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Global meta-analysis suggests that no-tillage favourably changes soil structure and porosity

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ABSTRACT

Role of soil to meet global food security, sustainable intensification and food nutritional quality has got renewed attention with a larger focus on soil physical condition. No-tillage (NT) practice can essentially contribute to develop a sustainable, low carbon and resource efficient agriculture, and encourage the use of crop residues for added soil benefits. Soil aggregation and pore size distribution, two most important soil physical factors controlling the mass and energy transport processes within the soil and between soil and environment, were evaluated under the NT through a global meta-analysis of 5065 pairs of data points from 419 peer-reviewed studies. Compared to conventional tillage (CT), NT increased mean weight diameter of aggregates, water stable aggregates, and macroaggregates by averages (0–30 cm) of 25, 10 and 22%, respectively, although predominantly in 0–10 and/or 10–20 cm layers, with an accompanying reduction in microaggregates. A small but significant 3% decrease in total porosity, a large reduction (20–32%) in macroporosity and a moderate increase (4–7%) in microporosity were realized under NT up to 20 cm soil depth. Bulk density remained stable, although a very large decrease (70% change over CT) in saturated hydraulic conductivity was recorded in 10–20 and >30 cm soil layers. Years of adoption of NT had an additive effect on mean weight diameter and macroaggregates, and the total and macroporosity. Increase in latitudes favoured soil aggregation and micropore volume under NT, while clay content was unfavourable to macro- and water stable aggregate contents. Improvement in structure and water retention properties relate to long-term sustainable development of soils by following no-till practice, which has far-reaching implications beyond the boundaries of agronomy.

1. Introduction

In the recent past, unsustainable agricultural management practices have threatened the health of the soil (Cerdà, 2000) and this necessitates the adoption of sustainable management practices to endure natural resources (Franzluebbers, 2010; García-Díaz et al., 2016). Tilling of soil for crop production is one of the most notable human interventions that disturb soil aggregation, pore-size distribution and water movement among others (Guo and Gifford, 2002). Conventional tillage (CT) which favours repeated tillage and residue burning for fine seedbed preparation has shown adverse effects on soil health (Somasundaram et al., 2017).

Recently, several resource conservation and management practices are being recommended to achieve better soil health, lower C emission, and higher productivity in a sustainable manner (Paustian et al., 2016). Conservation agriculture, which promotes minimum soil disturbance, protects the soil by surface residue or cover crops and favours crop rotation is one of such management practices (West and Post, 2002; Luo et al., 2010). Adoption of minimum or no-tillage (NT) against CT has been considered as a successful approach for better health and higher C stock of soil (Paustian et al., 2000; Six et al., 2004). In NT, seeds are placed in furrows without tilling the soil and therefore, has minimum soil disturbance (Soane et al., 2012), which has multiple benefits like erosion control, better fuel, labour and time economy, rise in microbial activity and improvement in water retention over CT. In addition to its multiple benefits, conservation agriculture is a way for sustainable use of crop residues (often a biowaste), other than the biochar which also has multiple benefits of soil quality improvement and C sequestration (Maroušek et al., 2019).

Soil aggregation, the spatial arrangement of voids and soil particles,

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is an important physical property and influences the important functions and processes of soil, like water and air movement and storage, mechanical impedance, biological and chemical processes. Thus, it has a great bearing on root development, plant growth and crop productivity (Berisso et al., 2013). Soil aggregates are formed by various binding agents and soil constituents simultaneously at different levels (Six et al., 2004; Bronick and Lal, 2005). CT affects the aggregation directly by breaking down macroaggregates and indirectly by altering the soil biological and chemical environments (Barto et al., 2010). Moreover, the network of mycelium gets destroyed by repeated tillage operations (Borie et al., 2006). Instead, NT favours crop residue retention and promotes aggregate formation (Bronick and Lal, 2005; Curaqueo et al., 2011). Macroaggregates, considered as a predictor of tillage-induced changes, play a dominant role in physically protecting the soil organic carbon and maintain better soil health.

The omission of tillage under NT can favour the formation of continuous pores, especially biopores, by decaying crop residues or faunal activities (like earthworms) which can affect the transport functions of the soil (Hartmann et al., 2012). Sometimes, the presence of biopores favours the preferential flow of soil nutrients and agrochemicals (Jarvis, 2007). Moreover, NT can also create a dense surface soil particularly during the initial years of adoption which hinders the root development, air and water movement (Kay and VandenBygaart, 2002; Nunes et al., 2015). In contrast, CT loosens the surface soil by breaking the pore continuity and promotes the formation of a subsurface hard layer (Kay and VandenBygaart, 2002; Schjønning and Thomsen, 2013; Nunes et al., 2015).

Meta-analysis is a powerful statistical technique to draw a general conclusion out of diverse, conflicting results (Gurevitch et al., 2001) and is now increasingly being used in agriculture. Without ignoring the soil and climate factors, a general agreement on the potential impact of NT can be reached through a comprehensive *meta*-analysis of global studies. Sustainable intensification and resilience in agriculture must ensure resource-use efficiency, which can be realized through microscale changes in soil. A soil without disturbance (by tillage) is closer to the natural state compared to a continuous tilled soil, and will exhibit favourable changes. We have selected soil aggregation and pore characteristics as the evaluation parameters due to their fundamental roles in mass and energy transport processes within the soil, and between the soil and the environment. We hypothesized that (i) NT can favourably change these parameters towards the soil functional improvement, and (ii) the effect will be higher for some climate and soil types where it can be advocated as a sustainable intensification option for agricultural production. Very few attempts have been made to synthesize the information in a statistical term (Blanco-Canqui and Ruis, 2018; Li et al., 2019; Mondal et al., 2020a), and the effect with depth of soil is lacking. A *meta*-analysis was therefore performed primarily on soil aggregation and pore-size distribution; and additionally on soil bulk density and saturated hydraulic conductivity, with 5065 pairs of data points collected from 419 peer-reviewed published literatures.

2. Materials and methods

2.1. Data extraction

Peer-reviewed published literatures were comprehensively searched with the keywords "'Soil' AND 'Tillage'" in the article abstract in the core collection of Web of Science indexing service and limited to 2000–2017. Publications other than those in the English language, and conference proceedings were excluded. Searched literatures were then screened individually by abstracts. Tillage which involved a complete disturbance of the surface soil layer (plough depth) by different tilling implements (mouldboard plough, disc harrow, rotavator, chisel plough, spade, etc.) for fine seedbed preparation was taken as 'Conventional Tillage' or 'CT'. In most of the studies, treatment was explicitly mentioned as CT. The number of passes of tillage in studies varied between 2 and 4 of primary and secondary tillage, followed by planking. The tilling depth was $\sim 20 \pm 5$ cm. Tillage which was mentioned in peer-reviewed literatures as 'CT' or 'mouldboard tillage' (MT), or 'plough-tillage' (PT) or 'chisel plough' (CP) or likewise, was considered as 'CT'. Chiselling or deep ploughing at $>$ 25 cm depth was excluded from our study as the purpose was not to prepare a fine seedbed but to break the soil hardpan, if any. Reduced or minimum tillage was also excluded from our study. Contrary, no-tillage (NT) was completely devoid of any physical manipulation of the soil before sowing, and there was no physical disturbance except planting/seeding implements (minimum disturbance only in row strips). We have selected no-tillage with residue retention on surface soil as 'NT'. In NT, furrows or drill holes were made by seeding implements or tools (i.e., NT planter, strip-till drill, paired row no-till seeder, dibble stick, hand hoe, etc.) for seed placement. Few studies also used the term 'conservation agriculture' to define no-tillage along with crop residue management and crop rotation. For these cases, conservation agriculture was taken as NT. Reduced tillage was excluded from our study. Studies were selected for data extraction based on the following criteria:

i) only field experiments having both NT and CT as treatments were selected, and tree systems or orchards were excluded;
ii) there was absence of any management effect between NT and CT other than the herbicide application;
iii) where many types of tillage operations were adopted, tillage that had the maximum soil disturbance was taken as CT;
iv) with residue applied or retained, NT was the treatment of no-tillage with residue, while CT was the conventional tillage without residue;
v) experiment has a duration of at least 3 years.

Screened literatures were then searched for the following parameters and respective data were extracted depth-wise: a) Bulk density (BD, g cm^{-3}); b) Macroaggregates (MacA, g kg^{-1}); c) Microaggregates (MicA, g kg^{-1}); d) Water stable aggregates (WSA, g kg^{-1}); e) Mean weight diameter of aggregates (MWD, mm); f) Macroporosity (MacP, %); g) Microporosity (MicP, %); h) Total porosity (TotP, %); i) Aeration porosity (AerP, %) and j) Saturated hydraulic conductivity (SHC, cm h^{-1}). Globally, a total of 5065 pairs of data points was extracted from 419 studies for the *meta*-analysis (Fig. 1). The list of studies used in *meta*-analysis is given in Annexure − 1.

2.2. Database preparation

Means of parameters for NT and CT were extracted from each study for each soil depth. Additional information like latitude-longitude, duration of adoption and soil texture (or sand, silt and clay content) was also noted for categorization of data. Data presented in figures were extracted by using WebPlotDigitizer version 3.12 (Rohatgi, 2016).

When latitude and longitude of a study location were unavailable, Google Map was used for extracting the coordinates of that place. For climatic classification, R-package "kgc" was used for extracting Köppen climatic class from latitude and longitude data of a location (Rubel et al., 2017). Four broad climatic classes were taken for our categorical analysis, e.g., tropical, continental, dry and temperate climate. Soil texture, if available was noted otherwise, sand-silt–clay data was used in NRCS Soil Texture Calculator for textural class determination. All textural classes were regrouped to get only 3 major textural groups viz. fine-textured (sandy clay, silty clay, clay), medium-textured (silty clay loam, clay loam, silt, silty loam, loam) and coarse-textured (sandy loam, sandy clay loam, loamy sand, sand) soils. If the study duration was mentioned in the study, it was taken, otherwise, the year of experiment onset was subtracted from the reporting year to get the experimental duration. Reclassification of duration was made into three periods viz., a) $<$ 10 years (short-term effect), b) 10–20 years (medium-term effect) and c) $>$ 20 years (long-term effect).

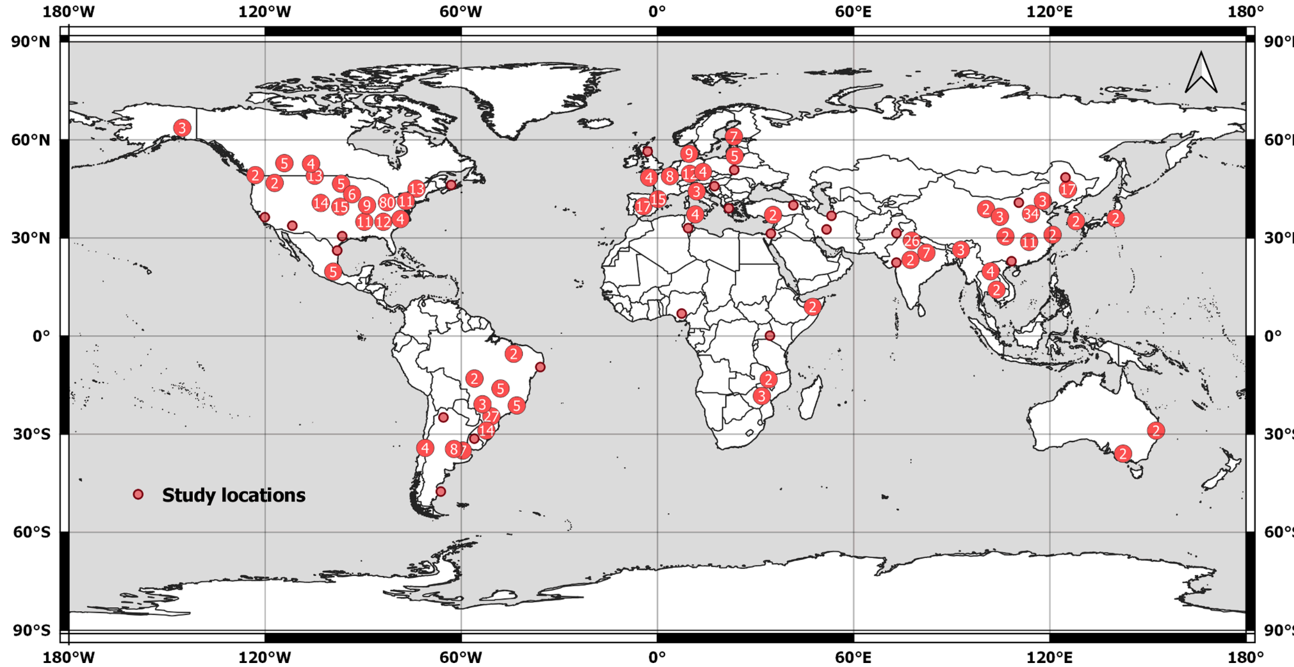

Fig. 1. Global cluster map showing study locations [Numbers within the circle represent the number of studies for the location. Dots with no number refer to a single study].

Various soil depths were mentioned in studies, of which some were more frequent than the others. Soil depths were reclassified into 0–10, 10–20, 20–30 and > 30 cm. The following rules were followed during the reclassification of a soil depth:

a) When the reported depth interval fell within a particular class, it was identified as that class (e.g., 0–5, 2–9 cm were included in 0–10 cm);
b) When the reported depth was spread over two successive classes, it was included in the class which has the maximum overlapping (e.g., 8–16 cm was included in 10–20 cm);
c) When the reported depth had equal overlapping with two successive classes, it was included in the latter class (e.g., 5–15 cm was included in 10–20 cm depth class);
d) When the reported depth had a minimum thickness of < 2.5 cm (e.g., 1–3, 5–7 cm), these were excluded; and
e) When reported depth was spread over more than two classes, it was excluded from the analysis (e.g., 5–25, 0–30 cm).

Soil bulk density (BD) was considered if determined by the core method, where cores were used to excavate soils from a specific layer, oven-dried, and dry weights were recorded. The BD was expressed as soil dry weight per unit volume of the core. In all the studies, Aggregate water stability data was extracted if only wet sieving method was followed, although the methods/instrumentation varied (e.g., Yoder apparatus, wet sieving apparatus, manual wet sieving). Similarly, the time of shaking, cycles per minute or frequency, amplitude of shaking and pre-soaking time varied greatly from article to article. Pre-soaking treatment was also not always done. In all the studies, 0.25- and 0.053-mm mesh sieves were used either alone or with other sieves. Soil aggregation parameters e.g., macro- (≥250 μm), micro- (<250 μm and ≥ 53 μm) and water stable aggregates (≥53 μm); and MWD were extracted. Pores that had a diameter of > 60 or > 50 μm or drained at −5 kPa matric potential were taken as macropores and measured either by sand box, hanging water column or pressure plate apparatus. Whereas micropores were pores with a diameter of < 60 or < 50 μm or remain water filled at −5 kPa matric potential. In a few studies, *meso*-pores (60–0.2 μm diameter) were also reported which were taken in micropores category. In absence of total porosity, the soil BD data were used for calculating total porosity by using the following equation:

$$Total\ porosity\ (\%) = \left(1 - \frac{Bulk\ density\ (g\ cm^{-3})}{Particle\ density\ (g\ cm^{-3})}\right) \times 100$$

Here particle density was taken as 2.65 g cm^{-3}. Saturated hydraulic conductivity was measured by permeameter. Data of steady-state infiltration rate, measured by double-ring infiltrometer, were extracted and added to the database as SHC for 0–10 cm soil layer. Aeration porosity was taken as the difference between total porosity and water content at field capacity.

2.3. Data analysis

The effect size was calculated as the natural log of response ratio (lnRR) i.e., ratio of NT and CT by following Eq. (1) (Hedges et al., 1999). For most of the studies, within-study variance was absent and moreover, variance-based weighing might cause extreme weights for some studies (Liu et al., 2018). By contrast, the replication-based weighing function generates less extreme weight (Van Groenigen et al., 2011) and therefore, experimental replications were used as weighing factors for individual observations (Adams et al., 1997; Pittelkow et al., 2015; Eq. (2)). In situations where more than one observation from a study was included in a category, the weight was divided by the total number of observations from that study (Pittelkow et al., 2015). The lnRR was finally back-transformed to get percent changes of parameters (Eq. (3)).

$$Effect\ size = lnRR = ln\left[\frac{Mean_{NT}}{Mean_{CT}}\right] \tag{1}$$

$$Weight = \frac{N_{NT} \times N_{CT}}{N_{NT} + N_{CT}} \tag{2}$$

$$Percent\ change = [\exp(lnRR) - 1]*100 \tag{3}$$

where, $Mean_{NT}$ and $Mean_{CT}$ are means of parameters under NT and CT, respectively; N is the number of replicates

Effect sizes from individual studies were combined using a random-effects model, and were considered significant if the 95% confidence intervals (CIs) did not overlap with zero. Meta-analysis was also performed for the groups (climate, duration and texture) but omitted when paired data points were 5 or less. Between the study variability, Cochran's Q-statistics and p-value of Q-statistics for different soil parameters are presented in Supplementary Table 1. A *meta*-regression analysis was performed to detect the linear trends between moderator variables (duration of the experiment, absolute latitude and clay content) and soil properties. The 'metafor' package (Viechtbauer, 2010) was used in the R statistical computing platform (R Core Team, 2020), and reported significant changes at $p < 0.05$ or $p < 0.01$. Publication bias was assessed through histograms (Rosenberg et al., 2000) and in none of the cases, effect sizes showed preferences towards positive or negative bias (Supplementary Fig. 1). Collinearity between predictor variables was checked by Pearson correlation coefficients (Supplementary Table 2) while residual heterogeneity in *meta*-regression is given in Supplementary Table 3. MS Excel was used for a few basic statistical analyses and the preparation of figures. The GIS map was produced by using QGIS version 2.18.

3. Results

3.1. Impact of no-tillage on soil aggregation:

Adoption of NT resulted in higher MWD of aggregates in comparison to CT throughout the soil profile. On the surface layer (0–10 cm), NT registered a 30.2% increase in MWD over the CT (Fig. 2a). Similar increases were recorded in other layers (14.7–28.2%). The change in MWD in temperate climate was through the entire soil profile (17.7–32.3%), although it was limited to 10 and 20 cm soil depths in tropical and continental climates, respectively (Table 1). Among textural classes, medium-textured soils had maximum advantages followed by fine-textured soils while no change in MWD was noted in coarse-textured soils. The effect was additive with the duration. A duration of < 10 yrs increased the MWD by 16.4%, and by 42.9 and 52.8% in 10–20 and > 20 yrs, respectively, in 0–10 cm soil layer. Changes in the entire profile were noted in > 20 yrs of duration.

Effect of NT on WSA was larger in the surface layer (a 19.4% increase) compared to 4.4 and 6.2% increases in 10–20 and 20–30 cm soil layer, respectively, and no change was recorded thereafter (Fig. 2b). It was similar across climates and soils, except in tropical climate and coarse-textured soils where either no change or a decrease in WSA was recorded (Table 1). Irrespective of soil texture, 12.1–22.2% increase in WSA was noted in the surface layer. In the 10–20 cm soil layer, fine- and medium-textured soils registered increase (5.8–10.3%) in WSA while a decrease (6.8%) was observed in coarse-textured soils. The impact of duration was the most distinct in upper layer; 10–20 yrs of NT practice caused a lesser increase (14%) in WSA in comparison to < 10 and > 20 yrs of duration (21.8–23.3%). In the 10–20 cm layer, NT of > 20 yrs registered 14.9% increase while in the 20–30 cm layer and with < 10 yrs of duration, it recorded a 7.6% change in WSA.

The adoption of NT over CT caused an increase of 39.0% in macroaggregates content in 0–10 cm soil layer (Fig. 2c). The magnitude of the effect decreased with increasing depth and even became negative for > 30 cm soil depth (17.1% decrease in NT). The effect of climate was distinct, and the increase in MacA content was 26.8% in continental

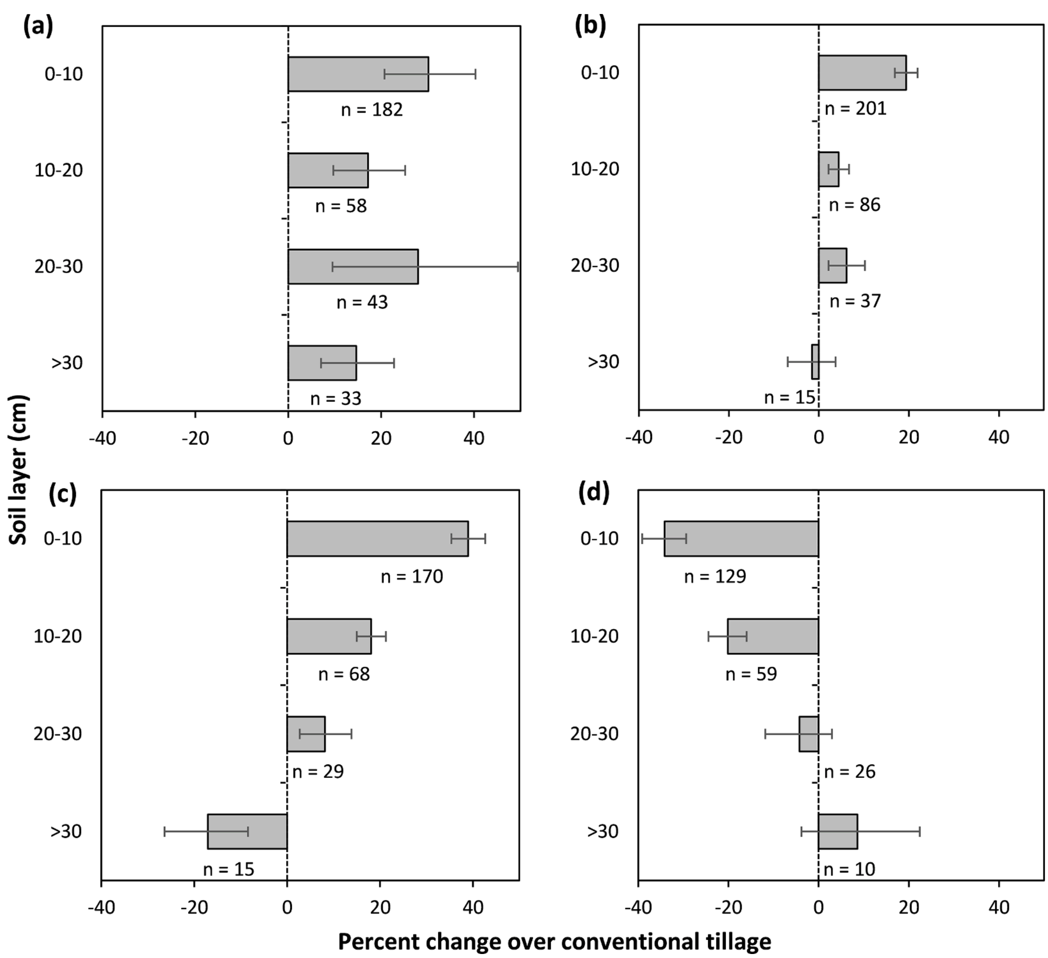

Fig. 2. Effect of no-tillage (% change over the conventional tillage practice) on (a) mean weight diameter of aggregates, (b) water stable aggregates, (c) macroaggregates and (d) microaggregates in different soil layers; [Vertical dotted line shows no change, horizontal bars indicate upper and lower confidence intervals, and 'n' is the number of paired data points].

Table 1
Impact of climate, soil texture and duration of the experiment on mean weight diameter, water stable aggregates, macroaggregates and microaggregates under no-tillage over conventional tillage (% change in no-tillage over conventional tillage).

Soil layer (cm)	**Climate**				**Texture**			**Duration (yrs)**		
	Tropical	Dry	Continental	Temperate	Coarse	Medium	Fine	<10	10–20	>20
Mean weight diameter of aggregates										
0–10	21.4**(21)	18.9(16)	44.4**(42)	30.9**(103)	7.3(46)	39.4**(91)	23.8**(39)	16.4*(85)	42.9**(64)	52.8**(33)
10–20	0.5(8)	–	38.0**(11)	17.7**(36)	16.8(17)	23.9**(19)	14.9*(16)	23.7**(24)	8.8(24)	25.6**(10)
20–30	4.4(9)	–	45.4(9)	32.3**(23)	10.4(14)	38.1**(22)	–	12.9(26)	38.5(12)	–
>30	–	–	0.0(15)	14.7**(16)	7.3(6)	15.1(23)	–	7.2(14)	26.0(13)	27.9**(6)
Water stable aggregates										
0–10	7.3(21)	16.7**(16)	20.7**(43)	21.4**(121)	18.6**(55)	22.2**(104)	12.1**(38)	23.3**(87)	14.0**(77)	21.8**(37)
10–20	−38.8*(7)	5.1**(7)	11.2**(23)	6.8**(49)	−6.8**(24)	10.3**(46)	5.8**(13)	1.1(31)	2.4(37)	14.9**(18)
20–30	−15.3(6)	–	15.6**(6)	6.6**(94)	4.4(12)	6.2*(17)	11.1*(6)	7.6**(21)	0.5(12)	–
>30	–	–	–	−2.0(11)	–	−4.2(6)	–	−2.5(7)	–	–
Macroaggregates										
0–10	1.2(6)	54.3**(16)	26.8**(26)	41.9**(122)	18.7**(32)	54.8**(107)	9.3**(27)	31.6**(76)	47.7**(68)	38.5**(26)
10–20	–	30.7**(8)	18.8**(16)	16.1**(42)	9.0**(16)	23.5**(40)	11.2**(11)	12.1**(27)	23.4**(29)	19.4**(12)
20–30	–	–	15.5**(6)	4.1(20)	–	7.9*(18)	–	11.9**(15)	6.3*(12)	–
>30	–	–	–	−17.1**(15)	–	−18.9**(8)	–	–	−10.4(7)	–
Microaggregates										
0–10	10.7(6)	−31.2**(16)	−32.4**(21)	−38.9**(86)	−19.0**(27)	−41.1**(73)	−29.9**(26)	−18.6**(51)	−46.9**(59)	−41.5**(19)
10–20	–	−22.2**(8)	−22.0**(13)	−20.0**(36)	−27.1**(15)	−17.7**(32)	−19.3**(11)	−7.2**(24)	−27.1**(26)	−36.7**(9)
20–30	–	–	−15.5*(6)	2.5(17)	–	−4.9(16)	–	−9.4(12)	−6.4(12)	–
>30	–	–	–	8.6(10)	–	–	–	–	–	–

Note: Mean values are given with number of paired data points in parentheses. * and ** indicate significant difference at $p < 0.05$ and $p < 0.01$, respectively. Categories that have five or less than five pairs of data points were not included in the analysis and represented as '-'

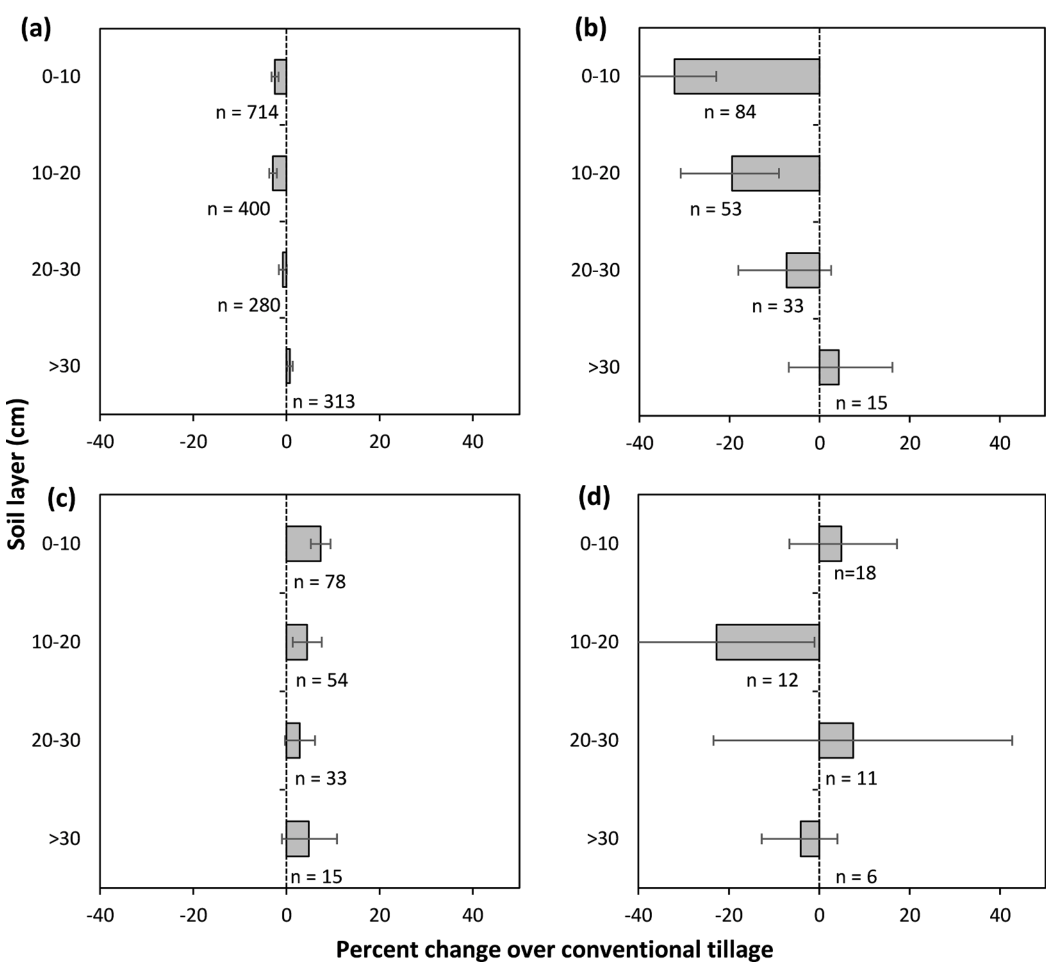

Fig. 3. Effect of no-tillage (% change over the conventional tillage practice) on (a) total porosity, (b) macroporosity, (c) microporosity and (d) aeration porosity in different soil layers; [Vertical dotted line is at no change, horizontal bars indicate upper and lower confidence intervals, and 'n' is the number of paired data points].

climate compared to greater but similar increases in dry and temperate climates (41.9–54.3%) (Table 1). The favourable effect of NT also sustained in 10–20 cm soil layer (16.1–30.7% increase). Soil texture had a prominent effect on MacA, and in 0–10 cm soil layer, medium-textured soil had a very high increase (54.8%) compared to near-similar changes in coarse- and fine-textured soils (9.3–18.7%). The trend was comparable in other soil layers and the increase was to the tune of 9.0–23.5%. In 0–10 cm layer, 10–20 yrs of duration resulted in an increase of 47.7% in MacA under NT followed by 38.5% and 31.6% changes in > 20 and < 10 years of duration, respectively. The effect drastically reduced in deeper layers and the range of increase was 12.1–23.4%.

In contrast to MacA, MicA content reduced under NT; the reduction was 34.2 and 20.1% compared to CT in 0–10 and 10–20 cm layers, respectively (Fig. 2d). Further down the profile, no effect of NT was visible. No differential effect of climate on MicA content was observed (Table 1). The effect of NT on MicA content in 0–10 cm layer was most conspicuous in medium-textured soils with a decrease of 41.1% followed by decreases in fine- (29.9%) and coarse- (19.0%) textured soils. In subsequent layers, there were 17.7–27.1% reductions. Duration of the experiment also had an impact on MicA content. It progressively decreased with increase in duration both in 0–10 and in 10–20 cm layers.

3.2. No-tillage effect on soil porosity

The adoption of no-tillage reduced the total porosity by 2.5–2.9% over conventional tillage up to a depth of 20 cm (Fig. 3a). The effect was absent in the 20–30 cm soil layer and beyond that, a subtle increase (0.7%) in TotP was noted. The tropical climate registered a greater change in 0–10 cm layer (5.9% decrease under NT) while in other climates, the reduction was 1.6–3.7% (Table 2). Near-similar changes were recorded in 10–20 cm layer, while tropical climate had a high 5.2% reduction in the 20–30 cm layer. However, continental climate had an increase (1.8%) in TotP under NT in deeper soil (>30 cm). Effect of soil texture was mostly limited to 10 cm depth where 2.3 and 4.5% reduction was noted for medium- and coarse-textured soils, respectively with no change in fine-textured soils. Only medium-textured soil registered a small ~ 1% decrease beyond 20 cm. The impact of NT in reducing TotP was visible with < 10 yrs period, but the trend appeared to reverse with the passage of time. The adoption of NT for > 20 years resulted in increase of TotP by 2.4% in 10–20 cm, and 2.3 and 2.1% in 20–30 and > 30 cm soil layers, respectively.

A shift to NT from CT resulted in reduction of macroporosity by 32.3 and 19.5% in 0–10 and 10–20 cm soil layers, respectively (Fig. 3b). Further down the profile, no changes in MacP were observed. The tropical climate caused a reduction in MacP by 75.4, 22.7 and 49.9% in 0–10, 10–20 and 20–30 cm soil layer, respectively (Table 2). In temperate climate, 25.6–37.8% decreases in MacP were observed up to 20 cm soil depth, while in dry and continental climates, there was either no change, or the data were insufficient for the analysis. The effect of soil texture was mostly limited to the surface layer and the largest 51.1% reduction was documented in coarse-textured followed by a 35.7% reduction in fine-textured, and no change in medium-textured soils. Thereafter, decrease in MacP in medium-textured soils in 10–20 cm (28.0%) and coarse-textured soils in 20–30 cm (13.5%), and no changes in other layers were recorded. Most of the changes in MacP happened within 10 years of duration. Thereafter, either the decrease was nonsignificant, or MacP increased with increasing duration.

In contrast to MacP, an increase (4.4–7.3%) in MicP was observed up to 20 cm of soil depth due to NT (Fig. 3c). Beyond 20 cm, no effect of tillage on MicP was observed. Tropical climate had the largest increase of 11.6% followed by 6.8% increase in temperate climate in 0–10 cm layer (Table 2). In other layers, increase was only realized in the temperate (6.7% in 10–20 cm) and in continental climate (5.3% in 20–30 cm). Irrespective of soil texture, NT always resulted in an increase in MicP content in the surface soil layer (6.5–8.7%). In subsequent layers (up to 30 cm), only medium-textured soils registered an increase (8.9–11.1%) in MicP content. The impact of duration on MicP content was limited to surface soil layer where a progressive change from 6.3% in < 10 yrs to 14.5% beyond 20 yrs of duration was noted in favour of NT. Change in aeration porosity was only recorded in 10–20 cm layer (22.7% decrease in NT); for other layers, no effects were noticed (Fig. 3d).

3.3. Impact of no-tillage on the bulk density and saturated hydraulic conductivity of soil

No significant effect of no-tillage was observed on bulk density throughout the soil profile and none of the categorical variables resulted in significant changes (Fig. 4a). However, the trend across depth is noteworthy. A comparatively greater increase in BD (1.9%; non-significant) was observed in 10–20 cm soil layer under NT while in rest of the layers, the changes were small: −0.1 to 0.3% (non-significant). In the surface layer, all the climates reported marginally increasing trends (1.6–6.2%) in BD except in temperate climate where a marginal decrease (1.6%) was apparent under NT (Table 3). Fine-textured soils were likely to cause a decrease (7.3%) in BD, while coarse- and medium-textured soils could increase it by 1.6–3.5%. The

Table 2
Effect of no-tillage (% change over conventional tillage) on total, macro- and microporosity as influenced by climate, soil texture and duration of the experiment over conventional tillage.

Soil layer (cm)	Climate				Texture			Duration (yrs)		
	Tropical	Dry	Continental	Temperate	Coarse	Medium	Fine	<10	10–20	>20
Total porosity										
0–10	−5.9**(52)	−3.7**(67)	−1.6*(267)	−2.3**(328)	−4.5**(139)	−2.3**(425)	−0.2(123)	−4.9**(149)	−3.2**(285)	2.4**(118)
10–20	−2.5*(27)	−2.6(34)	−3.0**(150)	−2.9**(189)	−1.5(79)	−3.5(232)	−1.5(68)	−4.3**(87)	−3.1(164)	0.6(58)
20–30	−5.2*(13)	−2.4(32)	0.8(95)	−1.1(140)	−0.3(61)	−1.2*(173)	−0.5(35)	−2.3**(52)	−1.3(117)	2.1*(48)
>30	−0.1(34)	−0.2(23)	1.8**(128)	0.2(20)	−1.0(29)	1.1**(192)	0.0(81)	0.6(49)	0.4(141)	2.3**(74)
Macroporosity										
0–10	−75.4**(21)	–	8.1(18)	−37.8**(42)	−35.7**(36)	−4.0(26)	−51.1**(19)	−39.4**(47)	−30.1**(28)	−15.0*(9)
10–20	−22.7**(11)	–	−17.7(14)	−25.6**(25)	−10.6(20)	−28.0*(15)	−1.6(12)	−40.3**(29)	−2.5(19)	–
20–30	−49.9**(8)	–	3.3(9)	0.7(13)	−13.5*(19)	−2.0(10)	–	−29.0**(18)	10.1*(11)	–
>30	–	–	–	0.4(9)	−3.0(7)	–	–	−1.0(6)	–	1.4(6)
Microporosity										
0–10	11.6**(21)	–	4.7(18)	6.8**(35)	6.5**(34)	7.8*(22)	8.7**(18)	6.3**(42)	6.9**(27)	14.5**(9)
10–20	1.8(11)	–	3.6(14)	6.7**(25)	1.3(20)	11.1*(16)	−0.2(11)	5.2*(31)	2.2(18)	–
20–30	7.0(8)	–	5.3*(9)	1.0(13)	0.7(19)	8.9*(10)	–	3.4(18)	−0.4(11)	–
>30	–	–	–	−0.9(9)	−1.3(7)	–	–	−0.1(6)	–	7.5(6)

Note: Mean values are given with number of paired data points in parentheses. * and ** indicate significant difference at $p < 0.05$ and $p < 0.01$, respectively. Categories that have five or less than five pairs of data points were not included in the analysis and represented as '-'

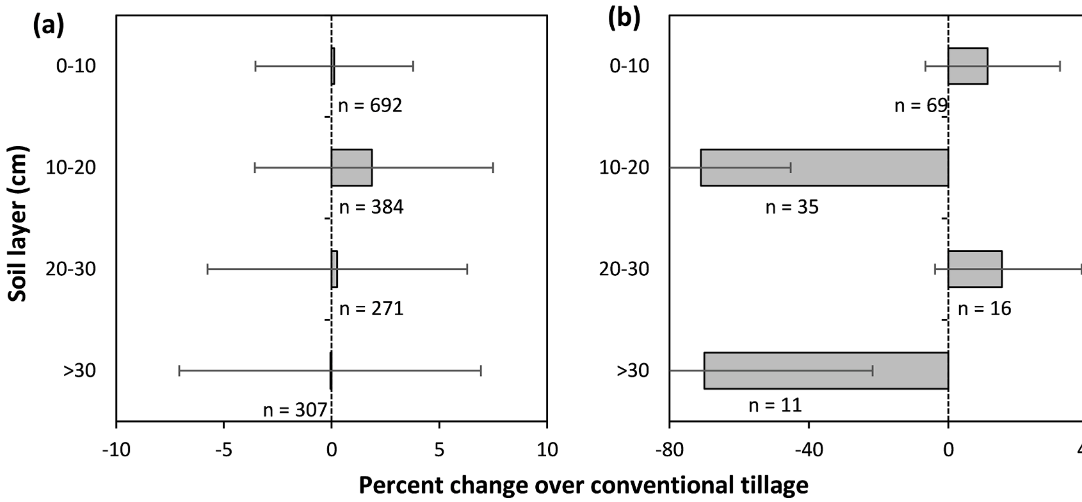

Fig. 4. Effect of no-tillage (% change over the conventional tillage practice) on (a) soil bulk density and (b) saturated hydraulic conductivity in different soil layers; [Vertical dotted line is located at 'no change', horizontal bars indicate upper and lower confidence intervals, and 'n' is the number of paired data points].

Table 3
Effect of climate, soil texture and duration of the experiment on soil bulk density and saturated hydraulic conductivity under no-tillage over conventional tillage (% change).

Soil layer (cm)	Climate				Texture			Duration (yrs)		
	Tropical	Dry	Continental	Temperate	Coarse	Medium	Fine	<10	10–20	>20
Bulk density										
0–10	6.2(50)	3.7(66)	1.6(254)	−1.6(322)	3.5(132)	1.6(412)	−7.3(121)	3.6(303)	3.1(274)	−5.9(115)
10–20	0.8(25)	2.5(33)	1.9(145)	1.8(181)	0.1(73)	2.6(222)	0.8(68)	1.9(172)	2.3(157)	0.8(55)
20–30	2.1(13)	2.3(31)	0.1(88)	−0.2(139)	−1.6(58)	1.3(165)	−0.2(37)	0.6(112)	0.2(113)	−0.3(46)
>30	−0.7(34)	0.4(23)	−0.8(124)	0.5(126)	2.1(29)	−0.4(188)	−0.1(79)	0.3(98)	−0.2(138)	−0.2(71)
Saturated hydraulic conductivity										
0–10	–	−27.1(8)	55.7**(18)	−7.1(41)	43.1**(16)	27.6*(43)	11.5(6)	−1.0(37)	21.3(22)	45.5(10)
10–20	−61.2**(7)	–	–	−100.2**(23)	−53.4**(11)	−23.8(13)	–	−57.3**(21)	−148.8(11)	–
20–30	–	–	–	5.0(11)	–	31.6*(9)	–	12.4(7)	−11.5(8)	–
>30	–	–	–	−70.8**(8)	–	−70.4**(9)	–	–	9.0(6)	–

Note: Mean values are given with number of paired data points in parentheses. * and ** indicate significant difference at $p < 0.05$ and $p < 0.01$, respectively. Categories that have five or less than five pairs of data points were not included in the analysis and represented as '-'

Table 4
Slope and significance of *meta*-regression of duration of the experiment, absolute latitude and clay content on soil parameters.

Soil layer (cm)	Duration		Latitude		Clay content		Soil layer (cm)	Duration		Latitude		Clay content	
	Slope	p-value	Slope	p-value	Slope	p-value		Slope	p-value	Slope	p-value	Slope	p-value
Mean weight diameter							**Total porosity**						
0–10	0.0069	<0.01	0.0004	0.90	0.0005	0.73	0–10	0.0022	<0.01	0.0004	0.36	0.0004	0.08
10–20	0.0042	0.25	0.0002	0.96	−0.0009	0.63	10–20	0.0018	<0.01	−0.0008	<0.05	0.0005	<0.05
20–30	0.0105	0.07	0.0077	0.24	−0.0037	0.40	20–30	0.0014	<0.01	−0.0005	0.29	0.0003	0.38
>30	0.0037	0.87	−0.0078	0.74	0.0043	0.78	>30	0.0011	<0.01	0.0002	0.57	0.0003	0.15
Water stable aggregates							**Macroporosity**						
0–10	0.0004	0.70	0.0034	<0.01	−0.0022	<0.01	0–10	0.0134	<0.01	0.0124	<0.01	−0.0015	0.58
10–20	0.0050	<0.01	0.0044	<0.01	−0.0002	0.75	10–20	0.0206	<0.01	0.0002	0.96	0.0043	0.13
20–30	0.0016	0.42	0.0044	0.05	−0.0011	0.47	20–30	0.0140	<0.01	0.0058	0.19	0.0011	0.72
>30	−0.0003	0.91	−0.0042	0.18	0.0001	0.93	>30	0.0015	0.73	0.0094	0.09	−0.0013	0.66
Macroaggregates							**Microporosity**						
0–10	0.0006	0.66	0.0171	<0.01	−0.0100	<0.01	0–10	0.0027	<0.05	−0.0021	<0.05	−0.0003	0.68
10–20	0.0014	0.27	0.0073	<0.01	−0.0028	<0.01	10–20	0.0025	0.11	0.0001	0.94	−0.0012	0.21
20–30	−0.0066	0.04	−0.0030	0.52	−0.0008	0.72	20–30	0.0036	<0.05	−0.0006	0.69	−0.0005	0.56
>30	0.0089	0.08	−0.0005	0.90	0.0028	0.12	>30	0.0024	0.19	0.0031	0.27	−0.0009	0.58
Microaggregates							**Aeration Porosity**						
0–10	−0.0045	<0.01	−0.0065	<0.01	0.0011	0.33	0–10	0.0286	<0.05	−0.0135	<0.01	0.0099	<0.05
10–20	−0.0078	<0.01	−0.0016	0.35	−0.0006	0.64	10–20	0.1112	<0.01	−0.0198	<0.05	−0.0019	0.87
20–30	0.0149	<0.01	0.0063	0.35	0.0033	0.17	20–30	0.0345	0.53	−0.0093	0.51	0.0294	0.13
>30	<0.0001	0.99	0.0183	0.06	−0.0029	0.42	>30	–	–	–	–	–	–
Bulk density							**Saturated hydraulic conductivity**						
0–10	−0.0034	0.06	0.0017	0.37	−0.0023	<0.05	0–10	0.015	0.08	0.0046	0.70	−0.0023	0.76
10–20	−0.004	0.89	0.0006	0.84	−0.0001	0.94	10–20	−0.0174	0.13	0.0078	0.50	0.0025	0.83
20–30	−0.0003	0.91	0.0009	0.81	<0.0001	0.99	20–30	0.0336	<0.05	0.0756	<0.01	−0.0161	0.20
>30	−0.0002	0.94	0.0006	0.87	−0.0003	0.91	>30	−0.0294	0.74	−0.0657	0.87	−0.0739	<0.05

initial increase in BD might diminish over the years, and a marginal decrease in BD could be recorded under long-term (>20 yrs) adoption.

The no-tillage adoption resulted in a significant decrease (~70%; $p < 0.01$) in saturated hydraulic conductivity in 10–20 and > 30 cm soil layers with no change in other layers (Fig. 4b). The effect of climate could not be clearly ascertained due to lack of data points, although an increase (55.7%) in SHC was noted in continental climate in 0–10 cm soil layer, and decreases (61.2–100.2%) in the next layer (10–20 cm) under tropical and temperate climates (Table 3). The SHC was favourably impacted by NT under coarse and medium soil texture in the upper layer (27.6 and 43.1% increase, respectively). In 10–20 cm layer, a large decrease in SHC was noted for coarse-textured soils. The effect of duration could not be obtained.

3.4. Meta-regression

Meta-regression of the duration of the experiment, absolute latitude and clay content on soil physical properties revealed that an increase in the duration under NT brought favourable changes in pore size distribution (TotP, MacP and AerP) even up to 30 cm soil depth (Table 4). However, the effect was less visible in case soil aggregation and changes were noted only in upper soil layers. The impact of the increase in absolute latitude was favourable for WSA, MacA and MacP, especially in the surface soil layer. In contrast, clay content had an adverse impact on soil aggregation and slopes of *meta*-regression were negative for WSA, MacA and BD. However, an increase in clay content increased the TotP and AerP in 10–20 and 0–10 cm soil layer, respectively.

4. Discussion

Water stability and MWD of aggregates have been extensively used to evaluate soil structural conditions, which are critical for soil water retention and movement, erosion and root growth. Both of these increased under NT to at least 30 cm soil depth. Amount of macroaggregates (≥250 μm) increased with an equivalent amount of decrease in microaggregates (<250 μm and ≥ 53 μm) except in 0–10 cm layer, where the former increased in higher proportions. It could be that NT favoured the formation of macroaggregates at expense of microaggregates. It had a compounding impact on MWD (dominant effect of macroaggregate size classes over microaggregates), but offset each other in WSA (macro-and microaggregates taken together). Thus, MWD recorded greater changes across the soil layers compared to WSA. Combination of no-tillage and residue retention favoured the formation of macroaggregates and their slow turnover. Macroaggregates are more transient than microaggregates and susceptible to degradation by tillage (Totsche et al., 2018). In the process of new macroaggregate formation, microaggregates get inside along with organic-binding agents, roots and hyphae (Six et al., 2000). Absence of inversion tillage had multiple effects. Firstly, aggregates were not physically broken by the abrasive action of tilling equipments (Sarker et al., 2018). Secondly, soil organic carbon holding particles together within the aggregates had limited exposure and loss by oxidation, and therefore increasing aggregate stability.

Majority of soil aggregation data belonged to temperate and continental climates in Köppen classification. The continental climate had the most favourable impact of NT on the MWD of soil aggregates, but it was limited to 20 cm depth. The effect of NT extended to deeper layers under the temperate climate possibly due to a slower rate of organic matter decomposition, thereby maintaining soil organic C (SOC) and facilitating aggregation (Six et al., 2002). However, change in WSA was realized to 30 cm depth with similar or higher changes in continental compared to the temperate climate. Other climates had agreeable impact of NT on MWD or WSA or both in 0–10 cm layer only. The WSA reduced in 10–20 cm layer under NT in the tropical climate. It could be that higher prevailing temperature and year-round rainfall accelerated microbial activity and organic matter oxidation, and consequently, there was either less aggregation or the effect of NT was short-lived. Residues protected the aggregates from slaking by rainwater, increasing their MWD. The effect was even less in sub-surface compared to CT where an inversion in CT might have facilitated C turnover and stability of aggregates. A faster rate of SOC turnover in tropical climate has been reported by Six et al. (2002). Moreover, NT favours the accumulation of residue on surface soil and has little or even negative contribution to the SOC in lower layers (Zhao et al., 2015; Mondal et al., 2020a). Lower crop biomass, limited soil water, lower SOC content and higher temperature might be responsible for limited impact of NT under the dry climate (Moret et al., 2006; Álvaro-Fuentes et al., 2008).

The effect of NT was best realized in the medium-textured soils with higher macro- and lower microaggregate contents, and an improvement in MWD and water stability of aggregates to a depth of 30 cm. Fine-textured soils contributed to a lesser extent, and the effect was limited to 20 cm. The increase in macroaggregates was either the same or in less proportion compared to the decrease in microaggregates content under NT in coarse-textured soils, resulting in no-change in MWD in either of soil layers, or even a decline in WSA in 10–20 cm layer. Medium-textured soils tend to strike a balance between soil water and air content, facilitating a better microbial activity for organic C turnover and soil aggregation, unlike the coarse- (lower water retention) and the fine- (poor aeration) textured soils. Increase in water stable aggregates was large in surface 0–10 cm layer, and to a less extent in 10–20 cm. Coarse-textured soils recorded a 19% increase in water stable aggregates in surface 0–10 cm layer, but a 7% decrease of the same in 10–20 cm layer compared to CT. No-tillage has a strong impact in the surface layer, but does not favour SOC built up in the subsurface (Luo et al., 2010; Mondal et al., 2020a). Thus, the small change in SOC in the subsurface in favour of NT might not have impacted the formation and stability of soil aggregates in coarse-textured soil, which is essentially poor in structure and less aggregated.

Impact of NT on soil aggregates was larger in 10–20 yrs period compared to initial 10 yrs, while continuing further with NT might not add much to this effect. Water stable aggregation appeared to attain an equilibrium, although MWD of aggregates increased with duration but with a decreasing rate. Soil aggregation is primarily related to the SOC content (Six et al., 2000), and the ample evidence that SOC reaches equilibrium (Caruso et al., 2018) indicates that the impact of NT on soil aggregation will reach the saturation. However, longer period would likely to make NT effect visible in deeper soil layers. As the fresh organic matter inputs in subsurface layers are limited, it could be that plant roots exudates (rhizodeposits) provide the required C for soil microbes and soil aggregation (Baumert et al., 2018) through increased root system under the NT (Mondal et al., 2020a).

The porosity and pore size distribution characterize voids in soil, which have critical roles in the movement and retention of water and air, and the residence of roots and soil biota (Nimmo, 2004). Small but significant reduction (2.5–2.9%) in total porosity, large decrease (19.5–32.3%) in macroporosity and moderate increase (4.4–7.3%) in microporosity were recorded under no-tillage in comparison to the conventional tillage up to 20 cm depth. A decrease in pore volume in 0–10 and 10–20 cm layers was indicative of soil compaction under the NT, although bulk density was marginally affected. Aeration porosity, synonymous to drainage (non-capillary) pores, decreased in 10–20 cm soil layer, resulting in a restricted movement of soil water (large reduction in saturated hydraulic conductivity) in this layer. Repeated pass of heavy machinery for agricultural operations might cause densification of upper soil layers in absence of tillage, where a part of macropores converted to micropores (Sasal et al., 2006). No-tillage improved the soil structure primarily in the surface layer (Mondal et al., 2020a; this study), which could endure changes in mechanical properties of the soil as related to its bulk density (Chaplain et al., 2011). Residue retention on the surface might have contributed in the reduction of machine-induced compaction in 0–10 cm, as evidenced by a relatively lesser change in bulk density in this layer compared to the change in

10–20 cm layer (Mondal et al., 2019). An increase in microporosity can facilitate higher water retention, which induces root growth and crop development, and reduce the adversity of marginally higher BD (Pastorelli et al., 2013).

The tropical climate had a stronger impact of NT on soil porosity, even in deeper layers. This is predominantly due to large reductions in macroporosity, while microporosity increased only in the surface 0–10 cm layer. Rainfall must be the primary influential factor, as changes were perceived only in surface layer in the dry climate. Warm and moist temperate climate also facilitated an increase in macropores and a decrease in micropores to a great extent. The apparent difference between the impact of no-tillage on soil aggregation (limited to surface layer) and that on soil porosity (extended down the profile) in tropical climate conditions could not be explained with our data. There are large uncertainties over the effect of no-tillage on changes in soil C across climates and soils (Ogle et al., 2019), or other contributing factors could not be ascertained.

The largest reduction in total porosity under NT was observed in coarse-textured followed by medium-textured soils. Although large changes in macro- and microporosity were evident in fine-textured soils, total porosity was not affected. Impact of medium textured soils was observed in lower soil depths, possibly due to near-similar proportion of coarse and fine soil separates.

Changes in porosity and pore size distribution during initial years of adoption (<10 yrs) of NT appeared to reverse with the increase in the duration. The extent of decrease in macroporosity reduced over time, and the increase in microporosity escalated, resulting in a lesser change (decrease) or an increase in total porosity. Continuing addition of crop residue over years might increase the SOC status of soil (Mondal et al., 2020b), which in turn offered greater stability to aggregates, and a continuous change in pore network in the longer run (VandenBygaart et al., 1999; Li et al., 2019).

Soil bulk density has been the most extensively studied and reported soil physical property. We have observed no change in soil BD in both the surface and subsurface layers under the NT practice. Blanco-Canqui and Ruis (2018) have reported no-tillage impact in reducing the susceptibility of soil to compaction through synthesis of published global data, while Li et al. (2019) concluded a 1.4% increase in soil BD in their global *meta*-analysis. The effect of NT in increasing soil BD was limited in temperate climate and fine-textured soils (Zuber et al., 2015), and also with longer duration of the NT practice (Mondal et al., 2020a). This study could not obtain effects of climate, soil or duration on changes in BD in either of the soil layers, but a transition from initial higher bulk density under NT to lower values compared to CT could be appraised. We also failed to obtain a relation between change in soil pores and saturated hydraulic conductivity, except in 0–10 cm layer. No-tillage effect on soil hydraulic conductivity was also inclusive in other studies (e.g., Blanco-Canqui and Ruis, 2018).

The duration of the experiment was the most dominant factor in modifying the NT effect on soil aggregation, and on the pore size distribution to a greater extent. Positive slope of the regression of duration with MWD and WSA indicated better soil structural changes with a longer period of NT practice. The effect of duration on pore size distribution was extended to deeper soil layers. Due to the absence of tillage, aggregates had a longer turnover time, and higher SOC content further induced stability under NT (Liu et al., 2014; Haddaway et al., 2017). Better aggregation facilitated good water (retention pores) - air (aeration pores) ratio in soils, and initial compactness could be avoided with a longer NT duration (Mondal et al., 2020a). This could be supported by the negative slope of BD (although non-significant). The positive slope of latitude with aggregation could be due to the lower annual temperature with increasing latitude, which stabilized SOC and reduced its losses. Negative relationship between clay content and water stable aggregates or macroaggregates contents can be ascribed to the slower decomposition of organic matter in soils with high clay contents (Balesdent et al., 2000; Liu et al., 2014).

Our analysis confirms significant positive effects of no-tillage on soil aggregation and pore characteristics. Although effects vary over climates and soil types, the surface 0–10 cm layer, which is also the most biologically active, receives the maximum benefits. High aggregate stability is related to improvements in soil fertility and crop productivity, which has strong economic implications, especially in alleviating poverty (Heger et al., 2020). As a component of conservation agriculture, no-tillage has been reported to bring major economic benefits (e.g., FAO, 2001; Cavalchini et al., 2013; Jat et al., 2020), although the soil structural changes have never been evaluated. Even if no-tillage is contemplated as an innovation to existing traditional practices (Marandola et al., 2019), its role in critical issues like soil structural improvement makes it a viable choice in most of intensive agricultural practice regions. A transition to no-tillage from conventional practice improves soil quality, and attempts to restore the soil as a natural capital, a loss of which cannot be replaced by manufactured capitals like mineral fertilizers (Knowler, 2004).

No-tillage has been claimed to be a potential option to mitigate climate change through C-sequestration in soils. However, evidences suggest large changes of soil C in the surface layers, but a little or no change in the sub-surface contributed to a mere limited scope of increasing the soil C stock in soil profile (e.g., Dimassi et al., 2014; Mondal et al., 2020a). However, no-tillage can bring substantial favourable changes in soil physical condition, which potentially lead to improve various soil functions and processes like water retention, nutrient mobility and biological activities (Powlson et al., 2014; Chakraborty et al., 2017; Blanco-Canqui and Ruis, 2018; Mondal et al., 2020a). Crop residues are difficult to manage, and can be put into recycle by adopting no-tillage practice. Synthesis of large global data in this study corroborates that no-tillage improved soil aggregation and porosity, two principal parameters of soil structural development, which have far-reaching implications including adaptation of agriculture to climate change (Powlson et al., 2014) and ensuring food security (Ogle et al., 2019)

5. Limitations of the study

Many a time, paired data points were insufficient to go for a detailed categorical analysis involving major explanatory factors. It was even fewer from lower soil depths. Reported soil depths were extremely variable, which were logically converted to depth intervals (layers) so as to include sufficiently large number of data points in each layer. Graphical data were extracted with the help of software and therefore, actual values could be slightly different.

6. Conclusions

Systematic *meta*-analysis of global studies confirmed no-tillage practice in contributing to soil structural development and increase in water retention pores even over a short-term period, although primarily in the surface 0–10 cm layer. Temperate climate and medium-textured soils appeared to be the most benefitted in the sub-surface layers by adopting no-tillage, however, large uncertainties prevailed. Improvement in soil quality leads to higher input use efficiencies, which add to the economics of the adoption of no-tillage practice. Agriculture can help in reaching a majority of sustainable development goals set by the United Nations, and no-tillage can best play a role. However, the best climatic conditions and soil types for realizing no-tillage impact need to be identified through a large number of experimentations across the globe.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2021.115443.

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