soybean in 2013, after wheat 2013, after wheat 2014 and after cotton and green manure 2014. These measurements were used as a surrogate for labour costs to maintain adequate soil tilth.

### 2.6 | Statistical analysis

The measured soil properties were statistically analyzed in SAS® Studio Release 3.8 (SAS Institute, Cary, USA) using the GLIMMIX procedure to compute analyses of variance (ANOVA) of a mixed model including block effects as a random factor in accordance with a previous analysis of the experiment with a randomized complete block design (Forster et al., 2013). More specifically, we used the restricted maximum likelihood as the estimation method, the Kenward-Roger approximation to compute denominator degrees of freedom and type-I tests to evaluate the effect of different properties on the organic and conventional systems after fitting of the block factor. We converted the pH values to the corresponding proton concentrations before the statistical analyses. The effect of organic and conventional agricultural systems on surface runoff was tested after adjustment of bulk density as a covariate (Cochran, 1957). Means were compared with Tukey's honestly significant difference (HSD) and evaluated significant if $p < 0.05$ and as tendency if $p < 0.1$. To assess the effect of farming systems, we reported the results comparing all four farming systems. In the text, we also evaluated the main differences between the organic systems (combining BIODYN and BIOORG) and the conventional systems (combining CON and CONBtC). To evaluate the effect of agricultural systems on the infiltration data, which follows a nonlinear trend, and enable the comparison of observations taken at slightly different times (readings of the double ring infiltrometers), we fitted the Philip's equation (Philip, 1957) to the data. Estimates of the sorptivity and the transmission factor were fitted for both field replicates. Afterwards, we computed the cumulative water intake after 3 and 20 hr and used the plot-wise average for further statistical evaluation.

## 3 | RESULTS

### 3.1 | Soil organic carbon and bulk density

In comparison with the initial SOC content, measured at the start of the long-term experiment (5.7 mg C $g^{-1}$), the average SOC content measured in this study, 7 years later was 9.6 mg C $g^{-1}$. To evaluate the general differences between organic (as average of BIODYN and BIOORG) and conventional farming systems (as average of CON and CONBtC), both treatments respectively were averaged according to the smaller differences between them. In the topsoil (8–12 cm) of both organic systems, the SOC content was on average 0.7 mg C $g^{-1}$ higher than of both conventional systems although this difference was not statistically significant ($p = 0.30$, Figure 1a, Table S1a). The bulk density did not indicate significant differences (Figure 1a). Accordingly, the SOC stocks did not differ between systems (Table S1a).

### 3.2 | Soil chemical properties

The average pH of both organic systems was 8.3 (Figure 1a). This was 0.14 units higher ($p = 0.0001$) than the average of both conventional systems, which was 8.15. The average electrical conductivity across all systems was 169 μS $cm^{-1}$. In the subsoil, the average pH of both organic systems (8.6) was 0.16 units higher than the average of both conventional systems (8.45, $p < 0.0001$) (Table S2).

The effective cation exchange capacity and exchangeable divalent cations did not show significant differences between the farming systems (Figure 1b, Table S1b). However, in case of the monovalent cations, the concentration of exchangeable sodium in both organic systems (1.6 cmol(+) (kg soil)$^{-1}$) was 48% greater than that in both conventional systems (1.1 cmol(+) (kg soil)$^{-1}$, $p < 0.0001$). The

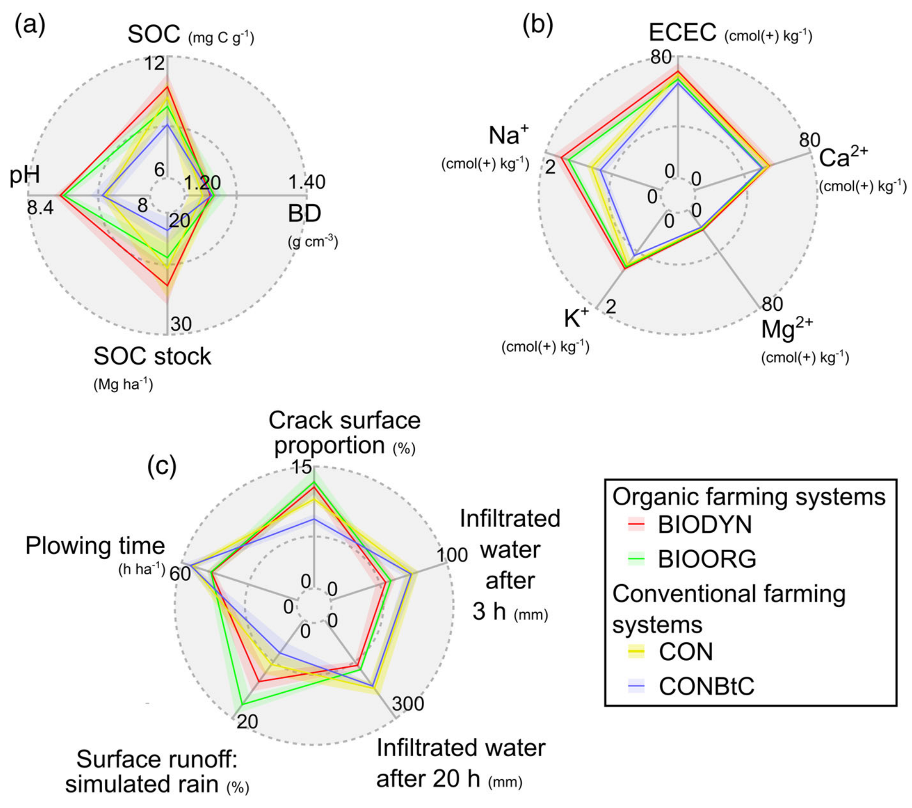


**FIGURE 1** Comparison of soil properties of two organic farming systems, biodynamic (BIODYN) and organic (BIOORG), and two conventional systems, conventional (CON) and conventional with genetically modified Bt cotton (CONBtC), from the topsoil (0–20 cm) of a Vertisol in India. (a) soil organic carbon content (SOC), bulk density (BD), SOC stock and soil pH. (b) effective cation exchange capacity (ECEC) and various exchangeable cations. (c) crack surface proportion, infiltrated water after 3 and 20 hr, surface runoff and ploughing time. Lines represent the mean values and the shading ± standard error. The statistical analysis of the effect of different farming systems on soil properties using ANOVAs and the Tukey tests for pairwise mean comparisons are given in Table S1 [Colour figure can be viewed at wileyonlinelibrary.com]

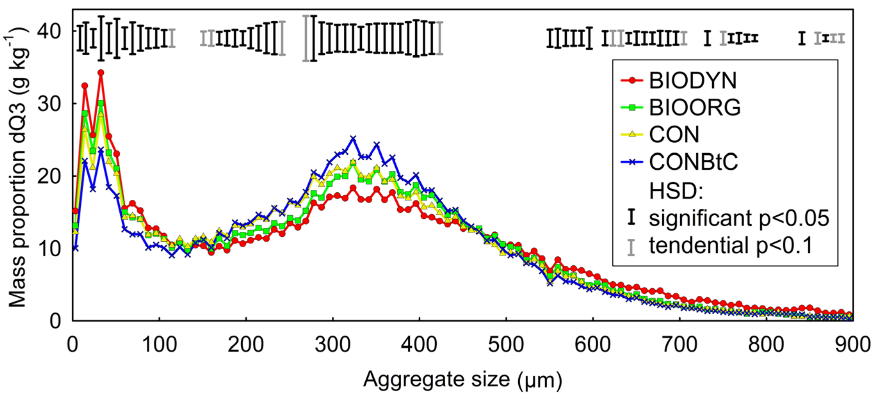


**FIGURE 2** Mass proportion of water-stable aggregates from the topsoil (0–20 cm) in two organic farming systems, biodynamic (BIODYN) and organic (BIOORG), and two conventional systems, conventional (CON) and conventional with genetically modified Bt cotton (CONBtC). Aggregate proportions are given according to volumetric distribution density. The black HSD bars represent Tukey's honestly significant difference as a measure for the minimum difference between means that is required for them to differ significantly where analysis of variance (ANOVA) $p < 0.05$ and in gray where ANOVA $p < 0.1$ [Colour figure can be viewed at wileyonlinelibrary.com]

concentration of exchangeable sodium correlated positively with the soil pH ($r = 0.62$, $p = 0.01$). The average ESP in both organic systems was 2.46 and in conventional systems 1.73.

## 3.3 | Water-stable aggregate diameters

The dynamic image analysis provided a detailed volumetric aggregate size distribution of water-stable aggregates sized 2–900 µm (Figure 2). We found distinct system differences between microaggregates sized <137 µm and macroaggregates sized 137–419 µm (Figures 2 and 3). The organic systems, BIODYN and BIOORG (17.3 mg $g^{-1}$), had 2.5 mg $g^{-1}$ more water-stable microaggregates on average than the conventional systems, CON and CONBtC (14.9 mg $g^{-1}$; $p = 0.002$; Figures 2 and 3). More specifically, among the organic systems, BIODYN (18.1 mg $g^{-1}$) showed a tendency to contain 1.5 mg $g^{-1}$ more microaggregates than ORG (16.6 mg $g^{-1}$; $p = 0.03$; Figure 3).

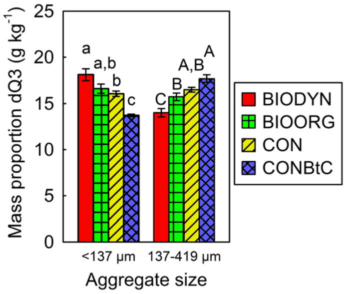


**FIGURE 3** Average proportion of aggregate size classes according to the volumetric density distribution (mg g$^{-1}$; $n = 4$) of water-stable microaggregates <137 µm (analysis of variance [ANOVA] $p = 0.0003$) and macroaggregates 137–419 µm (ANOVA $p < 0.0001$) from topsoil (0–20 cm) in four farming systems. Data are shown as means ± SE. Means with the same letter were not statistically different at $p < 0.05$ [Colour figure can be viewed at wileyonlinelibrary.com]

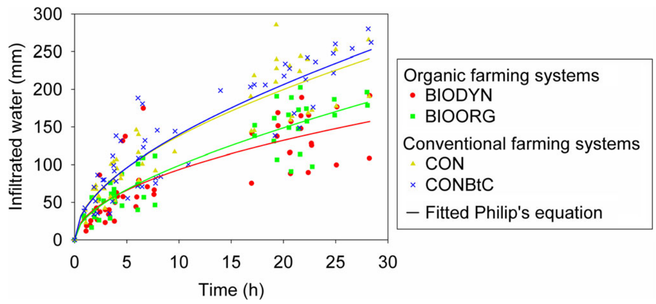


**FIGURE 4** Soil infiltration of organic and conventional farming systems over time according to double ring infiltrometer measurements. The individual measurements are shown as symbols whereas the models fitted to the different farming systems according to the Philip's equation are shown as lines [Colour figure can be viewed at wileyonlinelibrary.com]

Within the conventional systems, CON (16.0 mg g$^{-1}$) contained 2.4 mg g$^{-1}$ more microaggregates than CONBtC (13.7 mg g$^{-1}$; $p = 0.003$; Figure 3).

In contrast to the microaggregates, the water-stable macroaggregates sized 137–419 µm of both conventional systems (17.1 mg g$^{-1}$) were 15% greater than those in the organic systems (14.9 mg g$^{-1}$; $p = 0.0007$; Figures 2 and 3). The macroaggregates within the conventional systems in CONBtC topsoils (17.7 mg g$^{-1}$) showed a tendency to contain more macroaggregates than CON (16.5 mg g$^{-1}$; $p = 0.03$; Figures 2 and 3). Within the organic systems, ORG (15.7 mg g$^{-1}$) had 1.7 mg g$^{-1}$ more macroaggregates than BIODYN (14.0 mg g$^{-1}$; $p = 0.005$; Figures 2 and 3). In addition, water-stable aggregates sized 600–900 µm were more abundant in BIODYN than in the conventional systems CON and CONBtC ($p = 0.04$, Figure 2).

The observed changes of water-stable aggregate diameters were related with exchangeable monovalent cations like potassium and sodium but not with calcium or magnesium which did differ between treatments. Both exchangeable sodium and potassium, correlated positively with the water-stable microaggregates (Na: $r = 0.64$, $p = 0.008$; K: $r = 0.65$, $p = 0.007$) and negatively with macroaggregates (Na: $r = -0.63$, $p = 0.008$; K: $r = -0.50$, $p = 0.05$). The soil pH correlated positively with water-stable microaggregates ($r = 0.56$, $p = 0.02$) and negatively with macroaggregates ($r = -0.64$, $p = 0.01$).

## 3.4 | Crack spaces, infiltration, and surface runoff

The crack surface proportion in organic BIODYN and BIOORG (12.7%) was on average 4.2% higher than in CONBtC (8.4%; $p = 0.002$; Figure 1c; Table S1c). The crack surface proportion correlated positively with the bulk density ($r = 0.54$; $p = 0.03$). There were no differences between systems in crack depth.

The amount of infiltrated water after 3 and 20 hr in both organic systems, BIODYN and BIOORG, was approximately 30% lower than in both conventional systems, CON and CONBtC (after 3 h: $p = 0.004$; after 20 h: $p = 0.0001$; Figure 1c, Figure 4). The infiltrated water after 3 and 20 hr correlated positively with water-stable macroaggregates 137–419 µm (after 3 h: $r = 0.64$, $p = 0.007$; after 20 h: $r = 0.62$, $p = 0.01$) and negatively with the microaggregates <137 µm (after 3 h: $r = -0.55$, $p = 0.03$; after 20 h: $r = -0.60$, $p = 0.02$). The exchangeable sodium and potassium content correlated with the infiltrated water after 3 hr (Na: $r = -0.74$, $p = 0.001$; K: $r = -0.58$, $p = 0.02$) and after 20 hr (Na: $r = -0.79$, $p = 0.0003$; K: $r = -0.65$, $p = 0.007$).

In both organic systems, 15% of simulated rain ran off the watered area, which was twice the surface runoff of the conventional systems (8%) ($p = 0.02$; Figure 1c). The proportion of surface runoff from simulated rain was negatively correlated with infiltrated water after 20 hr ($r = -0.60$, $p = 0.01$). The collected surface runoff contained 0.2%–0.4% air-dried soil mass on average across all farming systems.

Concerning the relations to the soil hydraulic properties, the surface runoff showed a positive trend with the water-stable microaggregates ($r = 0.48$, $p = 0.06$) and pH in the top 40 cm ($r = 0.48$, $p = 0.06$). The soil dry matter content of surface runoff (data not shown) correlated positively with the concentration of exchangeable sodium ($r = 0.56$, $p = 0.03$).

## 3.5 | Time needed for ploughing

The organic systems, BIODYN and BIORG, needed 10.2 hr ha$^{-1}$ less for ploughing with bullocks ($p = 0.0008$) than the conventional systems, CON and CONBtC (Figure 1c, Table S1c). The time needed for ploughing increased in the order BIODYN, BIOORG, CON, and CONBtC and was negatively correlated to pH ($r = -0.52$, $p = 0.04$), exchangeable sodium cations ($r = -0.78$, $p = 0.0003$), potassium cations ($r = -0.68$, $p = 0.004$), and water-stable microaggregates ($r = -0.68$, $p = 0.004$). In addition, the time needed for ploughing was positively correlated to macroaggregates ($r = 0.58$, $p = 0.02$).

# 4 | DISCUSSION

## 4.1 | Impact of farming systems alone plays a lesser role in the uptake of organic carbon in soils

The observed increase of SOC content over time since establishing the cotton-soybean-wheat cultivation indicates a similar increase of SOC storage potential for the studied conventional and organic systems. When comparing the different systems after 7 years, we did not observe a significant difference between the organic systems with the conventional systems (Figure 1a). In contrast, in a comparable field experiment, the SOC content in the topsoil in organic farming was 4 mg C $g^{-1}$ higher than that of conventional farming after 11 years (Blaise, 2006). Unlike numerous previous comparison studies (Blaise, 2006; Jha et al., 2014), in which conventional farming systems were fertilized only with mineral NPK fertilizers, the conventional farming systems in our study received 2 Mg $ha^{-1}$ FYM, which reflects the local farming practices of conventional farmers. The integrated application of small amounts of FYM along mineral fertilizers in conventional systems seems to lead to a similar range of SOC content as in organic systems, which is further promoted due to higher crop residue input resulting from higher yields in the conventional plots. The application of small amounts of FYM in all systems as well as optimized crop management due to the scientific management and monitoring may explain the increase of SOC contents over the course of the experiment. Previous works on comparable soils in India showed that the application of FYM together with mineral NPK fertilizers resulted in higher SOC contents (Behera et al., 2007; Rudrappa et al., 2006). An Australian study showed that the SOC content of Vertisols does not always increase upon biomass addition as differences between stubble burning and stubble retention did not change the SOC contents after 50 years (Hati et al., 2021). A study on different types and amounts of organic amendments applied together with mineral fertilizers showed that the pure application of a larger amount of FYM led to approximately 1 mg C $g^{-1}$ more SOC on average and resulted in larger soil aggregates and higher porosity after 5 years on a Vertisol (Meena et al., 2019). In our study, the time for attaining significantly higher SOC contents in the organic farming systems compared to conventional systems with integrated fertilization of smaller amounts of FYM may be prolonged, as has been observed in temperate agroecosystems (Kaczynski et al., 2017). A pluri-decadal monitoring and comparison of farming systems on various tropical soils are therefore important to advance our knowledge on SOC storage. Based on our study of a 7-year old system comparison experiment, an increase of SOC by higher additions of organic amendments was not inevitable given possible constraints of SOC uptake by soil aggregate dynamics and soil chemical properties.

## 4.2 | Alteration of soil aggregate diameters

By taking advantage of dynamic image analysis to analyze the size distribution of water-stable fractions at a resolution of several μm, we found that the organic systems contained more microaggregates <137 μm, whereas the conventional systems contained more macroaggregates, 137–419 μm (Figure 3). A lower diameter of the water-stable aggregate on average for both organic systems compared with both conventional systems is in contrast to the expected enhancement of soil structure through additional biomass input in the organic systems. This might indicate a preferential stabilization of microaggregates <137 μm through the increased application of organic amendments. More microaggregates <137 μm were specifically found for BIODYN, which might be related with a higher input of cations due to the addition of biodynamic preparations compared with BIOORG, which was more similar to CON. However, such slight differences of additions were not reflected in the content of exchangeable cations, which limit the detection of systematic differences between BIODYN and BIOORG (Table S1b). A preferential stabilization of microaggregates might play a major role in Vertisols due to the high content and large specific surface area of clay-sized minerals and a high aggregate turnover (Coulombe et al., 1996). It was shown that young C preferentially adsorbed to structural units <200 μm compared to >200 μm in a Chromic Luvisol with 41% clay under Australian shrubland (Hobley et al., 2014). Our results demonstrate that the aggregate diameter declined rather than increased as a consequence of organic amendment application.

The cover cropping in the organic systems (1, 3, 5, and 7 years before sampling for this study) might have influenced the wet–dry cycle toward smaller aggregates. Previous studies related soil structural improvements of Vertisols to an increased evapotranspiration, more pronounced wet-dry cycle and crack development through standing crops compared with fallow fields (Dasog & Shashidhara, 1993; Pillai & McGarry, 1999). The pronounced influence of wet–dry cycles in Vertisols might also override the expected influence of biomass input on the soil structure. However, since all farming systems were equally supplied with water by multiple flood irrigations after the cover cropping the impact of wet-dry cycles is likely limited.

## 4.3 | Interactions of soil chemical properties with organic carbon and aggregation

Instead of the hypothesized impact of the farming systems on the SOC content, our analyses revealed a major effect on the soil chemical properties. We observed a higher pH (8.3) and more exchangeable sodium (1.6 cmol(+) (kg soil)$^{-1}$) in the organic systems compared with the conventional systems (pH 8.1; exchangeable sodium 1.1 cmol(+) (kg soil)$^{-1}$) (Figure 1). The corresponding ESP values (2.46 in organic systems and 1.73 in conventional systems) are lower than what would traditionally be expected to affect hydraulic properties according to the postulated threshold of ESP >15 for sodic soils (Richards, 1954). However, numerous rainfall simulation studies have highlighted that an ESP >1 (du Plessis & Shainberg, 1985) or an ESP >2 (Bloem & Laker, 1994; Laker & Nortjé, 2019) can already lead to a chemical dispersion of aggregates. Increased contents of exchangeable sodium are a widespread soil threat especially in semi-arid and arid landscapes depending on anthropogenic alteration of water hydrology and the redistribution of salts (Burch, 1986; Rengasamy & Olsson, 1991).

The higher content of exchangeable sodium in the organic systems was probably responsible for the higher content of microaggregates <137 μm and lower content of macroaggregates 137–419 μm compared to the conventional systems. The aggregate dispersion by sodium is likely explained by its high dispersive power in comparison with other prevalent exchangeable cations (Rengasamy et al., 2016). The content of microaggregates correlated positively with pH and the concentration of exchangeable sodium, whereas the content of macroaggregates correlated negatively. This indicates that the chemical properties may play an integral role for the aggregate stability in the analyzed experiment.

In addition to the effect of chemical properties on water-stable aggregates, a higher pH and more exchangeable sodium might have affected the uptake of SOC. The chemical properties may counteract the expected increase of SOC in the organic systems according to previous studies reporting a dispersive effect of adsorbed sodium ions and the increased solubility and leaching of organic compounds (Setia et al., 2013; Singh et al., 2016). According to a respiration experiment, in particular, lower sodicity like in our experiment may, however, decrease the microbial activity (Wong et al., 2008), which could affect SOC storage in our experiment over time. A study on various noncultivated Vertisols in Australia concluded that an increase of SOC mainly stabilizes aggregates >250 μm, whereas aggregates <250 μm are more related to exchangeable sodium and calcium (Smith et al., 2015). Since the cropped soil of our experiment contained less SOC than the uncultivated Vertisols with >20 g C $kg^{-1}$ for which Smith et al. (2015) found the most pronounced increases of aggregate stability, the different chemical properties may induce the higher abundance of microaggregates in the organic systems compared with the conventional systems.

More sodium in organic systems than in conventional probably occurred due to a high pH of the added compost and introduction of sodium, bicarbonate, and other ions to the compost (Tavakkoli et al., 2015; Whalen et al., 2000; Wong et al., 2010). Potential ion sources include river water and FYM itself (Ding et al., 2016; Minhas & Bajwa, 2001), especially from cow urine (Cardon et al., 1951), that are used to prepare the compost. The interactions of SOC uptake and aggregate stability with increased sodium concentrations require further investigation. In the topsoils of both conventional systems, a lower pH probably resulted from a proton release during urea turnover in the conventional systems (Liebig & Doran, 1999). Therefore, within the conventional systems, the increase of aggregate diameters was higher in CONBtC than in CON probably due to an additional annual urea fertilization of 20 kg N $ha^{-1}$ that led to a higher acidification during urea turnover.

### 4.4 | Interrelated changes of infiltration and surface runoff

The water-stable macroaggregates of 137–419 μm diameter were correlated with more infiltrated water and could be related to the stabilization of important transmission pores for infiltration in the conventional systems. Similar to the infiltration, the surface runoff showed a negative trend toward water-stable microaggregates <137 μm, that seem to reduce hydraulic properties in the organic systems. Both the higher pH and the concentration of exchangeable sodium in the organic systems were correlated with less infiltrated water and higher surface runoff. The smaller size of water-stable aggregates due to increased sodicity in the organic systems probably led to clogged pores, decreased infiltration and, thereby, increased surface runoff.

Our results are in contrast to previous experiments, in which FYM input increased hydraulic conductivity (Bandyopadhyay et al., 2010) and infiltration rate (Acharya et al., 1988). Probably, the difference to our study is that increased sodicity of the soil was not reported in these studies. Our finding of an aggregate dispersion and a decrease of infiltration when exposed to an increased sodicity is supported by analyses of comparable soils (Balpande et al., 1996; Cook et al., 1992; Gupta et al., 1984). Increased surface runoff and less infiltrated water promote the risk of erosion and pose a challenge to the sustainable management of soil resources (Le Bissonnais & Arrouays, 1997). Less infiltrated water in both organic systems indicates a lower leaching capacity of salts added through irrigation and compost, which could enhance the accumulation of salts leading to an even more pronounced aggregate dispersion in the long term.

In contrast to the lower infiltration of organic farming systems, we found the proportion of surface cracks in organic farming systems to be higher than in the conventional systems. The increase of cracks in our study is also in contrast to a decrease of crack surface proportion by 19%–37% in soils supplied with *Lantana* spp. (Bhushan & Sharma, 2002). Therefore, the larger crack spaces of organic topsoils in our study probably relate rather to a higher aggregate dispersibility due to sodification than the proposed stabilization through the hypothesized increase of SOC. An increase of water-stable microaggregates was also related to a shorter time needed for ploughing because they probably caused less physical resistance to ploughing than macroaggregates.

## 5 | CONCLUSIONS

After 7 years of comparing organic and conventional farming systems on a Vertisol, we found no significant differences in the SOC contents, despite a higher application of organic amendments in the organic systems. The time to attain a measurable increase of SOC may hence be longer at a decadal time scale. The lower amounts of FYM applied along mineral NPK fertilizers in conventional systems may have led to an equal increase of SOC contents compared with the initial starting value. In the organic farming systems, the water-stable soil aggregates were smaller than in conventional farming systems. A lower pH and more exchangeable sodium cations in the organic systems compared to the conventional systems reveal differences in chemical properties that might explain the decreased soil aggregate diameters and a restrained uptake of SOC under the subtropical, semiarid climate. As a consequence, the hydraulic properties were reduced: In the organic systems, smaller aggregates decreased the infiltrated water and increased the surface runoff compared to conventional systems. Our study underlines the importance of soil chemical properties which might outweigh changes resulting from the application of organic amendments in semi-arid environments. Under subtropical, semiarid climate, such interactions of chemical soil properties, soil aggregates, and hydraulic properties need to be taken into account in farming strategies toward sustainable agricultural intensification. Our results demonstrate how the application of organic amendments did not translate into higher SOC, but different chemical soil properties threatened the envisaged improvement of soil properties. This indicates that SOC may be decoupled from directly controlling soil aggregate stability. Our study shows that efforts to improve soil aggregate stability through the application of organic amendments may not necessarily increase SOC contents given possible constraints of chemical soil properties under subtropical, semi-arid climatic conditions.

## ACKNOWLEDGMENTS

We are greatly indebted to the local partner bioRe Association for the helpful assistance during sampling of the field experiment. This article is dedicated to the Foundation fiat panisfor their encouragement of early career scientists to work together with local stakeholders examining complex research questions in the vast area of food security in the tropics and subtropics. This work has been conducted in the framework of the long-term systems comparison program, which is financially supported by Biovision Foundation for Ecological Development, Coop Sustainability Fund, Liechtenstein Development Service (LED), and the Swiss Agency for Development and Cooperation (SDC). The QICPIC machine for dynamic image analysis was kindly provided by F. Lang (University of Freiburg). We thank the Foundation fiat panis or the travel grant that enabled the first author to visit India for data collection.

## CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

## DATA AVAILABILITY STATEMENT

The data analyzed in this work is accessible at https://doi.org/10.6084/m9.figshare.18665612.

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**How to cite this article:** Schweizer, S. A., Graf-Rosenfellner, M., Bhat, N. A., Kayser, G., Sisodia, B. S., Kirchhof, G., Zikeli, S., Cadisch, G., & Bhullar, G. S. (2022). Responses of soil organic carbon, aggregate diameters, and hydraulic properties to long-term organic and conventional farming on a Vertisol in India. *Land Degradation & Development*, *33*(5), 785–797. https://doi.org/10.1002/ldr.4216