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Using SoilGrids250m for Overlooking Spatial and Vertical Distribution of Soil Physico-chemical Properties Over Tropical Climate Asia

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ABSTRACT

Background: Understanding the interaction, spatial and vertical distribution of soil chemical properties over climate type in tropical Asia and various depths of soil is essential for sustainable land management, particularly in regions experiencing dynamic conditions.
Aims & Methods: This study investigates the relationships of each parameter such as cation exchange capacity (CEC), soil pH, and soil organic carbon (SOC) tropical Climate Asia. Using stratified random sampling based on Köppen–Geiger climate classifications and a consistent spatial resolution of 0.25° × 0.25°, we analyzed 45 sample points distributed across tropical rainforest, monsoon, and savanna climates. The data were extracted from SoilGrids 250m and reconciled using conservative remapping and bilinear interpolation techniques. Corresponding soil chemical data were obtained from validated regional databases.
Result: The results show that a correlation matrix analyzing relationships among key soil physico-chemical properties across multiple depths. Strong positive correlations were found between soil organic carbon (SOC) and total nitrogen (N) ($r > 0.8$), reflecting their shared origin in organic matter. Bulk density (BD) exhibited moderate to strong negative correlations with SOC and N ($r \approx -0.5$ to -0.8), particularly in surface layers, indicating the influence of organic matter on soil structure. Correlations weaken with depth, reflecting reduced nutrient interaction. These patterns highlight the importance of organic matter inputs and minimal soil disturbance in maintaining soil health and guiding sustainable land management strategies.

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1. Introduction

Spatial distribution analysis has emerged as a critical tool in environmental science, agriculture, and land management. By examining the variation of different parameters across space, researchers can detect patterns, diagnose anomalies, and make informed decisions about land use, conservation, and resource allocation (Hovhannissian *et al.,* 2019). In soil science, spatial variability is particularly important, as properties like nutrient content, organic matter, pH, and water retention can vary significantly even across small distance (Arrouays *et al.,* 2020). Overlooking this variability risks inefficient resource use, poor land management, and accelerated environmental degradation (Libohova *et al.,* 2024).

For example, soil pH, controls nutrient solubility, which has deeviations from a neutral to slightly acidic pH can inhibit plant nutrient uptake and disrupt soil processes (Barrow & Hartemink, 2023). Bulk density reflects soil structure and compaction, affecting root penetration and water movement; higher bulk density often signals degraded soil conditions (Tian *et al.,* 2020). Nitrogen is a key macronutrient whose availability is sensitive to pH, moisture, and organic matter dynamics (Lai *et al.,* 2024; Wenzhu *et al.,* 2023). SOC serves as a critical driver of soil fertility, improving aggregation, increasing CEC, and supporting microbial communities (Wang *et al.,* 2025). CEC reflects the soil's ability to retain essential nutrients and buffer pH changes, closely linked to organic matter and higher SOC can enhance both water retention and CEC, while bulk density influences the availability of both water and nitrogen (Hailegnaw *et al.,* 2019).

Understanding the spatial distribution of soil chemical properties is essential for promoting sustainable agricultural practices. Key soil attributes—such as pH, organic carbon, nitrogen content, and cation exchange capacity (CEC)—directly impact nutrient availability, soil health, and crop productivity. Spatial analysis enables precision farming approaches that optimize the application of fertilizers and water, ultimately increasing yields, reducing costs, and minimizing environmental impacts (Ismail *et al.,* 2025; Sainju & Liptzin, 2022).

Despite growing recognition of spatial variability's importance, past studies often faced limitations, such as sparse sampling and oversimplified mapping methods. Much research has also focused only on surface soils, neglecting deeper layers critical for long-term fertility and water storage. Advances in remote sensing and machine learning now provide opportunities to overcome these challenges (Baltensweiler *et al.,* 2021; Diaz-Gonzalez *et al.,* 2022). Therefore, this study aimed to analyse the spatial distribution of soil chemical properties in the multi-depth of soil and using multi-parameter spatial datasets over tropical climate Asia for supporting climate-resilient and sustainable agricultural practices.

2. Methods

2.1 Study area

Southeast Asia encompasses a diverse climatic landscape, primarily dominated by tropical climate types as classified by the Köppen–Geiger system, including tropical rainforest (Af), tropical monsoon (Am), and tropical savanna (Aw) zones. These climate regimes, characterized by high temperatures and distinct wet and dry seasons, exert a strong influence on the region's soil formation and chemical properties. The selection of sampling points was conducted using a stratified random sampling method, based on the Köppen–Geiger climate classification, data availability, and the grid resolution of 0.25° × 0.25°, consistent with the resolution of the validation datasets. Based on these criteria, a total of 45 sampling points were identified, distributed across the Southeast Asian region.

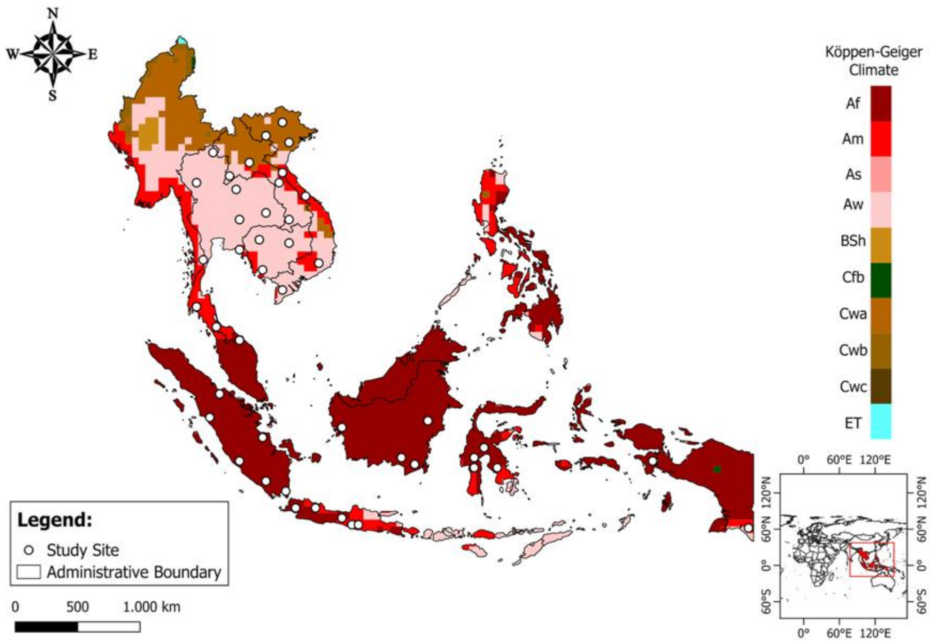

Figure 1. Study area

2.2 Datasets

SoilGrids250m represents a major advancement in global digital soil mapping, offering high-resolution (250 m) gridded predictions of soil properties and classes using machine learning and the dataset based on ISRIC (ground-truth database over each region or countries) (Hengl *et al.,* 2017). Utilizing over 150,000 harmonized soil profiles and 158 environmental covariates from remote sensing and global datasets, the system predicts key soil attributes—such as organic carbon, pH, texture fractions, bulk density, and depth to bedrock—at seven standard depths. Ensemble modeling approaches, including random forest and gradient boosting, achieved substantial accuracy, explaining up to 83% of the variance in some soil properties. Compared to its predecessor (SoilGrids1km), accuracy improvements range from 60% to 230% (Hengl *et al.,* 2014). The inclusion of expert-informed pseudo-observations addresses gaps in data-sparse regions like deserts and glaciers. Results are openly available via web-based platforms under an Open Database License. While limitations remain in highly variable landscapes, SoilGrids250m offers a scalable and reproducible framework that supports global soil assessment, agricultural planning, and climate resilience initiatives.

Using population GPS coordinates, SoilGrids250m data were obtained for pH, carbon, nitrogen, and water volume content. The data were accessed directly from the SoilGrids website (https://soilgrids.org/) in January 2025 for soil chemical properties under various soil depths (0 – 15, 15 – 30, 30 – 60, 60 – 100, and 100 – 200 cm) over tropical climate Asia. Selected primary soil properties as defined and described in the GlobalSoilMap specifications with the following steps are: a) input soil data preparation, b) covariates' selection, c) model tuning and cross-validation, d) final model fitting for prediction, and e) predictions with uncertainty estimation.

2.3 Methodology

The dataset reconsialization is done with Cygwin and Rstudio software with netcdf data format. Data reconsialization aims to equalize the data, so that all data have the same coverage, spatial and temporal resolution. Spatial delineation was performed to limit the geographic extent of the data to the administrative boundaries of Southeast Asia. This was necessary as the original datasets were global in scope, leading to large file sizes and computational inefficiencies during data extraction. By restricting the spatial extent, the processing time was significantly reduced and the data volume optimized for regional analysis. Due to differences in the native spatial resolution of the datasets, resolution harmonization was required to ensure compatibility and consistency during validation.

All datasets were standardized to a uniform spatial resolution of 0.25° × 0.25°. The final phase involved the extraction of gridded data values from NetCDF files to tabular format (.xlsx) based on preselected geographic sampling points. The extraction and conversion processes were executed using RStudio and relevant geospatial packages (e.g., ncdf4, raster, and tidyverse).

To examine the relationship among soil chemical properties in the various soil depth over tropical Asi, we used Pearson's correlation coefficient (r) quantifies the linear relationship between two variables, with values ranging from -1 (perfect negative correlation) to +1 (perfect positive correlation) and stepwise multiple linear regression analysis was undertaken (Munny *et al.,* 2021).

3. Results

3.1 Soil pH

Figure 2. illustrates the spatial distribution of soil pH at different depths (5, 15, 30, 60, 100, and 200 cm) across tropical climate Asia. The spatial patterns also suggest potential management priorities. Areas with already neutral to slightly acidic soils may only need minimal interventions, whereas highly acidic regions must integrate soil pH management strategies to sustain productivity. With the intensification of agriculture and climate change, maintaining optimal pH is critical to avoid problems like aluminum toxicity and poor nutrient uptake (Hartemink & Barrow, 2023).

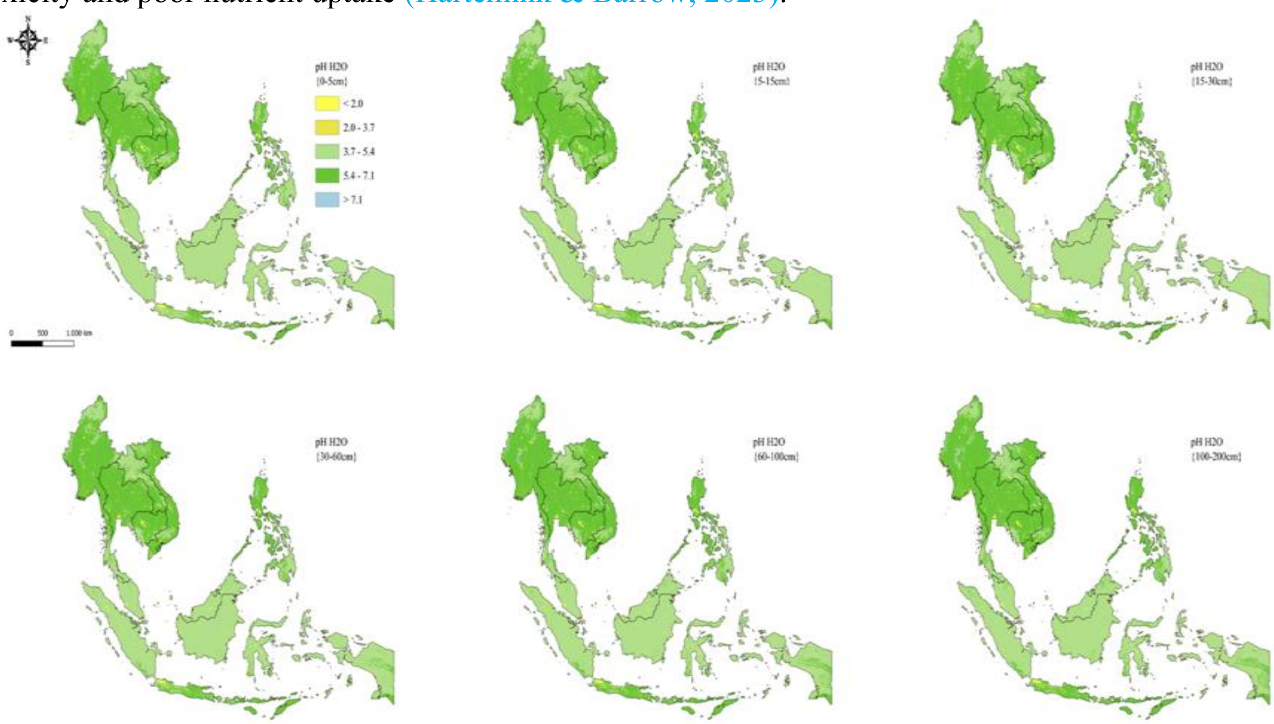

Figure 2. Spatial distribution analysis of soil pH over tropical climate Asia

The results shows that much of tropical climate Asia countries has soils ranging from moderately acidic to slightly acidic conditions, predominantly in the pH range of 5.4 to 7.1. Northern regions, such as Thailand, Laos, and parts of Vietnam, display relatively higher pH values, trending toward neutral (>5.4), depicted in medium to lighter green shades. In contrast, parts of Indonesia, Malaysia, and the Philippines show slightly more acidic soils (pH 4.7–5.4), visible in darker green hues. Some isolated areas, particularly in southern Indonesia and Papua, exhibit even lower pH values (below 4.7), suggesting the presence of highly weathered and leached soils. At the surface (5 cm), soil pH tends to be more acidic in tropical zones, a pattern consistent with high organic matter inputs and intense rainfall leading to leaching of basic cations (Mg^{2+}, Ca^{2+}) (Hailegnaw *et al.,* 2019). Deeper layers (e.g., 100 and 200 cm) show a slight increase in pH, suggesting a reduction in organic matter influence and possible accumulation of weathered mineral components that are less acidic (Wang & Kuzyakov, 2024).

3.2 Cation Exchange Capacity (CEC)

The spatial distribution of Cation Exchange Capacity (CEC) at different soil depths (5, 15, 30, 60, and 100 cm) over tropical climate Asia shows in Figure 3, which has a critical CEC that measures a soil's ability to hold and exchange positively charged ions (Ma *et al.,* 2024), which is, high CEC is associated with greater soil fertility and better nutrient retention, essential for sustainable agricultural productivity (Ma *et al.,* 2024). From the maps, northern regions, particularly parts of Vietnam, Laos, and northern Thailand, show relatively higher CEC values compared to southern parts like Indonesia and Malaysia. This trend may reflect the dominance of finer-textured soils (clay and silt) and higher soil organic carbon in the north (Bi *et al.,* 2023).

At shallow depths (5 cm), CEC is higher in many areas, especially where organic matter accumulation is significant due to plant residue and microbial activity. However, as depth increases to 100 cm, CEC generally decreases. In addition, most of locations (e.g., Thailand, Vietnam, Cambodia) shows moderate CEC values in the range of 10–30 cmolc/kg (depicted in medium shades of blue). In contrast, parts of Indonesia and the Philippines exhibit areas with much higher CEC, with values reaching above 30 cmolc/kg, even exceeding 60 cmolc/kg in specific southern and eastern islands, represented in darker purple shades. Importantly, CEC influences not just fertility but also soil buffering capacity, impacting soil pH stability and vulnerability to acidification (Li *et al.,* 2020).

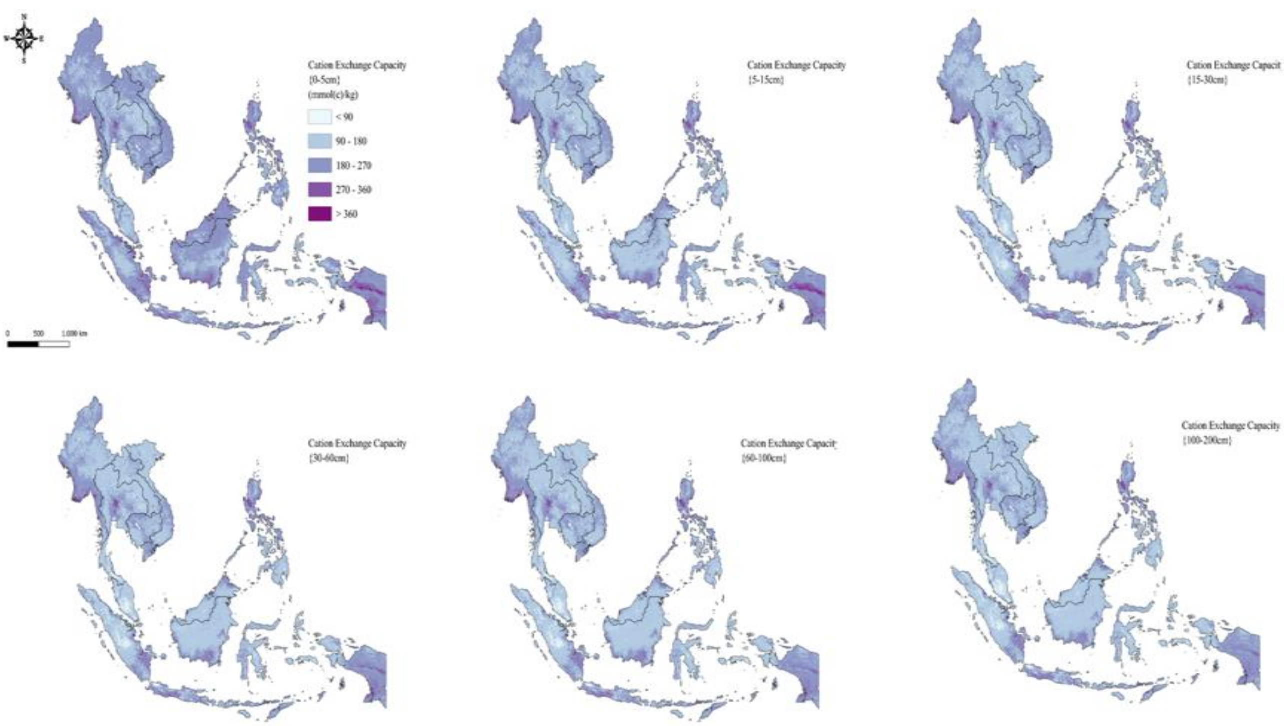

Figure 3. Spatial distribution analysis of CEC over tropical climate Asia

3.3 Soil Organic Carbon (SOC)

SOC levels are highly heterogeneous over tropical climate Asia countries and various soil depth, largely reflecting patterns of vegetation, climate, topography, and land use history. The highest SOC concentrations (> 2000 dg/kg) are concentrated in Borneo, Sumatra, and parts of Papua, areas dominated by dense tropical rainforests and peatlands as showed in Figure 4. These ecosystems are well known for their high carbon sequestration capacities due to abundant biomass inputs and slow decomposition rates under saturated soil conditions (Bhattacharyya *et al.,* 2022). These spatial variations have major implications for climate-smart agriculture and carbon accounting (Abdelrahman *et al.,* 2020).

Figure 4 shows at a consistent trend is observed where SOC concentrations are highest at the surface (0–20 cm) and decrease sharply with increasing soil depth, in agreement with recent finding, which is the deeper soil layers (100–140 cm) exhibit sharp declines in SOC content, often dropping below 100 dg/kg in most regions except Kutai Kartanegara. The high SOC persistence in Kutai Kartanegara even at depth suggests either unique soil formation processes, less disturbance, or higher clay content that promotes carbon stabilization (Niu *et al.,* 2023). In addition, Chiem Hoa, Chanthaburi, and the other sites show relatively moderate surface SOC concentrations (generally below 500 dg/kg). Interestingly, the relatively low SOC values across Gunung Kidul and Fak Fak could be associated with poor vegetation cover, intensive land use, or inherently low productivity soils (Zhu *et al.,* 2021). This vertical distribution highlights the importance of protecting topsoil layers for carbon sequestration and climate mitigation efforts.

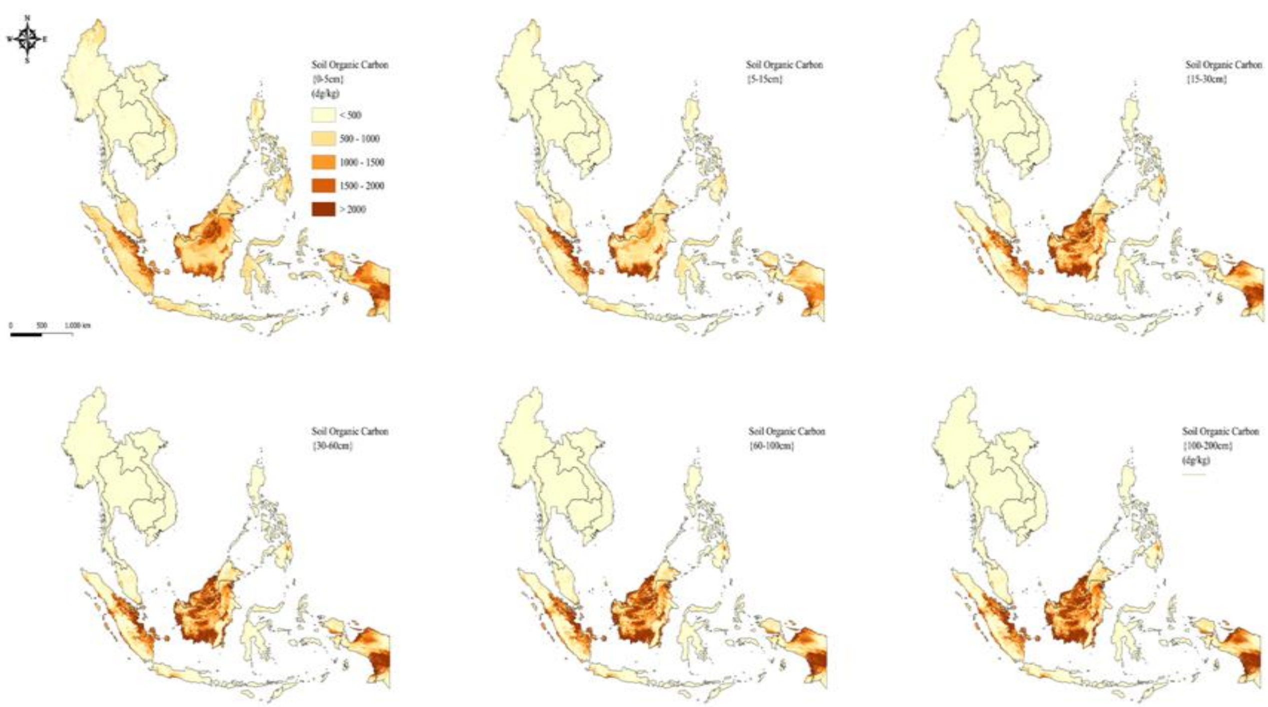

Figure 4. Spatial distribution analysis of SOC over tropical climate Asia

3.4 Soil density

The spatial variability of soil physical conditions among sites and underscores the importance of maintaining low bulk density, particularly in the rooting zone, for sustainable land management and ecosystem services. Figure 5 shows that the spatial distribution of bulk density (BD) over tropical climate Asia countries at varying soil depths: 0–5 cm, 5–15 cm, 15–30 cm, 30–60 cm, 60–100 cm, and 100–200 cm. Bulk density, expressed in kg/m³, is a key physical property that influences root penetration, water infiltration, and soil aeration. Higher BD values typically indicate soil compaction, reduced porosity, and impaired root growth, while lower BD values are generally associated with higher organic matter and better soil structure (Wang *et al.,* 2022).

The locations with low BD (< 85 kg/m³) are predominantly found in coastal and lowland peatlands, especially in Sumatra, Kalimantan, and Papua. These areas are rich in organic matter, which contributes to lower density and higher porosity (Guo *et al.,* 2024). Conversely, higher BD values (> 114 kg/m³) are observed in northern mainland Southeast Asia, such as Thailand, Laos, and parts of Vietnam, particularly at deeper depths. This pattern may be attributed to lower organic matter content (Qiu *et al.,* 2015).

The relationship between soil bulk density (kg/m³) and soil depth (cm) across six sites: Chiem Hoa, Chanthaburi, Kutai Kartanegara, Fak Fak, East Lampung, and Gunung Kidul. Overall, bulk density tends to increase with depth, a trend consistent with recent findings in soil studies (Panagos *et al.,* 2024). At surface layers (0–20 cm), lower bulk densities are observed, particularly in Kutai Kartanegara and Gunung Kidul, with values around 110–120 kg/m³. This reflects higher organic matter content and greater soil porosity near the surface, typical in less compacted soils (Topa *et al.,* 2021). As depth increases, soils become denser, reaching values up to 140 kg/m³ in deeper layers, notably in Chiem Hoa. Increased bulk density with depth is often due to reduced organic matter, greater soil compaction, and finer particle arrangement (Yang *et al.,* 2022).

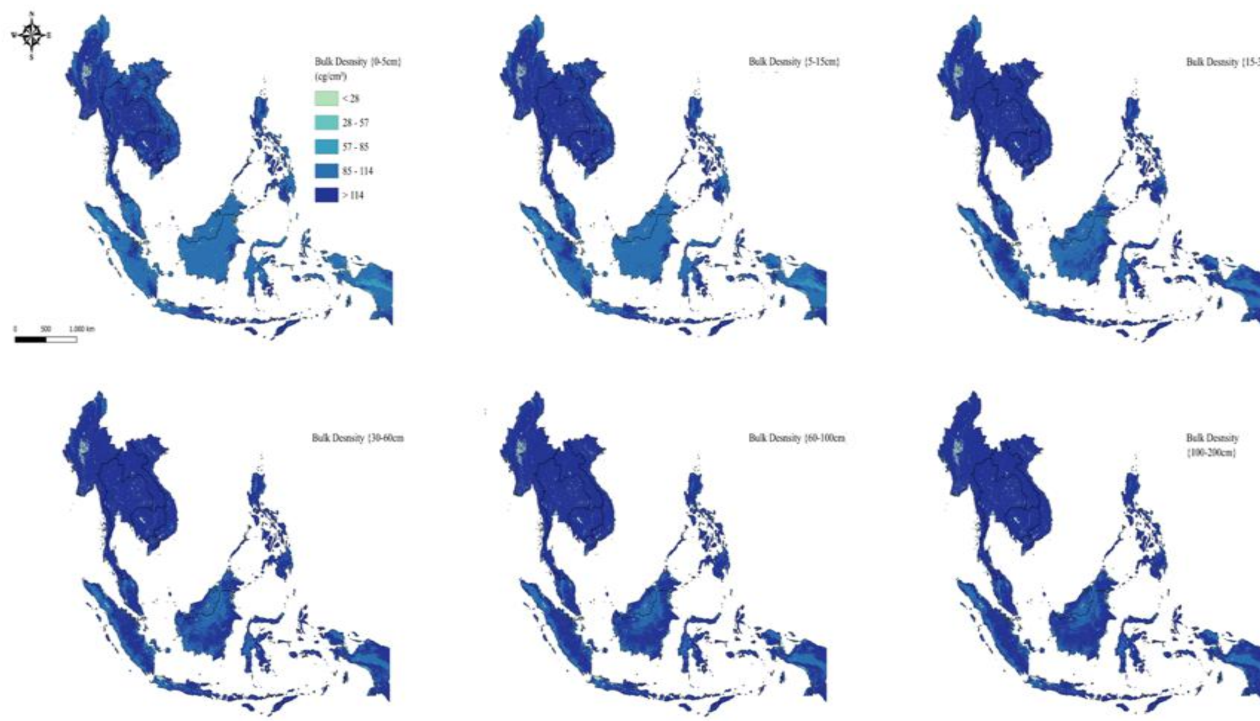

Figure 5. Spatial distribution of soil bulk density in various soil depth

3.5 Nitrogen content

Figure 6. presents the spatial distribution of soil nitrogen (N) content (cg/kg) across Southeast Asia, from surface (0–5 cm) to subsoil layers (100–200 cm). The topsoil (0–5 cm) map reveals high nitrogen concentrations (> 4200 cg/kg) in forested and peat-rich areas such as Borneo, Sumatra, and parts of Papua. These regions are characterized by dense vegetation, high litterfall, and organic matter accumulation, which contribute to greater nitrogen retention in the surface layers (Yeung *et al.,* 2025). In contrast, lower N values (≤ 1400 cg/kg) are observed in drier or intensively cultivated areas of mainland Southeast Asia, including Thailand and parts of Vietnam, where nitrogen is often depleted due to leaching, volatilization, or overextraction by crops (Guan *et al.,* 2023).

The relationship between nitrogen (N) content (mg/kg) and soil depth (cm) across six locations: Chiem Hoa, Chanthaburi, Kutai Kartanegara, Fak Fak, East Lampung, and Gunung Kidul. The general trend observed is a decrease in nitrogen content with increasing soil depth, which aligns with recent studies emphasizing nutrient stratification in soil profiles (Wang *et al.,* 2022). At surface layers (0–20 cm), nitrogen content is highest, particularly in Chiem Hoa and Chanthaburi, where values approach or exceed 2800 mg/kg.

Surface accumulation of nitrogen is commonly attributed to higher organic matter inputs, root activity, and microbial biomass concentration (Zhang *et al.,* 2024). As soil depth increases (60–140 cm), nitrogen levels decline significantly, with Kutai Kartanegara and East Lampung showing a steeper decrease. This suggests limited nitrogen movement to deeper layers, likely due to strong immobilization in the topsoil or limited vertical water transport (Qiao *et al.,* 2018).

The decreasing nitrogen trend highlights the importance of surface soil management for maintaining soil fertility. Understanding the vertical distribution of nitrogen is crucial not only for nutrient management but also for mitigating environmental issues like nitrate leaching and groundwater contamination, which have become pressing concerns under changing climate conditions (Huang *et al.,* 2021).

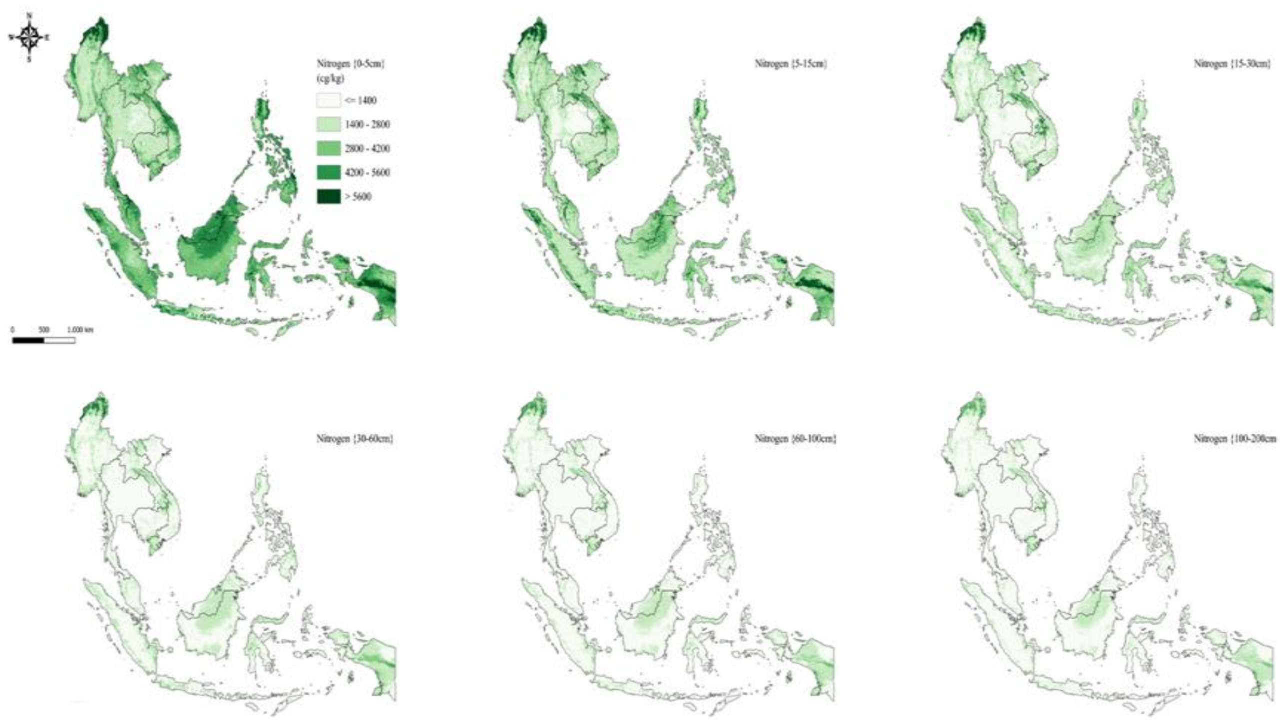

Figure 6. Spatial distribution of soil total nitrogen within the various of soil depth

3.6 Interaction of each parameter

This Figure 7 shows that four vertical profile plots in some parts area (Chiem Hoa, Chanthaburi, Kutai Kartanegara, Fak Fak, East Lampung, and Gunung Kidul) showing changes in soil chemical properties with depth (from 0 to 150 cm). In addition, the correlation matrix shows the relationships among various soil properties across different depths as shown in Figure 8. Soil organic carbon (SOC) content shows strong positive correlations with total nitrogen (N) across all depths ($r > 0.8$), a relationship widely documented in soil science (Yeung *et al.,* 2025). Bulk density (BD) generally shows moderate to strong negative correlations with SOC and nitrogen ($r \approx -0.5$ to -0.8). Soils with higher organic matter tend to have lower bulk densities due to increased porosity and aggregation (Crnobrna *et al.,* 2022).

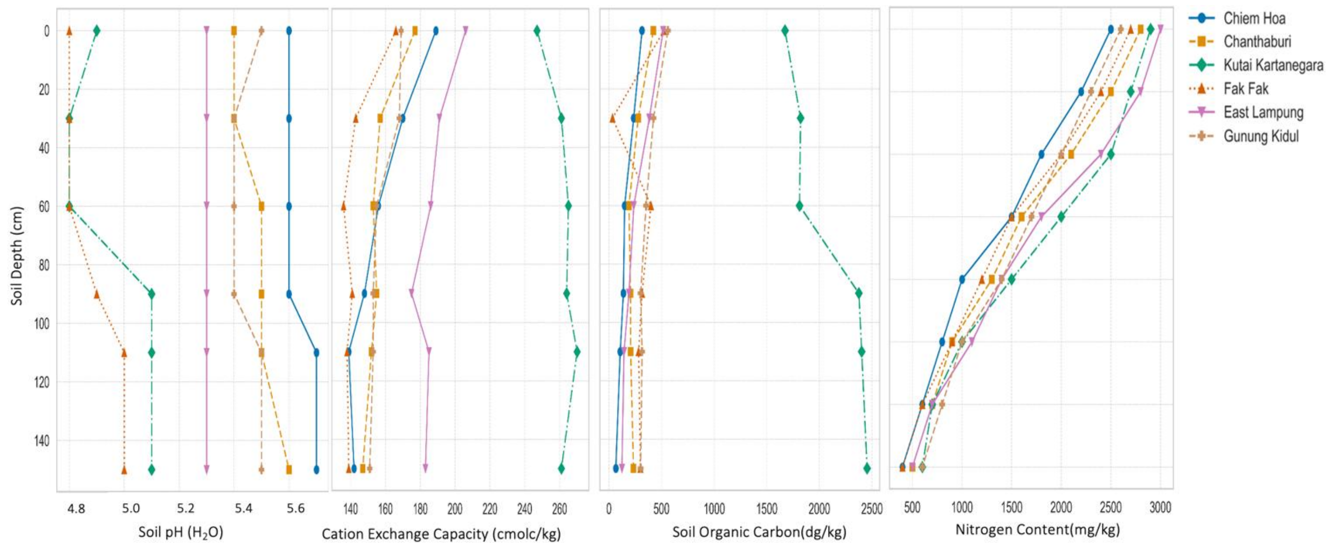

Figure 7. Vertical distribution soil chemical properties in the various soil depth

Interestingly, certain depths show weaker or even slightly positive correlations between BD and nutrient contents. Another notable observation is the strong inter-correlation among soil chemical parameters within the topsoil layers (0–40 cm), gradually weakening with depth. In contrast, deeper layers tend to be more stable, with slower nutrient turnover and less interaction between parameters. The negative correlations among some parameters, especially involving bulk density and chemical properties, are critical when considering land management practices. For instance, intensive agricultural practices that increase compaction can severely reduce SOC and nitrogen stocks (Abdelrahman *et al.*, 2020). The correlation matrix can guide future modeling efforts and provides crucial insights into the interconnectedness of soil physical and chemical properties. High SOC and nitrogen levels are associated with better soil structure (lower BD), especially in surface horizons.

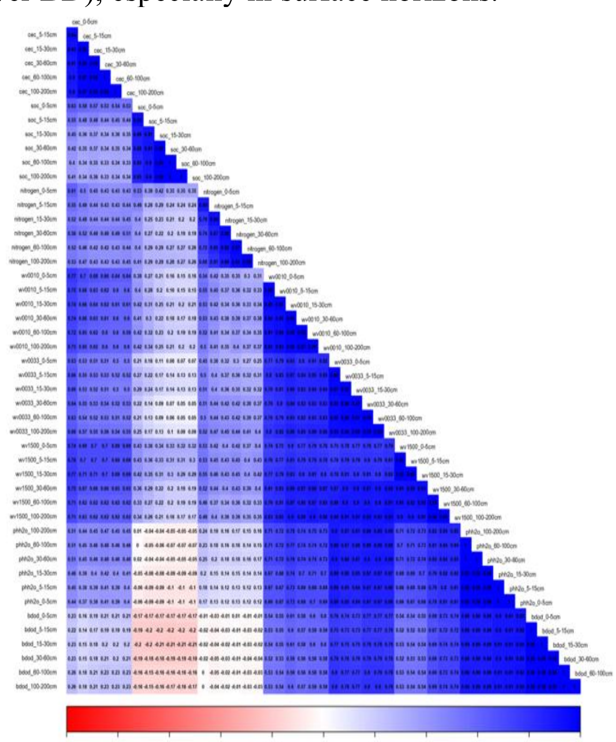

Figure 8. Correlation coefficients matrix of Pearson's correlation analysis of soil properties

4. Conclusions

This study highlights the spatial and vertical variability of key soil properties—pH, CEC, SOC, bulk density (BD), and nitrogen (N)—across tropical climate Asia, with significant implications for sustainable agriculture. Soils are generally moderately to slightly acidic, with lower pH observed in regions like Indonesia and Papua, where targeted management is essential. Cation Exchange Capacity (CEC) is higher in northern areas and surface layers, supporting nutrient retention and buffering capacity. Soil Organic Carbon (SOC) and nitrogen concentrations are highest at the surface, especially in forested regions, and decline with depth, emphasizing the importance of topsoil conservation. Bulk density increases with depth and shows a strong negative correlation with SOC and N, linking soil structure to fertility. These interconnected properties underscore the need for integrated land management strategies—such as organic matter application and reduced tillage—to enhance soil health, support crop productivity, and build resilience under changing climatic conditions.

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