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Whether Digital Soil Mapping Products May Fulfil the Requirement of Soil Testing Services to Farmers for Sustainable Nutrient Management in Agricultural Croplands of West Bengal?

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ABSTRACT

Digital soil maps may be a potential tool to enable farmers to apply right amount of fertilizers in their field. It is highly appropriate in the recent era of digital applications when our every activity of life is entangled with digital applications and solutions. Farmers of the country are also capable of handling these digital tools because of intensive use of smartphone even by small and marginal farmers. With this background, a case study application of digital soil map of available nitrogen (N), phosphorus (P) and potassium (K) content is presented here. For this purpose, 169 spatially distributed soil samples were used for which available N, P and K were measured through conventional soil testing procedures. Spatial variation parameters (nugget, sill and range) of N, P and K content were calculated through fitting semivariogram models. Further, these spatial variation parameters were used to prepare digital maps of N, P and K content in West Bengal through ordinary kriging approach. The accuracy of the developed maps were checked through 10-fold cross validation. Although the accuracy of the developed maps was not satisfactory due to limited number of samples but this may be improved by increasing number of sampling locations and by applying advanced digital soil mapping and modelling tools. Such digital maps of N, P and K content may help farmers for sustainable nutrient management and fertilizer use.

Keywords : Digital soil map, Available NPK, West Bengal, Sustainable soil management

Introduction

Digital Soil Mapping (DSM) has emerged as a powerful approach for generating spatially explicit soil information by integrating field and laboratory observations with spatial and non-spatial inference systems (Martinez-Graña *et al.*, 2016). Unlike conventional soil survey methods, which are time-consuming, costly, and often limited in

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spatial coverage and resolution, DSM enables the prediction of soil properties across continuous landscapes using a relatively limited number of soil samples (Santra *et al.*, 2017). In DSM, point-based observations of soil properties are interpolated to produce a spatial datasets, thereby enhancing the accessibility and applicability of soil information for land-use planning and agricultural management (Malone *et al.*, 2017). This approach holds particular promise for regions where comprehensive soil testing services are constrained by logistical and financial limitations.

Soil nutrients, especially nitrogen (N), phosphorus (P), and potassium (K), are key determinants of soil quality, crop productivity, and sustainable agricultural systems (Gao *et al.*, 2021; Van Der Westhuizen *et al*, 2023). Their spatial variability is influenced by factors such as parent material, land use, management practices, and topography. Mapping this variability accurately is essential for site-specific nutrient management and for optimizing fertilizer use efficiency (Panday *et al.*, 2018). A wide range of spatial interpolation techniques has been developed to address this challenge, broadly classified into deterministic and stochastic methods (Cambardella and Karlen, 1999). While deterministic methods such as inverse distance weighting and splines are simple to implement, they do not provide estimates of prediction uncertainty (Myers, 1994). In contrast, stochastic approaches, particularly geostatistical methods like kriging, not only generate unbiased predictions at unsampled locations but also quantify the associated uncertainty, making them more suitable for soil fertility assessment and decision-making (Singh *et al.*, 2016).

Kriging has been widely recognized as a robust geostatistical interpolation technique for mapping soil properties, as it accounts for spatial autocorrelation and provides statistically optimal estimates (Panday *et al.*, 2018; Singh *et al.*, 2016). By reducing the need for dense soil sampling without compromising prediction accuracy, DSM products derived from kriging can potentially lower the cost and effort associated with conventional soil testing services. However, the reliability of such products depends on the representativeness of sampling data and the accuracy of spatial interpolation models. In an agrarian state like West Bengal, where agriculture plays a vital role in livelihoods and food security, evaluating the capability of DSM products to substitute or complement traditional soil testing services is of critical importance (Chatterjee *et al.*, 2014). Therefore, the objective of this study is to determine and map the spatial variability of nitrogen (N), phosphorus (P), and potassium (K) in the agricultural croplands of West Bengal. Accurate information on the spatial distribution of soil nutrients is essential for effective soil fertility management and for assessing whether digital soil mapping products can fulfil the requirements of conventional soil testing services and support sustainable nutrient management. As India's economy relies heavily on agriculture, any advancement in soil mapping technologies has the potential to substantially benefit farmers by enabling informed, site-specific nutrient management practices.

Materials and Methods

Study area

The study was carried out in West Bengal, situated in the eastern part of India, stands out as one of the predominantly agrarian states in the country. It spans from approximately 21°31′ north to 27°13′ 14″ north latitude and 85°45′ east to 89°53′ east longitude (Figure 1). West Bengal has six agro-climatic zones and proffers a diverse range of conditions suitable for production of agricultural and horticultural produce. West Bengal exhibits a tropical to humid subtropical climate with distinct seasonal variability, ranging from Himalayan foothills in the north to coastal plains in the south. The state is dominated by fertile alluvial soils of the Gangetic plains, supporting intensive agriculture primarily rice, along with jute, potato, mustard, pulses, and tea across six agro-climatic zones. However, agricultural productivity is constrained in some regions by erratic monsoon rainfall, flooding, and soil-related issues such as salinity, acidity, and nutrient depletion.

Soil sampling and laboratory analysis

Surface soil samples (0–15 cm depth) were collected from 169 locations across nineteen districts of West Bengal, ensuring representative coverage of the region's major soil types (Figure 1). The collected samples were air-dried, manually ground, and passed through a 2 mm sieve before being stored in plastic containers for subsequent laboratory analysis. The soil nitrogen, phosphorus and potassium estimated by following Subbiah and Asija (1956), Olsen (1954) and neutral normal ammonium acetate (NH_4OAc) (Hanway and Heidel, 1952) method respectively.

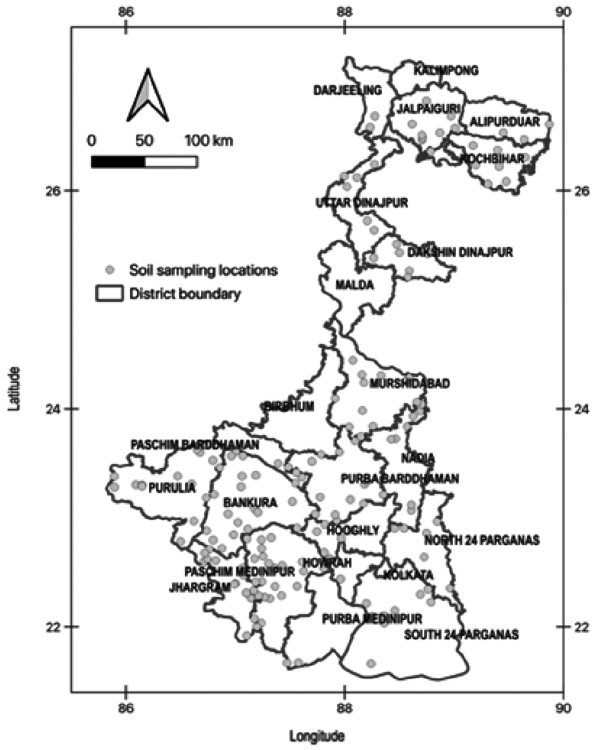

Figure 1. Location of soil sampling points in West Bengal

Semi-variogram modelling

Spatial variation of N, P, and K content within West Bengal was determined through semi-variogram, $\gamma(h)$, which measures the average dissimilarity between the data separated by a vector h (Goovaerts, 1998; Webster and Oliver, 2007).

$$\gamma(h) = \frac{1}{2N(h)}\sum_{i=1}^{N(h)}[Z(S_i) - Z(S_i + h)]^2 \quad (1)$$

where, $N(h)$ is the number of data pairs within a given class of distance and direction, $Z(S_i)$ is the value of the variable at the location S_i with coordinates of (xi, yi), $Z(Si + h)$ is the value of the variable at a lag of h from the location S_i. Experimental semi-variograms $\gamma(h)$ as obtained from Equation (1) were fitted in standard model using weighted least square technique and three standard spatial variations parameters were calculated: nugget (C_0), sill $(C + C_0)$ and range (*a*). Weight was assigned as directly proportional to number of pairs and inversely proportional to lag distance. All geostatistical analyses were carried out using the 'gstat' package of R (Pebesma, 2003).

Four commonly used semi-variogram models, e.g., Gaussian, spherical, exponential, and Matern models were fitted. The model with lowest sum of squared error (SSE) was selected as the best fit model, the methodology in detail described in (Santra *et al.*, 2017).

Digital soil mapping

Ordinary kriging (OK)

Surface maps of N, P, and K were prepared using the semi-variogram parameters through ordinary kriging. The range is the distance at which the spatial dependence disappears, and the sill value correlates with the maximum distribution in lack of spatial correlation. OK estimates of soil attributes at unknown locations, $Z(S_0)$, are made using weighted linear combinations of known soil attributes $Z(S_i)$ located within a neighborhood centered around S_0 (Webster and Oliver, 2007).

$$Z(S_0) = \sum_{i=1}^{n(S_0)} \lambda_i \, Z(S_i) \quad (2)$$

where λ_i is the weight assigned to datum $Z(S_i)$ located within a given neighbourhood centered on S_0. Weights for n number of neighbourhood points were chosen as such so as to minimize the estimation or error variance under the constraint of no-bias of the estimator. The kriged map was prepared using krige() function of 'gstat' package of R (Pebesma, 2003). The resolution of prediction grid was kept 1 km × 1 km.

Results and discussion

Descriptive statistics of soil macro-nutrient contents in West Bengal

Available nitrogen (N) content shows substantial variability, ranging from ~125 to 753 kg ha^{-1}, with higher values predominantly observed in the alluvial plains of North 24 Parganas and comparatively lower levels in parts of northern districts. Available phosphorus (P) exhibits a wide spread (~1 to 215 kg ha^{-1}), reflecting pronounced management- and soil-controlled variability, with several locations showing critically low P status. Available potassium (K) demonstrates the largest dispersion, ranging from ~25 to over 2100 kg ha^{-1}, indicating strong influence of parent material and textural differences (Figure 2).

Spatial variation of soil macro-nutrients contents in West Bengal

The figure 3 presents frequency histograms of soil macronutrients across the study area. The available N is broadly distributed, with most observations concentrated between 250–450 kg ha^{-1} and a right-skewed tail extending toward higher values, indicating substantial variability (Figure 5a). The available P content, which is strongly right-skewed, with a high frequency of samples in the low P range

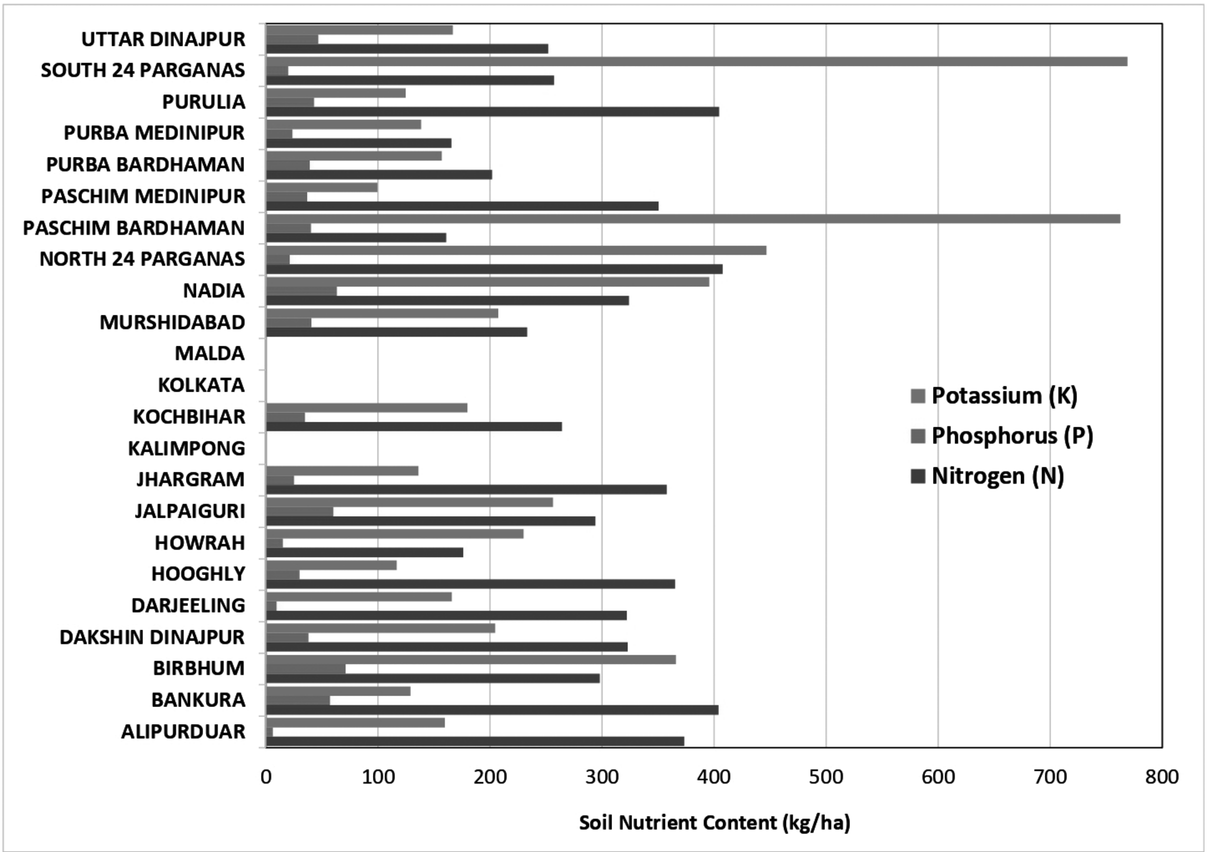

Figure 2. Average contents of nitrogen, phosphorus and potassium contents in different districts of West Bengal

(≤40 kg ha^{-1}), suggesting widespread P deficiency (Figure 5b). The Figure 5c depicts available K, where most values cluster around 100–200 kg ha^{-1}, but with a noticeable right tail reflecting a smaller number of sites with elevated K status. Overall, the histograms highlight non-normal, skewed distributions and pronounced heterogeneity in soil nutrient availability.

Semi variogram modelling

Figure 4 illustrates the experimental semivariograms and fitted theoretical models for soil N, P, and K across districts of West Bengal, highlighting distinct spatial dependence structures. Nitrogen is best described by a spherical model with a moderate sill and a range of ~103 km, indicating moderate spatial continuity beyond short-range nugget effects. Phosphorus also follows a spherical model but with a shorter range (~74 km) and a relatively higher nugget-to-sill ratio, suggesting stronger microscale variability and management influence. In contrast, potassium fits a Gaussian model with a large range (~189 km), implying stronger and smoother spatial continuity, likely controlled by parent material and regional-scale soil-forming processes.

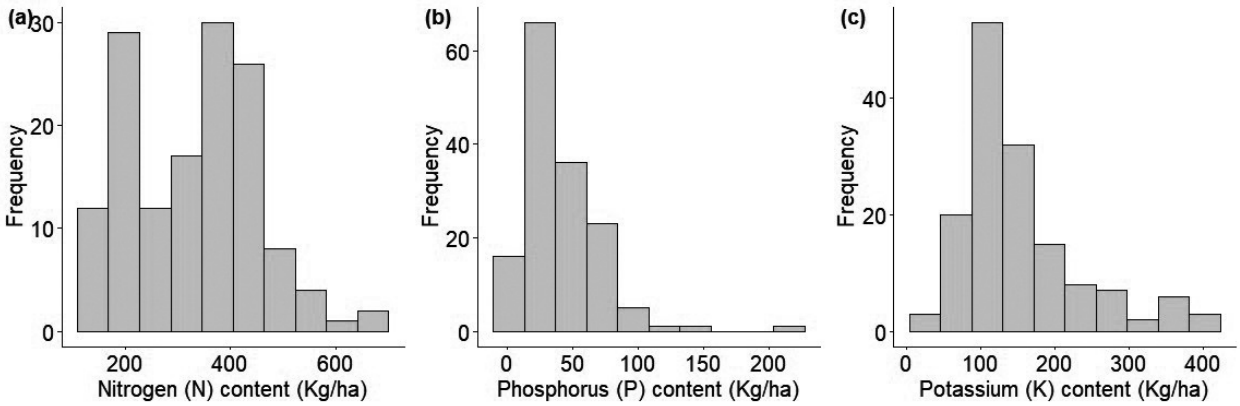

Figure 3. Histogram of soil nitrogen, phosphorus and potassium contents in different districts of West Bengal

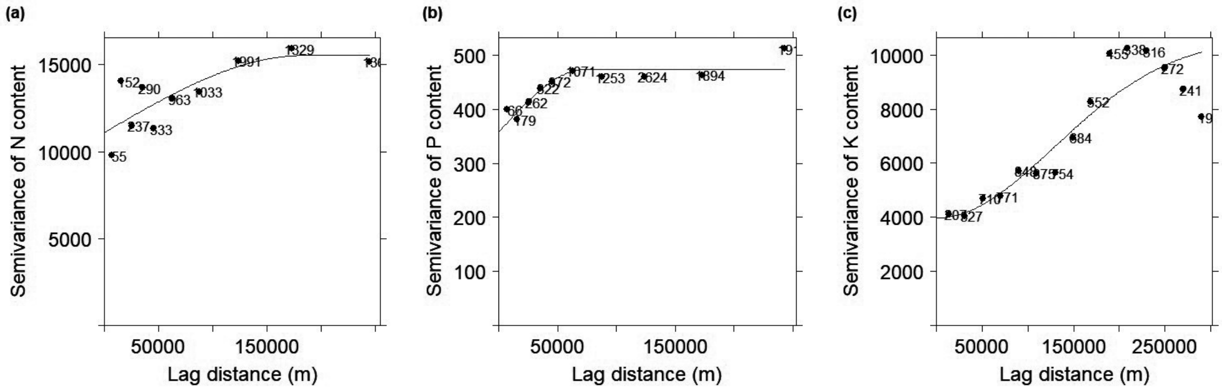

Figure 4. Semi variogram describing the spatial variation of soil nitrogen, phosphorus and potassium contents in different districts of West Bengal

Digital soil map of available nitrogen (N) content in West Bengal

A pronounced spatial variability in soil nitrogen content was observed across the state, with concentrations ranging from 220 to 420 kg ha^{-1}. Nevertheless, most of the agricultural area is characterized by medium nitrogen status (240–480 kg ha^{-1}). In the Purba Bardhaman district, isolated pockets exhibited low nitrogen levels (<240 kg ha^{-1}), suggesting the presence of localized nutrient limitations that warrant site-specific management interventions (Figure 5). Model validation yielded a Lin's concordance correlation coefficient (LCC) of 0.28 and a root mean square error (RMSE) of 108 kg ha^{-1}, indicating moderate agreement between observed and predicted nitrogen values.

Digital soil map of available phosphorus (P) content in West Bengal

A marked spatial variability in soil phosphorus content was observed across the state, with values ranging from 20 to

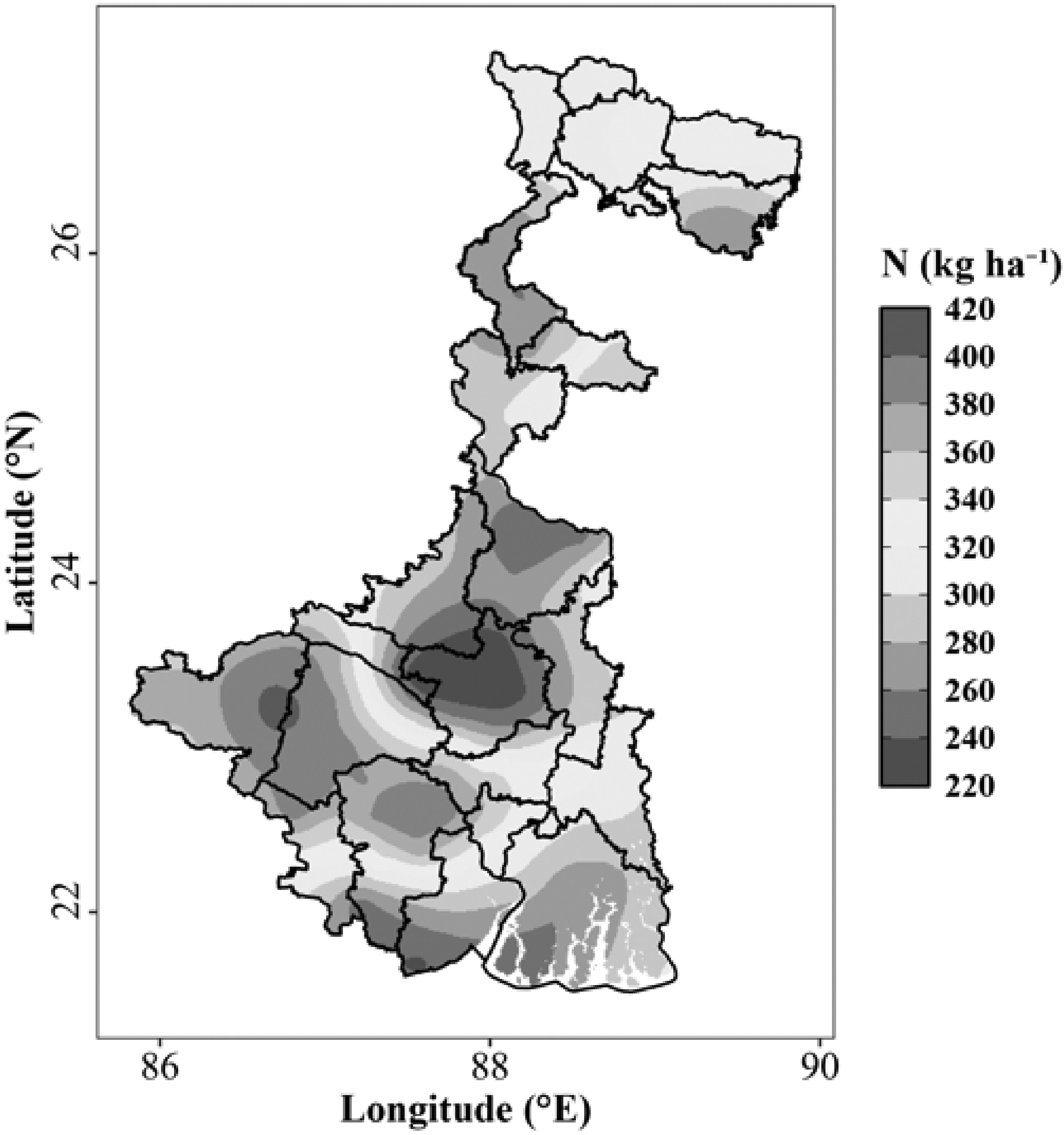

Figure 5. Digital soil map of available nitrogen (N) content in West Bengal

55 kg ha^{-1}. The majority of the agricultural area exhibited high phosphorus status (>22 kg ha^{-1}); however, parts of the South 24 Parganas district were characterized by medium phosphorus levels (11–22 kg ha^{-1}), indicating localized variability in nutrient availability (Figure 6). Model validation resulted in a Lin's concordance correlation coefficient (LCC) of 0.09 and a root mean square error (RMSE) of 21.47 kg ha^{-1}, reflecting low agreement between observed and predicted phosphorus values.

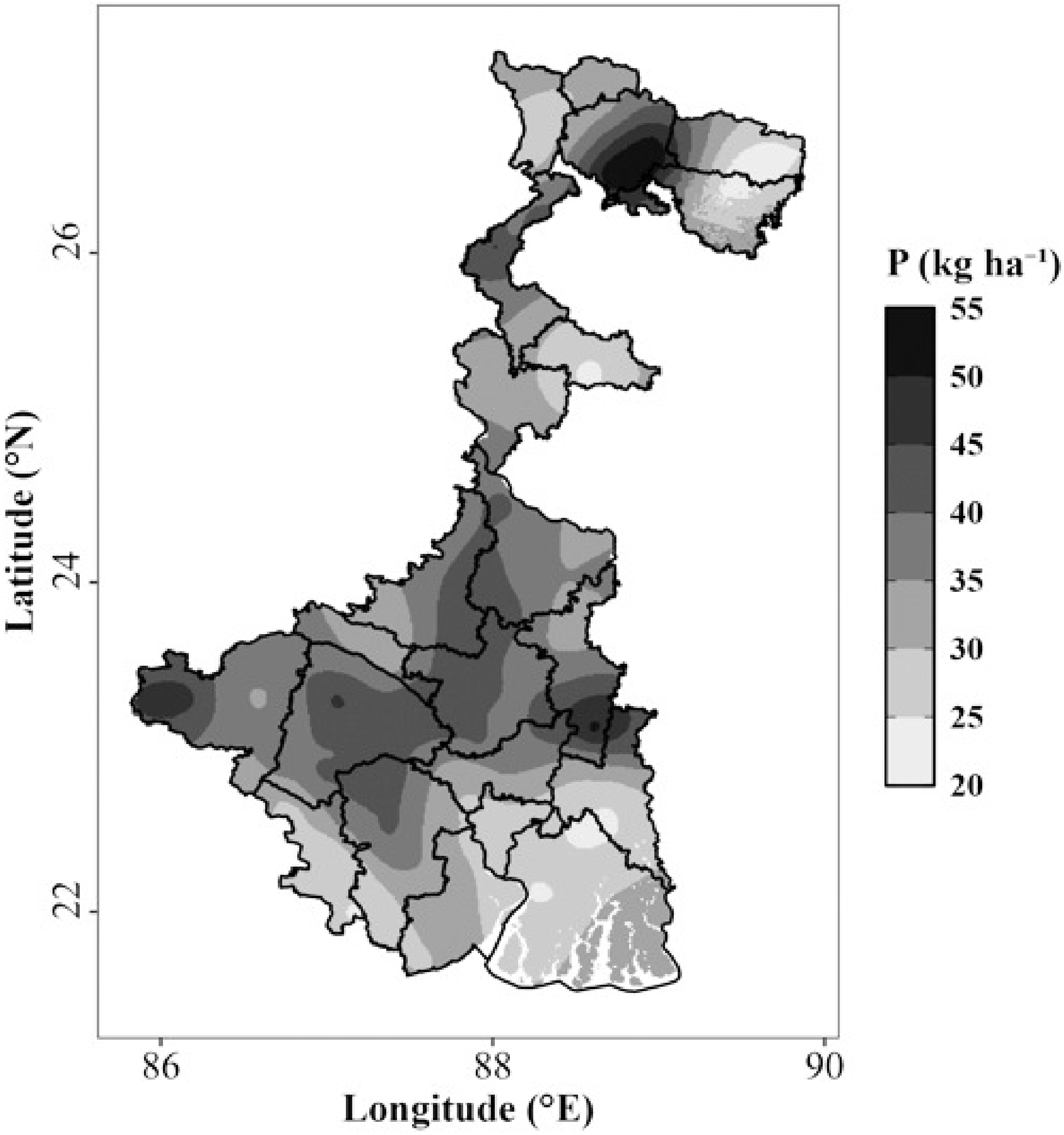

Figure 6. Digital soil map of available phosphorus (P) content in West Bengal

Digital soil map of available potassium (K) content in West Bengal

A pronounced spatial variability in soil potassium content was observed across the state, with concentrations ranging from 100 to 250 kg ha^{-1}. Most of the agricultural area was characterized by high to medium potassium status (110–250 kg ha^{-1}) across the state (Figure 7). Model validation yielded a Lin's concordance correlation coefficient (LCC) of 0.18 and a root mean square error (RMSE) of 72 kg ha^{-1}, indicating low agreement between observed and predicted potassium values.

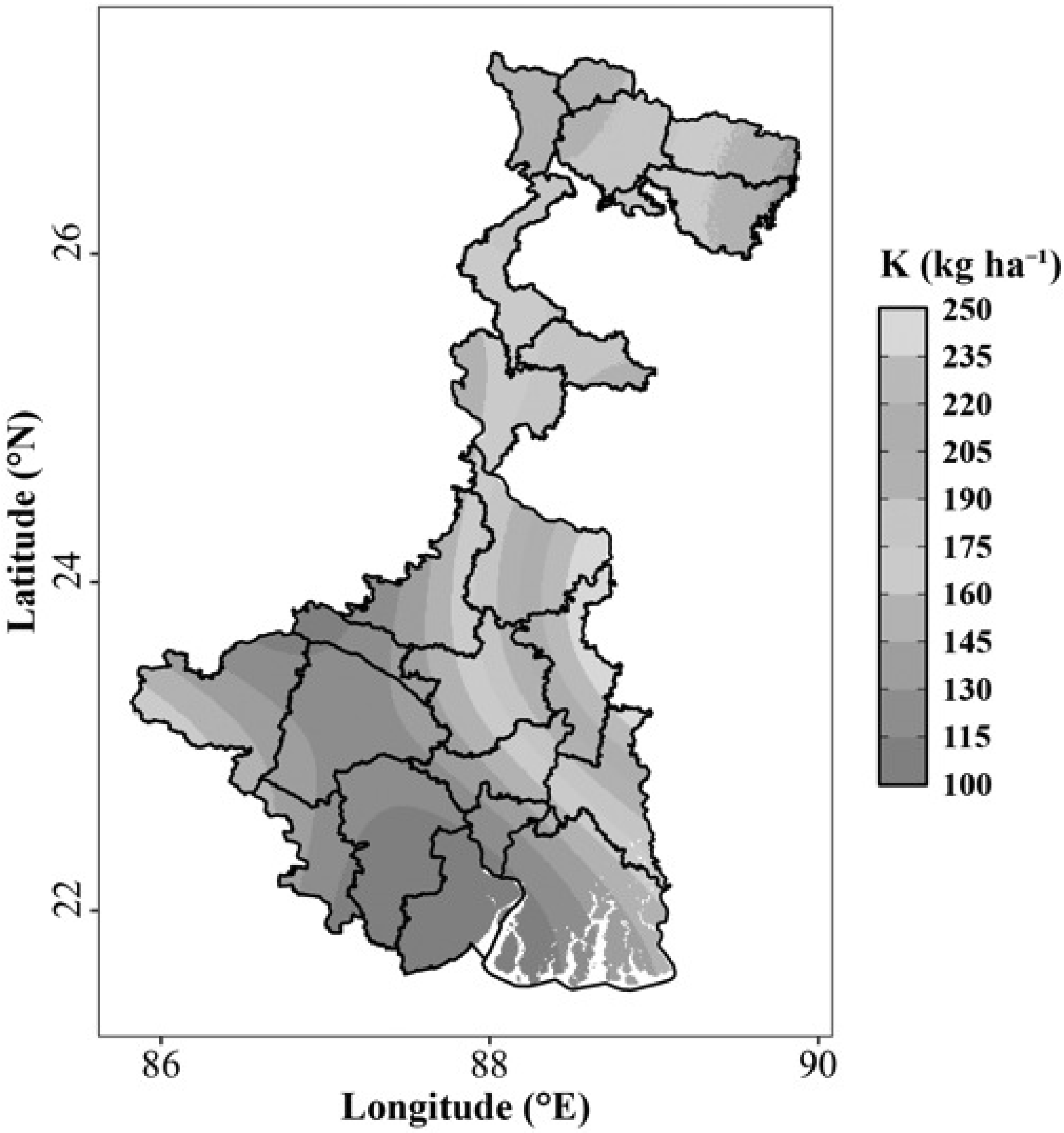

Figure 7. Digital soil map of available potassium (K) content in West Bengal

Average macronutrient content in West Bengal and sustainable nutrient management

West Bengal boasts a high cropping intensity, often exceeding 170-180%, due to its rich alluvial soils, high irrigation potential, and favourable wet climate, with recent technology interventions boosting intensity even further for smallholders. Cropping pattern in the state is primarily driven by rice, especially aman (*kharif*) rice, but is shifting towards more lucrative crops like potatoes, pulses, maize, oilseeds (mustard), jute, and high-value horticultural produces due to economic factors and changing demands. Major horticultural crops include fruits like mango, litchi, pineapple, and banana etc, vegetables such as potato, cabbage, carrot, cucumber, and eggplant etc, and flowers like rose, tuberose, and gladiolus, alongside spices, medicinal plants, and mushrooms, reflecting a diversification towards high-value crops in recent decades, supported by favourable agro-climatic conditions. Recent data suggests around 5.8 million hectares under rice in West Bengal, with average productivity of 2.6 tonnes/ha with a total production of 15.687 million tonnes, which is about 11.38% of India's total rice production.

Fertilizer use in West Bengal has significantly increased, driven by high-yielding crop cultivation, with total consumption rising from ~1.54 million tonnes (2021-22) to ~1.615 million tonnes (2022-23), though specific nutrient trends vary, showing fluctuations like a decrease in potash usage in 2022 compared to 2021. Urea is the most dominant fertilizer used in West Bengal, serving as the primary source of nitrogen for the state's intensive agricultural practices. Di-ammonium Phosphate (DAP) is extensively used for meeting the need for P, particularly during the early stages of crop growth whereas muriate of potash (MOP) is used to meet K requirements. Complex fertilizers like NPK 12-32-16 (DAP-based) are popular for balancing P and K, while water-soluble NPK 19-19-19 or 20-20-20 offer balanced foliar/drip applications. A high portion of the fertilizer consumption (approximately 65%) occurs during the *rabi* (winter) season, with the remaining 35% used in the *Kharif* (monsoon) season. Rice, jute, potato, and vegetables are the major crops consuming these fertilizers. The state shows high reliance on NPK fertilizers, especially for rice, but research highlights the need for balanced use, linking increased application to better yields. In this context, information on N, P, K contents to farmers may help in balanced use of fertilizer and digital soil maps prepared in this study will provide such information. For example, average content of N, P and K in soils of different districts of West Bengal as extracted from digital soil maps is shown in Table 1.

Table 1. Available soil nitrogen (N), phosphorus (P) and potassium (K) content in each district of West Bengal as estimated in digital soil maps

District	**Nitrogen (kg ha^{-1})**	**Phosphorus (kg ha^{-1})**	**Potassium (kg ha^{-1})**
Alipurduar	325 (301-338)	30 (22-49)	159 (139-179)
Bankura	360 (249-404)	40 (32-46)	127 (112-148)
Birbhum	272 (224-333)	39 (32-45)	150 (111-183)
Dakshin Dinajpur	320 (275-352)	28 (24-32)	184 (170-200)
Darjeeling	307 (298-312)	30 (27-35)	196 (189-200)
Hooghly	331 (259-382)	35 (28-47)	154 (121-210)
Howrah	337 (305-373)	28 (27-32)	128 (109-155)

Jalpaiguri	319 (307-330)	43 (30-54)	186 (172-196)
Jhargram	332 (251-392)	29 (25-39)	126 (105-152)
Kalimpong	311 (307-317)	32 (30-36)	194 (188-198)
Kochbihar	292 (262-327)	32 (22-52)	160 (139-183)
Kolkata	312 (303-324)	26 (25-28)	146 (136-155)
Malda	297 (274-329)	33 (26-38)	168 (147-192)
Murshidabad	266 (244-313)	38 (31-45)	205 (152-253)
Nadia	290 (244-333)	39 (33-51)	225 (184-260)
North 24 Parganas	306 (282-336)	32 (24-48)	191 (152-250)
Paschim Bardhaman	309 (226-373)	35 (32-43)	121 (103-148)
Paschim Medinipur	344 (245-398)	35 (25-44)	111 (96-126)
Purba Bardhaman	248 (221-340)	40 (34-45)	170 (133-218)
Purba Medinipur	285 (237-379)	30 (26-34)	99 (93-117)
Purulia	379 (351-405)	39 (32-47)	141 (110-174)
South 24 Parganas	280 (250-327)	29 (24-35)	133 (99-170)
Uttar Dinajpur	274 (259-305)	38 (30-45)	174 (164-190)

Available N content is found highest in Purulia district with an average value of 379 kg ha^{-1}, followed by Bankura (360 kg ha^{-1}) and Paschim Medinipur (344 kg ha^{-1}). Lowest N content was found in Purba Bardhaman district with average content of 248 kg ha^{-1}. If we consider the soil fertility rating of available N content (Low: <240 kg ha^{-1}, Medium: 240-480 kg ha^{-1} and High: >480 kg ha^{-1}), Purulia, Bankura and Paschim Medinipur district lies in medium category whereas Purba Medinipur district falls in the lower borderline of medium category. Cropping intensity in Purulia district is relatively low as compared to the West Bengal state average, with studies showing significant portions of land under single cropping and limited double/triple cropping. In contrast, cropping intensity in Purba Bardhaman district, a highly irrigated district in West Bengal, is generally high, often exceeding 180%, driven by extensive paddy cultivation (97% of gross cultivated area) and multi-cropping patterns like paddy-wheat-vegetables, with irrigation from the Damodar Valley Corporation (DVC) being a key enabler. This intensive cultivation in Purba Bardhaman district leads to higher crop intake of N and decrease in soil fertility. Available phosphorus content was found highest in Jalpaiguri district with an average content of 43 kg ha^{-1} and lowest in Kolkata district (26 kg ha^{-1}). Considering the soil fertility rating chart of P (Low: <11 kg ha^{-1}, Medium: 11-22 kg ha^{-1} and High: >22 kg ha^{-1}), all districts in West Bengal lie in high category of P content. Availble K content is highest in Nadia district (245 kg ha^{-1}) and low in Purba Medinipur district (99 kg ha^{-1}). Fertility rating chart of K (Low: <110 kg ha^{-1}, Medium: 110-280 kg ha^{-1} and High: >280 kg ha^{-1}) indicates that soil K content is medium in category for almost all districts of West Bengal except Purba Medinipur and Paschim Medinipur.

Sustainable nutrient management in agricultural fields requires knowledge on soil test values and accordingly right amount of fertilizer may be applied. To know the soil test values, farmers often depend on soil testing laboratories, which is time consuming and tedious in most cases because of limited availability of nearby soil testing laboratories and pressure of large number of farmers. Although efforts have been initiated by Govt of West Bengal to implement the mobile laboratories and mini laboratories at village levels, however, this often does not fulfil the demand by farmers. Under such situation, if digital soil maps are made available on digital platform e.g. android application in smartphone, farmers may know the real estimate of soil nutrient content of their respective fields. The accuracy of these digital soil maps may be improved by increasing the number of soil sampling locations. Moreover, these digital soil maps may be updated at a regular interval for increasing the reliability of the product. Under the digital agriculture mission and with the availability of huge information on different earth features affecting soil processes, the task of preparing the digital soil maps has become easy using advanced data computation tools.

Conclusion

Digital maps of soil nutrient content may play a key role in sustainable management of nutrient by farmers. Such maps may be prepared by knowing the spatial variation pattern from a selected number of spatially distributed samples within a region. More dense is the sampling location, higher will be the accuracy of developed digital soil maps. In this study, such digital maps of soil available N, P and K content in West Bengal were prepared through geostatistical approach (semivariogram fitting followed by ordinary kriging). Although the accuracy of the developed maps in this study was not highly reliable, however, it shows a spatial pattern of N, P and K content to judge the comparatives among different districts of West Bengal. Reliability of digital maps may be further improved by incorporating large number of samples and by applying advanced digital soil mapping and modelling tools. Therefore, the efforts of different soil testing laboratories in West Bengal state may be integrated together to a large spatially distributed soil dataset which may help in developing suitable digital soil maps for right application by the farmers.

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