Journal of Experimental Agriculture International

Volume 46, Issue 1, Page 77-86, 2024; Article no.JEAI.111683
ISSN: 2457-0591
(Past name: American Journal of Experimental Agriculture, Past ISSN: 2231-0606)

Soil Dynamics for Carbon Buildup in Different Land Use Systems in the South Region of Gujarat, India

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/JEAI/2024/v46i12296

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/111683

Original Research Article

Received: 14/11/2023
Accepted: 18/01/2024
Published: 22/01/2024

ABSTRACT

Soil dynamics for carbon build-up vary across different land use systems. Understanding the soil dynamics and land use system management practices that contribute to carbon build-up is essential for designing effective carbon sequestration strategies. In a recent study, fifteen different land use systems were examined, including agriculture land-use systems, tree plantation land-use systems, and agroforestry land-use systems. The study assessed the potential of these land use systems to store carbon based on the extent of tree components. Various physical and chemical characteristics of the soil and their impact on soil carbon conservation were also investigated. The results showed that as the number of tree components increased, the soil pH and bulk density decreased from 6.10 to 5.55, and 1.48 to 1.33g/cm3. The available soil nitrogen was significantly higher in tree plantation land-use systems than in agriculture land use systems while soil moisture was higher in the latter. Tree components increase soil carbon build-up and agroforestry land use systems fulfill the requirement for human and environmental balance.

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Keywords: Agroforestry; bulk density; land use systems; soil carbon; soil dynamics.

1. INTRODUCTION

Soil dynamics, or the physical, chemical, and biological processes that occur within the soil, can be significantly influenced by different land use systems. The repercussions of soil dynamics within different land use systems are multifaceted, wielding significant implications for the environment, agriculture, and the sustainability of ecosystems. Carbon buildup, a term encapsulating the accumulation and storage of carbon in diverse forms across ecosystems, predominantly in the soil and vegetation, stands as a pivotal facet of these consequences [1]. This process plays a crucial role in mitigating climate change by removing carbon dioxide (CO_2) from the atmosphere and storing it in long-term reservoirs. Carbon buildup is a key component of carbon sequestration, which involves capturing and storing carbon to reduce the concentration of greenhouse gases in the atmosphere. Several key facets characterize carbon buildup, with one pivotal aspect being the accumulation of organic matter through the incorporation of plant residues. In this intricate process, decomposed plant materials, including leaves, branches, and roots, actively contribute to the organic matter content in the soil. This assemblage forms a substantial reservoir of stored carbon, playing a crucial role in the intricate carbon cycle within ecosystems. Soil microorganisms, functioning as nature's recyclers, play a dynamic role in this ecological drama. These microscopic actors break down organic matter through a myriad of biochemical processes, effectively converting it into stable forms of carbon. As microbial communities thrive in the soil, their enzymatic prowess transforms once-living plant material into enduring carbon structures, fostering the resilience and carbon storage capacity of the soil. This microbial activity plays a vital role in the buildup of soil carbon. Global climate change, considered to be one of the most serious threats to the environment, has been at the center of scientific and political debate in recent years. The undeniable reality of climate change, specifically global warming, is accompanied by a notable degree of uncertainty regarding the dynamics of this warming phenomenon. Addressing this challenge involves exploring options such as reducing carbon emissions and sequestering carbon in plant biomass. However, it's crucial to recognize that soils, too, emerge as a potent player in mitigating climate change, serving as an effective carbon sink [2]. Scientists estimate that the global potential of soil carbon sequestration is 0.4 to1.2 Gt C/yr, or an amount equal to roughly 5 to 15 percent of total man-made CO_2 emissions [3]. To be most effective, CO_2 must be fixed into long-lived pools (or "sinks"). The soil organic carbon sinks capacity depends on land use and its management. Soil management strategies for carbon sequestration include three approaches. First, management of soil to maintain higher than existing levels of soil organic matter. Second, to manage carbon degraded soils so as to restore soil organic matter levels. Third, enlarging soil organic carbon and micro-aggregation. Sub-soil organic carbon can be increased by growing deep rooted plants (trees/crops) and deep ploughing. Eco-friendly farming practices like organic farming, precision farming and agroforestry a great potential to enrich soil with organic carbon through sequestrating carbon in soils. In order to exploit this vastly unrealized potential of C sequestration through agroforestry in both subsistence and commercial enterprises in the tropics and the temperate region, innovative policies, based on rigorous research results, have to be put in place. Research efforts are needed to quantify the carbon sequestration capacity of these practices and recommend sustainable land use systems with better carbon sinks and promising economic gains that can be adopted by farmers.

2. MATERIALS AND METHODS

Study site: Geographically, Navsari is situated at 20.95^o North latitude, 75.90^o East longitude and at an altitude of 12.0 meters above mean sea level (MSL). It is located in South Gujarat with heavy rainfall zone I (Agro-ecological situation-III) according to agro-climatic conditions, and within the Collge instructional farm which is 12 km away east of the Arabian Seashore Dandi. The average annual precipitation is 1355 mm. Monsoon commences mostly from the second week of June and lasts until the first week of October. Most of the rainfall is received from Southwest monsoon, concentrating in the months of July and August. Winter starts from November with mild cold and lasts up to February. December and January are the coldest months of the year. Summer commences in mid-february and ends in mid-June. April and May are the hottest months of the year. The soil of the experimental site is dark grayish brown type with flat topography. The soil has medium to poor drainage and good water-holding capacity.The predominant clay mineral is montmorillonite.Fifteen different land use systems, in order of increasing tree component with sole agriculture and horticulture crops, representing agriculture field, paddy- *Oryza sativa* L. (OS), horticulture field sugarcane- *Saccharum officinarum* L. (SO) and banana- *Musa paradisiaca* L. (MP), tree plantation sapota- *Manilkara achras* L. (MA), Mango- *Mangifera indica* L.(MI), teak- *Tectona grandis*L.f. (TG), Killai- *Albizzia procera* (Roxb.)Benth. (AP), Eucalyptus- *Eucalyptus clones* (EC), Casuarina- *Casuarina equisetifolia*L.ex J.R.&C.Fraser (CE), Shisham- *Dalbergia latifolia*Roxb. (DL), Jatropha- *Jatropha curcas* L., (JC) Arjun- *Terminalia arjuna* (Roxb.ex DC.) Wight & Arn. and three agroforestry land use systems Rice + Boundary plantation (*Tectona grandis* L.f.) (RTG), Sugarcane + Boundary Plantation (*Casuarina equisetifolia* L. ex J.R. & C. Fraser), (SCE) and Banana + Boundary plantation (*Tectona grandis*) (BTG) were selected for comparison their carbon sequestration potential. Table 1; showed the detail of different land use systems with 15 treatments with 03 replication, number of tree/hectare, crop and plant space etc. were taken for observations.

Table 1. Details of different land use systems

S.no	Treatments (Land use systems	Tree spacing (m)	Crop spacing (cm)	Season of crop/ Planting Year	No of trees (Per hectare)	Plot size m^2
1	**Agriculture land use systems (S_1)**					
a	*Oryza sativa* L. (OS)	---------	20 x 20	Kharif	-------	10 x 10
b	*Saccharum officinarum* L. (SO)	----------	30 x 90	Kharif	---------	
c	Banana- *Musa paradisiaca* L. (MP)	----------	1.8 x 1.8 (m)	Kharif	300	
2	**Tree plantation land use systems (S_2)**					
a	*Manilkara achras* L. (MA),	8 x8	------------	1994	156	10 x 10
b	Mango- *Mangifera indica* L. (MI)	8 x8	------------	1990	156	
c	Teak- *Tectona grandis*L.f. (TG),	3 x3	------------	1990	1111	
d	Killai- *Albizzia procera* (Roxb.) Benth. (AP)	3 x3	------------	1995	1111	
e	Eucalyptus- *Eucalyptus clones* (EC),	2 x2	------------	2009	2500	
f	Casuarina- *Casuarina equisetifolia*L.ex J.R.&C.Fraser (CE),	2x 2	------------	2009	2500	
g	Shisham- *Dalbergia latifolia*Roxb. (DL),	3 x 3	------------	1991	1111	
h	Jatropha- *Jatropha curcas* L.,(JC)	2 x 2	------------	2006	2500	
i	Arjun- *Terminalia arjuna* (Roxb.ex DC.) Wight & Arn. (TA)	4 x 4	------------	1990	400	
3	**Agroforestry land use systems (S_3)**					
a	Rice + Boundary plantation (*Tectona grandis* L.f.) (RTG),	5 x 5	20 x 20	1999	400	10 x 10
b	Sugarcane + Boundary Plantation (*Casuarina equisetifolia*L.ex J.R.&C.Fraser), (SCE)	3 x 3	30 x 90	2006	1111	
c	Banana + Boundary plantation (*Tectona grandis*) (BTG)	5 x 5	1.8 x 1.8 (m)	2002	400	

Table 2. Different methods used for soil sample analysis

Sr. No.	Parameters	Method employed
1.	Organic carbon (%)	Walkley and Black [4]
2.	Available N (kg/ha)	Alkaline permanganate method [5]
3.	pH of soil	Potentiometric method [5]
4.	Bulk density (g/cm^3)	Core sample method [6]

2.1 Soil Sample Collection and Preparation

Soil specimen samples from different land-use systems were collected from different soil depths of 0-10cm, 10-20cm, and 20-30 cm in triplicate. The composite soil samples for each depth were obtained by mixing three samples. For analysis of soil physio-chemical, samples were air dried in the shade, ground with a wooden pestle, passed through 2 mm sieve and stored in cloth bags. Table 2 showed the different depth soil sample physio-chemical analysis methodology. Soil organic carbon pool inventory (Mg/ha) for a specific depth was computed by multiplying the soil organic carbon expressed as g/kg with bulk density (g/cm^3) and depth of soil (cm) [7].

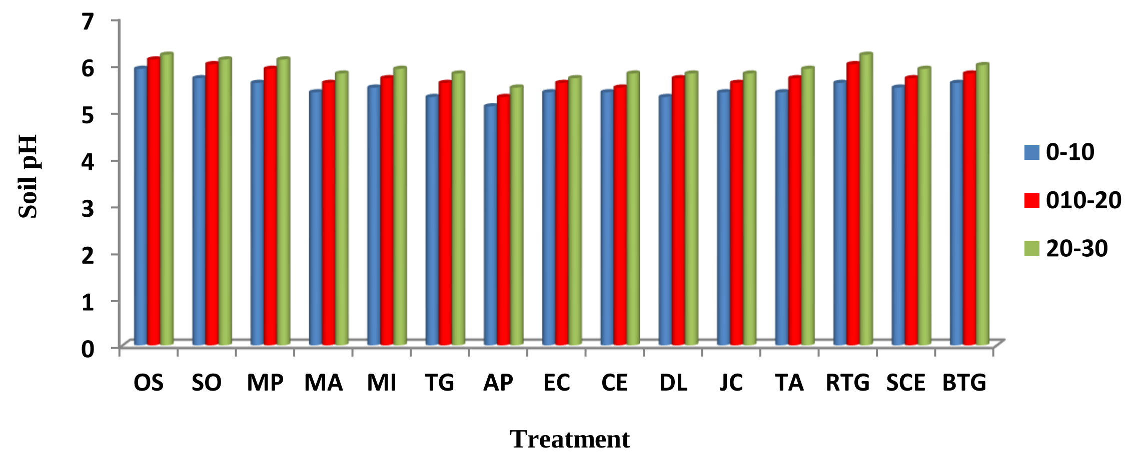
2.2 Data Analysis

The experimental data were subjected to statistical analysis per the procedure suggested by Gomez and Gomez [8]. The treatment differences were tested by an 'f' test of significance based on the null hypothesis. The appropriate standard error (S.Em.±) was calculated in each case and critical difference (C.D.) at 5 percent level of probability was worked out to compare the treatment means, where the treatment effects were significant.

3. RESULTS AND DISCUSSION

The soil pH was observed **to** decrease in the land use systems where the number of trees increased in sole tree plantation. In the sole agriculture field, the paddy (OS) pH was 6.20 and the tree plantation of *Albizzia procera* (AP) had a pH of 5.5 (Fig. 1a). The reaction among soil in each land use system, approached neutral as the soil depth increased. The decrease in soil pH observed in tree component land use systems such as in *Albizzia procera* (AP) can be ascribed to a higher organic matter decomposition rate which results in the production of organic acid during decomposition. As well as similarly extent of organic matter was higher in surface layers and low in the deeper layer as a result the pH in the deeper layer approached neutral. Similar results were found in Chavan et al. [9]; Bhalawe et al. [10]; Contractor and Badnur [11]. Chakravarty and Barthakur [12] reported the low soil pH under tree plantation which is attributed to the leaching of base and enhancement of the weathering process giving rise to high A1 levels. Soil bulk density was higher in the agriculture field than in tree plantation land-use systems. Paddy soil (OS) mean bulk density was 1.48g/cm3 and 1.33g/cm3 in *Albizzia procera* (AP) tree plantation. The decrease in soil bulk density in all treatments (agriculture land-use system, agroforestry land-use system and Tree plantation land-use systems) is directly proportional to the depth of soil sample. Higher bulk density is expected in the agriculture field (Paddy) as a result of tillage intensity. Lower bulk density is influenced by tree components. Results of the study showed that bulk density decreases in tree plantation land-use systems and agroforestry land use system. Tree components increase organic matter which leads to better soil structure and porosity of the soil. Moreover, tree components decrease the area for tillage (agroforestry land-use systems) as bulk density is inversely proportional to tillage intensity [13-15]. Soil moisture content was found higher in the paddy (OS) field and generally lower in both the tree plantation land-use systems and agroforestry land use systems. Soil moisture content also increased with the soil depth in all land use management systems (Fig. 1c). The soil moisture content was higher in paddy (OS) field due to the management practices for rice cultivation. The observed increase in soil moisture content with an increase in tree component in Fig. 1c is attributed to the conservation of water by an increase in organic matter and better soil structure. More [16] reported that a one percent increase of soil organic carbon, can store 14.4 liters of extra available water per square meter in top 30 cm of soil. The lowest soil moisture content was found in the plantation of *Casuarina equisetifolia* (CE) due to the needle-like leaf structure of the plant which is less effective in conserving soil moisture (Lots of literature can support this claim) as well as absence of any management practices for a long time. The available nitrogen in the soil is influenced by the different land-use systems. In the agriculture land-use systems, the soil available nitrogen ranges from 237.52kg/ha to 287.78 kg/ha (Fig. 1d), slightly lower than in tree plantation land-use systems. The higher soil nitrogen in *S. officinarum* was the result of land management practices where gypsum and farm yard manure (FYM) were applied. Gypsum enables nutrient availability by correcting pH while farm yard manure increases microbial activity. *O.sativa* on the other hand requires intensive cultivation and harvesting. As a result, N is lost through biomass removal, soil leaching, and volatilization [17-21]. The tree plantation land-use systems showed comparable soil nitrogen with *T. grandis* having the highest mean of (315.65kg/ha and *C. equisitefolia* having the lowest soil nitrogen. Tree litters have significant impact on the available N in the soil. The degree of accumulation of organic matter, and their decomposition determines the extent of available N. Soil Nitrogen is usually higher in areas with tree or mixed vegetation. The same observation was reported in a study of several species such *B. bambos, C. siamea, C. equisetifolia, E. tereticornis, L.leucocephala, T.grandis*, and *Ceiba pentandra* where soil nitrogen was significantly higher in areas with tree cover than barren land. Similar observation was also reported by Tandel [22]. However, the amount of nutrient available in the soil also depends on the nature and characteristics of litters found on the soil surface. Litters of high lignin and cellulose decompose slowly than litters with higher starch content. Thus, decomposition is positively correlated to soil N content [23]. This simply explains the variability of soil N among various Land-use systems. The combined crops and tree cultivation practices in same plot shows maximum available nitrogen in the soil when *O. sativa* is grown with *T. grandis* (RTG; 296 kg/ha) as compared to *M. paradisiaca* grown with *T. grandis* (MTG;295 kg/ha) and *S. officinarum* grown with *C. equisetifolia* (SCE;295 kg/ha), respectively. The probable reason is higher amount of tree leaf litter biomass returns to soil, combined with decay of roots contribute to the improvement of nitrogen status in soil as well as higher availability of cellulose and hemicelluloses in leaf litter, easy decay and release nutrient availability in soil as well in cropping *O. sativa* uptake of nitrogen may be lower as compared to *M. paradisiaca* and *S. officinarum.* Similar results were reported by Bhusara [24] during experiment in Valsad, District, Gujarat. Soil organic carbon is a function of vegetation, rainfall and temperature, and a determining factor of soil quality, productivity and C sequestration potential. Soil organic carbon of different land-use systems vary greatly. This observation is also reported [25] where vegetation types lead to variation in soil organic carbon. In agriculture land-use systems, higher organic carbon (0.70%) was observed in *S. officinarum* while lower organic carbon was obtained in O. sativa. (0.50%). The percentage of organic carbon decreases with increasing soil depth as a higher amount of plant biomass was confined within the surface and subsurface layer of soil.

Fig. 1a. Soil pH characteristics under different land use systems



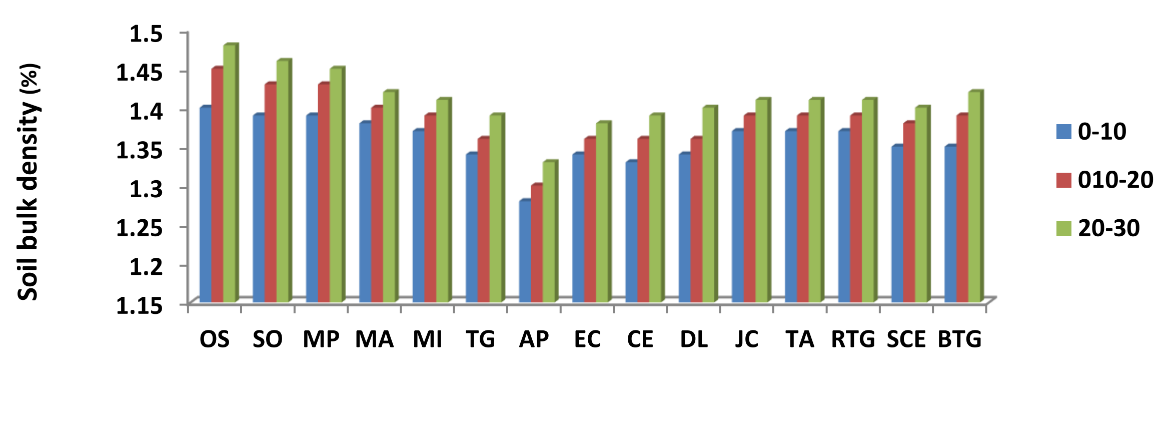


Fig. 1b. Soil Bulk density (%) under different land use systems

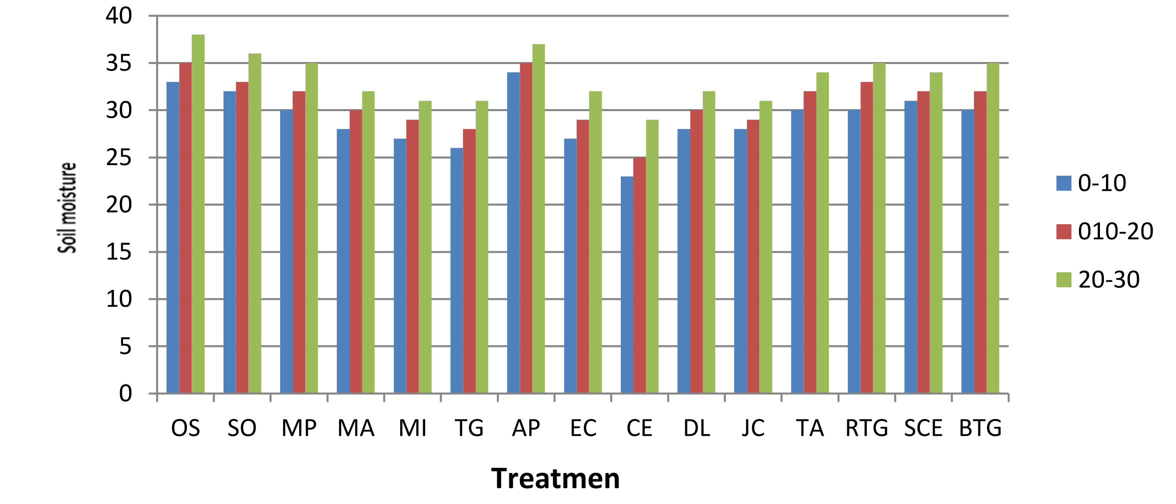


Fig. 1c. Soil moisture under different land use systems

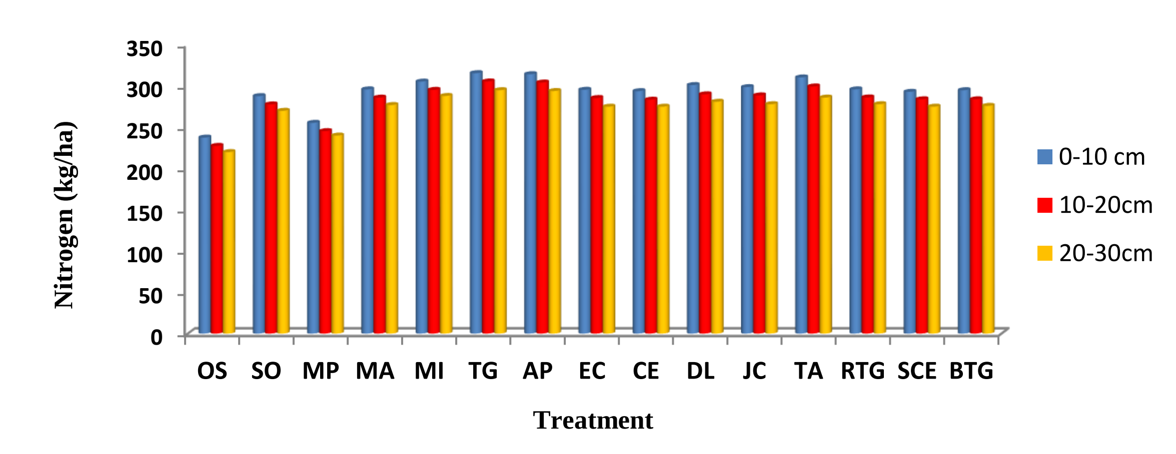


Fig. 1d. Soil nitrogen properties under different land use systems

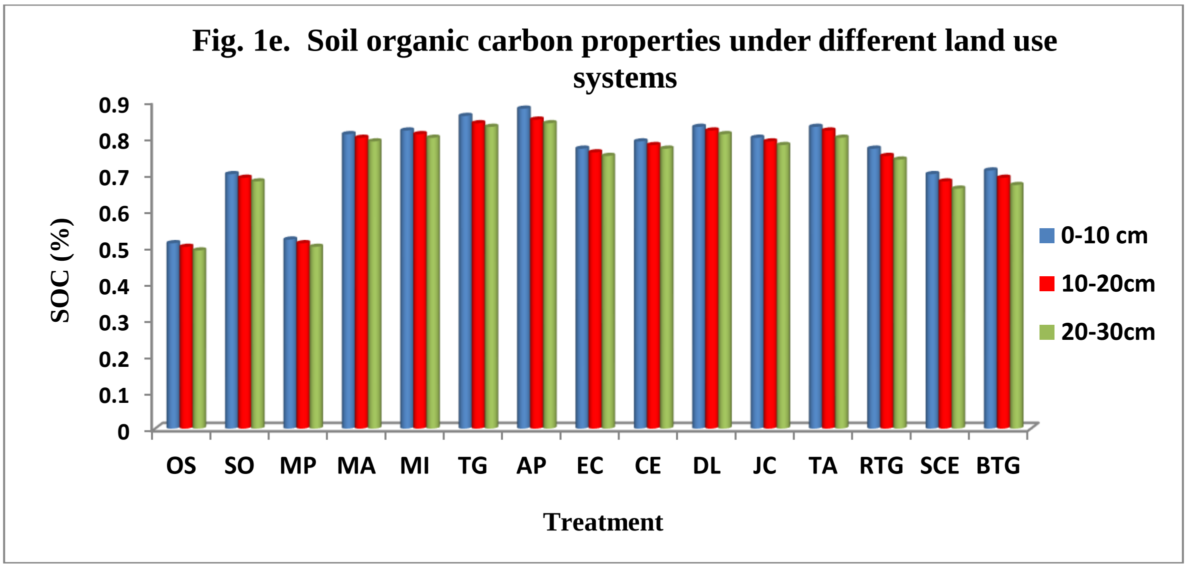


Fig. 1. Effect of soil physical and chemical characteristics under land use systems

Table 3. Land use systems with soil depth for soil organic carbon stock (t/ha)

S.no.	Treatments (Land use systems)	Soil depth (0-10 cm)	(10-20 cm)	(20-30 cm)	Average
1	**Agriculture land use systems (S_1)**				
a	*Oryza sativa* L. (OS)	7.95	7.10	6.25	7.10
b	*Saccharum officinarum* L. (SO)	8.20	7.58	6.99	7.59
c	Banana- *Musa paradisiaca* L. (MP)	8.00	7.50	6.80	7.43
2	**Tree plantation land use systems (S_2)**				
a	*Manilkara achras* L. (MA),	14.10	11.95	9.80	11.95
b	Mango- *Mangifera indica* L. (MI)	14.88	12.64	10.20	12.57
c	Teak- *Tectona grandis*L.f. (TG),	17.42	14.50	12.80	14.91
d	Killai- *Albizzia procera* (Roxb.)Benth. (AP)	18.5	17.20	16.35	17.35
e	Eucalyptus- *Eucalyptus clones* (EC),	11.50	10.45	9.20	10.38
f	Casuarina- *Casuarina equisetifolia*L.ex J.R.&C.Fraser (CE),	12.98	11.10	9.50	11.19
g	Shisham- *Dalbergia latifolia*Roxb. (DL),	15.95	13.60	11.20	13.58
h	Jatropha- *Jatropha curcas* L.,(JC)	13.50	11.40	10.10	11.67
i	Arjun- *Terminalia arjuna* (Roxb.ex DC.) Wight & Arn. (TA)	16.10	13.64	12.10	13.95
3	**Agroforestry land use systems (S_3)**				
a	Rice + Boundary plantation (*Tectona grandis* L.f.) (RTG),	13.45	11.25	10.10	11.60
b	Sugarcane + Boundary Plantation (*Casuarina equisetifolia*L.ex J.R.&C.Fraser), (SCE)	11.85	10.22	9.44	10.50
c	Banana + Boundary plantation (*Tectona grandis*) (BTG)	12.98	10.65	9.20	10.94
	Average	13.16	11.39	10.00	

Note: CD $_{(p=0.05)}$, land use-1.62, soil depth-0.65, interactions: land use x soil depth $_{1\text{---}n}$ -1.84, soil depth x land use $_{1\text{---}n}$ -2.24

Higher plant population and farm yard manure in *S. officinarum* (So) also helped increase soil organic carbon while intensive cropping practices as in O. sativa (OS) reduced SOC through crop harvesting. Similar results were reported by (18, 19, 20 and 21). The plantation of trees data indicate that the available soil organic carbon was found highest (AP; 0.88%) in *A. procera*, which was at par with tree plantation of *T. grandis* (TG; 0.86%), *T. arjuna* (TA; 0.82%), *D. latifolia* (DL; 0.82%) and *M. indica* (MI; 0.81%), *M. achras* (MA; 0.80%) and it was lowest in Eucalyptus clones (EC; 0.77%) respectively (Fig. 1e). This may happen because of enhanced stock of leaf litter in the tree based land use systems. The abundant leaf litter or pruned biomass returns to soil, combined with decay of roots contribute to the improvement of organic matter under complex land use systems [26]. Our findings are also supported by (22). From the agroforestry land use system combined crops and trees practices shows that maximum (0.76%) available soil organic carbon in (RTG) *O.sativa* grown with *T.grandis,* which was at par with *M.paradisiaca* grown with *T.grandis* (BTG;0.70%) and *S.officinarum* grown with *C.equisetifolia* (SCE;0.69%), respectively. This may be due to abundant tree leaf litter biomass returns to soil, combined with decay of roots contribute to the improvement of organic matter. Similar observations were recorded by Singh et al. [27] in *Acacia nilotica* based agroforestry systems and that tree canopy contribute toward nutrient conservation, soil amelioration and nutrient availability. Tree plantation land-use systems topped the overall soil carbon stock in tons per hectare followed by agroforestry land-use systems and agriculture land-use systems (Table 3). The highest average soil carbon stock was recorded in *A. procera* (AP) (17.35t/ha) then *T.grandis* (TG), *T.arjuna* (TA), and finally *D. latifolia*. The Agroforestry land-use systems RTG recorded 13. 45t/ha and agriculture land-use systems paddy recorded the lowest SOC. Land use influences largely SOC storage [28]. In land-use systems where the tree predominates, differences in SOC are attributed to differences in tree species [29], and their characteristics. Consequently, higher SOC is greater in ecosystems with fast-growing species [30] or ecosystems associated with arbuscular mycorrhiza [31]. Moreover, more organic matter returns to the soil in the form of leaves, bark, fruits and flowers that promote SOC [32]. Loss of SOC is mainly due to crop removal and erosion during intensive cultivation as in the case of paddy (SO).

4. CONCLUSION

Fifteen land uses systems have been studied for this. In which it was seen that agricultural land use, which is a very good source of business along with food, but is unable to maintain environmental balance, whereas in another study, the environment can be balanced by planting trees, but the food requirement for country cannot fulfilled. Therefore, the need is to take a middle path, a land which can provide income and food and still has a capability of storing sufficient carbon. These are called agroforestry, in which trees are planted along with agricultural crops, which can balance the environment and also fulfill the need for food. Along with fulfill the purpose of carbon storage. Thus agroforestry land use system is the best option like Rice + Boundary plantation (*Tectona grandis*) Sugarcane + Boundary Plantation (*Casuarina equisetifolia*), (SCE) and Banana + Boundary plantation (*Tectona grandis*) (BTG) compare to sole tree plantation and sole cropping land use systems.

ACKNOWLEDGEMENT

The authors are very much thankful to Department of Agroforestry, College of Forestry, Navsari Agriculture University, Navsari (Gujarat) for providing facilities.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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