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Spatial variability of soil physical health indicators in Karnal and Kaithal districts of Haryana

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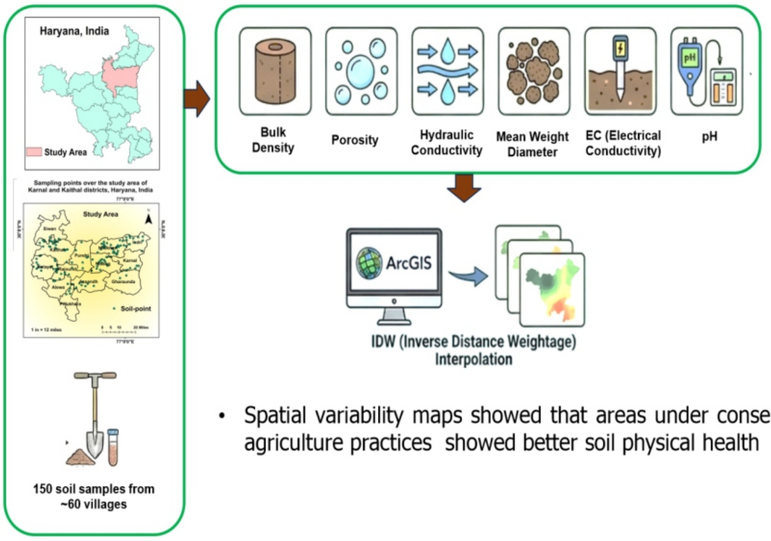
Abstract

Aim: Geospatial data is essential for delineating the geographical distribution of soil physical attributes across various agricultural systems.The study aimed to determine the spatial variability of different soil physical properties under conservation agriculture practice as well as conventional practices at district level.

Methodology: Different soil physical parameters, namely bulk density, porosity, Hydraulic conductivity, mean weight diameter, EC, and pH, were analysed in laboratory after collecting 150 samples from approximately. 60 villages of Karnal and Kaithal district. Spatial mapping was done through the inverse distance weightage (IDW) method in ArcGIS version 8.7.

Results: The spatial variability map of soil properties for the study area revealed that the eastern part of the study area, *i.e.,* Nilokheri blocks, and some parts of the Karnal district where conservation agriculture was followed had the highest value of soil properties, porosity, hydraulic conductivity, mean weight diameter and lower value of bulk density, electrical conductivity and pH. On the other hand, the areas where Conservation tillage was practised, *i.e.,* some parts of Assandh, Gharaunda, Alewa, and Kalayathad, had contrasting values.

Interpretation: Spatial variability mapping effectively identified areas with degraded soil physical properties under Conservation tillage and demonstrated the positive impact of conservation agriculture on soil physical health. These maps serve as a baseline for targeted soil management interventions and monitoring long-term changes in soil physical health across the study districts.



- Spatial variability maps showed that areas under conservation agriculture practices showed better soil physical health

Key words: Bulk density, Electrical conductivity, Hydraulic conductivity, Inverse distance weightage, Soil aggregate

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Introduction

Globally, declining soil health is a major challenge to increasing subsistence crop yields and a major cause of food insecurity (Lal, 2007). Therefore, adopting appropriate tillage and management techniques is crucial to preserving soil quality and environmental sustainability. While improper tillage can result in consequences such soil structure degradation, increased erosion, loss of soil organic matter (SOM) and fertility, and disturbance of the water, organic carbon, and nutrient cycles, effective tillage can alleviate soil restrictions (Lal, 1998). Seasons of continuous tillage have led to the development of subsurface pans and to the degradation of soil structure due to SOM loss (Sadiq *et al.,* 2024). To lessen these physical limitations of the soil, conservation agriculture has recently been suggested (Shafeeq *et al.,* 2020). To determine which conservation agriculture technique is best for a given area and cropping system, tests should be conducted on a variety of conservation agriculture techniques, including residue retention, zero tillage, shallow and reduced tillage, and permanent bed systems (Mandal *et al.,* 2025). Conservation agriculture is a method that simultaneously protects soil and water resources, maintains agricultural yields, and guarantees ecological stability (Jat *et al.,* 2019). Determining the spatial extent of soil physical attributes requires geospatial data and their subsequent integration with evaluation ranking, which facilitatesthe creation of simple, fluid maps (Burkhard, 2017).

According to Boyd and Banzaf (2007), a geographic information system is essential for both visual and numerical representation of service-providing units. Environmental evaluation frequently uses geospatial methods. These systems produce maps that are essential for evaluating spatial trade-offs among ecological services. To prioritise areas of concern for sustainable agriculture, this procedure is more than a mere technicality. To understand the soil's physical health status and the management techniques required to maximise crop yield, maps of spatial variability in soil salinity and sodicitymust be created. Spatial variability maps that effectively predict parameter values at unsampled locations can be created using various spatial methods, such as semivariograms, kriging, co-kriging, and regression kriging (Bhunia *et al.,* 2018). As a geostatistical method, kriging is generally considered more accurate than other models for evaluating the spatial variability of soil aggregate stability (Vogel *et al.,* 2010). Important factors can be detected using interpolated maps, whereas traditional approach of evaluating soil physical attributes require substantial financial, temporal, and other resources (Bhattacharya *et al.,* 2021). Accordingly, location-specific management can be implemented, thereby reducing errors and costs (Bhattacharya *et al.,* 2018; Nawar *et al.,* 2017). Given this context, a study was conducted to generate maps of spatial variability in Haryana's Karnal district and to identify regions with distinct soil physical characteristics under conservation agriculture and conservation tillage.

Materials and Methods

Study area: The administrative region of Karnal within Haryana state is geographically located at 29º25'05''N and 76º27'40''E, with a mean elevation of 240 m above sea level, and extends across 2,520 km² (Fig. 1). Adjacent to this, the Kaithal administrative region occupies the north-eastern sector of Haryana, spreading over 2,317 km^2. Kaithal's geographical boundaries extend from 29°31' to 30°12' northern latitude and from 76°10' to 76°42' eastern longitude. Monsoon systems originating from the south-west direction account for approximately 82.39% of annual precipitation, predominantly manifesting during the three-month period spanning July through September. Geologically, both districts are underlain by Indo-Gangetic alluvial deposits. Particle size distribution analysis reveals that sandy clay loam and clay loam represent the dominant textural categories. Taxonomically, these soils are classified within the Entisol order, specifically under the Fluvents suborder and the Ustifluvents Great Group.

Soil sampling and analysis: Soil samples were procured from agricultural fields in Karnal and Kaithal districts of Haryana during the post-harvest period of wheat cultivation across two consecutive cropping seasons (2021-22 and 2022-23). Sampling was conducted at 0-15 cm depth stratum (Fig. 1). The sampling framework encompassed 150 georeferenced locations distributed across thirteen administrative blocks: six from Karnal district (Karnal, Nilokheri, Nisang, Gharaunda, Assandh, and Indri) and seven from Kaithal district (Kaithal, Pundri, Kalayat, Siwan, Rajound, Alewa, and Pillukhera). Field investigations were conducted across agricultural landscapes and rural settlements in both districts, with particular emphasis on wheat cultivation zones under contrasting tillage regimes. The study specifically targeted fields practicing zero tillage with crop residue retention (ZT) and those employing conventional mechanical tillage without residue incorporation (Conservation tillage). The fields were visited regularly. The villages covered during sampling are listed in Table 1. During the visit, farmers were asked about their farming practices, yields, and other relevant questions.

Analysis of soil sample: The bulk density (ρb) of soil was calculated following the standard procedure of Blake and Hartge (1986). Total porosity (%) was calculated by the following equation (1):

$$\text{Total porosity } (p_t) = [1 - (BD/PD)] \times 100 \ldots\ldots\ldots\ldots(1)$$

Where, BD = Bulk density: PD = Particle density of soil (normally taken as 2.65 Mg m^{-3} formineral soils).

The collected soil samples were sieved and classified into large macroaggregates (aggregate size >2000 μm), small macroaggregates (250–2000 μm), and microaggregates (53–250 μm). The aggregate parameter, such as mean weight diameter (MWD), was calculated as follows (Kemper and Rosenau, 1986).

$$MWD = \sum_{i=1}^{n} W_i \times D_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

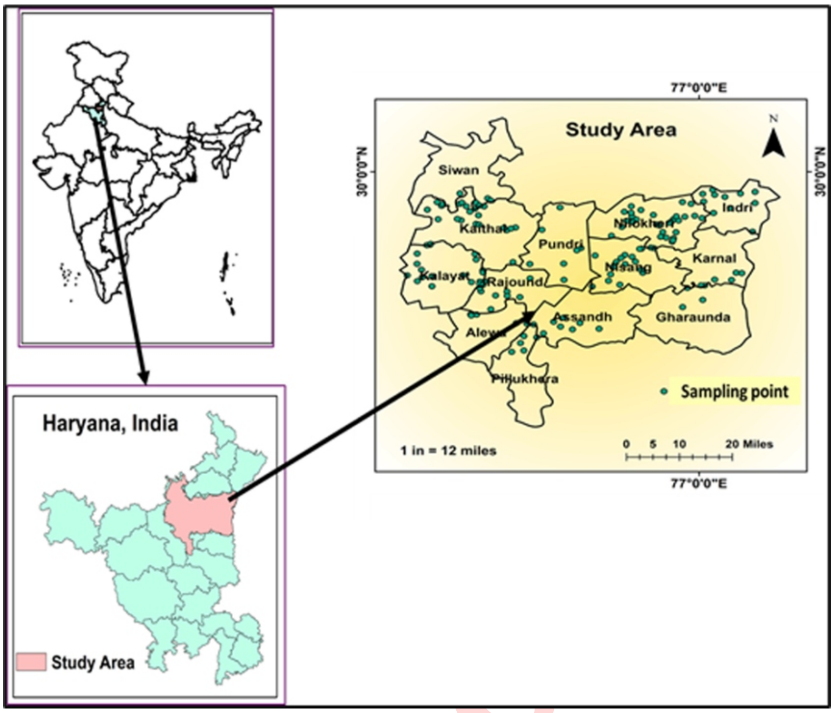

Fig. 1: Study site for farmers' fieldsin Karnal and Kaithal districts of Haryana, and location of sampling points.

Where, 'W_i' represents the proportion of aggregates retained over the sieves in relation to the whole sample, 'D_i'represents the mean diameter of aggregate class (mm).

Saturated hydraulic conductivity was measured by the constant-head permeameter method (Klute and Dirksen, 1986). A consistent head difference, h+L, was applied across the test. If the total volume and time required for water to pass through the cylindrical sample were known, the soil's saturated hydraulic conductivity (K_{sat}) could be determined using the equation. The test was replicated until a constant rate was obtained. With the help of Darcy's law and using the input of the above-mentioned parameters in this law, the saturated hydraulic conductivity was estimated (Eq. 3).

$$K_{sat} = \frac{V \times L}{A \times t \times (h+L)} \text{........................(3)}$$

Ks is the Saturated hydraulic conductivity (cm hr^{-1}); V is the Water volume (collected) (cm^3); L is the Soil column length (cm), A is the cross–sectional area of the core (cm^2), t is the Time interval (hr), h is the head of the water above the soil (cm). Walkley and Black (1934) method was used to estimate the soil organic carbon. The pH was determined using the soil water suspension method (Smith *et al* ., 1997). A pH meter was used to estimate the soil pH. A soil: water suspension (1:5) was used to estimate electrical conductivity (EC). The values were obtained with the conductivity meter. The data were analysed using descriptive statistics. All variables underwent data normalization prior to training phase. All variables underwent linear transformation, and both input and output variables were normalized within the range [0, 1] (Bhattacharya *et al.,* 2021). A spatial variability map of soil physical parameters and ecosystem service enhancement in the Karnal and Kaithal districts was produced using the inverse distance weighting (IDW) method in ArcGIS version 8.7. Inverse distance weighted (IDW) interpolation is predicated on the premise that proximity enhances similarity across entities. Inverse Distance Weighting (IDW) estimates a value for any unmeasured site by employing the measured values in its vicinity. The values closest to the prediction site have a greater impact on the estimated value than those farther away. Each measured point was deemed to possess a localized influence that decreases with distance. This technique assigns higher weights to point nearest to the prediction location, with the influence diminishing with increasing distance.

$$Zp = \frac{\sum_{i=1}^{n}\left(\frac{z_i}{d_i}\right)}{\sum_{i=1}^{n}\left(\frac{1}{d_i}\right)} \text{..................(4)}$$

Where, Zp is the estimated value z of an unsampled point as a function of the z-values of the nearest n points; di is the distance between the unsampled point and the measured point; n is the no. of nearest measured points used for interpolation

Results and Discussion

Understanding variability in soil health indicators is essential for site-specific soil management and for regional

Table 1: Name of the villages surveyed alongwith cropping history

District	Block Name	Village name	Cropping system	Method of cultivation	Average year of adopt
Karnal	Karnal, Nilokheri, Nisang, Gharaunda, Assandh, and Indri	Taraori, Nilokheri, Anjanthali, Pakhana, Brahman majra, Bir naraina, Khurana, Bahola, Sagga, Butana, Nissang, Laliani, Assandh, Gorgarh, Tatarpur, Singhra, Haibatpur, Pakhana, Daha, Chopri, Galb Kheri, Sohana, Bir Bhadson, Lalkhera, Mundh, Ranwar, Sitamadh, Singhra	Rice-Wheat	Zero Tillage with Residue	6-9 years
Kaithal	Kaithal, Pundri, Kalayat, Siwan, Rajound, Alewa, and Pillukhera	Khurana, Guhna, malakpur, kalayat, Pai, Santokh Majra, Kheri Lamba, Siwan, Kithana, Balu, Kathwar, Kasan, Karora, Dohar, Sitra, Rohera, Chandana, Deoban, nagal, kasana, Ladana Baba, Habri, Kwartan, Dhand, Dubal, Pati afgan.	Rice-Wheat	Zero Tillage with Residue	3-6 years

Table 2: Descriptive statistics of the studied soil parameters in the study area

Parameter	Min	Max	Mean	SD	Skewness	Kurtosis	CV (%)	SE	Variability
BD (Mg m^{-3})	1.34	1.77	1.49	0.09	0.389	-0.504	5.84	0.007	Low
Porosity (%)	33.21	49.43	43.85	3.28	-0.389	-0.504	7.48	0.268	Low
MWD (mm)	0.25	1.40	0.80	0.23	0.091	-0.413	29.20	0.019	Medium
HC (cm hr^{-1})	3.03	9.83	6.06	1.68	0.205	-0.568	27.69	0.137	Medium
pH	7.26	8.40	7.89	0.26	-0.279	-0.676	3.31	0.021	Low
EC (dS m^{-1})	0.34	0.86	0.59	0.11	0.208	-0.454	19.07	0.009	Medium

agricultural productivity. The descriptive statistical analysis of soil health indices across the research region revealed significant variability, indicating heterogeneity in soil properties under different management regimes (Table 2). This variability is caused by complex interactions among soil qualities, management approaches, environmental conditions, and the temporal dynamics of agricultural systems. To optimise regional agricultural productivity and establish site-specific soil management techniques, this diversity must be understood. Bulk density ranged from 1.34 to 1.77 Mg m^{-3}, with a mean of 1.49 and a CV of 5.84%, showing low variability. The low CV and minor positive skewness (0.389) indicate that most sampling locations had moderate bulk density values, but some had higher compaction levels. Bulk density affects root penetration, water infiltration, and aeration and indicates soil compaction (Bengough *et al.,* 2011). Soil porosity was 33.21% to 49.43% with a mean of 43.85% and CV of 7.48%, indicating modest variability. The mean porosity indicates that 44% of soil volume was pore space, which is essential for air and water flow, root growth, and microbial activity. The moderate porosity range represented the soil structural conditions across the research area, with higher values in conservation agriculture systems, where minimal disturbance and organic matter accumulation increased the pore space development (Bhattacharya *et al.,* 2021). MWD values ranged from 0.25 to 1.40 mm, with a mean of 0.80 mm and a CV of 29.20%, indicating medium variability compared to bulk density and porosity. This large fluctuation is relevant because MWD is an integrated measure of soil structural quality, biological activity, and organic matter dynamics (Liu *et al.,* 2024). Hydraulic conductivity ranged from 3.03 to 9.83 cm hr^{-1}, with a mean of 6.06 cm hr^{-1} and a medium variability of 27.69%. It varied substantially due to soil structure, pore-size distribution, and pore connectivity across the research area (Archer *et al.,* 2002). Soil pH ranged from 7.26 to 8.40 with a mean of 7.89 and a CV of 3.31%, indicating minimal variability and alkaline conditions. For electrical conductivity (EC), the range was 0.34 to 0.86 dS m^{-1}, with a mean of 0.59 and a CV of 19.07%, indicating substantial variability.

Spatial interpolation maps were generated employing the inverse distance weighting (IDW) method to illustrate and examine the regional variability of diverse soil physical properties in the Karnal and Kaithal regions (Fig. 2-4). The IDW method, a deterministic spatial interpolation technique, estimates values at unsampled locations by weighting measured values inversely according to their distance from the prediction point, rendering it especially appropriate for soil property mapping, where proximal locations are anticipated to exhibit greater similarity than those further away (Li and Heap, 2014). The resulting maps provide a comprehensive depiction of spatial distribution patterns, enabling the identification of regions with differing soil physical characteristics and supporting targeted management strategies. The bulk density map (Fig. 2a) showed distinct spatial patterns with values ranging from 1.34 to 1.77 Mg m^{-3}. The eastern region of the study area, particularly the Nilokheri blocks and certain portions of Karnal district, had the lowest bulk density (1.34-1.45 Mg m^{-3}), indicating well-structured soil with moderate compaction. These were long-term CA adoption zones with 6-9 years of zero-tillage, continuous crop residue retention, and diversified crop rotations. These zones have low bulk density due to reduced mechanical disturbance, increased accumulation of organic matter, and increased biological activity, particularly earthworm populations that create extensive burrow networks (Capowiez *et al.,* 2009). Conversely, regions under Conservation tillage management, such as Assandh, Gharaunda, Alewa, and Kalayat blocks, had higher bulk density (1.60-1.77 Mg m^{-3}), limiting root growth and water transport. CT zones have higher bulk density because repeated tillage operations destroy soil aggregates and create fine particles that pack tightly; heavy machinery traffic compacts the subsurface, especially in the plow pan zone at 15-30 cm depth; crop residue removal or burning eliminates organic binding agents; and reduced biological activity limits natural soil loosening (Bhattacharya *et al.,* 2021).

The porosity map (Fig. 2b) showed inverse spatial patterns relative to bulk density, as expected given their mathematical relationship. The highest porosity was in CA-managed regions (45-49%) and the lowest in CT zones (33-38%). CA systems have higher porosity, which improves water retention across all pore-size classes, aeration, infiltration, aerobic microbial processes, root respiration, and soil-organism habitat. conservation agriculture systems increase macro-porosity for water transport and root exploration, and microporosity for plant water retention during dry periods (Zhang *et al.,* 2022). Conservation tillage methods markedly influence soil physical characteristics, with studies indicating that conservation agriculture systems often decrease bulk density by 3-8% and concurrently improve porosity compared with conventional tillage systems (Sadiq *et al.,* 2024). The mechanisms driving these enhancements are complex: ongoing retention of crop residues increase the soil organic matter, serving as a binding agent that decreases soil density; zero-tillage maintains existing soil structure and facilitates natural pedogenic processes that establish stable pore networks; diverse crop rotations featuring deep-rooted species generate channels that endure post-root decomposition; and heightened biological activity, especially from earthworms and other soil organisms, fosters continuous macropores through bioturbation (Zhang *et al.,* 2021). The enduring nature of these advantages underscores the necessity of persistent conservation agriculture adoption, as complete realization of soil physical enhancements generally necessitates 5-10 years of continuous application.

The regional distribution maps of mean weight diameter (MWD) and saturated hydraulic conductivity (HC), produced via IDW interpolation, demonstrated significant spatial heterogeneity in soil structural stability and water transmission characteristics throughout the research area (Fig. 3). These indices are essential markers of soil quality, with MWD indicating aggregate stability and resistance to structural degradation, while HC measures the soil's ability to transfer water under saturated conditions. The regional patterns of these properties offer significant insights into the functional implications of various tillage management strategies on soil hydraulic behaviour and structural resilience. The mean weight diameter across the study area ranged from 0.25 to 1.38 mm (Fig. 3a), indicating more than a fivefold variation and highlighting significant disparities in soil structural quality.

The maximum MWD values (1.0-1.38 mm) were found in Nilokheri blocks and sections of Karnal district under CA management, signifying the existence of substantial, stable macroaggregates (>0.25 mm) that withstand disintegration during wet-sieving. Stable aggregates are formed through a hierarchical process in which primary particles adhere to create microaggregates (<0.25 mm), which then coalesce into macroaggregates via organic binding agents such as fungal hyphae, plant roots, microbial polysaccharides, and particulate organic matter (Adak *et al.,* 2023). The formation of persistent macroaggregates in conservation agriculture systems indicate a consistent supply of new organic residues, a lack of physical disturbance from ploughing, and improved fungal-to-bacterial ratios that facilitate aggregate-binding processes. Conversely, regions subjected to conventional tillage displayed significantly reduced MWD values (0.25-0.50 mm), signifying a predominance of microaggregates and unstable structural units.

Tillage mechanically fractures macroaggregates via shearing pressures, dismantles fungal networks that adhere soil particles, hastens organic matter decomposition by exposing sequestered carbon to microbial degradation, and establishes conditions that favour bacterial over fungal communitie. Weidhuner *et al.* (2021) showed that no-till systems sustain markedly higher proportions of large aggregates and greater aggregate stability than conventional tillage, with these disparities becoming more pronounced as duration of management practice increases. The spatial patterns identified in the present investigation validate these findings, revealing major differences between long-term CA and CT zones regarding aggregate size distribution and stability. Hydraulic conductivity exhibited spatial patterns like MWD, ranging from 3.05 to 9.74 cm hr^{-1} (Fig. 3b). The highest HC values were recorded in the Nilokheri and Karnal districts, where MWD was also highest, indicating a robust functional correlation between aggregate stability and water transmission capacity. The augmented hydraulic conductivity in conservation agriculture zones arise from multiple interrelated mechanisms: well-aggregated soil forms continuous macropore networks that act as preferential flow pathways; zero-tillage maintains existing biopores established by roots and soil fauna; earthworm burrows generate vertical channels extending to significant depths; and a stable soil structure inhibits pore collapse during wetting-drying cycles (Schlüter *et al.,* 2020). The triadic variation in hydraulic conductivity (HC) across the research area significantly affects water management: high-HC soils promote rapid infiltration, thereby reducing runoff and erosion and replenishing

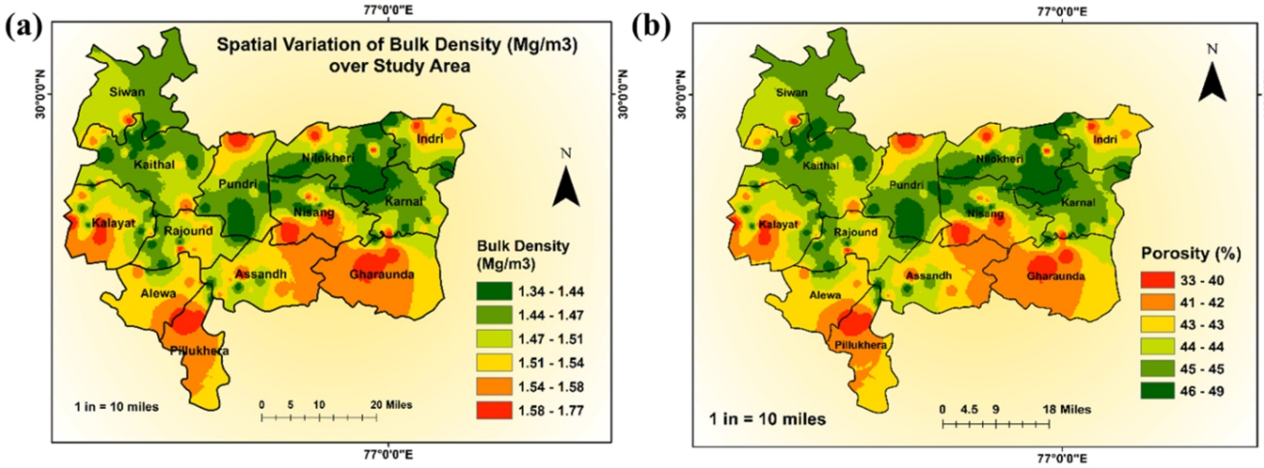

Fig. 2: Spatial variability map of soil bulk density (a) and porosity (b) in Karnal and Kaithal.

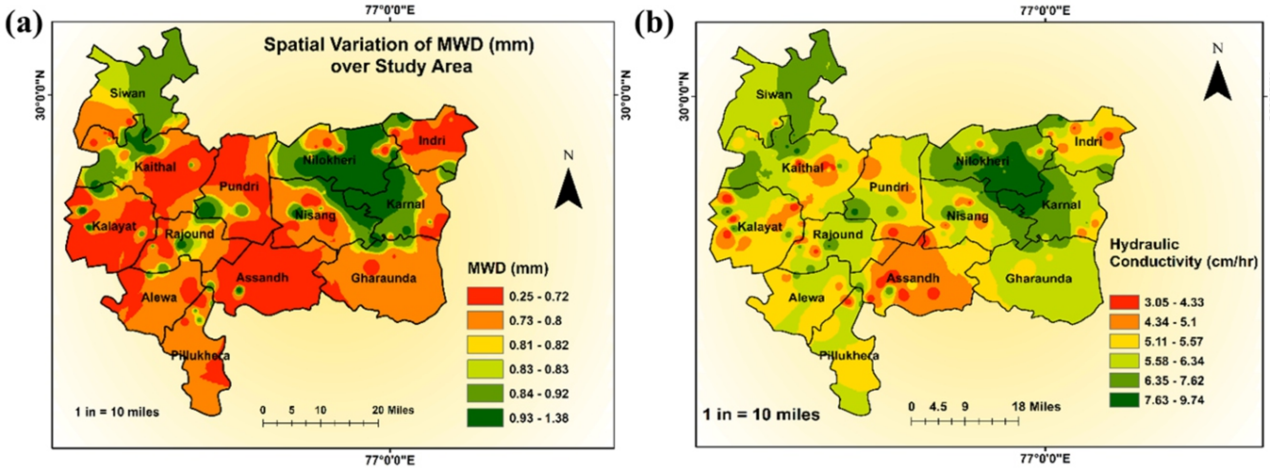

Fig. 3: Spatial variability map of mean weight diameter (a) and hydraulic conductivity (b) in Karnal and Kaithal districts.

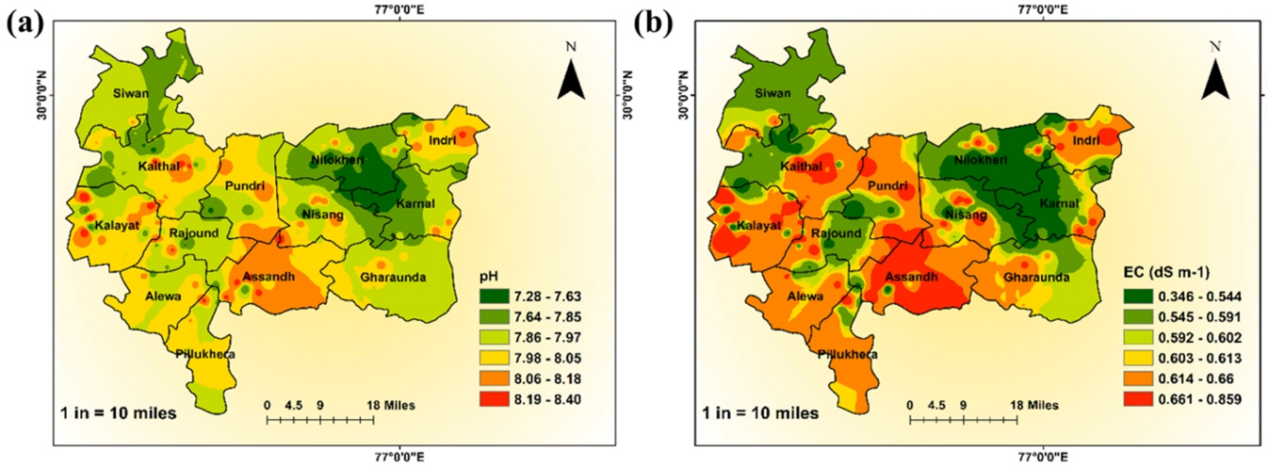

Fig. 4: Spatial variability map of soil pH (a) and EC (b) in Karnal and Kaithal districts.

groundwater, whereas low-HC soils increase flooding risk and restrict plant water availability. Conventional tillage areas in Assandh, Gharaunda, Alewa, and Kalayat demonstrated reduced HC values (3.0-5.0 cm hr^{-1}), indicative of compromised pore networks and diminished structural integrity. Repeated tillage destroys continuous macropores, resulting in a fragmented pore system with insufficient connections that impede water movement. The development of plough pans due to compaction inhibits vertical water circulation, resulting in perched water tables and anaerobic conditions. Furthermore, the obliteration of earthworm burrows eliminate crucial conduits for rapid water transport (Blanco-Canqui and Ruis, 2018).

Interpolated spatial distribution maps of soil pH and electrical conductivity (EC) in the Karnal and Kaithal districts (Fig. 4) revealed regional patterns in soil chemical characteristics and their correlations with management approaches. These chemical indicators are essential for evaluating soil fertility, predicting nutrient availability, and assessing crop production potential. The soil pH in the study region ranged from 7.28 to 8.40 (Fig. 4a). The range includes neutral to moderately alkaline conditions typical of alluvial soils in semi-arid and sub-humid areas with calcareous parent materials. The spatial distribution indicates that regions employing conservation agriculture management, specifically the Nilokheri block, sections of the Karnal and Nissang blocks in Karnal district, and the Siwan and Rajound blocks in Kaithal district, demonstrated markedly lower pH values (7.28-7.70) in contrast to conventionally managed areas. The pH moderation in CA systems arises from various interrelated processes: ongoing decomposition of residues generates organic acids such as humic, fulvic, and other low-molecular-weight organic acids that facilitate acidification; heightened microbial respiration produces CO_2, which dissolves in soil water to form carbonic acid; augmented biological nitrogen fixation and nitrification processes release H+ ions; and enhanced organic matter content improves buffering capacity (Nunes *et al.,* 2024). The slightly lower pH in conservation agriculture zones, although still within the neutral-to-moderately alkaline range ideal for most crops, confers numerous agronomic benefits. The enhanced availability of micronutrients under conservation agriculture may reduce fertiliser requirements and improve crop nutritional quality. The moderate pH range supports diverse and active microbial communities that facilitate key soil processes, including organic matter decomposition, nutrient cycling, nitrogen fixation, and disease suppression (Bhattacharyya *et al.,* 2022).

Electrical conductivity in the research region varied from 0.34 to 0.85 dS m^{-1} (Fig. 4b), signifying non-saline conditions in most places (EC <2.0 dS m^{-1} is classified as non-saline). The spatial variability in EC indicates significant patterns associated with management and site characteristics. Regions managed under Conservation Agriculture consistently show reduced electrical conductivity values (0.34-0.55 dS m^{-1}) in comparison to conventionally tilled areas. The reduction in electrical conductivity under conservation agriculture systems is due to enhanced soil structure that promotes drainage and leaching of soluble salts, improved water infiltration that hinders salt accumulation in surface layers, increased organic matter that buffers against salinity stress, and better pore connectivity that facilitates more efficient salt removal during monsoon leaching events (Husson *et al.,* 2018). Husson *et al.* (2018) showed that conservation agriculture systems regulate electrical conductivity, reducing EC when initially high and enhancing it when low, particularly in surface horizons. The buffering action establishes more stable soil chemical conditions conducive to crop growth. The method entails enhanced soil structure under conservation agriculture, facilitating water movement and salt leaching in high electrical conductivity soils, whereas in low electrical conductivity soils, organic matter mineralisation liberates nutrients that marginally elevate electrical conductivity to ideal values. The self-regulating nature of CA systems enhances their resilience and durability across diverse soil conditions. Conventional tillage areas demonstrated increased pH values (7.90-8.40) and elevated EC levels (0.60-0.85 dS m^{-1}), indicating soil chemical deterioration linked to intensive farming practices. The elevated electrical conductivity in CT zones signifies the accumulation of soluble salts resulting from a compromised soil structure that restricts drainage and leaching, the development of compacted layers that obstruct vertical water movement, diminished infiltration that amplifies surface evaporation and salt concentration, and inadequate water management that intensifies salinity problems. These chemical restrictions diminish crop productivity by inducing osmotic stress, causing particular ion toxicity, and hindering nutrient availability.

The identified spatial patterns align with prior studies conducted in the area. In the Kaithal district, Barman *et al.* (2021)also found that conservation agriculture-managed fields had lower pH and electrical conductivity than conventional fields. Sarkar *et al.* (2022) found considerable regional variation in electrical conductivity in the Karnal district, attributable to irrigation water quality, drainage, and management. The high coefficient of variation for EC (19.07%) in the study demonstrates regional variability attributable to localised factors, including irrigation management, groundwater quality, topographic position affecting drainage, and variations in soil texture.

The findings demonstrate that conservation agriculture system exhibits enhanced soil physical health indicators relative to conventional tillage systems, which showed lower bulk density, pH, and electrical conductivity. This study demonstrates the efficacy of IDW interpolation for mapping spatial variability to identify regions with degraded soil quality and to evaluate the district-level advantages of adopting conservation agriculture. The geographical maps establish a new foundational framework for implementing precision soil management methods and tracking long-term improvements in soil health across the Karnal and Kaithal regions.

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