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Spatial variability of some soil properties in west coastal area of India having oil palm (*Elaeis guineensis* Jacq.) plantations

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Running title: Soil property distribution in oil palm plantations of coastal India

Abstract. Mapping spatial variability of soil properties is the key to efficient soil resource management for sustainable crop yield in coastal areas. Therefore, the present study was conducted to assess the spatial variability of soil properties like – acidity (pH), salinity (Electrical Conductivity (EC)), organic carbon, available K, available P, exchangeable Ca^{2+}, exchangeable Mg^{2+}, available S and hot water soluble B in surface (0-20 cm) and subsurface (20-40 cm) soil layers of oil palm plantations in south Goa and north Goa districts of Goa situated in west coastal area of India. A total of 128 soil samples were collected from 64 oil palm plantations of Goa located at an approximate interval of 5-7 km and analyzed. Soil was acidic to neutral in reaction. Other soil properties varied widely in both the soil layers. Correlations between soil pH and exchangeable Ca^{2+}, between soil EC and available K, between available P and available S and between exchangeable Ca^{2+} and exchangeable Mg^{2+} in both the soil layers were found to be positive and significant ($P = 0.01$). Geostatistical analysis revealed different spatial distribution pattern for the measured soil properties. Best fit models of measured soil properties were spherical, linear, exponential, circular and Gaussian with weak to strong spatial dependency. The results revealed that site-specific fertilizer management options needed to be adopted in the oil palm plantations of the study area owing to variability in soil properties.

Keywords: Soil management, Spatial distribution, Precision agriculture, Soil fertility, Coastal zone

1 Introduction

Soil is the key part of the earth system which controls hydrological, biological, and geochemical cycles and it offers goods, resources and services to mankind (Keesstra et al., 2012; Smith et al., 2015; Decock et al., 2015; Brevik et al., 2015; Berendse et al., 2015). Un-sustainable soil management practices lead to soil degradation, which is a worldwide topic, mainly because of loss of soil organic matter (SOM), soil erosion, changes in soil structure, degradation of the biota in the soils and soil chemical degradation (Cerda et al., 2009; Mupenzi et al., 2011; Novara et al., 2013; Mukherjee et al., 2014 Lieskovsky and Kenderessy, 2014; Stanchi et al., 2015; Seutloali and Beckedahl, 2015; Novara et al., 2015;). Soil degradation along with natural processes results in degradation of coastal areas, which covers more than 10% of the earth surface area with 35, 6000 and 7517 km coast line in world and India respectively (Misdorp, 1990; Sanil Kumar et al., 2006). Therefore, there is a need to describe and characterize these areas for adoption of effective land use practices including application of agri-inputs (Arakel et al., 1993; Guneroglu et al., 2015).

Geographical distribution maps of soil properties, obtained from soil surveys, help in correct management of soil nutrients (Brevik et al., 2016). These maps are required to understand the patterns and processes of soil spatial variability, which is the combined effect of soil physical, chemical and biological processes operating at different spatio-temporal scales combined with anthropogenic activities (Goovaerts, 1998). The distribution maps are prepared by analysing spatial distribution pattern of soil properties. Geostatistical tools are useful in preparation of the maps based on limited number of samples collected from agricultural landscapes. These tools predict the values at un-sampled locations by spatial correlation and reducing variance of estimation error and investigation costs (Saito et al., 2005; Pereira et al., 2015). Spatial variability of soil properties is assessed effectively by geostatistical methods (Mueller et al., 2003) for site-specific management of nutrients through variable rate fertilizer application to avoid over and under application of nutrients. Li et al., 2011, Behera and Shukla, 2014 and Behera and Shukla, 2015 have reported different spatial variability pattern of soil properties and soil nutrients in eroded areas of south China and some cultivated acid soils of India. Information regarding variability of soil properties in soil profile is helpful to assess the contribution of sub-surface soil layers to crop nutrition and potential capacity of the soil to supply nutrients during crop growth. It also helps in understanding the effect of different management practices, under a given cropping system, on the downward movement as well as recycling of nutrients to the surface layers (Behera and Shukla, 2013, Parras-Alcantara et al., 2015).

Oil palm (*Elaeis guineensis* Jacq.) is a high oil yielding crop (Lamade et al., 2015). On average, it produces ten times more oil than any leading oil seed crop from a hectare of land and some efficient farmers get as high as eight tonnes of oil yield per hectare. World-wide, oil palm produces 32% oils and fats output from 5.5% land use for cultivation (Palm Oil Research, 2016). Indonesia and Malaysia are the leading producer of oil palm. According to Rethinam et al. (2012), oil palm can be cultivated as irrigated crop in 1.93 million ha area in 18 states of India. At present, oil palm is being grown in an area of about 2, 68, 000 ha covering twelve states of the country, having different soil types, with productivity levels reaching as high as 30-35 Mg fresh fruit bunches (FFB) ha^{-1} year^{-1} (Kalidas et al., 2015).

Rationale use of fertilizer results in environmentally sustainable and economically viable oil palm yield (Goh et al., 2003). Oil palm uses about 162, 30, 217, 38 and 36 kg of N, P, K, Mg and Ca ha^{-1} year^{-1} respectively, to produce 2.5 Mg of oil ha^{-1} year^{-1} (Mengel and Kirkby, 1987). Considering oil to bunch ratio of 1:4, 2.5 Mg oil ha^{-1} is equivalent to 10 Mg FFB ha^{-1} year^{-1}, but average FFB yield in well-managed plantations is much higher (Narsimha Rao et al., 2014). Nutrient content in 1 Mg of FFB obtained from Dura palms is 2.94, 0.44, 3.71, 0.77, 0.81 kg of N, P, K, Mg and Ca, respectively, whereas, Mn, Fe, B, Cu and Zn content per 1 Mg of FFB is 1.51, 2.47, 2.15, 4.76 and 4.93 g, respectively of Mn, Fe, B, Cu and Zn (Ng and Thamboo, 1967). According to Narsimha Rao et al. (2014), nutritional problems like N/K imbalance, K deficiency, Mg deficiency and B deficiency affect oil palm production in oil palm plantations of India. Calibrated soil and leaf analysis helps in effective fertilizer recommendations in most of the crops (Smith and Loneragan, 1997; McLaughlin et al., 1999). In oil palm, leaf nutrient analysis is commonly used for estimating fertilizer requirement (Fairhurst and Mutert 1999; Corley and Tinker, 2003). The relationship between leaf analysis and palm productivity is generally evident, and an assessment of fertilizer needs can be based on such an analysis. However for a cost-effective approach, leaf analysis has to be integrated with soil analysis (Goh et al., 2009). It is therefore pertinent to assess soil and leaf nutrient status for effective and sustainable fertilizer management programme in oil palm.

The nutrient management recommendations in oil palm plantations in India in general and oil palm plantations in the area under study are generic ones. Prasad et al. (2013) reported wide range in quantity of fertilizer applied indicating that oil palms were either under-fertilized or over-fertilized. Also, low cost and easy availability of some fertilizers have encouraged farmers to make excessive applications with the belief that high yields would be ensured. However, this management adversely affects soil fertility, productivity, fruit quality and ground water quality. It is therefore pertinent for the farmers to economize on fertilizer adopting a strategy for site-specific and/or area-specific management based on spatial variability of soil properties to make oil palm production environmentally sustainable and economically viable. Spatial variability of soil properties in oil palm plantations have to be carefully evaluated to carryout sustainable soil management practices. Thus, the present study was carried out in soils of oil palm plantations of Goa state of India with the following objectives, (i) to estimate the spatial variability of some soil properties through semivariogram analysis, (ii) to develop spatial maps for soil properties using the parameters of the best fitted semivariogram model and interpolation by ordinary kriging technique and (iii) to assess the relationship among the estimated soil properties.

2 Material and methods

2.1 Study site

A survey was carried out in Goa state of India during 2012-13 to find out soil and plant nutritional status in randomly selected 64 tenera oil palm plantations (with 5 to 21 years of age)

(Figure 1). Oil palm is cultivated in an area of approximately 1000 ha which is 1% of agricultural land in the state. The sampling area lies between 15° 6.8′ 96″ N to 15° 41.7′26″ N latitudes and 74° 76′ 60″ to 73° 56′ 78″ E longitudes with altitude ranging from 4 to 90 meter above sea level. The climate of the area is tropical monsoon type. Hot and humid climate prevails for most of the year. Annual mean rainfall (average of 30 years) is 2926 mm, concentrated from early June to late September. On average, May is the warmest month, with temperature peaks over 35 °C (during 24 h) and relative humidity of 70%. Goa experiences short winter seasons between mid-December and February and these months are marked by mean night temperature of approximately 21 °C and mean day temperature of around 28 °C with relative humidity of 65%. According to Bhattacharyya et al., (2013), the main soils in the study area are Inceptisols (26, 000 ha), Ultisols (4, 000 ha), Entisols (3,000 ha) and Alfisols (3, 000 ha) (classified as in Soil Survey Staff, 2014), sandy loam to silty loam texture, developed from granite, granite-gneiss, quartzite/schistose and basalt.

2.2 Soil sampling, processing and analysis

A total of 128 soil samples i.e. 64 from 0-20 cm (surface) and 64 from 20-40 cm (sub-surface) depths were collected at random points inside 3-m radius from the palm during the survey to assess soil properties of oil palm plantations at an approximate interval of 5 to 7 km. All the samples were collected with a hand auger. The latitude, longitude, and elevation at each sampling point were recorded using a hand held global positioning system (GPS). The soil samples were dried at room temperature (25 ± 3 ^{0}C). Roots and debrises were removed from the samples by hand. Samples were processed following standard procedures. The processed soil samples were tested for acidity (pH), salinity (EC), organic carbon (OC) content, available K (NH_4OAc-K), available P (Bray’s P-1) (Bray’s-P), exchangeable Ca^{2+}, exchangeable Mg^{2+}, available S ($CaCl_2$-S) and hot water extractable B (HWB). Determination of soil pH and EC (1:2 soil water ratio (w/v) suspension) were carried out using pH-meter and conductivity meter (Jackson, 1973). Walkley-Black method (Walkley and Black, 1934) was followed for assessing soil OC content. NH_4OAc-K was estimated after extracting soil samples with neutral 1 N ammonium acetate solution (Hanway and Heidel, 1952) followed by flame photometry estimation. Available P was extracted using Bray's P-1 reagent (Bray and Kurtz, 1945) and estimated through spectrophotometry. Ca^{2+} and Mg^{2+} were extracted using neutral normal ammonium acetate solution (Jones, 1998) and estimated through atomic absorption spectrometry. Available S was estimated by the turbidity method (Williams and Steinbergs, 1969). HWB content was estimated through Azomethine-H reagent (Gupta, 1967) using spectrophotometry.

2.3 Statistical and geostatistical analysis

The descriptive statistics like minimum, maximum, mean, standard deviation (SD), coefficient of variation (CV), and skewness for soil properties were computed using the SAS 9.2 software pack (SAS, 2011). Relationship among the estimated soil properties were established using Pearson's correlation coefficient analysis at $p \le 0.05$ and $p \le 0.01$.

ArcMap 10.1 (ESRI, 2012) was used to analyze the spatial structure of soil properties. Before using geostatistics, normality of data distribution were checked by Shapiro-Wilk test at 5% (Shapiro and Wilk, 1965). Soil properties like pH and OC content in both the soil layers and $CaCl_2$-S content in subsurface soil layers exhibited normal distribution (Table 1). While, data transformation to normal distribution was carried out for rest of the soil properties. Trend of the data set was checked and removed. The semivariogram models of soil properties were derived as described by Goovaerts (1997) and Tesfahunegn et al. (2011).

$$\gamma(h) = \frac{1}{2m(h)} \sum_{i=1}^{m(h)} [Z(X_i + h) - Z(X_i)]^2 \qquad (1)$$

Where $\gamma\ (h)$ is the experimental semivariogram, $m(h)$ is number of sample value pairs, $Z(X_i)$, $Z(X_i+h)$ are sample values at two points. Best fitted semivariogram model for each soil property was selected by using the cross validation technique.

Semivariogram parameters like nugget/sill ratio and range were obtained for soil properties. The nugget/sill ratio expressed in percentage was used to classify the spatial dependence of variables (Oliver and Webster, 2014). Ratio values less than or equal to 25%, between 25 and 75%, more than 75% were considered strongly, moderately and weakly spatially dependent, respectively (Behera et al., 2011). Best-fit semivariograms models were selected by cross-validation technique. Mean square error (MSE) was estimated to predict the accuracy of models (Utset et al., 2000).

$$\mathrm{MSE} = \frac{\sum_{i=1}^{n} [z(x_i, y_i) - z*(x_i, y_i)]^2}{n} \qquad (2)$$

Accuracies of interpolated maps were checked by the goodness-of-prediction criterium G (Agterberg, 1984). According to Parfitt et al. (2009), positive and negative and close to zero values of G indicate that the map obtained by interpolating data from the samples is more accurate than average value of the area and the average value predicts the values at un-sampled locations as accurately as or even better than the sampling estimates, respectively. Ordinary kriging interpolation was carried out to develop spatial distribution maps for soil properties.

3 Results and discussion

3.1 Descriptive statistics of soil properties

The descriptive statistics revealed considerable variability of soil properties in both surface and sub-surface soil layers of oil palm plantations (Table 1). The values of CV for soil acidity in both the soil layers revealed their low variability (CV < 10%) (Nielsen and Bouma, 1985). The rest of the soil properties exhibited moderate (CV 10 to 100%) variability except salinity in surface soil layers and Bray's-P in both the soil layers, which had high (CV > 100%) variability. Low CV values for soil acidity was due to transformed measurement of hydrogen ion concentration. Skewnees coefficient values of 0.18 to 3.89 for different soil proprieties revealed that some soil properties were not normally distributed. This variation and non-normal distribution of soil properties in the studied areas may be due to adoption of different soil management practices including variation in fertilizer application and other crop management practices (Tesfahunegn et al., 2011; Srinivasarao et al., 2014; Ferreira et al., 2015).

The mean values of soil pH were acidic in both surface (5.35) and subsurface (5.28) soil layers (Table 1). The acidic nature of soil in the studied area may be due to acidic parent material and prevailing rainfall pattern. The values of soil EC indicate the non-saline nature of soils. Soil OC contents varied widely in both surface and subsurface soil layers. Principal reason for variation in soil OC content may be due to adoption of different cultural practices including addition of crop biomass to the soils. Surface soil layers had slightly higher OC content (mean value 19.8 g kg^{-1}) than OC content in subsurface soil layers (mean value 13.2 g kg^{-1}). Surface soil layers had higher NH_4OAc-K, Bray's-P, $CaCl_2$-S and HWB content compared to that in subsurface soil layers (Table 1). The content of these nutrients varied greatly among the soils because of heterogeneity in fertilizer application in the area. The mean values of exchangeable Ca^{2+} were 914 and 795 mg kg^{-1} for surface and subsurface soil layers, respectively. Whereas, surface soil layers were having 203 and 225 mg kg^{-1} of mean exchangeable Mg^{2+} content, respectively. Other studies reported similar results highlighting different distribution pattern of soil properties, primary, secondary and micronutrients under different soil-crop management situations (Franzlubbers and Hons, 1996; Sharma et al., 2005; Behera and Shukla, 2013).

3.2 Relationship among soil properties

The exchangeable Ca^{2+} content increased with pH (Table 2). Behera and Shukla (2015) also recorded positive and significant relationship of soil pH and soil OC with K, exchangeable Ca^{2+} and exchangeable Mg^{2+} content in some cropped acid soils of India. Soil OC content in surface layers was positively and significantly correlated with exchangeable Ca^{2+} and HWB ($P \leq 0.05$). Most of the soil properties which influence nutrient storage and availability to plants are influenced by soil organic matter (SOM) type and content (Foth and Turk, 1972). Increased soil EC content led to higher NH_4OAc-K in both soil layers ($P \leq 0.01$), and higher $CaCl_2$-S in surface layer and Bray's–P in subsurface layer ($P \leq 0.05$). Soil EC does not directly affect plant growth but has been used as an indirect indicator of the amount of nutrients available for plant uptake and salinity levels (Corwin and Lesch, 2005). EC has been used as a surrogate measure of salt concentration, organic matter, cation-exchange capacity, soil texture, soil thickness, nutrients, water-holding capacity, and drainage conditions. In site-specific management and high-intensity soil surveys, EC is used to partition units of management, differentiate soil types, and predict soil fertility and crop yields.

3.3 Spatial structure and distribution of soil properties

The best-fit semivariogram models and parameters of studied soil properties are given in Table 3. The best fit models for soil properties of studied areas were spherical, linear, exponential, circular, and Gaussian depending on soil layer and parameter. Our findings are in line with the observations made by Tesfahunegn et al. (2011).

Cross-validation technique was used to select semivariograms models for soil properties with the lowest MSE values (Table 3). Lowest MSE values indicate that kriging predictions of soil properties are closer to measured values. The accuracy of kriged interpolation maps of soil properties was also measured by the G values (Table 3) which varied from 26 (for exchangeable Ca^{2+} in subsurface layer) to 76% (for HWB in subsurface layer). Positive G values for all the soil properties revealed the developed maps are more accurate than the maps generated using the average value of the area.

Soil pH in both the soil layers of oil palm plantations was having moderate spatial dependency class. Soil EC had strong and moderate spatial dependency for surface and sub-surface soil layers respectively. Soil OC content in oil palm plantations had weak spatial dependency for surface soil layers and moderate spatial dependency for sub-surface soil layers. Spatial dependency classes were weak for NH_4OAc-K and strong for exchangeable Ca^{2+} for both the soil layers of oil palm plantations. Bray's–P and $CaCl_2$-S had weak spatial dependency for surface layers and moderate spatial dependency for sub-surface layers. Whereas, exchangeable Mg^{2+} and HWB had moderate spatial dependency in surface soil layers and weak spatial dependency for sub-surface soil layers in oil palm plantations. Weak spatial dependency of soil properties like NH_4OAc-K, Bray's–P and OC (in surface layer) in oil palm plantations is ascribed to the anthropogenic activities like adoption of cultural practices including application of fertilizers. In these oil palm plantations, activities like application of irrigation water, weeding, basin cleaning, mulching and application of N, P, K and Mg fertilizer are carried out at regular intervals. Whereas, moderate and strong spatial dependency of soil pH, EC and exchangeable Ca^{2+} is due to soil type and parent material.

According to Webster and Oliver (1990), range value is a measure of the spatial extension within which autocorrelation exists. Spatially related samples were separated by distances closer than range values. The range values of soil properties in studied area varied widely (Table 3). The range values for surface soil properties were 554 to 4530 m and for subsurface soil properties were 581 to 4530 m. Among the soil properties, higher range values were recorded for NH_4OAc-K and $CaCl_2$-S for both the soil layers. The possible causes for spatial variability of soil properties in studied areas are adoption of different soil management practices (Bodi et al., 2013; Pereira et al., 2013; Ochoa-Cueva et al., 2015). The difference in annual average temperature in the state of Goa was more than 12 °C, indicating temperature could be important factor influencing soil nutrient mineralization and accumulation. Moreover, this area is having rising slope from the coast line towards *ghats* i.e. from western side to eastern side, which could also affect distribution of nutrients probably wash by surface runoff or subsurface water movements.

Interpolation maps (Figure 2) of different soil properties revealed that oil palm plantations of the area could be divided into homogenous small zones depending upon the different nutrient ranges. Overlying of the spatial distribution maps on map of Goa revealed that the spatial distribution map of pH in surface soil layers revealed almost all the area having pH of 5.00 to 6.00. Low pH values occurred in north-western and south-eastern parts. In sub-surface soil layers, low pH of 4.75 to 5.00 occurred in south-eastern part whereas relatively higher pH prevailed in north-western part. Areas having low pH values compared to other areas may be due acidic parent material from which the soil developed and different soil management practices.

Accordingly, different management options may be adopted in different parts of the area with different levels of pH. Soil EC had irregular distribution pattern in surface soil layers whereas low values of EC were recorded in north-western part. This may be due to sandy loam soil texture and presence of low OC in north-western part. Higher EC values in other parts of surveyed area probably due to silt loam soil texture with high water table. Higher amount of soil OC was found to be distributed in the south-eastern parts in surface as well as sub-surface soil layers. This may be ascribed to prevalence of higher slope and low rate of SOM mineralization in south-eastern parts compared to other areas. Higher amount of NH_4OAc- K and $CaCl_2$-S was found to be distributed in almost all parts in both the soil layers. Higher amount of Bray's-P was found to be distributed in almost all parts in surface soil layers whereas low amount of Bray's-P occurred in north-central and south-western parts in sub-surface soil layers. Build up of P in surface layers may be due to continuous P addition and their fixation in soil which is acidic in nature. Exchangeable Ca^{2+} exhibited irregular distribution pattern in both the soil layers. In surface as well as sub-surface soil layers, lower amount of Exch. Mg was found to be distributed in southern parts as compared to that in northern parts. Similar distribution of exchangeable Ca^{2+} and exchangeable Mg^{2+} was recorded in these soils which corroborate our finding of significant and positive correlation between exchangeable Ca^{2+} and exchangeable Mg^{2+} in both the soil layers. Higher amount of HWB was found to be distributed in north-eastern part in surface soil layers and in central and south-western parts in sub-surface soil layers. The different distribution variability of the soil properties in oil palm plantations of this area is predominantly due to climate and landscape along with farm practices including application of different quantities of nutrients through fertilizers. The kriged distribution maps for different soil properties providing quantitative information about soil properties in both the soil layers is of great use for plantation staff, farm managers, extension officers and farmers. This will help in visualizing soil fertility status for planning appropriate strategies for efficient site specific soil nutrient management and variable-rate fertilizer application technology. It leads for obtaining optimum output and oil palm yield which can provide environmentally sustainable maximum return to famers with optimum input utilization combined with best management practices (Fu et al., 2010; Behera et al., 2012). The areas with low and medium nutrient status require more amount of fertilizer application as compared to areas having high nutrient status. For example, exchangeable Mg^{2+} status is low in southern part of the area compared to northern part. Therefore, the requirement of Mg fertilizer application is more in southern part compared to northern part.

4 Conclusions

Geostatistical analysis is the key for studying the spatial variability of soil properties for sustainable soil resource management. The present study divulged that the measured soil properties had large variability in spatial distribution pattern in both surface and subsurface soil layers of oil palm plantations of the studied area. Positive and significant correlations were recorded between soil pH and exchangeable Ca^{2+}, soil EC and NH_4OAc-K, Bray's-P and $CaCl_2$-S and exchangeable Ca^{2+} and exchangeable Mg^{2+} in both the soil layers. The prediction maps generated by geostatistical analysis are useful for site-specific soil nutrient management in oil palm plantations of the area by delineating management zones and adoption of variable fertilizer application strategies.

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Table 1. Soil properties of surface (0-20 cm) and sub-surface (20-40 cm) layers (n = 64 at each case).

Variable	Soil layer	Mean ± SD	CV (%)	Minimum	Maximum	Skewness coefficient	Distribution
pH	Surface	5.35± 0.45	8.64	4.25	6.77	0.18	Normal
	Subsurface	5.28± 0.46	8.63	4.53	6.52	0.65	Normal
EC	Surface	0.13±0.17	125	0.05	1.06	4.06	Transformed
	Subsurface	0.08±0.06	75.3	0.03	0.41	3.02	Transformed
OC	Surface	19.8±8.77	44.4	5.07	48.4	0.83	Normal
	Subsurface	13.2±7.33	55.5	1.95	31.2	0.75	Normal
NH_4OAc-K	Surface	270±29.9	88.7	58.1	1167	1.80	Transformed
	Subsurface	199±165	82.8	16.1	856	2.16	Transformed
Bray's-P	Surface	24.7±3.39	127	0.86	141	2.14	Transformed
	Subsurface	9.78±13.2	135	0.90	42.3	2.52	Transformed
Ca^{2+}	Surface	914±588	64.3	200	2997	1.56	Transformed
	Subsurface	795±724	91.1	194	5177	3.89	Transformed
Mg^{2+}	Surface	203±141	69.3	36.0	744	1.75	Transformed
	Subsurface	225±156	69.4	24.0	720	1.27	Transformed
$CaCl_2$-S	Surface	23.2±16.4	70.7	3.00	87.7	1.60	Transformed
	Subsurface	16.3±10.1	62.0	1.50	43.5	0.93	Normal
HWB	Surface	0.70±0.38	54.7	0.09	2.10	1.43	Transformed
	Subsurface	0.64±0.44	68.6	0.04	2.56	1.70	Transformed

SD-standard deviation; CV-coefficient of variation; EC-electrical conductivity, dS m^{-1}; OC-organic carbon, g kg^{-1}; K, mg kg^{-1}; P, mg kg^{-1}; exchangeable Ca$^{2+,}$ mg kg^{-1}; exchangeable Mg^{2+}, mg kg^{-1}; S, mg kg^{-1};HWB, hot water soluble B, mg kg^{-1}.

Table 2. Pearson's correlation coefficients between soil properties at the surface (0-20 cm) and subsurface (20-40 cm) layers. Only significant coefficients are shown (*, p ≤ 0.05; **, p ≤ 0.01) (n=64).

Layer		pH	EC	OC	P	Ca^{2+}
Surface	K		0.45**			
	P					
	Ca^{2+}	0.67**		0.26*		
	Mg^{2+}					0.37**
	S		0.31*		0.44**	
	HWB			0.30*		
Sub-surface	K		0.48**			
	P		0.32*			
	Ca^{2+}	0.42**				
	Mg^{2+}					0.33**
	S				0.36**	

EC-electrical conductivity, dS m^{-1}; OC-organic carbon, g kg^{-1}; K, mg kg^{-1}; P, mg kg^{-1}; exchangeable Ca^{2+}, mg kg^{-1}; exchangeable Mg^{2+}, mg kg^{-1}; S, mg kg^{-1};HWB, hot water soluble B, mg kg^{-1}.

Table 3. Semivariogram parameters of soil properties of studied areas.

Variable	Soil layer	Model	Nugget	Sill	Nugget: Sill ratio	Spatial class	Range (m)	MSE	G (%)
pH	Surface	Spherical	0.098	0.130	0.715	Moderate	1416	0.754	62
	Subsurface	Spherical	0.110	0.160	0.687	Moderate	1468	0.681	58
EC	Surface	Spherical*	0.001	0.004	0.025	Strong	554	0.0003	55
	Subsurface	Linear*	0.003	0.004	0.750	Moderate	2186	0.0002	51
OC	Surface	Exponential	54.10	67.70	0.797	Weak	1131	2.31	48
	Subsurface	Circular	20.80	51.10	0.407	Moderate	581	3.12	56
NH_4OAc-K	Surface	Spherical*	36371	40122	0.906	Weak	4530	28.31	65
	Subsurface	Linear*	21523	22506	0.956	Weak	4530	30.01	60
Bray's-P	Surface	Gaussian*	875.0	940.0	0.930	Weak	1996	40.02	53
	Subsurface	Gaussian*	97.60	149.9	0.651	Moderate	770	39.58	50
Ca^{2+}	Surface	Linear*	0.000	263780	0.000	Strong	1585	221.01	33
	Subsurface	Exponential*	0.000	330416	0.000	Strong	581	198.65	26
Mg^{2+}	Surface	Gaussian*	11244	21059	0.533	Moderate	885	89.56	50
	Subsurface	Exponential*	19839	20685	0.959	Weak	1114	70.04	53
$CaCl_2$-S	Surface	Linear*	234.0	245.0	0.955	Weak	4530	0.067	45
	Subsurface	Gaussian	62.10	93.20	0.666	Moderate	4530	0.071	42
HWB	Surface	Gaussian*	0.046	0.073	0.630	Moderate	1424	0.023	71
	Subsurface	Linear*	0.111	0.147	0.755	Weak	1148	0.018	76

*Transformation for normal distribution.

EC-electrical conductivity, dS m^{-1}; OC-organic carbon, g kg^{-1}; K, mg kg^{-1}; P, mg kg^{-1}; exchangeable $Ca^{2+,}$ mg kg^{-1}; exchangeable Mg^{2+}, mg kg^{-1}; S, mg kg^{-1};HWB, hot water soluble B, mg kg^{-1}; MSE-mean square error; G-goodness-of-prediction criterium.

Figure 1. Spatial distribution of sampling points in Goa state (western India)

Figure 2. Kriged interpolation maps of soil properties in surface (0-20 cm) and subsurface (20-40 cm) soil layers

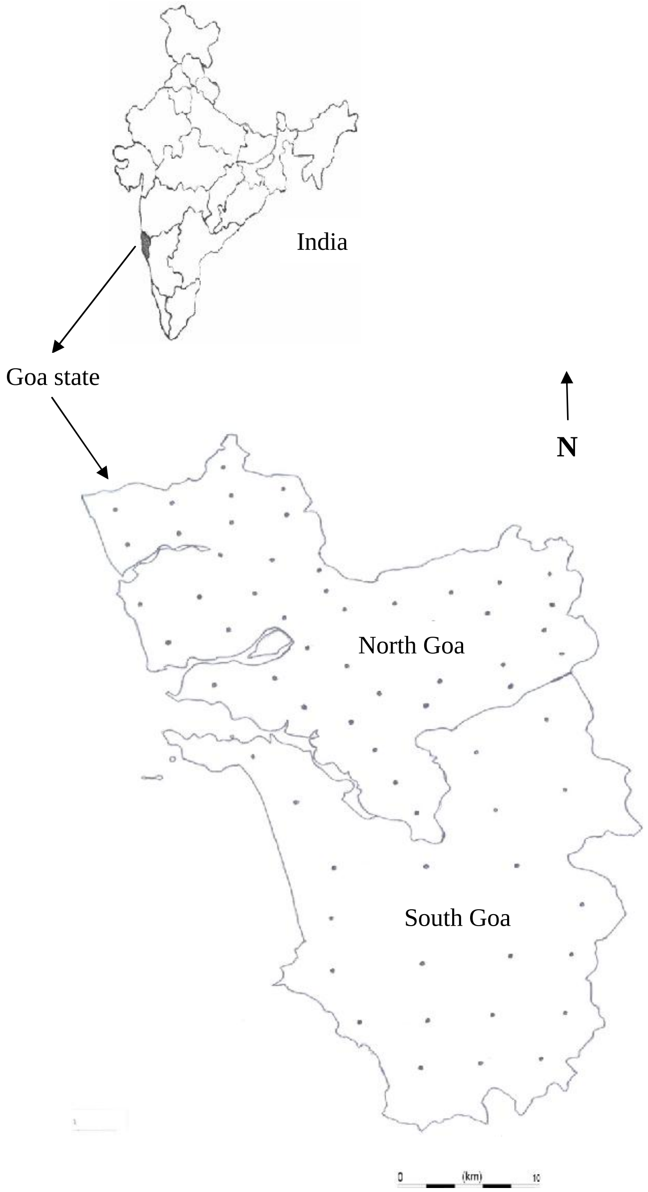
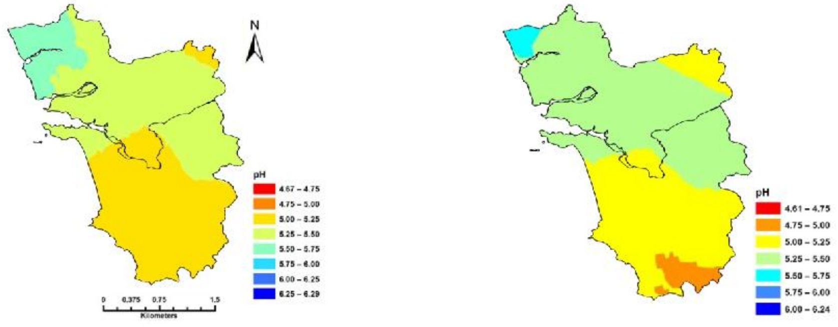


Figure 1. Spatial distribution of sampling points in Goa state (western India)

pH

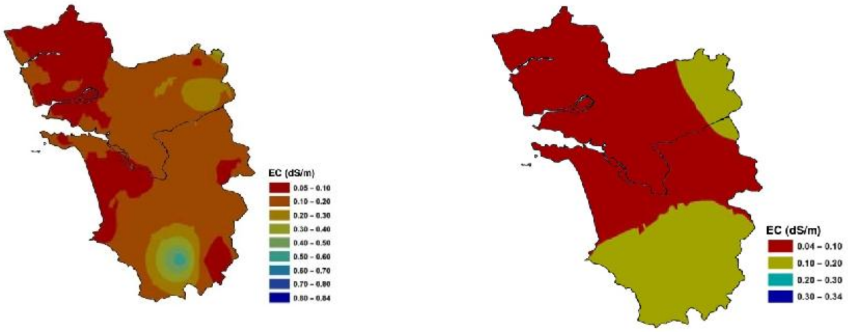
pH

Surface
Subsurface



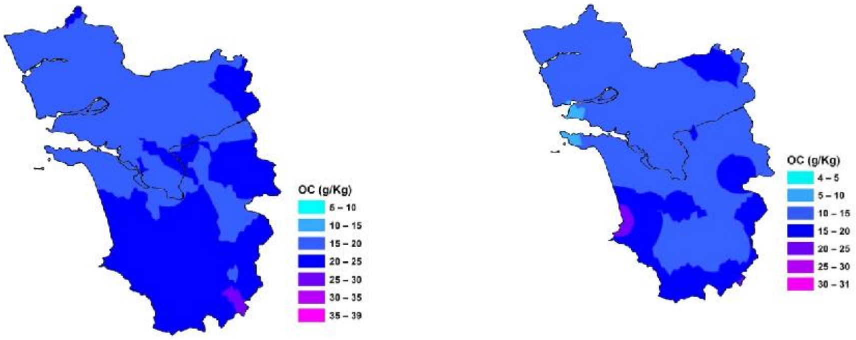
EC

Surface
Subsurface



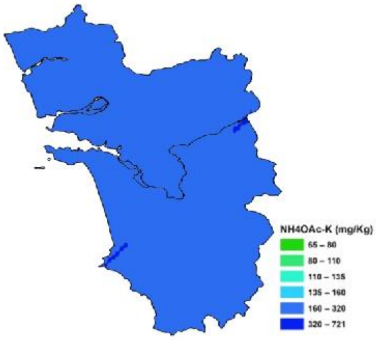
OC

Surface
Subsurface

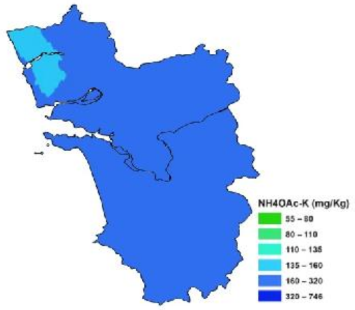


NH$_4$OA$_C$-K

Surface

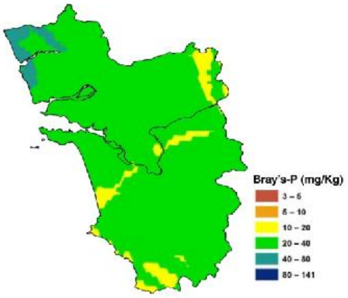


Subsurface

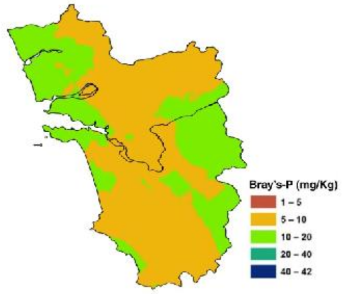


Bray’s-P

Surface

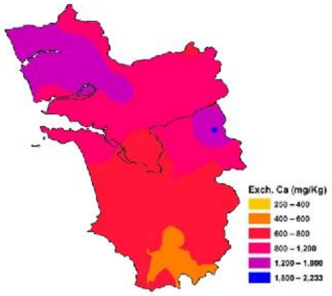


Subsurface

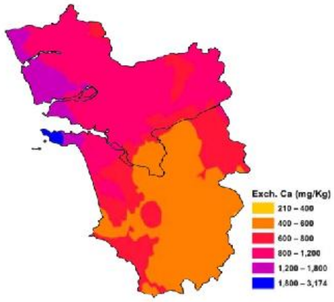


Exch. Ca

Surface

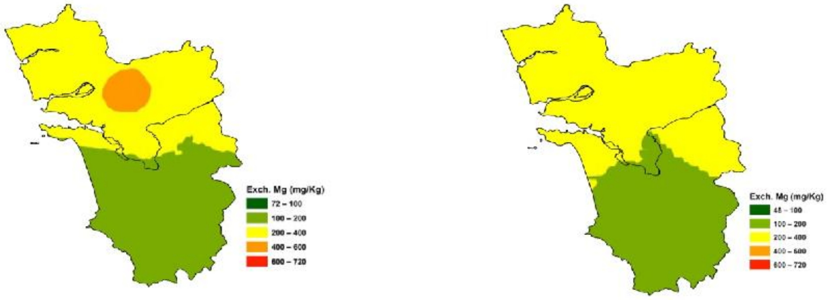


Subsurface



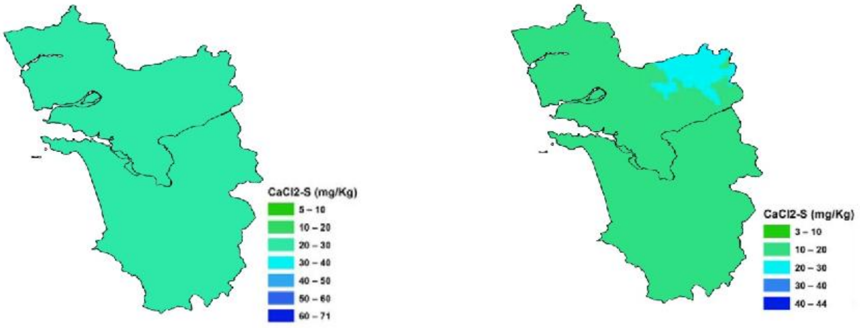
Exch. Mg

Surface Subsurface



$CaCl_2$-S

Surface Subsurface



HWB

Surface Subsurface

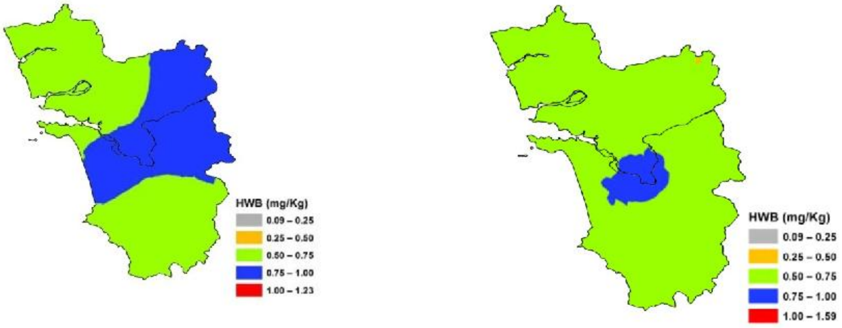


Figure 2. Kriged interpolation maps of soil properties in surface (0-20 cm) and subsurface (20-40 cm) soil layers