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Effects of soil properties on organic carbon density and potential for enhancing maize productivity in shrink-swell soils of Karnataka, India

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Abstract : The present study investigates the influence of soil properties on soil organic carbon density (SOCD) in maize-growing regions of Karnataka using path coefficient analysis. A total of 31 soil samples were collected from potential maize-growing areas under the Sujala project in Karnataka. Standard procedures were employed to analyse the physical and chemical properties of the fine-earth fraction. Statistical techniques such as descriptive analysis, correlation, regression, and path analysis were used to study the interrelationships of soil properties as a function of soil organic carbon density (SOCD). The soils were mildly alkaline (mean pH: 7.7±1.0), non-saline (mean electrical conductivity: 0.3±0.5 dSm^{-1}) and have fine-grained loam particles (mean clay content: 27.6±13.9 % and mean sand content: 62.1±18.1 %). Soils have a high CEC with low exchangeable potassium and DTPA-Zn. The SOCD distribution was symmetric (skewness: 0.3) and platykurtic (kurtosis: -1.0). Correlation and regression analyses revealed a statistically significant relationship between SOCD and clay/silt content. At the second- and fourth-order levels, pH and CEC exhibited a nonlinear relationship with SOCD. Path analysis indicated that clay, silt, $CaCO_3$, available phosphorus, and DTPA-extractable copper had direct effects on SOCD. Cations such as Ca^{2+} and Cu^{2+} played a crucial role in SOC stabilization, as evidenced by the strong correlation of CEC with clay (r = 0.798**) and silt (r = 0.73**), highlighting their role in forming stable organo-mineral complexes. These findings enhance our understanding of SOC dynamics and contribute to soil management strategies for sustainable maize production in Karnataka.

Keywords: *Correlation, Karnataka, Maize yield, Path analysis, Regression, Semiarid regions, Soil organic carbon*

Introduction

Soils play a critical role in the global carbon (C) cycle, serving as a major reservoir of terrestrial carbon. Globally, the terrestrial biosphere holds approximately 75% of the total carbon stock (Tarnocai et al., 2009; Jiao et al., 2020). Studies on soil carbon balance in Europe indicate that forests and grasslands act as net carbon sinks, sequestering 20 ± 12 g C m^{-2} yr^{-1} and 57 ± 34 g C m^{-2} yr^{-1}, respectively, while croplands exhibit a lower sequestration rate of 10 ± 9 g C m^{-2} yr^{-1} (Schulze et al., 2009). These variations highlight the influence of land use on soil carbon dynamics and the need for targeted management strategies to enhance soil carbon sequestration. Further, carbon research in agricultural soils showed significant potential to sequester soil organic carbon (SOC) so as to mitigate climate change and to maintain crop productivity (Zhang *et al*., 2014). The sequestered carbon in agricultural soils depends on

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management strategies and environmental conditions (Luo *et al*., 2010). India's soil carbon stocks are estimated to be only one-third to two-thirds of the global average, primarily due to its long history of cultivation, intensive land use, and agricultural management practices (Lal, 2004).

The key biophysical factors influencing SOC dynamics include climate, vegetation, topography, intrinsic soil properties, land use, and management practices (Wang et al., 2012). Changes in SOC content are strongly correlated with soil structural stability (Nayak et al., 2019), temperature and moisture conditions (Lal, 2004), and the incorporation and composition of crop residues (Gao et al., 2016). Path analysis has been widely used in soil studies to explore the cause-and-effect relationships between soil properties and various processes, including heavy metal adsorption (Krishnasamy & Mathan, 2001), potassium dynamics (He & Chen, 2013), and phosphorus retention in acidic soils (Ige et al., 2007; Boke et al., 2015). An integrative approach of correlation and path analyses is needed to organize and present relationships between dependent and independent variables controlling soil organic carbon density (Zhongkui *et al*., 2017).

The interrelationships between soil organic carbon and soil properties in the humid hilly region of Cameroon showed that, SOC and exchangeable Al^{3+} has strong relationships in the Mollic Endoaquents. Total SOC stocks up to 1m depth is varied from 260.1 and 363.5 t ha^{-1}, and controlled by genetic horizon depth, while land-use type influences across genetic surface horizons (Kame *et al*., 2021). The path analysis and correlation studies in Assam soils reported the strong influence of soil texture on soil organic carbon over other environmental factors (Baruah *et al*, 2020).

The nonexistence of a SOC database at landscape level in drought-hit maize growing areas of Karnataka could limit its ability to, estimate SOC stocks at local scales and demands for baselines for large-scale inventories to improve the accuracy of state-level SOC databases. In Karnataka, there is a dearth of soil information on the SOC stocks. Dryland agriculture is dominant and constitutes areas of intensive maize production that would significantly impact the soil carbon storage potential. Hence, this study aims to assess SOC content and analyze its interrelationships with key biophysical factors across Karnataka. Path coefficient analysis was employed to interpret complex pedological processes and express them as functions of conceptual environmental factors, providing a structured approach to understanding SOC dynamics.

Materials and methods

Details of the study area, soil sampling, and determination

The study area under Sujala 3 project is confined to 7 agro-climatic zones where maize is predominantly grown (Table 1). The detailed soil survey on the 1:10,000 scale was carried out during 2016-2019 as per the guidelines of Soil Survey Staff (2017). During this survey, 596 micro watersheds were selected covering 285105 ha (Hegde *et al*., 2017). Two hundred and two soil profiles were studied and classified up to subgroup level as per Soil Survey Staff (2014). Horizon wise soil samples were collected and air-dried for fine earth fraction. The soil samples were, air-dried, ground, and passed through a 0.15 mm sieve for determination of both SOC and SIC. The particle size distribution was done using the Bouyoucos method (Bouyoucos, 1962). The cation exchange capacity was determined as per the distillation method (Sarma *et al.*, 1987). The organic carbon was determined using the wet oxidation method (Walkey and Black, 1934). The calcium carbonate was determined using the acid neutralization method (Jackson, 1973). The pedotransfer function was used to estimate the bulk density of soils (Kaur *et al.*, 2002) as::

$$\ln \rho b = 0.313 - 0.191\ OC + 0.02102\ Clay - 0.000476\ (Clay)^2 - 0.00432\ Silt$$

Estimation of soil organic carbon density

Estimation of SOC density at depth (0-30 cm) was calculated using the formula as given in Equation 1 (IPCC, 2003):

$$SOC_i = \sum \frac{(1-\delta I\%) \times \rho_i \times C_i \times T_i}{100} \quad (1)$$

Farmer's survey

A structured questionnaire was used to collect data on fertilizer use patterns and maize yield from maize farmers through personal interviews. The current general fertilizer recommendations were compared with soil test-based recommendations for specific yield targets, ensuring a balanced fertilizer application approach. The actual nutrient doses applied by farmers were analyzed against the calculated optimal doses to quantify fertilizer misapplication. Both overuse and underuse of nutrients were considered detrimental—excess application leading to wastage and environmental concerns, while deficiencies contributing to soil nutrient depletion. The financial implications of misapplication were assessed based on the market value of nitrogen (N), phosphorus (P), and potassium (K). The net change in income per hectare was determined by comparing the potential additional benefits of balanced fertilization with the costs involved in correcting fertilizer misapplication

Statistical analysis

Descriptive statistics, Correlation, and regression analysis was performed using SPSS version 23.0. The path analysis was performed to estimate the direct and indirect effects of soil properties (sand, silt, clay, CEC, pH, EC, and exchangeable cations) as well as environmental factors (rainfall and elevation) on SOCD of major maize growing areas in Northern transitional dry zone of Karnataka using SPSS 23.0.

Results and Discussion

Descriptive statistics of exploratory variables

Thirteen soil variables of 31 sites of maize growing areas were used for estimation of descriptive statistics and K-S test of normality (Table 1). The mean SOCD is 20.5±9.3 Mg ha^{-1} with a CV of 45.3%. The skewness is fairly symmetrical (0.3) with platykurtic (-1.0) and a significant K-S test at a 5% level of significance. These soils are slightly alkaline (mean pH=7.7±1.0) within the range of moderately acid (pH of 5.8) to strongly alkaline (pH of 9.0). The particle size class is fine loamy with mean clay of 27.6±13.9% with high variability (CV of 50.36%) and sand content of 62.1±18.1% (moderate variability-CV of 29.57 %). The particle size distribution shows that sand, silt, and clay are highly skewed and paltykurtic just in the case of sand and clay but leptokurtic in the case of silt(K≈3.0). The mean silt is 11.2±5.3% with high variability (CV of 47.32%). The K-S test values for particle size are highly significant at the 1% level. These soils are non-saline with mean electrical conductivity of 0.3±0.5 dS m^{-1} with highly skewed and leptokurtic. The elevation is 508 m to 861.0 m above mean sea level with a mean of 582± 83.7 m. These soils have high CEC (mean of 16.7±14.4 cmol kg^{-1}) (Moore, 2004) with a maximum of 53.8 cmol kg^{-1}. These soils have low exchangeable Ca (mean of 2.8±4.1 cmol kg^{-1}) and potassium (mean of 0.2±0.2 cmol kg^{-1}), medium in exchangeable magnesium (1.2±1.7 cmol kg^{-1}) and high exchangeable Na (mean of 1.0±1.7 cmol kg^{-1}). The area receives a mean rainfall of 675.9± 69 mm with a CV of 10.22 per cent. The K-S test is significant at 1% level for all these variables.

Table 1: Descriptive statistics of soil variables under study

Parameters	Mean±SD	CV(%)	Minimum	Maximum	Skewness	Kurtosis
Carbon density (t ha^{-1})	20.49±9.33	45.55	8.35	39.65	0.34	-1.04
Clay (%)	27.56±13.86	50.28	13.16	67.22	1.26	1.37
Silt (%)	11.21±5.32	47.50	6.75	29.07	1.70	3.02
pH	7.67±0.98	12.81	5.78	8.99	-0.61	-0.30
CEC (cmol kg^{-1})	16.66±14.44	86.68	0.00	53.81	1.25	0.92
ESP	2.99±1.86	62.15	0.25	8.24	0.74	0.43
Ex. Ca (cmol kg^{-1})	2.77±4.14	149.41	0.00	12.00	1.29	0.29
Ex. K (cmol kg^{-1})	0.23±0.19	81.24	0.09	0.88	2.41	6.46
Ex. Na (cmol kg^{-1})	0.99±1.72	173.74	0.08	6.89	2.47	5.05
$CaCO_3$ (g kg^{-1})	2.38±4.43	186.59	0.00	13.28	1.99	2.40
Available P (kg ha^{-1})	7.63±5.65	74.04	1.20	23.00	1.21	1.69
Available B (mg kg^{-1})	0.64±0.38	59.46	0.19	1.80	2.03	4.27
DTPA -Cu (mg kg^{-1})	1.20±1.04	86.11	0.29	5.80	3.35	13.41
DTPA- Fe (mg kg^{-1})	5.70±4.91	86.13	1.53	16.88	1.30	0.36
DTPA -Zn (mg kg^{-1})	0.30±0.13	44.88	0.11	0.83	2.21	7.68

Correlation and regression

SOCD exhibited a significant negative correlation with sand content, indicating that an increase in sand reduces SOC storage in maize-growing soils of Karnataka. A similar relationship has been reported in Central C under grasslands and broad leaf forest soils (Zhong et al., 2018). The positive relation of SOCD with silt (R^2 = 0.252*) and clay (R^2 = 0.283*) clearly shows that accumulation of SOC stocks is largely regulated by clay minerals (Xu, *et al.* 2016).

The relation SOCD with particle sizes can be explained with theory of SOC saturation (Hassink 1997), the sand fraction is weak capacity to stabilize organic compounds on mineral surfaces as compared to silt and clay, which in turn affects the rate of SOC storage (Feng, *et al*. 2013). These findings support the hypothesis that the relationship between SOC dynamics and clay content may vary depending on climatic conditions and land use patterns. The relation of SOCD and clay is expressed in linear regression equation as: SOCD (t/ha) = 0.358(clay, %) +10.60 (R^2 =0.283* significant at 5% level). It means that the shrink-swell soils have capacity to absorb more organic C molecules owing to the larger surface area and the presence of polyvalent cations to control the protection of SOC from microbial and enzymatic decay, in turn increasing SOC storage (Zaffar and Lu 2015). Finely textured soils are generally assumed to contain higher amounts of protected SOC as compared to more coarsely textured soils (Rasmussen et al. 2018).

Path coefficient analysis

The path analysis was performed for having quantitative insights on contributing paths of predictors variable (14) to a response variable (dependent variable (SOCD)). The path analysis has two components like direct and indirect effects quantified with path coefficients as shown in Figure 1. and Table 2. The sequence of direct effects on SOCD has positive with available P (0.94) > clay (0.82) > $CaCO_3$ (0.68) > silt (0.63) > DTPA-Cu (0.54) but negative with Ex.Na (-.10) > Av.B (-0.24) > Ex.K (-0.40) > ESP (-0.48) > pH (-0.61).

DTPA-Fe > (-0.87) > DTPA-Zn (-0.89) and CEC (-1.67). The path model has a high explanatory power with adjusted R^2 of 1.00. The significant direct effects of soil properties like clay, silt, $CaCO_3$, Available P and DTPA Cu are positively contributing factors for top soil organic carbon density. The total effect of clay and silt on SOCD is contributing 44 and 31 % of SOCD.The indirect effects are partitioned as 37 % from silt and 31% from calcium carbonate for SOCD through clay. The CEC has a negative direct effect on SOCD (-1.66) buts zero order correlation is positive (r = 0.33) implying there is a true association between CEC and SOCD in these soils. However, CEC has yield positive on SOCD through pH (0.27). It is already stated that at pH > 5.5, the exchangeable Ca contributes more than 60 per cent to subsoil CEC and its strength relation depends on pH of soil (Solly *et al*. 2020)) .The pedological substrates in Karnataka contain carbonates in many soil horizons and have pH higher than 8.0 previously (Slessarev *et al*. 2016). The study further suggested that Ca^{2+} plays vital a role in stabilizing organic compounds in alkaline soils with less precipitation and a drier climate favor the development of clay minerals with a high abundance of negatively charged sites in alkaline soils (Douglas, 1989). In Karnataka, geological factors play a dominant role in shaping the relationship between precipitation and the prevalence of alkaline soils in drier regions. Polyvalent cations such as Ca^{2+} and Cu^{2+} occupy negatively charged exchange sites on clay minerals, facilitating strong interactions with negatively charged carboxylic acids commonly found in soils. These interactions lead to the formation of stable organo-metal complexes, which play a crucial role in protecting soil organic carbon from decomposition. (Mikutta *et al*. 2007). The influence of soil pH in shaping the relationship between CEC and organic C strongly corroborates the evidences from earlier studies suggesting that soil pH can act as an essential indicator of the controlling SOC (Rasmussen *et al*. 2018; Rowley *et al*. 2018). The simple correlation between CEC and clay is 0.798**and with silt (0.73**) and favours for the stabilization of SOC, through cation bridging and by creating complexes with organic molecules when their hydration shells are displaced (Xu, *et al*. 2016).

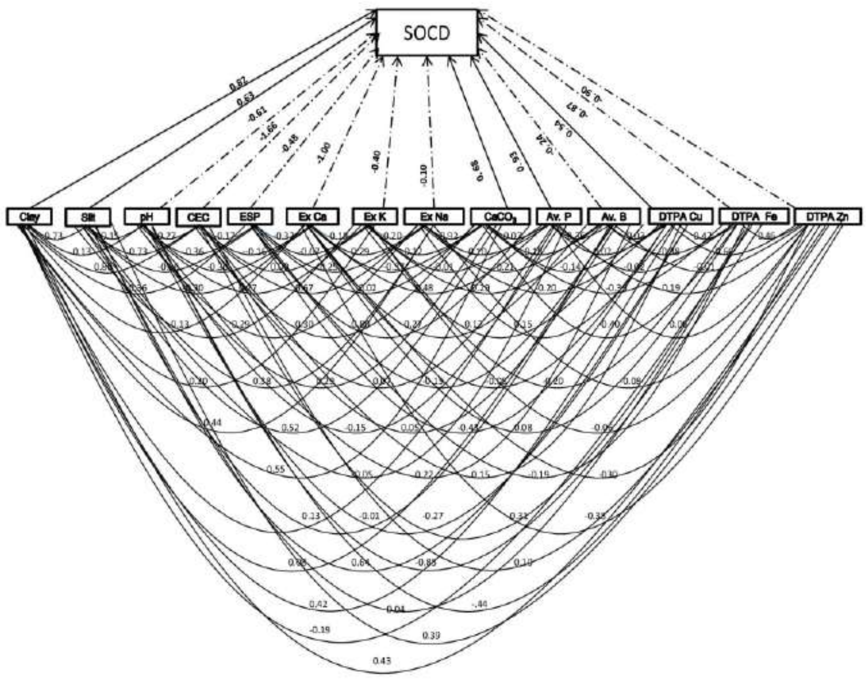

Fig. 1: Direct and indirect effects of soil properties on soil organic carbon density

Table 2: Correlation coefficient and path analysis coefficients to SOCD

Parameters	Correlation	Direct effect	Indirect effect														Total Effect
			Clay	Silt	pH	CEC	ESP	Ex.Ca	Ex.K	Ex.Na	$CaCO_3$	Availab	le Availab	le B DTPA -	Cu DTPA -	Fe DTPA -	Zn
Clay (%)	0.82	0.67		0.37	-0.06	-1.09	0.14	0.10	-0.06	-0.04	0.31	0.10	-0.02	0.19	0.14	-0.32	0.44
Silt (%)	0.63	0.39	0.37		-0.06	-0.76	0.11	0.19	-0.07	-0.02	0.22	-0.03	0.00	0.22	-0.02	-0.22	0.31
pH	-0.61	0.38	-0.06	-0.06		0.27	0.11	-0.18	0.07	0.02	-0.12	0.09	0.03	0.09	-0.45	-0.24	-0.07
CEC (cmol kg^{-1})	-1.66	2.76	-1.09	-0.76	0.27		-0.14	-0.27	0.00	0.11	-0.90	-0.11	0.02	-0.14	-0.45	0.15	-0.55
ESP	-0.48	0.23	0.14	0.11	0.11	-0.14		-0.15	-0.01	0.01	-0.01	0.12	-0.02	0.11	-0.08	-0.16	0.26
Ex.Ca (cmol kg^{-1})	-1.00	1.00	0.10	0.19	-0.18	-0.27	-0.15		-0.08	-0.03	0.25	-0.45	0.03	0.04	0.07	-0.27	0.24
Ex.K (cmol kg^{-1})	-0.40	0.16	-0.06	-0.07	0.07	0.00	-0.01	-0.08		0.01	-0.03	0.00	0.03	-0.03	-0.07	-0.02	-0.12
Ex.Na (cmol kg^{-1})	-0.10	0.01	-0.04	-0.02	0.02	0.11	0.01	-0.03	0.01		-0.06	-0.01	0.00	0.01	-0.03	-0.01	-0.03
$CaCO_3$ (g kg^{-1})	0.68	0.46	0.31	0.22	-0.12	-0.90	-0.01	0.25	-0.03	-0.06		0.05	-0.03	-0.05	0.23	-0.03	0.27
Available P (kg ha^{-1})	0.93	0.87	0.10	-0.03	0.09	-0.11	0.12	-0.45	0.00	-0.01	0.05		-0.08	-0.01	0.02	-0.16	0.40
Available B (mg kg^{-1})	-0.24	0.06	-0.02	0.00	0.03	0.02	-0.02	0.03	0.03	0.00	-0.03	-0.08		0.00	-0.08	0.00	-0.05
DTPA –Cu (mg kg^{-1})	0.54	0.29	0.19	0.22	0.09	-0.14	0.11	0.04	-0.03	0.01	-0.05	-0.01	0.00		-0.22	-0.32	0.18
DTPA-Fe (mg kg^{-1})	-0.87	0.75	0.14	-0.02	-0.45	-0.45	-0.08	0.07	-0.07	-0.03	0.23	0.02	-0.08	-0.22		0.36	0.16
DTPA -Zn (mg kg^{-1})	-0.90	0.81	-0.32	-0.22	-0.24	0.15	-0.16	-0.27	-0.02	-0.01	-0.03	-0.16	0.00	-0.32	0.36		-0.45

Potential for increasing maize yield

The fertiliser use pattern and the maize yield was collected from the maize farmers in a structured questionnaire through personally interview. The analysis of fertilizer uses patterns among maize farmers revealed significant insights on fertilizer applicators. The difference in additional benefits likely to be obtained by adopting the balanced fertilizers and cost involved in correcting fertilizer misapplication is the net change in income per hectare (Table 3).

Table 3: Economic value of balanced fertiliser uses in maize cultivation

Particulars	Value
Mean value of farmers Practices (FP)	
FYM (t ha^{-1})	2.6
Nitrogen (kg ha^{-1})	97.2
Phosphorus (kg ha^{-1})	81.3
Potash (kg ha^{-1})	11.6
Grain (q ha^{-1})	21.7
Market Price of grain (Rs q^{-1})	1398
Soil test-based fertilizer Recommendation (STBR)	
FYM (t ha^{-1})	8.6
Nitrogen (kg ha^{-1})	124.9
Phosphorus (kg ha^{-1})	73.5
Potash (kg ha^{-1})	31.1
Grain (q ha^{-1})	40
Misapplication (%)/yield gap (STBR-FP) / (STBR)	
FYM (%)	69.8
Nitrogen (%)	22.2
Phosphorus (%)	-10.6
Potash (%)	62.7
Grain (%)	45.8
Impact of Soil Information (Rs)	
Additional Cost (Rs ha^{-1})	6432.0
Additional Benefits (Rs ha^{-1})	43547.5
Net change Income (Rs ha^{-1})	37115.5

The estimated benefits of soil test-based fertilizer recommendations for maize cultivation are presented in Table 3. In the study, maize farmers currently apply an average of 2.6 t ha^{-1} of farmyard manure, 97.2 kg ha^{-1} of nitrogen (N), 81.3 kg ha^{-1} of phosphorus (P), and 11.6 kg ha^{-1} of potassium (K). However, the soil test-based recommendations for optimal maize yield (8.6 t ha^{-1}) suggest fertilizer applications of 124.9 kg ha^{-1} N, 73.5 kg ha^{-1} P, and 31.1 kg ha^{-1} K. The difference between soil test-based requirements and farmers' current practices indicates misapplication of fertilizers. If extension agencies promote soil test-based recommendations considering soil fertility status, farmers could reduce excess phosphorus application by 10.6% while addressing deficiencies in nitrogen (22%) and potassium (63%). The additional cost of correcting fertilizer misapplication is Rs. 6,432 per hectare, whereas the additional benefits from adopting soil test-based fertilization amount to Rs. 43,547 per hectare. This results in a net gain of Rs. 37,115 per hectare per year. Moreover, the cost of soil testing, estimated at Rs. 300 per sample, is significantly lower than the net additional benefits per hectare, highlighting the economic feasibility of adopting soil test-based fertilizer management.

Conclusion

The study on SOCD in Karnataka soils revealed that while the relationship between Cation Exchange Capacity (CEC) and SOCD is weak, it is significantly influenced by soil pH and the semi-arid climate, which largely influences the region's soil physicochemical conditions. The combination of pedological factors, a range of elevation, and mean annual rainfall in Karnataka provides a direct relationship for exploring the interrelationships between soil properties and SOCD using a path model. A key finding of this study is the protective role of Ca^{2+} in stabilizing organic carbon through the formation of organo-metal complexes, which clarifies the functional relationship between **c**lay, silt, and SOC and helps predict future changes in soil carbon storage. This pedological insight from soil surveys can serve as a baseline for regional soil carbon monitoring programs. These findings highlight that clay and SOC content are strongly correlated, with clay acting as a key factor in stabilizing organic carbon through its interaction with metal cations. Hence, clay, silt, $CaCO_3$, available phosphorus, and DTPA-Cu are identified as critical traits for improving SOCD per hectare in the shrink-swell soils of Karnataka. Additionally, the economic analysis of soil test-based fertilizer recommendations demonstrated substantial financial benefits. The per hectare cost of correcting fertilizer misapplication is Rs. 6,432, while the additional benefits from balanced fertilization amount to Rs. 43,547 per hectare, resulting in a net gain of Rs. 37,115 per hectare per year. These findings highlight the importance of adopting soil test-based fertilizer management for enhancing both soil productivity and economic returns in maize cultivation.

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