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Soil Carbon Stock under Different Agro-climatic Zones and its Economic Valuation for Productivity Enhancement of Pigeon Pea (*Cajanus cajan*) in Southern Deccan Plateau

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Abstract: Soil Carbon (SC) storage is a key indicator of soil function used to monitor and predict crop response to management decisions. Under the SUJALA-3 Watershed Development Project, a total of 202 soil series representing major pigeon pea-growing soils were studied in seven agro-climatic zones of Karnataka. The organic and inorganic carbon stocks status were estimated at different soil depths to arrive at the economic value and assessed its relation with crop production. The SOC and SIC stock was 23.8 and 11.2 t ha^{-1} at 0-30 cm, 42.0 and 32.1 t ha^{-1} at 30-100 cm and 66.9 and 42.8 t ha^{-1} at 0-100 cm depth, respectively. The yield of pigeon pea was high (12.18 q ha^{-1}) under high OC status of clay textured soils followed by medium SOC (11.11q ha^{-1}) and low OC soils (11.52 q ha^{-1}) in NETZ region. Using the agglomeration method, five groups were derived to determine the soil organic carbon management clusters. The soil organic carbon deficit (t ha^{-1}) calculated to arrive investment requirement showed the order of cluster-4>cluster-3>cluster-1>cluster-5>cluster-2 and the investment required to bridge the gap of Rs. 30228, 26508, 26190, 22674 and 21990, respectively. As soil structure stability has an important role in carbon sequestration, the polynomial equation was constructed between soil carbon density and soil structural stability index, which yielded a threshold soil carbon stock value of 66.6 t ha^{-1} to attain a stable soil structure index value of nine. The ANOVA analysis showed statistically significant differences in SOC stock between regions ($p = 0.022$) and soil subgroups ($p = 0.001$). The study concludes an average investment of ₹ 25,000 ha^{-1}yr^{-1} for 20 yr is required for enhancing the soil carbon status in Karnataka and to achieve the Pigeon pea potential yield of 20 q ha^{-1}

Keywords: *Soil carbon stock, agro-climatic zones, pigeon pea, economic evaluation, potential yield*

Introduction

Soil is a carbon sink and a key factor in sequestering atmospheric carbon in soil and regulating greenhouse gases and climate change (Bispo *et al*. 2017). Assessing soil carbon stock through soil resource inventory is essential for monitoring soil carbon stocks (SOC) at the national level and for assessing the factors affecting the carbon dynamics under agro-ecological research (Adger and Brown 1994; Chaplot *et al*. 2009). The soils of semi-arid tropics have SOC content well below the critical range of 1 to 2% as it is influenced by climatic conditions, soil characteristics, environmental conditions, and crop management practices (Loveland and Webb 2003; Lalitha and Praveen Kumar 2016;

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Oldfield *et al*. 2019). Thus, it is obligatory to buildup the SOC content between 1.1 to 1.5 **%** to reduce the risk of soil degradation and improve the environmental quality (Lal 2015). As the soil organic carbon has a significant role in environmental and ecosystem viability, the benefits of soil carbon society are determined based on the societal value of carbon (Lal 2014). Ramesh Kumar *et al.* (2009) assessed the economic value of soil organic carbon at a micro-watershed scale using nutrients replacement value. Besides, the carbon emission method was used by different researchers across the globe for estimating the monetary value of soil carbon data sets (Mikhilaova *et al*. 2019; Grashans *et al.* 2019). The Indian soils have a soil organic carbon stock of 9.8 Pg and 30 Pg at 0-30 cm and 0-150 cm soil depths, respectively (Bhattacharyya *et al.* 2000). The study on economic valuation of soil organic carbon for Indian soils is scanty except few carbon studies reported for grasslands and forest soils. As carbon trading is one of the main criteria being recommended to improve carbon sequestration across the globe, the study on the economic valuation of SC stocks on crop production may be a path-breaking process in exploring soil as a key ecosystem function. Carbon accounting in semiarid regions lacks a detailed soil resource and socio-economic database for improving agro-environments. Hence, the present study was undertaken to estimate SOC stocks and their economic value for major soils in different agro-climatic zones of Karnataka and to assess its relation with pigeon pea crop production.

Materials and Methods

Study area and Land Resource Database

The total geographical area of Karnataka (19.1 million hectares, 5.8% of TGA of India) state (11° 40' N and 18° 27' N; 74° 5' E and 78° 33' E) The study area under SUJALA 3 project is confined to 7 agro-climatic zones as shown in table 1. The transitional zones are confined to the eastern part of the hill zones, the west of the dry zones, and a small portion in the northeastern part of the state where rainfall is high but somewhat erratic (Department of Agriculture, Government of Karnataka 2010).

The major land-use systems are pigeon pea production systems. The detailed soil survey on 1:10000 scale was carried out during 2016-2019 as per the guidelines of Soil Survey Staff (2017). During this survey, 596 micro watersheds were selected in 7 agro-climatic regions of Karnataka covering 285105 ha (Hegde *et al.* 2017). A total of 202 soil profiles were studied and classified up to subgroup level in the orders of Vertisols, Alfisols, Inceptisols, and Entisols as per Soil Survey Staff (2017).

Table 1. Details of agro-climatic zones with the number of soil subgroups and major crops

Agro-Climatic Zones	Number of Micro Watersheds (Mws)	Area of Mws (Ha)	Rainfall (Mm)	Soil Series	Major Crops Grown
North Eastern Transition Zone	14	2422	845	17	Pigeon pea
North Eastern Dry Zone	275	154110	847	68	Pigeon pea
Northern Dry Zone	240	106929	636	57	Maize
Central Dry Zone	9	7574	620	17	Finger millet
Eastern Dry Zone	9	1708	715	9	Finger millet
Southern Dry Zone	26	8938	771	24	Pigeon pea
Northern Transitional Zone	23	3424	701	10	Pigeon pea

Soil carbon and inorganic storage estimation

Horizon-wise soil samples from different pedons were collected and air-dried for fine earth fraction (<2 mm). The soil samples were ground and passed through a 0.15 mm sieve for the determination of SOC. 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 pedo-transfer function was used to estimate the bulk density of soils (Kaur *et al.* 2002) as per the following formulae

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

The soil organic carbon stock and soil inorganic carbon stock was calculated as per the following formulae

$$SOCS = \sum_{i=1}^{m} area\ X\ SOCDi$$

$$SICS = \sum_{j=1}^{m} area\ X\ SICDi$$

Where, m is the number of agro-climatic zone types, SOCDj is the SOC density (kgm^{-2}) over three depth intervals in the j^{th} agro-climatic zone, SICDj is the mean SIC density (kgm^{-2}) over three depth intervals in the j^{th} agro-climatic zone, j is the area of the j^{th} soil type in agro-climatic zone m, SOCS is SOC storage and SICS is SIC storage in soil (kg). Descriptive statistics analysis, ANOVA, and Turkey honest significant difference (HSD) post hoc multiple mean comparisons were worked out using the SPSS version 20.0

Economic valuation of soil carbon

Estimation of soil **o**rganic carbon stock and inorganic carbon stocks and its valuation was made based on the nutrients replacement value of organic carbon at ₹ 12000 t^{-1} of soil organic carbon (SOC) or ₹ 3270 CO_2 t^{-1}. The replacement value of soil inorganic carbon was estimated by considering the average market price of agricultural lime at the rate of ₹ 3800 t^{-1} to substitute the naturally occurring SIC levels in the soils under semi-arid climates (Ramesh Kumar *et al.* 2007; Goulding 2016).

Results and Discussion

Soil carbon in top soils (0-30 cm)

The top-soil carbon stocks (0-30 cm) are important to address the issues of climate change with time (IPCC 2006). In the present study, topsoil SOCS are considered for comparative assessment between agro-climatic zones of Karnataka. Agro-climatic zone-wise, the mean soil organic carbon stock was estimated and presented in table 2. The overall mean of SOC was 23.8 t ha^{-1} however displaying distinct zonal variations ranging from 20.3±6.5t ha^{-1}, in Northern Transitional Zone (NTZ) to 28.8±7.5 t ha^{-1} in North Eastern Transition Zone (NETZ). The high coefficient of variation was more than 35% in Eastern Dry Zone (EDZ) (43.4), Northern Dry Zone (NDZ) (39.3%), and North Eastern Dry Zone (NEDZ) (36.5%). The mean SOC in SDZ, NTZ, and EDZ was below the zonal mean of SOC was 23.8 t ha^{-1}. The mean SOC was higher than the total zonal mean in NETZ and EDZ. The high coefficient of variation was more than 35% in EDZ (43.4), NDZ (39.3%), and NEDZ (36.5%). The mean SOC in SDZ, NTZ, and EDZ was less than the zonal mean of SOC was 23.8 t ha^{-1}. The mean Soil Inorganic Carbon (SIC) was 11.2 t ha^{-1} with a Coefficient of Variation (CV) exceeding 100 percent. The high zonal variations were recorded with a mean of 19.5±23.6 t ha^{-1} in NEDZ and 18.2±24.1 t ha^{-1} in NDZ. In CDZ, SDZ, and EDZ, the mean SIC was below that of the zonal mean (11.2 t ha^{-1}). The mean total carbon stock (sum of SOC+SIC) was high in NEDZ (43.2±26 t ha^{-1}) and NDZ (41.8±24.4 t ha^{-1}). The overall mean T C was 25t ha^{-1} in SDZ 31.4±20.7 t ha^{-1} in EDZ and 32.7±21 t ha^{-1} in CDZ. The per cent contribution of SOC to TOC was 68 per cent whereas SIC was 32 per cent. SOC contributes 83 per cent of TOC in NETZ and 92 per cent in SDZ. The SIC contributes greater than 40 per cent in NEDZ, NDZ, and NTZ.

Table 2. Soil carbon stocks in different agro-climatic zones of Karnataka (tons ha^{-1})

Zones	SOC	SIC	TC	SOC	SIC	TC	SOC	SIC	TC
	0-30 cm			30-100 cm			0-100 cm		
North Eastern Transition Zone (NETZ)	28.8 (± 7.5)	5.9 (± 6.4)	34.7 (± 9.1)	54.6 (±12.4)	19.7 (± 8.1)	74.4 (±36.4)	84.3 (± 17.6)	26.1 (± 42.9)	110.4 (± 42.4)
CV (%)	26.1	109.4	26.1	22.7	192.8	48.9	20.9	164.3	38.4
North Eastern Dry Zone (NEDZ)	23.6 (±8.6)	19.5 (±23.6)	43.2 (± 26)	39.7 (± 18.9)	58.6 (± 58)	98.3 (±61.3)	63.8 (± 23.9)	78.3 (± 1.4)	142.1 (± 85.5)
CV (%)	36.5	120.7	60.2	47.5	99	62.4	37.5	104	60.2
Northern Dry Zone (NDZ)	23.6 (±9.3)	18.2 (± 24.1)	41.8 (± 4.4)	45 (± 18)	46.4 (±71.1)	91.5 (± 78)	69.3 (±24.9)	58.6 (± 82.6)	127.9 (± 87.7)
CV (%)	39.3	132.4	58.3	39.9	153.1	85.2	35.9	141	68.6
Central Dry Zone (CZD)	24.5 (±7.9)	8.3 (± 16)	32.7 (± 21)	40.8 (± 14.7)	23.6 (± 8.6)	64.5 (±47.4)	65.3 (±20.2)	31.9 ±52.8)	97.1 (± 67.5)
CV (%)	32.4	193.8	64.2	36.1	163.3	73.5	31	165.6	69.5
Eastern Dry Zone (EDZ)	22.9 (± 10)	8.5 (± 1.1)	31.4 (±20.7)	33.4 (± 9.8)	25.1 (± 74.6)	58.5 (±74.1)	58.7 (±21.8)	33.8 (±95.)	92.4 (± 92.8)
CV (%)	43.4	249.1	66	29.5	297	126.6	37.2	282.8	100.4
Southern Dry Zone (SDZ)	23 (± 8)	1.9 (± 5.3)	25 (± 10.5)	39.3 (± 10)	5.4 (±15.1)	44.7 (±19.6)	65.1 (± 17)	7.4 (±20)	72.5 (± 28.7)
CV (%)	34.6	270	42.1	25.4	277.5	43.9	26.1	273.5	39.6
Northern Transition Zone (NTZ)	20.3 (± 6.5)	16.3 (±16.6)	36.6 (±17.4)	41.3 (± 14.1)	45.6 (± 41.7)	86.9 (±45.6)	61.6 (± 20)	63.4 (±58.1)	125.1 (± 62.5)
CV (%)	32	102.1	47.4	34.1	91.5	52.5	32.5	91.5	50
Pooled Mean	23.8	11.2	35.1	42.0	32.1	74.1	66.9	42.8	109.6

Soil carbon in sub-soil (30-100 cm)

The overall SOC in sub-soil was 42 t ha^{-1}. The mean of SOC was more than the zonal mean in NETZ (mean of 54.6±124 t ha^{-1}) and in NDZ (45.0±18 t ha^{-1}). The CV was moderate for CDZ and EDZ and in other zones, CV was high. The zonal mean of SIC was 32.1 t ha^{-1} with 43% of TOC. The SDZ has mean of 5.4±15.1 t ha^{-1} with a CV of 277 per cent. The mean SIC was high in NEDZ (58.6±58 t ha^{-1}) and NDZ (mean of 46.4±71.1 t ha^{-1}) with a CV of >100%. The mean TOC for ACZ was 74.1 t ha^{-1}. However, the high TOC was found in NEDZ, (98.3 t ha^{-1}), NDZ (91.5 t ha^{-1}) and NTZ (86.9 t ha^{-1}). The per cent SIC contribution to TC was 60 per cent in NEDZ, 52 per cent in NTZ, and 51 per cent in NDZ.

Soil carbon in 0-100cm

The zonal mean of SOC at 0-100 cm soil depth was 66.9 t ha^{-1} showing variation between the zones. The mean SOC was above the zonal mean in NETZ (84.3±17.6 t ha^{-1}) and NDZ (69.3±24.9 t ha^{-1}) but, in the remaining zones had mean SOC below zonal mean with moderate (NETZ and SDZ) to high variability. The zonal mean of SIC was 42.8 t ha^{-1} with a high value of SIC in NEDZ (78.3±81.4 t ha^{-1}) and NTZ (63.4±58.1 t ha^{-1}) with high CV. The ACZ mean for TC was 109.6±24.0 t ha^{-1}. The mean TC was high in NEDZ (142.1t ha^{-1}), NDZ (127.9 t ha^{-1}), and NTZ (125.1 t ha^{-1}). The per cent variation was high in all climatic zones. The NEDZ and NTZ have shown greater than 50% of the contribution of SIC in TC. The results of this study with a high variation of soil organic carbon are in line with the findings of Bogunovic *et al*. (2017) and Rosemary *et al*. (2017).

Two ways ANOVA

Two ANOVA analysis was performed to evaluate the significant effect of agro-climate and soil subgroups on top-soil carbon storage potential (0-30cm), clay, calcium carbonate content, and CEC. The ANOVA analysis confirmed a statistically significant variation of SOC stocks between the zones (p =0.022), soil subgroups (p = 0.001), and its interaction (zones versus soil subgroups (Table 3). The results point out the relative distribution of soil organic, inorganic, and total carbon stocks in the location are related to clay, CEC, and calcium carbonate contents. These parameters can be used as best predictors of top SOC (Jobbagy and Jackson 2000).

Table 3. Two way ANOVA analyses of soil properties in relation to agro-climatic zones

Source of variation	df	SOC (t ha^{-1})		TC (t ha^{-1})		SIC (t ha^{-1})		Clay (%)		CEC (cmolkg^{-1})		OC (%)		$CaCO_3$ (%)	
		F	Sig.	F	Sig.	F	Sig.	F	Sig.	F	Sig.	F	Sig.	F	Sig.
Zones	6	2.563	0.022	1.966	0.078	2.350	0.037	1.883	0.088	2.782	0.014	2.573	0.021	0.463	0.683
Subgroup	17	2.611	0.001	2.489	0.005	2.554	0.004	6.479	0.000	9.036	0.000	2.725	0.001	20.180	0.046
Zones * Subgroup	33	1.793	0.010	1.698	0.038	1.970	0.011	1.419	0.084	0.960	0.537	1.734	0.015	0.100	0.782
R^2		0.41		0.46		0.52		0.70		0.75		0.42		0.91	

Crop yield versus soil organic carbon

The pigeon pea crop yield was assessed against the soil organic carbon status of the soil. The productivity of pigeon pea was 553.7 kg ha^{-1} in 2005 it has declined to 482.3 kg ha^{-1} with negative growth of 12.9 per cent over a decade. The NDZ yields were below the Karnataka (7.0 q ha^{-1}) and the national average (8.87 g ha^{-1}). The SOM content is known to improve soil fertility by stabilizing soil structure, increasing nutrient availability, and improving water-holding capacity (Johnston *et al*. 2009; Watts and Dexter 1997). Besides, the SOC content of the soil is influenced by soil depth and soil texture. Hence, the study assessed the interaction effect of soil texture and SOC and also soil depth and SOC on crop yield.

Interaction effect of texture and SOC on yield

The interaction effect of texture and organic carbon status on the yield of pigeon pea in two agro-climatic zones was worked out. The results confirmed that NETZ had two dominant textural classes as clay and sandy clay. In clay soils, under high organic carbon status (0.75%), the yield of pigeon pea was 10.54 q ha^{-1} however in medium OC, the yield was 9.49 q ha^{-1} (Fig.1). The yields were directly related to SOC status, as the yield was low (6.07 q ha^{-1}) under low SOC soil. In NEDZ, the yield of pigeon pea was 12.18 q ha^{-1} under high OC status of clay textured soils but slightly reduced in yield under medium SOC (11.11q ha^{-1}) and in low OC soils (11.52 q ha^{-1}). In the case of sandy clay loam soils, the OC effect on pigeon pea yield was subtle from low to high. The soil organic carbon pools (active, slow, or passive) are physically stabilized with their strong association of silt and clay particles (Feller and Beare 1997; Six *et al.* 2002) or for forming micro or macro aggregates (Tisdale and Oades 1982). Despite these positive attributes, crop yields do not always increase with higher SOM contents (Loveland and Webb 2003). This discrepancy between improvements in soil quality and lack of yield response has been explained by De Haan (1977) and Janssen (2002).

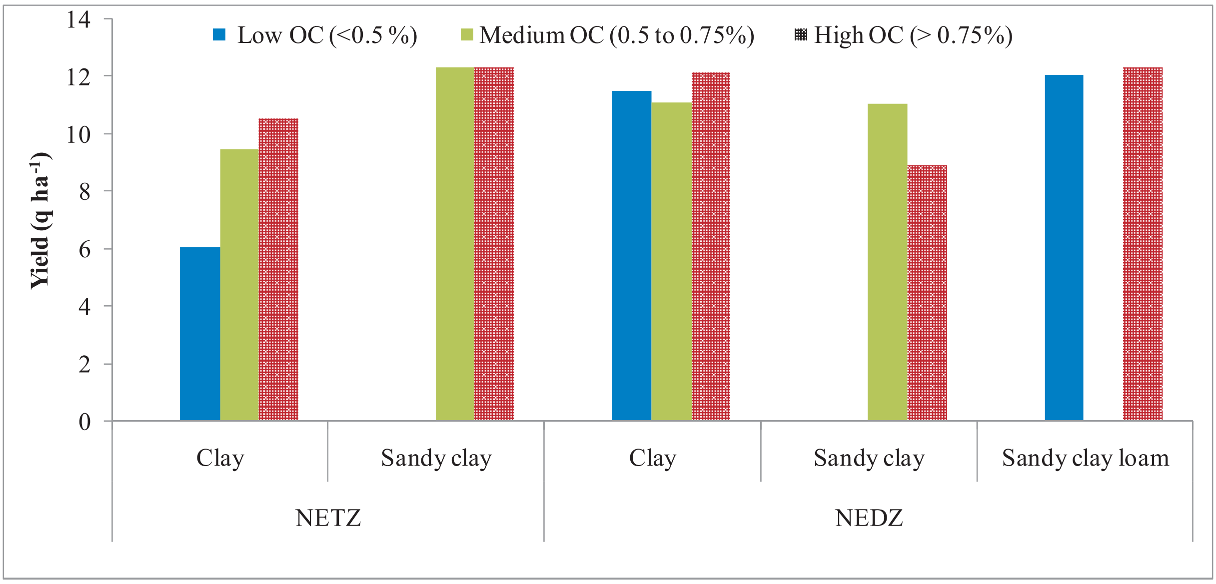

Fig. 1. Pigeon pea yield versus texture in relation to soil organic carbon

Interaction effect of soil depth and SOC on yield

The pigeon pea yields were analysed with soil depth class in two prominent agro-climatic zone of Northern Karnataka. The NETZ had five depth classes of which slightly deep soils recorded mean yield of 12.35 q ha^{-1} as compared to deep (11.65 q ha^{-1}) and very deep (9.49 q ha^{-1}) below high OC status (Fig. 2). The NEDZ had mean yield of 14.39 in very deep (>150cm) under excessive OC status as compared to moderately deep soil (12.88 q ha^{-1}). The Histogram is constructed using 34 soil series records in two agro-climatic zones. NETZ has nine soil series, of which Mustarwadi (MED, Kanhaplic Rhodustalfs), Dinsi (DSI, Typic Haplusterts) had 12.4 q ha^{-1}. The yield 7.3 q ha^{-1} was recorded in Mahagaon (MAN, calcareous Typic Haplusterts) and extremely shallow Margutti series (MGT, Typic Ustorthent).

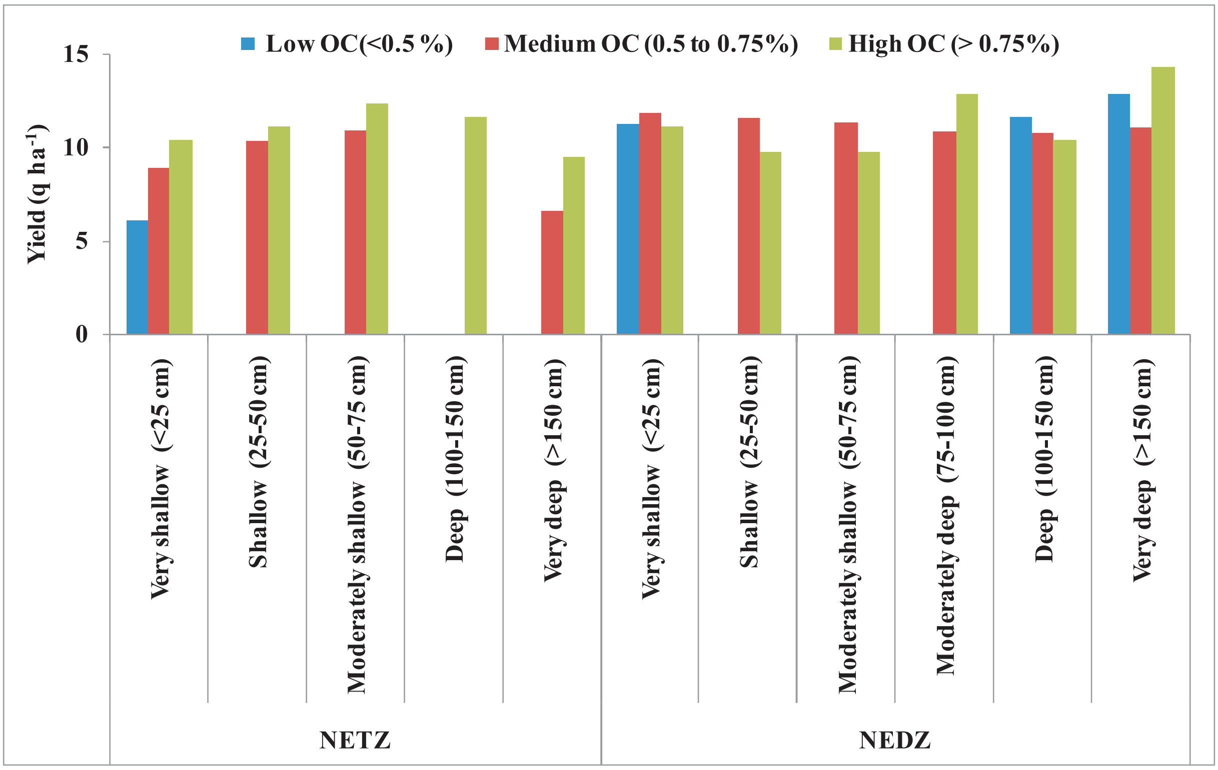

Fig. 2. Pigeon pea yield versus soil depth in relation to organic carbon

Clustering of soils

The cluster analysis used eleven soil variables of 202 soil series and derived five clusters using the Agglomerate ward method. The outcomes of cluster-1 evaluation confirmed the affiliation of 39 soil series in cluster-1 overlaying 18 percentage (52331 ha) of the total survey area (Table 4). The cluster-1 consisted of 17 soils series of Alfisols order accounting 43.58 per cent of 39 series whereas the sub corporations of Inceptisols accounted 23.1 per cent of the total series. The mean soil organic carbon in cluster-1 is 0.62 ±0.15 per cent and had a density of 22.95±5.16 t ha^{-1} with a monetary value of Rs 27 per sq meter. Cluster-2 had 45 soil series classified under the subgroups of Inceptisols (46%) and Alfisols (26.67%). This cluster occupied 51,591 ha accounting for 18 percent of the total survey area. The mean organic carbon was 0.73 ±0.27 % with 37 % clay and 27 cmol kg^{-1} CEC. The cluster means for SOC density was 26.95±9.66 t ha^{-1} with a monetary value of Rs 32.34 per sq meter.

The cluster-3 included 44 series, having soil affiliation of subgroups of Alfisols (29.5%), Inceptisols (27.3%), Vertisols (18%), and Entisols (18 %). The mean organic carbon of the cluster was 0.65±0.23 per cent with a density of 22.42±7.57 t ha^{-1}, having a monetary cost of Rs 26.90 per sq meter. This cluster covers 27 percentage of the total surveyed area (77,726 ha).

Cluster-4 included 32 series covering 36,253 ha (11 % of total survey area). This cluster had 33 series of which 44 percent belong to the subgroup of Alfisols (44%), Inceptisols (28 %), and Vertisol (20%). This cluster had a mean organic carbon of 0.44±0.2 percent to classify as low organic carbon stock (Venkanna *et al.* 2014). The mean soil organic carbon density of the cluster was 16.22±6.48 t ha^{-1} with an economic value of Rs 19.47 per sq meter (Table 4).

High organic carbon 0.78± 0.22 % was recorded in Cluster-5. This cluster had 41 soil series with a dominant soils association of subgroups of Alfisols (43%) and Inceptisols (33.3%). This cluster covers 70,799 ha with a carbon density of 28.81±7.97 t ha^{-1}. The per sq meter economic value of organic carbon density was Rs 34.57. The ANOVA analysis was carried out to recognize the significant variation of soil carbon and carbon density between the clusters. The results of ANOVA showed significant variation with an F value of 12.0 (0.001).

Soil organic carbon and Soil structural stability (SSI)

The critical range of SOC and investment requirement for 20 years for bridging the SOC deficient requires the assessment secondary variable, controlling the SOC. The plot between the soil organic carbon density (SOCD) and SSI was built and derive second-orderer polynomial regression model to predict the threshold degree of SOCD for achieving stable soil structure. The model estimated a threshold value of SOCD of 66.6 t ha^{-1} required for maintaining SSI of 9 in pigeon pea cultivated soils of Karnataka. The relationship of actual and expected SOCD had been computed with a coefficient of determination of R^2 = 0.997. The regression equation developed from the study is as follows

Predicted SOCD =1.183* (Actual SOCD)^2 - 49.30* Actual SOCD + 532.7 (Fig. 4).

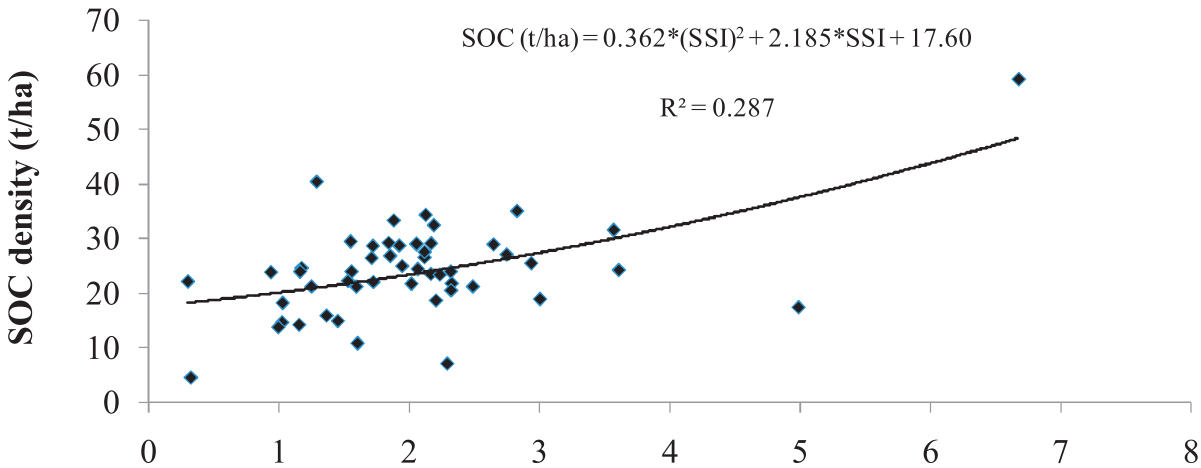

Fig. 4. Relationship between SOCD and SSI

Table 4. Investment requirement for bridging the SOC deficient in Karnataka

Particulars	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster Mean
SOC Deficit (t ha^{-1})	43.65	36.65	44.18	50.38	37.79	42.75
Total Area (ha)	52331	51591	77726	32653	70799	285101
Annual Investment (Rs.ha^{-1})	26190	21990	26508	30228	22674	25650
Cumulative Investment (Rsha^{-1}) for 20 years	523800	439800	530160	604560	453480	513000

Note: The cost of SOC was @ Rs 12000 per ton.

Economic valuation SOC deficit

The SOCD deficit value was 42.75 t ha^{-1} and the total investment required for bridging the SOCD was Rs 5, 13,000. Assuming 20 years for building the SOC stock, the estimated annual investment is around Rs 25650 ha^{-1}. The investment priority for building SOC density is in Cluster-4 (Rs 30, 228 ha^{-1}) followed by Cluster 1, 2, 3 (Rs 26,508), and Cluster 2 to 5.

As the topsoil (0-30 cm) was considered for cluster analysis, using the mean SIC density for the analysis showed subtle modifications among the cluster. Soil inorganic carbon density was excessive with a mean of 17.7 ±25.5 t ha^{-1} in clusters-4 due to high clay content and moderate alkalinity. All the soils are structurally degraded (structural stability index-SSI), having a value of < 5 (Pieri 1992).

The study summarize that in shallow soils, the SOCD in Alfisols was comparatively high (28.72 t ha^{-1}) as compared to Vertisols (21.84 t ha^{-1}). The difference in SOCD in Alfisols and Vertisols was 6.88 t ha^{-1}. The difference in pigeon pea yield was 5.13 q ha^{-1} between Alfisols (17.82q ha^{-1}) and Vertisols (12.69 q ha^{-1}). In moderately deep soil, the SOCD was 29.31 t ha^{-1} in Alfisols and 26.37 t ha^{-1} in Vertisols with a difference of 2.94 t ha^{-1}. The yield was increased over shallow soils with 14.67 q ha^{-1} in Vertisols and 18.15qha^{-1} in Alfisols with a difference of 3.48 q ha^{-1}. The increasing trend of yield and SOCD was evident across the depth. In the case of deep soil, the SOCD was comparatively low to that of very deep soil however yield showed a slight increase. The yield of pigeon pea in deep soils suggests moderate enhancement but not SOCD. The partial factor productivity of SOCD was worked out. The results showed that in shallow shrink-swell soils, 1kg of organic carbon density is required to produce 58.13 of pigeon pea grain but in moderately deep soils, it is 55.62 g and 64.91g in deep soils. In contrast to the Vertisols, the Alfisols produced more than 60 g kg^{-1} carbon across the depth. The partial factor productivity of SOCD was excessive in Alfisols over Vertisols. The soil variability in different agro-climatic zones of pigeon pea cultivating soils of Karnataka needs to be viewed in the built-up of SOC and the estimation of investment requirement. The study brought out high per hectare investment (>₹ 3000) is needed in Vertisols over Alfisols. A critical limit of 20 g SOC kg^{-1} was determined for soil quality in the analyzed areas.

Conclusions

A land resource database of 596 micro-watersheds generated under the SUJALA-3 project in 7 agro-climatic zones of Karnataka was evaluated for the economic evaluation of carbon stocks for pigeon pea production. The soil organic and inorganic carbon estimated for about 202 profiles pedons were assessed in relation to secondary variables such as depth, CEC, and soil order. The replacement value approach was used to estimate soil carbon storage and decide its economic value from the accumulation of total soil carbon pools. In the seven agro-climatic zones, the carbon density of the surface soil (0-30 cm) showed obvious changes. The average value of NEDZ was 43.2±26 t ha^{-1}, whilst the average value of NEDZ was 25 ± 10.5 t ha^{-1}. The sub-soil carbon density (30-100 cm) showed similar zonal trends with a high mean of 98.3±61.3 t ha^{-1} in NEDZ and 91.5±78 t ha^{-1} for NDZ with high variability (CV >35%). The total carbon stock up to one meter was high in NEDZ followed by NDZ. Generally, the per cent contribution of SOC to TC is 68 per cent whereas SIC was 32 per cent in soils of Karnataka. The results of a two-way analysis of variance showed that there are significant variations in soil carbon density and interactions between agro-climatic zones and soils. Soil properties such as clay, and CEC are closely related to soil carbon density. Grouping the data with the depth and texture performance of the pigeons in the three organic carbon groups, it was observed that the very deep clay textured soil performed well, with a yield of 12.18 q ha^{-1}. Alfisols had a higher soil carbon density and yield, with an average of 68 gkg^{-1} C compared to Vertisols (58 gkg^{-1} C). The derived second-order polynomial equation determined the soil organic carbon density threshold value of 66 t ha^{-1} will have a stable structure. Taking this threshold into account, it was estimated that these soils require funding of Rs 25,000 per hectare per year to accumulate soil natural carbon in 20 years. The soil carbon stability helps to hold the ecosystem services and functions of the soil to realize the potential yield of peas in the region (20 q ha^{-1}).

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