



## SOIL AND CLIMATE IN INDIAN CLIMATIC ZONES: A SPATIAL DATABASE FOR INFORMED DECISION MAKING IN AGRICULTURE AND FORESTRY

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**Abstract:** Geographical diversity of soil and climate regulates the suitability of a landscape as a niche for each specific plant species, depending on their requirements for optimum growth and tolerance limits to soil and climate conditions. Geographical refinement of management planning for sustainable agriculture, forestry or controlling infestation of invasive plant species e.g. through identifying edapho-climatic zones (ECZ), can be performed if such parameters are accounted for and compared with the available conditions, additionally supporting climate resilience. In this study, five climatologically homogeneous regions (CHR) of India, *namely* Central Northeast Region (CNE), Northeast Regions (NE), Northwest Region (NW), Peninsular Region (PEN) and West Central Region (WC), with known potential climatic scenarios for 2020s, 2050s and 2080s, are taken into consideration. Through linking benchmark soil properties for FAO/UNESCO soil classes and grouping them in generalised classes based on homogeneity indicator properties, 78 ECZs of India under the five CHR are identified with specific sets ECZs under each CHR 18 under CNE, 22 under NE, 22 under NW, 17 under PEN and 18 under WC. The database would support choosing ideal plant species/cultivar for sustainable agriculture, forestry or horticulture for informed decision making based on availability of ideal niche conditions.

**Keywords:** Climate change, Edaphoclimatic zones, Rain fall, Soil geography, Sustainable land use.

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### INTRODUCTION

Soil supplies 14 essential nutrients and water, required to maintain photosynthesis, nutrient uptake, metabolism and cytosolic activity for plants (White and Brown, 2010; Elbasiouny *et al.*, 2022). The availability of nutrients in soils is more or less inherent for each soil and can be modified by application of organic and inorganic fertilisers. Whereas nutrient uptake and other physiological processes in plants

depend on soil moisture content, nutrient retention, root penetration and soil aeration, driven by soil's pH, bulk density (BD), texture, porosity (PRS), drainage and organic matter content (SOM). These factors shape a landscape's suitability for specific plant species (Brady and Weil, 2004). Climatic factors also influence plant growth, nutrition and overall sustainable development (Kurina *et al.*, 2018; Leon Duran *et al.*, 2018; Verma, 2021). While increased



temperature can increase nutrient supply in soil by increasing SOM decomposition, it can limit nutrient uptake due to reduced soil moisture. Soil moisture drives the mobility of the nutrients and influences its uptake (Elbasiouny *et al.*, 2022).

Waterlogged or flooded soils can have reduced nutrient and water uptake by plants, due to reduced root growth under anaerobic conditions (Manghwar *et al.*, 2024). Increased rainfall can increase loss of soil nutrients by increased leaching and runoff (Wang *et al.*, 2024). Besides, climate can also directly regulate the survival of species. Very low temperature can cause stress in plants, leading to reduced growth, e.g. heaving, smothering, physiological drought and freezing of the plant tissues, while extreme high temperature can negatively impact enzymatic activity and membrane disruption. Stress generated by inadequate water supply can impede leaf area, cell size, cell division intercellular volume, plant size, photosynthesis and reproductive growth (Gusta and Chen, 1987). Waterlogging or submergence of plants causes stress from hypoxia that negatively impacts its metabolic and physiological processes (Phukan *et al.*, 2015).

A rich diversity of soil and climate is observed across India. Plants' adaptation and capacity of survival are dependent availability and uptake of nutrient and water from soil- that is ultimately the outcome of interaction of water holding capacity of soil and climatic factors like precipitation and rainfall, other than the fertility of soil itself (Niu *et al.*, 2014). Thus, classifications of landscapes in terms of homogeneity, soil and climate to inform policy refinement for sustainable land use for agriculture, forestry etc. and climate preparedness becomes important (Gusta and Chen, 1987; Kurina *et al.*, 2018; Leon Duran *et al.*, 2018).

Indian climatic diversity has been grouped into climatologically homogeneous regions by Patwardhan *et al.* (2016) with identifying potential changes in average daily maximum and minimum temperature and monsoon rainfall, for 2020s (year 2011 to 2044), 2050s (year 2041 to 2070) and 2080s (year 2071 to 2098) from the baseline of 1961-1990 through climate modelling approach. Mahto and Mishra (2020) identified the susceptibility of these regions to monsoon drought from the database of 1951 to 2018. Whereas major types of soils in India, as per traditional classification, are Alluvial (30.4 %), Coastal Alluvial (3.1 %), Red (26.8 %), Laterites (5.5 %), Brown Forest (0.2 %), Hill (0.7 %), Terai (0.1 %), Mountain meadows (0.0002 %), Sub-montane, Black (16.6 %) and Desert (8.0 %), as well as a total of 8.6 % of other type soils

(Bhattacharyya *et al.*, 2013). With the help of collection of representative soil data (Kumar *et al.*, 2020), attempts have been made to identify soil diversity within agroecological zones, connecting the soils to the FAO/UNESCO nomenclature.

However, at national scale, there is a gap in availability of databases that combine soil and climate information into classes of landscapes that can help to determine ideal plant species / cultivars for optimum productivity and sustainably in forestry, agriculture and horticulture. Also, associated gap remains to be addressed on such classification of landscapes that accounts for projected future climatic conditions, required to refine management plans for climate preparedness (Conradi *et al.*, 2024). This research aims to bridge these gaps and support informing for decision making on sustainable land use planning in India.

The objective is to create a nationally applicable database to support the research and policy refinement by identifying suitability of landscape for species-specific or cultivar-specific plant biomass management in terms of soil and climatic conditions (Kurina *et al.*, 2018; Leon Duran *et al.*, 2018). In this research classification of soils under five major climatologically homogeneous regions (CHR) based on indicators of soil health and behaviour was performed and was grouped based on homogeneity into 32 generalised classes. The generalised classification was performed to support easier interpretation of the database for end users associated with policy making and implementation. This exploration ultimately explained a total of 78 edaphoclimatic zones (ECZ) of Indian landscape under 5 CHRs (Patwardhan *et al.*, 2016), accounting for spatial variation of both soil and climate and temporal variation of climate.

## MATERIALS AND METHODS

As development of this database is to support creating spatial zoning of Indian landscape into edaphoclimatic zones for sustainable land use in agriculture and forestry, one of the aims was to use a climatic information resource that classifies landscape of India into CHRs, along with informing on potential climate change scenario to support for climate preparedness also (Conradi *et al.*, 2024). The aim of this research is to integrate the global common soil database that represents the World Soil Reference (IUSS Working Group WRB, 2022), so that the derivatives of this work can provide a replicable global framework.

### 1. Climate data

Considering the challenges with data availability, authors found the map of CHRs of India, based on

rainfall homogeneity from Parthasarathy *et al.* (1995) and the corresponding data from Patwardhan *et al.* (2016) to ideally fitting with the objective of this study. They classified Indian landscape, excluding the group of islands at Andaman and Nicobar and at Lakshadweep, into 6 climatologically homogeneous regions (CHR) *namely* Hilly region, Northwest Region (NW), Central Northeast Region (CNE), Northeast Regions (NE), West Central Region (WC) and Peninsular Region (PNR). Except for the Hilly Region, they estimated climate (maximum and minimum air temperature and monsoon rainfall using 1961 to 1990 as baseline scenario in PRECIS model) for 2020s (year 2011 to 2044), 2050s (year 2041 to 2070) and 2080s (year 2071 to 2098) (Table 1). However, there are several other factors that regulate plants growth, e.g. humidity, solar radiation, wind speed etc. (Bang *et al.*, 2010; Kläring and Krumbein, 2013; Chia and Lim, 2022), that were not considered in this study due to a lack of availability of data specific to these CHRs.

## 2. Soil data

For referencing the soils under the 5 targeted CHRs to a global soil database, authors chose to use the shapefile of global soil map developed by Vargas (2022) based on FAO/UNESCO Soil Map of the World at 1:5000000 scale, from which the distribution of soils in India was extracted using a relevant outline shapefile. Representative benchmark properties of soil classes were available in the existing literature (Batjes, 1997), that contain information on median soil pH, median cation exchange capacity in cmolc/kg (CEC), median soil organic carbon percentage (OC %), median bulk density in g/cm<sup>3</sup> (BD), median total porosity percentage (P %), average water holding capacity to a depth of 100cm for range 33 to 1500 kPa (AWC).

## 3. Identifying soils in five CHRs in India

From Patwardhan *et al.* (2016), authors geo-referenced and digitised the 5 CHRs, *namely* NW, CNE, NE, WC, PNR, and the Hilly Region, using QGIS 3.40 Bratislava (QGIS), using an outline shapefile of India, into a new shapefile - available as SHP1 in Bhowmik and Ray (2025). The FAO/UNESCO soil for India (Bhowmik and Ray, 2025) was extracted from Vargas (2022) for India in which only the ID for dominant unit of soil according to FAO/UNESCO (DOMSOIL) was kept as attribute. Authors intersected shapefile of SHP1 with that of SHP 2 and extracted the area that comes only under the 5 CHRs and do not include the Hilly regions (Himalaya) and the marine islands of India at Andaman & Nicobar and at Lakshadweep (Bhowmik and Ray, 2025) with attributes indicating the CHR and DOMSOIL for each polygon. The inland water bodies are removed from the map. The reference physicochemical properties of the dominant soil types present in India, available in Batjes (1997), the median

topsoil's properties and drainage category for each DOMSOIL were used to group the soils in the 5 targeted CHRs of India for a more generalised classification. The modified classification was based on pH, soil organic carbon (SOC) (Li *et al.* 2016), cation exchange capacity (CEC) (Liu *et al.*, 2013), porosity (PRS) (FAO, 2006) and drainage (Batjes, 1997). Modified classes were assigned with class numbers as shown in Table 4 (Bhowmik and Ray, 2025) and the soils of same generalised classes were dissolved. Also, individual shapefiles for each of the 5 CHRs were extracted from SHP 3 and SHP 4 (Bhowmik and Ray, 2025.) However, a separate shapefile is also created from CHR SHP Series 3, where the classification of soil types is available, but the assigned class number is removed to show the general properties of the soils in the CHRs of India (Bhowmik and Ray, 2025).

## RESULTS AND DISCUSSION

### 1. Climate in CHRs and relevance for plant biomass

The climate of baseline period 1961-1990, and in 2020s, 2050s and 2080s, from Patwardhan *et al.* (2016), is shown in Table 1. For CNE, NE and WC a continuous increase in monsoon rainfall is expected from 2020s to 2050s and from 2050s to 2080s. During this timeline stress for plants from water deficiency may reduce while increase potential of stress from waterlogging and submergence can also be expected in CNE, NE, WC (Gusta and Chen, 2015; Phukan *et al.*, 2015). For NW and PEN, rainfall may reduce in 2050s from 2020s that may increase stress from water deficiency in plants which may potentially reduce along with increasing stress from waterlogging and submergence in 2080s with increased rainfall. However, intensity of such stresses in plants can further vary spatially and temporally based on water retention and drainage capacity-driven by soil physicochemical properties—at a local scale (Saco *et al.*, 2021). As NW and PEN zones are expected to see a reduced monsoon rainfall in the 2050s from the current scenario of 2020s, potential susceptibility to monsoon droughts may also increase. Similarly in 2080s, as monsoon rainfall expected to be higher than 2050s at NW and PEN, the corresponding decrease in occurrence or intensity of monsoon drought may also occur. However, alternatively an estimated increase in rainfall can also be an indicator of potential susceptibility to flooding for CNE, NE and WC throughout 2020s, 2050s and 2080s, while for NW and PEN it may decrease in 2050s from 2020s and increase in 2080s again (Kumar *et al.*, 2010) that can lead to stress in plants from excess, that may vary depending on growth stage and tolerance limits, soil moisture leading to increased anaerobic conditions and accumulation of carbon dioxide and ethylene (Phukan *et al.*, 2015; Tian *et al.*, 2021).

The average maximum and minimum daily temperature in each region are projected in Patwardhan *et al.* (2016) to increase throughout 2020s, 2050s and 2080s, in line with the global climate change scenario (Conradi *et al.*, 2024). Thus, across the 5CHRs, stress due to warming can potentially leading to impede vegetative and reproductive growth throughout this timeline (Gusta and Chen, 2015). More than optimum temperature can reduce photosynthesis and carbon assimilation that can damage above-ground biomass through scorching,

abscission and senescence (Bita and Gerats, 2013; Balfagón *et al.*, 2020). However, tolerance of plants to heat induced stresses varies at interspecific and intra specific level (Duan *et al.*, 2014; Otálora *et al.*, 2022). Evaporation and drying of soil moisture driven by higher temperatures is a contributing factor to drought besides reduced rainfall (Dai, 2012) which otherwise may reduce impact of excess soil moisture on plants whereas heat stress can aggravate negative effects of drought stress in plants growth (Cohen *et al.*, 2020).

**Table 1: Baseline Climate and Climate of 2020s, 2050s and 2080s of five major CHRs (NE, CNE, NW, PEN, WC) in India (Patwardhan *et al.*, 2016).**

| Time Period             | CHR | Rainfall (mm) | Maximum Daily Temperature (°C) | Minimum Daily Temperature (°C) |
|-------------------------|-----|---------------|--------------------------------|--------------------------------|
| 1961-1990<br>(Baseline) | NW  | 410.7         | 38.4                           | 8.1                            |
|                         | CNE | 889.2         | 39.4                           | 9.3                            |
|                         | NE  | 1115.8        | 30.5                           | 7.9                            |
|                         | WC  | 868.0         | 39.3                           | 12.7                           |
|                         | PEN | 603.3         | 36.9                           | 18.5                           |
| 2020s                   | NW  | 473.6         | 40.0                           | 9.8                            |
|                         | CNE | 913.2         | 41.1                           | 11.1                           |
|                         | NE  | 1171.6        | 31.7                           | 9.6                            |
|                         | WC  | 917.5         | 40.9                           | 14.6                           |
|                         | PEN | 631.7         | 38.3                           | 19.9                           |
| 2050s                   | NW  | 447.7         | 41.4                           | 11.7                           |
|                         | CNE | 978.2         | 42.5                           | 12.9                           |
|                         | NE  | 1208.4        | 33.0                           | 11.3                           |
|                         | WC  | 986.9         | 42.3                           | 15.9                           |
|                         | PEN | 617.2         | 39.6                           | 21.2                           |
| 2080s                   | NW  | 487.5         | 42.5                           | 12.2                           |
|                         | CNE | 1058.2        | 43.8                           | 13.7                           |
|                         | NE  | 1279.9        | 34.2                           | 11.6                           |
|                         | WC  | 1013.0        | 43.4                           | 16.8                           |
|                         | PEN | 631.7         | 40.7                           | 22.3                           |

## 2. Soils under five CHRs

Analysis revealed the diverse soil types within each CHR. While many dominant soil units (DOMSOILs) occurred across multiple of the CHRs, some remained region-specific (Table 2). As per traditional soil classification, these soils are from any of Acrisol, Cambisol, Gleysol, Phaeozem, Lithosol, Fluvisol, Luvisol, Nitosol, Histosol, Arenosol, Regosol, Vertisol, Xerosol, Yermosol and Solonchak, and further are classified into FAO soil unit subgroups (i.e. DOMSOILs) as per Batjes (1997) and FAO-UNESCO (1974) (Table 2).

The median values of representative benchmark soil physicochemical properties for topsoil classes of each DOMSOIL (Batjes, 1997) is shown in Table 3 and the distribution across India, including the Hilly Region (Patwardhan *et al.*, 2016) and some parts of the marine islands of India, is shown in Figure 1 along with FAO/UNESCO Soil Units (Batjes, 1997). However, since the source shapefile from Vargas (2022) did not include the soils of Indian Union Territory Lakshadweep and some islands of Andaman & Nicobar, is not a complete representation of Indian landscape.

**Table 2: Soils under five major CHRs in India (Vargas, 2022).**

| Traditional | FAO Soil Unit     | Acronym | CNE | NE | NW | PEN | WC |
|-------------|-------------------|---------|-----|----|----|-----|----|
| Acrisol     | Humic Acrisol     | Ah      |     | ✓  |    | ✓   |    |
|             | Orthic Acrisols   | Ao      | ✓   |    | ✓  |     | ✓  |
|             | Ferric Acrisols   | Af      |     | ✓  |    |     |    |
|             | Plinthic Acrisols | Ap      |     |    |    | ✓   | ✓  |
| Cambisol    | Chromic Cambisol  | Bc      | ✓   |    |    |     | ✓  |
|             | Dystric Cambisol  | Bd      |     | ✓  |    |     |    |
|             | Eutric Cambisol   | Be      | ✓   | ✓  | ✓  |     | ✓  |
|             | Ferralic Cambisol | Bf      |     | ✓  |    |     |    |
|             | Humic Cambisol    | Bh      | ✓   | ✓  |    |     |    |
|             | Calcic Cambisol   | Bk      | ✓   |    |    |     |    |
|             | Vertic Cambisol   | Bv      |     |    | ✓  | ✓   | ✓  |
| Gleysol     | Calcaric Gleysol  | Gc      |     | ✓  |    |     |    |
|             | Dystric Gleysol   | Gd      |     | ✓  |    |     |    |
|             | Eutric Gleysol    | Ge      |     | ✓  |    |     |    |
|             | Humic Gleysol     | Gh      |     | ✓  |    |     |    |
| Phaeozem    | Haplic Phaeozem   | Hh      |     |    | ✓  |     | ✓  |
| Lithosols   | Lithosols         | I       | ✓   | ✓  | ✓  | ✓   | ✓  |
| Fluvisol    | Calcaric Fluvisol | Jc      | ✓   | ✓  | ✓  | ✓   |    |
|             | Eutric Fluvisol   | Je      | ✓   | ✓  | ✓  | ✓   | ✓  |
|             | Thionic Fluvisol  | Jt      |     | ✓  | ✓  | ✓   |    |
| Luvisol     | Chromic Luvisol   | Lc      | ✓   |    | ✓  | ✓   | ✓  |
|             | Ferric Luvisol    | Lf      | ✓   | ✓  |    | ✓   | ✓  |
|             | Orthic Luvisol    | Lo      | ✓   | ✓  | ✓  | ✓   | ✓  |
|             | Plinthic Luvisol  | Lp      |     |    |    |     | ✓  |
| Nitosol     | Dystric Nitosol   | Nd      | ✓   | ✓  |    | ✓   | ✓  |
|             | Eutric Nitosol    | Ne      | ✓   | ✓  | ✓  | ✓   | ✓  |
| Histosol    | Dystric Histosol  | Od      |     |    |    | ✓   |    |
| Arenosol    | Cambic Arenosol   | Qc      |     |    | ✓  |     |    |
| Regosol     | Calcaric Regosol  | Rc      |     |    | ✓  |     |    |
|             | Dystric Regosol   | Rd      | ✓   | ✓  |    | ✓   | ✓  |
|             | Eutric Regosol    | Re      | ✓   |    | ✓  |     |    |
| Vertisol    | Chromic Vertisol  | Vc      | ✓   |    | ✓  | ✓   | ✓  |
|             | Pellic Vertisol   | Vp      |     |    |    |     | ✓  |
| Xerosol     | Haplic Xerosol    | Xh      |     |    | ✓  |     |    |
|             | Calcic Xerosol    | Xk      |     |    | ✓  |     |    |
| Yermosol    | Haplic Yermosol   | Yh      |     |    | ✓  |     |    |
|             | Calcic Yermosol   | Yk      |     |    | ✓  |     |    |
| Solonchak   | Gleyic Solonchak  | Zg      |     |    | ✓  |     |    |
|             | Orthic Solonchak  | Zo      | ✓   | ✓  | ✓  |     |    |

✓ : Indicates presence of the soil in the homogeneous climatic region

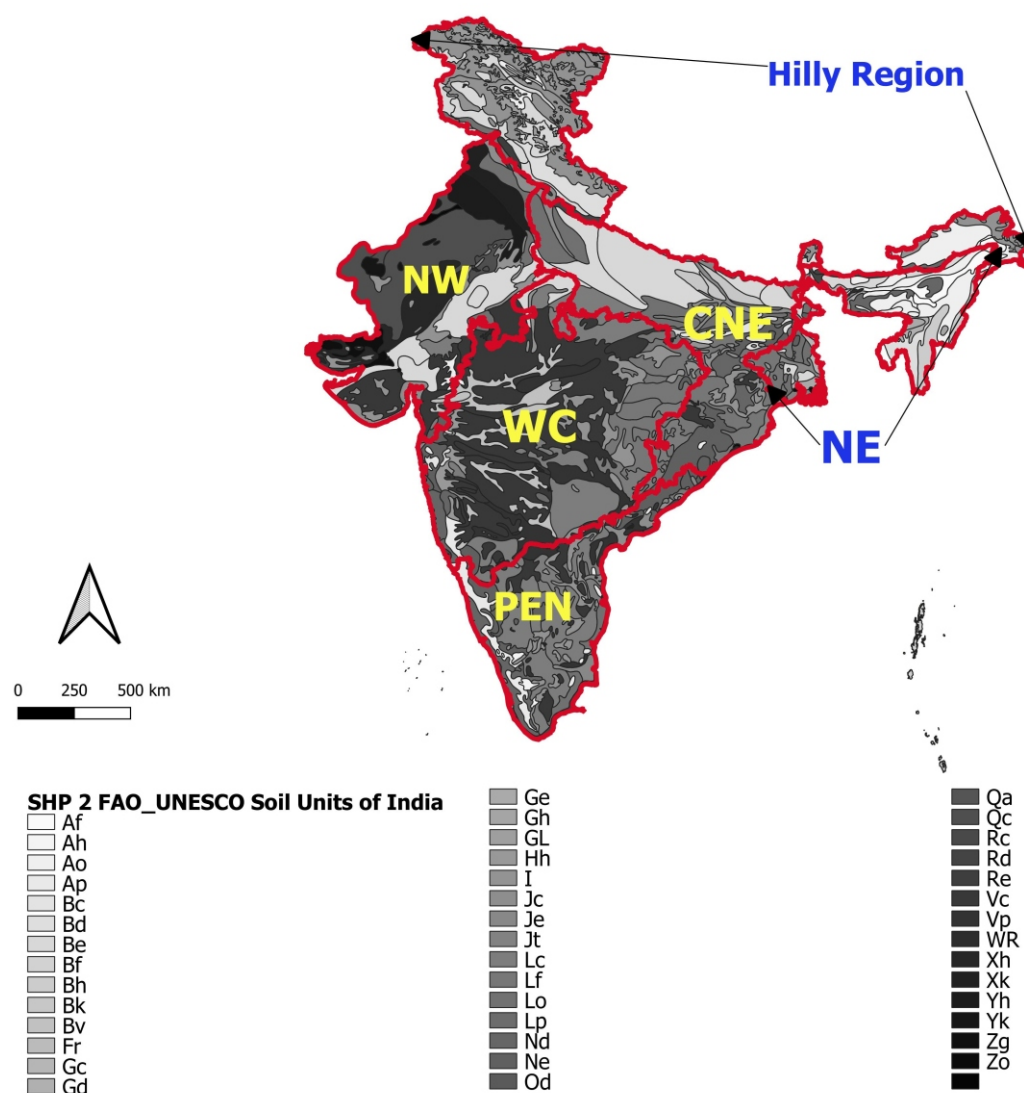


Fig. 1: DOMSOILs of India (excluding soils of Lakshadweep and some islands of Andaman & Nicobar)

Table 3: Median values of soil quality indicators for FAO/UNESCO dominant soils (DOMSOILs) under 5 CHRs of India (Batjes, 1997).

| Acronym | pH  | SOC  | CEC  | BD   | PRS | AWC | DRAIN |
|---------|-----|------|------|------|-----|-----|-------|
| Af      | 5.0 | 0.75 | 6.4  | 1.44 | 46  | 122 | W     |
| Ah      | 4.9 | 2.3  | 13.0 | 1.32 | 50  | 128 | W     |
| Ao      | 4.9 | 0.78 | 7.5  | 1.38 | 48  | 113 | W     |
| Ap      | 4.7 | 1.04 | 6.2  | 1.53 | 42  | 112 | M     |
| Bc      | 6.9 | 1.02 | 20.4 | 1.33 | 50  | 128 | W     |
| Bd      | 5.1 | 1.94 | 17.6 | 1.27 | 52  | 132 | W     |
| Be      | 6.7 | 0.90 | 18.6 | 1.45 | 45  | 128 | W     |
| Bf      | 5.1 | 0.95 | 7.3  | 1.28 | 52  | 130 | W     |
| Bh      | 5.1 | 3.04 | 25.8 | 1.15 | 56  | 137 | W     |
| Bk      | 8.1 | 0.63 | 20.6 | 1.45 | 45  | 130 | W     |
| Bv      | 6.9 | 0.84 | 39.2 | 1.41 | 47  | 130 | M     |

|    |     |      |      |      |    |     |   |
|----|-----|------|------|------|----|-----|---|
| Gc | 7.5 | 0.78 | 33.3 | 1.65 | 38 | 128 | I |
| Gd | 5.0 | 1.50 | 16.4 | 1.20 | 55 | 118 | P |
| Ge | 6.2 | 1.19 | 20.4 | 1.43 | 46 | 122 | P |
| Gh | 5.1 | 3.04 | 15.0 | 1.45 | 45 | 125 | P |
| Hh | 6.4 | 1.76 | 24.2 | 1.43 | 46 | 120 | W |
| I  | 7.7 | 1.8  | 12.3 | 1.42 | 46 | 13  | S |
| Jc | 8.1 | 0.48 | 11.8 | 1.45 | 45 | 110 | M |
| Je | 7.0 | 0.78 | 16.8 | 1.42 | 46 | 119 | M |
| Jt | 4.8 | 2.51 | 18.3 | 1.07 | 60 | 130 | P |
| Lc | 6.4 | 0.72 | 13   | 1.53 | 42 | 89  | W |
| Lf | 5.9 | 0.47 | 5.5  | 1.55 | 52 | 82  | W |
| Lo | 6.3 | 0.63 | 11.5 | 1.55 | 42 | 91  | M |
| Lp | 5.8 | 0.46 | 4.3  | 1.66 | 37 | 80  | M |
| Nd | 4.9 | 0.87 | 7.9  | 1.42 | 46 | 70  | W |
| Ne | 6.2 | 0.60 | 11.0 | 1.49 | 44 | 75  | W |
| Od | 4.5 | 35.0 | 75.5 | 0.31 | 88 | 480 | V |
| Qc | 6.6 | 0.20 | 3.3  | 1.62 | 39 | 42  | W |
| Rc | 4.0 | 0.40 | 17.9 | 1.46 | 45 | 117 | W |
| Rd | 5.1 | 0.88 | 8.0  | 1.51 | 43 | 94  | W |
| Re | 6.4 | 0.60 | 10   | 1.56 | 41 | 94  | W |
| Vc | 7.9 | 0.70 | 46.1 | 1.71 | 35 | 130 | M |
| Vp | 7.2 | 0.92 | 45.3 | 1.59 | 40 | 130 | I |
| Xh | 8.0 | 0.59 | 23.5 | 1.52 | 43 | 110 | W |
| Xk | 7.9 | 0.70 | 12.5 | 1.43 | 46 | 108 | W |
| Yh | 8.1 | 0.32 | 5.5  | 1.54 | 42 | 105 | W |
| Yk | 8.0 | 0.28 | 12.6 | 1.49 | 44 | 105 | W |
| Zg | 8.3 | 0.50 | 17.4 | 1.47 | 45 | 138 | P |
| Zo | 8.1 | 0.36 | 11.3 | 1.49 | 44 | 134 | M |

## Index

- PH = Median soil pH
- SOC = Median soil organic carbon (%)
- CEC=Median cation exchange capacity (cmolc/kg)
- BD= Median bulk density (g/cm<sup>3</sup>)
- PRS = Median total porosity (%)
- AWC = Available water capacity in mm to a depth of 100 cm or less for shallower soils
- DRAIN = Drainage class

(S= somewhat excessively drained; W = well drained; M = moderately well drained; I = imperfectly drained; P = poorly drained; V = very poorly drained)

### 3. Generalised classification of soils in 5 CHRs

The generalised classification of the soil was performed using the median representative values for the selected properties are shown in table 3 (Batjes, 1997). For classification of the soils based on pH the

classification (Li *et al.*, 2016) that designates soils as strongly acid (pH < 5.5), slightly acid (pH 5.5 - 6.5), neutral (pH 6.5-7.5), slightly alkaline (pH 7.5-8.5) and strongly alkaline (pH > 8.5) was followed. Whereas considering that soil organic matter (SOM) contains 58

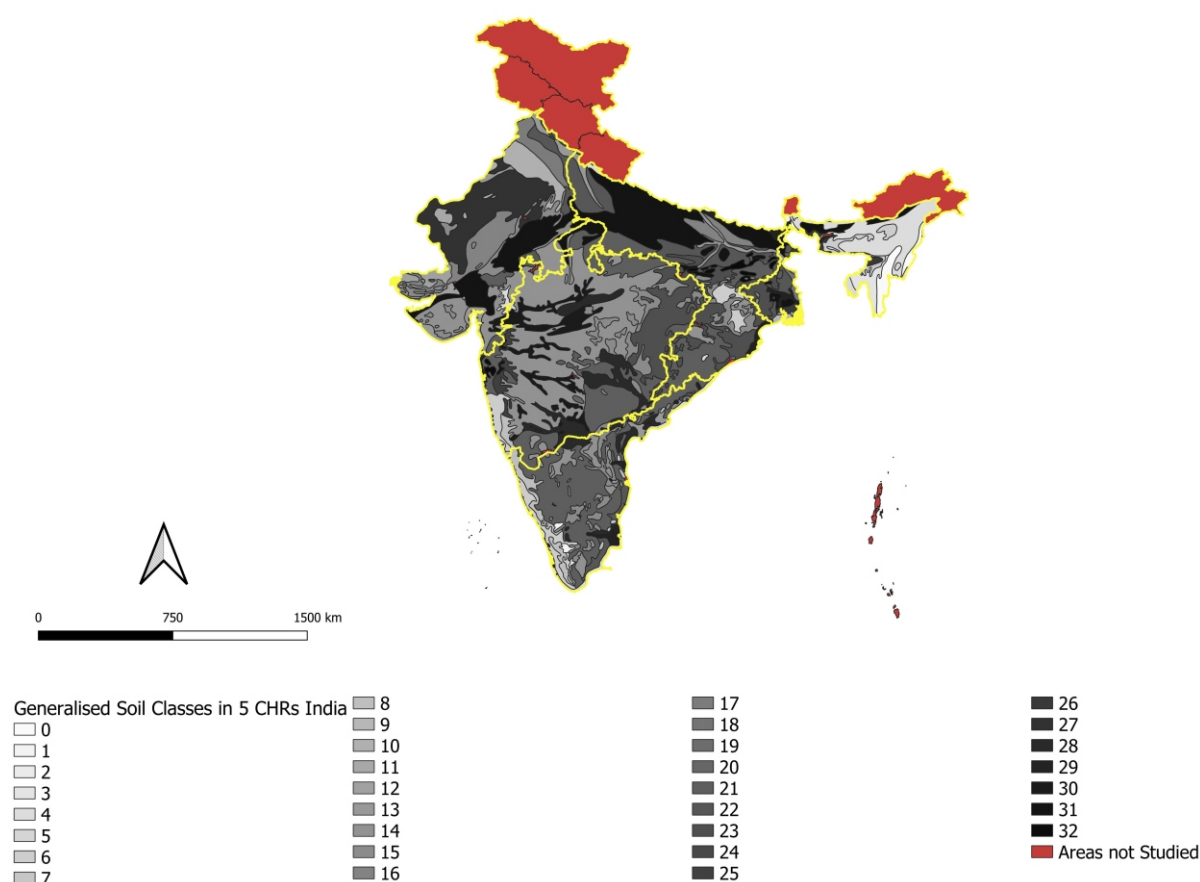
**Table 4: Generalised classes of soils in 5 CHRs.**

| Generalised Classes | pH                | CEC         | PRS       | Drainage                     | SOC            |
|---------------------|-------------------|-------------|-----------|------------------------------|----------------|
| 0                   | Strongly Acidic   | Very Strong | Very High | Well Drained                 | Extremely High |
| 1.                  | Strongly Acidic   | Moderate    | Very High | Well Drained                 | Very High      |
| 2.                  | Strongly Acidic   | Very Strong | Very High | Very Poorly Drained          | Extremely High |
| 3.                  | Strongly Acidic   | Strong      | Very High | Well Drained                 | Very High      |
| 4.                  | Strongly Acidic   | Weak        | Very High | Well Drained                 | Medium         |
| 5.                  | Strongly Acidic   | Moderate    | Very High | Poorly Drained               | Extremely High |
| 6.                  | Strongly Acidic   | Weak        | High      | Well Drained                 | Medium         |
| 7.                  | Strongly Acidic   | Strong      | Very High | Poorly Drained               | High           |
| 8.                  | Strongly Acidic   | Weak        | Very High | Moderately Drained           | Medium         |
| 9.                  | Strongly Acidic   | Strong      | Very High | Poorly Drained               | Extremely High |
| 10.                 | Slightly Alkaline | Very Weak   | Very High | Well Drained                 | Very Low       |
| 11.                 | Slightly Alkaline | Moderate    | Very High | Well Drained                 | Very Low       |
| 12.                 | Slightly Alkaline | Strong      | Very High | Poorly Drained               | Low            |
| 13.                 | Slightly Alkaline | Moderate    | Very High | Moderately Drained           | Low            |
| 14.                 | Slightly Alkaline | Very Strong | High      | Moderately Drained           | Medium         |
| 15.                 | Slightly Alkaline | Moderate    | Very High | Somewhat Excessively Drained | Very High      |
| 16.                 | Slightly Alkaline | Very Strong | Very High | Well Drained                 | Medium         |
| 17.                 | Slightly Alkaline | Moderate    | Very High | Well Drained                 | Medium         |
| 18.                 | Slightly Alkaline | Very Strong | High      | Imperfectly Drained          | Medium         |
| 19.                 | Slightly Alkaline | Strong      | Very High | Well Drained                 | Low            |
| 20.                 | Slightly Acidic   | Very Weak   | Very High | Moderately Drained           | Low            |
| 21.                 | Slightly Acidic   | Moderate    | Very High | Well Drained                 | Medium         |
| 22.                 | Slightly Acidic   | Moderate    | Very High | Moderately Drained           | Medium         |
| 23.                 | Slightly Acidic   | Very Weak   | Very High | Well Drained                 | Low            |
| 24.                 | Slightly Acidic   | Weak        | Very High | Well Drained                 | Medium         |
| 25.                 | Slightly Acidic   | Very Strong | Very High | Well Drained                 | Very High      |
| 26.                 | Slightly Acidic   | Very Strong | Very High | Poorly Drained               | High           |
| 27.                 | Neutral           | Very Weak   | High      | Well Drained                 | Very Low       |
| 28.                 | Neutral           | Very Strong | High      | Imperfectly Drained          | Medium         |
| 29.                 | Neutral           | Strong      | Very High | Moderately Drained           | Medium         |
| 30.                 | Neutral           | Very Strong | Very High | Moderately Drained           | Medium         |
| 31.                 | Neutral           | Strong      | Very High | Well Drained                 | Medium         |
| 32.                 | Neutral           | Very Strong | Very High | Well Drained                 | Medium         |

% of soil organic carbon (SOC) (Pribyl, 2010), authors classified the SOC of these soils as with as extremely high (> 2.32 %), very high (1.74-2.32 %), high (1.16-1.74 %), medium (0.58–1.16 %), low (0.35-0.58 %) and very low (< 0.35 %) (Li *et al.*, 2016). Following the classification used by Liu *et al.* (2013), CEC of the soils were designated to be with very strong (> 20 cmolc/kg), strong (15.4-20 cmolc/kg), moderate (10.5-

15.4 cmolc/kg), weak (6.2-10.5 cmolc/kg) and very weak (< 6.2 cmolc/kg).

As, Bulk density (BD) is ultimately an indicator of soil porosity (PRS) (FAO, 2006) that determines soil's capacity for water retention and drainage, aeration and nutrient availability for plants, and thus is important for regulating suitability of a soil for a specific plant



**Fig. 2: Distribution of the generalised soil classes across the 5 CHRs of India.**

species and potential of abiotic stresses (Gusta and Chen, 2015; Phukan *et al.*, 2015; Ghosh *et al.*, 2020; Yang *et al.*, 2021; Han *et al.*, 2022). Since the median value of PRS for the topsoils for the 5 CHRs (Batjes, 1997) already available, hence authors grouped the soils by PRS only, instead of looking into BD. For this authors followed the classification system for PRS suggested by FAO (2006) as High (15-40 %), Very High (> 40 %), Medium (5-25 %), Low (2-5 %) and Very Low (< 2 %). As available water capacity (AWC) is the soil water content between field capacity and permanent wilting point of plants (Blaschek *et al.*, 2019) for which authors did not include a further grouping as permanent wilting point can vary for different species (Torres *et al.*, 2021). Instead, the classification used by Batjes (1997) based on drainage provides a more general overview of the soil quality, that categorises the soils as, well drained (W), moderately drained (M), excessively drained (S), imperfectly drained (I), poorly drained (P) soils are Gd, Ge, Gh, Jt, Zg, and Very Poorly Drained (V).

Using this classification, it was found that soils in the 5 CHRs in India belong to 32 generalised classes (Table 4; Figure 2). Each of the 5 CHRs contains soils that are strongly acid, slightly acid, neutral and slightly alkaline

soils. The SOC in soils in WC varied from low, medium and very high; low, medium, very high and extremely high in PEN and CNE; very low, low, medium, very high and extremely high in NW; low, medium, high, very high and extremely high in NE. CEC in all of the 5 CHRs (WC, PEN, NW, NE and CNE) varied among very weak, weak, moderate, strong, very strong. In all CHRs the soils with high and very high PRS could be seen. The drainage classes of soils present in WC are I, M, W, S; in PEN - I, M, W, S, P, V; in NW - M, W, S, P; in NE - I, M, W, S, P and in CNE - M, W, S.

#### 4. Potential utility of dataset

In this work the soils in India are characterised and grouped based on FAO/UNESCO classification and generalised classes based on representative soil properties as well, along with projected climatological conditions for 2020s, 2050s and 2080s, shown through CHRs. This dataset (Bhowmik and Ray, 2025) can inform decision makers and researchers to determine the scope of sustainable land use and relevant research approaches for sustainable agriculture, forestry, and controlling infestation of invasive plant species, landscape restoration and so on (Ambasht, 2024; Banerjee *et al.*, 2026). In line with Kurina *et al.* (2018) and Duran *et al.* (2018), this study developed 78 ECZs

for the landscape of India under the 5CHRs from 32 generalised soil classes 14 generalised soil classes under CNE, 18 in NW, 17 in NE, 14 in WC and 15 in PEN, that can inform such decision making for targeting propagation or management of plants in the ECZs based on existing information on their adaptability and tolerance limits (Farrelly *et al.*, 2009; Reyer *et al.*, 2012; Schwinning and Kelly, 2013; Hernández *et al.*, 2021).

The classification used in this study provides an upscaled spatial database in comparison to the reference soils identification from Kumar *et al.* (2020), however, it indicates a requirement of rethinking about identifying the benchmark soil soils to represent soils under diverse CHR at a higher spatial resolution to increase support towards more precise and spatially refined land use planning. Relevant random data collection can be performed for the 39 DOMSOILs zones seen across India or at the level of ECZs (higher spatial resolution) to reflect localised variation of soils with integrating climate information in corresponding CHR (Brevik, 2013). The dataset can be further improved for use in India if soil and climatic conditions of present and future in Hilly region of India and the islands of Lakshadweep and Andaman & Nicobar are added. Improvement can be achieved if additional information on humidity, solar radiation, wind speed etc. in 2020s, 2050s and 2080s in these CHRs or further increasing the resolution of zoning as these environmental factors also influence survival and growth of plants (Bang *et al.*, 2010; Kläring and Krumbein, 2013; Chia and Lim, 2022).

Furthermore, the 78 ECZs, each representative of unique combination of soil quality parameters and climatic conditions, enables to identify locations for site-selection to perform empirical studies and data collection for research in agriculture and forestry, and the spatial extent of the applicability of the outcomes of such studies (Belaj *et al.*, 2010; Woyann *et al.*, 2019; Nardino *et al.*, 2020; Bassi *et al.*, 2025). For agricultural purpose these ECZs can be useful to determine ideal species and cultivar to improve farm's profitability and productivity along with increased precision in agricultural land use planning (Ramírez-Ojeda *et al.*, 2021; Zimaroeva *et al.*, 2021; Almeida-Furtado *et al.*, 2025). In afforestation activities ECZs can help to select ideal species for successful growth and performance in achieving environmental sustainability objectives or identifying susceptibility to invasion by alien plant species (Sanderson *et al.*, 2014; Silveira *et al.*, 2020; Raposo *et al.*, 2021; Buendía-Espinoza *et al.*, 2022). Knowing the future of climatic conditions for 2020s, 2050s and 2080s, with

distribution of soil types may help refine management plans and policies for forestry and agriculture under the sustainability principles to adapt with the altered climate scenario and capacity building (Altieri *et al.*, 2015; Kandel *et al.*, 2023; Kumar *et al.*, 2024; Banerjee *et al.*, 2026). Similar principles can also be applied to control future infestation of the landscapes by invasive plant species (Crall *et al.*, 2013).

## CONCLUSIONS

This study classified landscape of India within five CHRs into 78 edaphoclimatic zones (ECZs), with producing associated spatial data, that can inform and support decision making processes to manage plant species selection and determine optimum management input requirements for sustainable agriculture, forestry and controlling infestation by invasive plant species. The homogeneous soils in terms of pH conditions, cation exchange capacity (CEC), soil organic carbon (SOC), porosity (PRS) and drainage, are grouped within same generalised class across the 5 CHRs and the generalised classes that are present in each individual CHRs are identified. This classification can be used, not only as indicators of soil conditions specific to individual CHRs, but also at the national scale as the classification system and class number is consistent for each suite of combination of pH class, CEC class, SOC class, PRS class and drainage class. The study also explored the potential changes in soil behaviour, as per the class characteristics identified, with the changing climatic conditions from baseline (1961-1990 for temperature and precipitation and 1951 to 2018 for drought) for each CHR that may help in decision making for preparedness for such landscape management in terms of capacity building, financing and strategy development.

## CONFLICT OF INTEREST

There is no conflict of interest to declare.

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