Impact of sustainable land-use management practices on soil carbon sequestration and soil quality in the west coast of India

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ABSTRACT

The evaluation of sustainable land management practices is imperative under particular soil type, climate, and cropping sequence following area-specific best management practices to sustain soil fertility and health. The alternative land-use system (ALUS-natural forest, pasture, cashew, areca nut, coconut) on hills and agricultural land-use system (AGLUS-rice-rice, rice-pulse) in the coastal plains of west coast India was evaluated in this study. The present study assessed the impact of sustainable land-use management practices on different fractions of SOC and soil quality under ALUS and AGLUS. The total SOC stocks under different land-use systems varied from 14.4 Mg ha^{-1} in rice–rice rotations to 133.7 Mg ha^{-1} in cashew, and more than 75% of total SOC stock were found as a passive carbon pool. The higher lability index, available nutrients, and biochemical properties were found in ALUS. This variation in the levels of SOC and soil quality was due to land use and management practices. The results indicated land use with areca nut (0.8) on the hills and rice–pulses (0.25) rotations on the coast had maintained soil quality of high order. We recommend promoting sustainable agriculture with ALUS on the hills and with AGLUS on the coastal plains of Goa for enhancing SOC sequestration and improving soil quality.

Keywords: Landscape ecological variables, land use management, sustainable area, soil organic carbon fractions

1. INTRODUCTION

The well-being and livelihoods of rural communities depend heavily on the health and productivity of the land. In many countries, including India, land degradation through inappropriate land management practices are compounded by diverse on-farm and off-farm constraints (Nath et al., 2018). Sustainable Land Management (SLM) helps to integrate land, water, biodiversity, and environmental management to meet rising food and fibre demands while sustaining ecosystem services and rural livelihoods (Garcia-Franco et al., 2018). Moreover, to meet the growing population's food security needs, efforts are needed to halt land degradation and restore land already lost or degraded (Nath et al., 2018). India has witnessed drastic shifts in land use (Brahma et al., 2018; Jha et al., 2000; Nagaraja et al., 2018; Prasad et al., 2010) to meet the growing market demands. Consequently, during 1980–2010, the area under cropland increased from 92 million hectares to 140 million hectares in response to policies that encouraged farm mechanization, usage of high-yielding crop varieties to achieve self-sufficiency in food production (Tian et al., 2014). During the period, the concept of SLM was ignored. Thus, market-based land use triggered widespread degradation of natural resources, including land and water, which is particularly severe in hilly areas and plateaus than on the plains (Kuriakose et al., 2009). Market-based land use management involves growing high-yielding crop varieties that demand a larger quantity of nutrients and water and the use of chemical fertilizers and pesticides. Such a management system lead to undesirable changes in soil structure (Bhardwaj et al., 2011), decline in soil organic carbon (SOC) stocks, soil fertility, soil productivity (Bhaduri and Purakayastha, 2014; LIAO et al., 2009), and soil quality (Kale et al., 2016). Additionally, the soil is becoming increasingly acidic in the floodplains of the Ganga basin in West Bengal (Singh et al. 2018). Aerosols (Singh and Singh, 2011) and arsenic contamination (Singh et al. 2018; Srivastava et al., 2015) compounded the situation in the desert region of western India and the Ganga basin, respectively. Thus, greater attention may be given to alternative models of intensification, particularly the potential of SLM technologies. Such practices can generate private benefits for farmers by improving soil fertility and structure, conserving soil and water, enhancing the activity and diversity of soil fauna, and strengthening the mechanisms of elemental cycling (Branca et al., 2013).

The west coast of India covers the states of Gujarat, Karnataka, Maharashtra, Goa, and Kerala. The area encompasses eco-sensitive zones as coastal plains, undulating lands, marshy lands, mountain passes (*ghat*s), estuaries, rivers, and saline (*Kazan*) lands. Currently, the area under different land uses in Goa are as follows: cashew (55,732 ha), rice (47,104 ha), coconut (25,686 ha), pulses (7890 ha), and areca nut (*Areca catechu*) (1600 ha) (Paramesh et al., 2019). Now only about 125,000 ha remained under natural forests. The land-use system in Goa is divided into two types, namely that practised on the coastal plains (agricultural land use system-AGLUS) and the alternative land use (ALUS) practised in the hills and undulating areas. Both AGLUS and ALUS occupy distinct pockets of the state and deploy a range of soil and water conservation measures. Rice–fallow rotations remain the traditional practice in the coastal plains, representing a unique landscape made up of a mosaic of different systems of cultivation: paddy fields, fallow land, barren land, pastures, plantations, and natural forests. The implementation of SLM can lead to increased productivity and stability of agricultural production systems (Pretty et al., 2011; Verma et al., 2018). They thus offer a potentially necessary means of enhancing agricultural returns and food security and reducing the vulnerability of farming systems to climatic risk (Branca et al., 2013).

The hypothesis tested in the study is that land area under AGLUS and ALUS with better crop management practices will enhance the SOC content and improve the soil quality. A great deal of information is available on how land use and management influence SOC, which serves as a proxy for soil quality (Bhattacharyya et al., 2016; Brahma et al., 2018). Simultaneously, information is scanty on the influence of sustainable land-use systems on active and passive pools of SOC, stocks, and SOC sequestration potential under the coastal region of west coast India. In this regard, the present study was formulated to assess the impact of sustainable land-use management practices on soil carbon sequestration and soil quality in Goa, the west coast of India.

2. MATERIALS AND METHODS

2.1. Study area

The study area (14°53′47″ – 15°47′59″ N, 73°40′54″ to 74°20′11″ E) is part of the Western Ghats and has a 110 km long coastline separating the land from the Arabian Sea. The climate is warm and humid most of the year with a mean annual temperature of 27.8°C, a mean maximum temperature of 30.2°C, typically reached in May, and a mean minimum temperature of 26.4°C, typically reached in January. The period from December to February is calm and pleasant. The difference between the mean annual summer temperature and mean annual winter temperature is 4°C (Sehgal and Mandal, 1994). The annual mean precipitation, almost entirely from the southwest monsoon, is 2910.5 mm. The maximum rainfall is in June (828.8 mm), and some pre-monsoon showers are received in April and May. The study area encompasses both hills and plains along the coast. Soils in the hills are shallow, slightly to moderately acidic gravelly. Soils of the coastal plains are very deep, moderately acidic to strongly acidic, phosphorus- and alumina-rich Inceptisols and sandy loam to sandy Entisols (Singh et al. 2018). ALUS is practised in hills, and AGLUS, mainly rice fields, is practised on the coastal plains. Under ALUS, six land uses were selected: natural forest, plantations of cashew, coconut, and areca nut, pasture, and fallow land (check or control). These sites had been maintained for more than 70 to 80 years by farmers who had been following the recommended soil and water conservation practices to prevent erosion (in hills) or protect agriculture from the inundation of seawater (along the coast). In the present study, we chose three land-use systems to represent AGLUS: the sites comprised of a rice fallow (which served as a check or control), a rice–rice rotation, and rice–pulses rotation. The management practices at all the chosen sites are presented in Table 1.

2.2. Soil sampling, processing of samples and laboratory analysis

Ten samples were collected from each of the chosen sites (land-use system) mentioned above. Equal numbers of samples were collected from the rice–fallow site along the coast and fallow on the hills to serve as controls. A part of the sample was stored at a low temperature (4^{o}C) for analysing microbial activity. Core samples for determining bulk density were also collected. Thus, a total of 90 samples were collected from the chosen sites. The soil samples collected during the surveys were initially air-dried in the laboratory at room temperature, screened through a 2 mm sieve.

Bulk density was determined as described by Blake (Blake, 1986) following the protocols for core samples. Labile, non-labile, and total carbon content was determined for all 90 samples. Total carbon content was determined by the dry combustion method using a Vario EL cube analyzer in the CHNS mode (Elementar, Langenselbold, Germany). Oxidizable SOC was fractionated by mixing 1N dichromate solution and extracted by H_2SO_4, using 5, 10, and 20 mL of 36.0 N H_2SO_4 equivalent to 12.0, 18.0, and 24.0 N H_2SO_4, respectively (Chan 2001; Ghosh et al., 2012). SOC extracted in 5 mL H_2SO_4 is termed very labile carbon (VLC) and the difference between SOC extracted in 5 mL H_2SO_4 and that in 10 mL H_2SO_4 is characterised labile carbon (LC). Similarly, the difference between SOC extracted in 10 mL H_2SO_4 and 20 mL H_2SO_4 is analysed for less labile carbon (LLC). Total organic carbon minus LLC is the non-labile carbon (NLC), and VLC and LC together constitute the active pool (AP) of carbon, whereas LLC and NLC have taken together as the passive pool of carbon (Chan et al., 2001).

Other related soil properties such as available nitrogen (N) (Subbiah and Asija, 1956), available phosphorus (P) (Bray and Kurtz, 1945), available potassium (K) (Hanway and Heidel, 1952), and available sulfur (S) (Chesnin and Yien, 1951) were determined. The concentration of micronutrients (zinc, copper, iron, and manganese) was also estimated using an atomic absorption spectrophotometer (Lindsay and Norvell, 1978). Boron (B) was determined by the hot-water-extract method (Berger and Truog, 1939); microbial biomass carbon (MBC) by the fumigation and extraction method (Vance et al., 1987); and basal soil respiration (BSR), by the incubation and titration method (Anderson, 2015). Dehydrogenase activity was assessed using 2-3-5-triphenyl tetrazolium chloride reduction (Casida Jr et al., 1964) and urease activity by measuring the hydrolysis of urea (Kandeler and Gerber, 1988).

2.3. Stocks of soil organic carbon (SOC)

The stocks of SOC in each land-use systems were also calculated by multiplying the SOC concentrations (0–30 cm), bulk density, and gravel content.

$$SOC\,Stock\left(Mg\,ha^{-1}\right) = Area\left(ha\right) \times Soil\,depth\left(m\right) \times Bulk\,Density\left(Mg\,m^{-3}\right) \times SOC\left(\%\right) \quad (2)$$

2.4. Lability index

The lability index of SOC was calculated by the following equation.

$$Lability\,index = \frac{VLC}{TOC} \times 3 + \frac{LC}{TOC} \times 2 + \frac{LLC}{TOC} \times 1 \quad (3)$$

In the expression, VLC was given a weighting of 3; LC, of 2; and LLC, of 1, depending upon their oxidation (Datta et al., 2015).

2.5. Soil quality index

Soil quality index (SQI) for different land uses in AGLUS and ALUS was calculated as described by Andrews et al. (Andrews et al., 2002). The minimum data set (MDS) was constructed using principal component analysis (PCA) (SPSS ver. 10.0). The principal components (PCs) with eigenvalues >1 were retained for constructing the MDS. For each PC, only highly weighted parameters having a significant influence on soil quality were retained (Doran and Parkin, 2015). Subsequently, the MDS indicators were normalized using a non-linear scoring method with a score ranging from 0 to 1 (Karlen and Stott, 2015; Wymore, 1993). The standard scoring function in the study was estimated using the following equation:

$$NL(x) = \frac{1}{1 + \left(\frac{x}{B}\right)^{-b}} \quad (4)$$

where *x* is the observed value of the soil variable, B is the baseline (the midpoint between the upper and the lower thresholds), and −b is the slope of the equation. Further, the weighted additive SQI (Doran and Parkin, 2015) was computed using the following equation:

$$SQI = \sum_{i=1}^{n} W_i S_i \quad (5)$$

Wi is the weight of the indicator based on PCA, Si is the indicator score, and n is the number of indicators.

2.6. Statistical analysis

The effect of ALUS and AGLUS on soil properties, soil carbon stocks, and SQI was tested using a one-way analysis of variance and SAS ver. 9.4. The mean values of the results were compared at a 5% level of significance. Principal component analysis for selection of the MDS and indicator scoring was carried out using SPSS ver. 10.

3. RESULTS

3.1. Influence of land-use system on soil organic carbon fractions

The SOC content in ALUS increased significantly compared to those in the control plots by 3.3 times under cashew, 1.8 times under coconut, 2.3 times under rice–pulses rotations, and 0.8 times under rice–rice rotations (Table 2). Similarly, VLC increased by 3.5 times under cashew, 2.3 times under coconut, 1.3 times under rice–pulses rotations, and 1.7 times under rice–rice rotations. LC increased by 2.3–2.7 times in ALUS and by 2.0–9.0 times in AGLUS. LLC increased by 2.2–3.7 times in ALUS and by 0.3–0.8 times in AGLUS and NLC, by 1.2–2.9 times in ALUS and 1.1–1.2 times in AGLUS. The active pool (VLC and LLC) increased by 2.2–3.7 times in ALUS and by 0.4–1.6 times in AGLUS and the passive pool (LLC and NLC) by 1.6–3.2 times in ALUS and by 0.7–2.0 times in AGLUS (Table 2). Values of the other fractions of SOC under ALUS were the highest in cashew and the lowest in coconut, whereas rice–pulses rotations had the highest in AGLUS.

The share of VLC in total organic carbon (TOC) was 4%–5% in ALUS and 3%–11% in AGLUS. The contribution of LC was 19%–23% in ALUS and 5%–18% in AGLUS (Fig. 1). Less labile carbon contributed 14%–42% to the TOC under AGLUS and 39%–42% under ALUS. NLC constituted 47%–68% and 29%–44% of TOC under ALUS and AGLUS, respectively. The active pool in TOC was 22%–28% and 11%–21% in ALUS and AGLUS, whereas the corresponding figures for the passive pool were 72%–78% and 79%–90% (Table 3 & Figure 1). Within ALUS, the active pool was the highest in areca nut, and the passive pool was in cashew. Statistically, active and passive pools were on par in cashew, areca nut, and natural forests. Within AGLUS, rice–rice and rice–pulses rotations were on par concerning both the carbon pools. Across the land-use systems, the stock of VLC (5.8 Mg ha^{-1}) and LC (30.3 Mg ha^{-1}) was the highest in cashew (Table 4). Stocks of LLC (54.1 Mg ha^{-1}) and NLC (55.7 Mg ha^{-1}) were also the highest in cashew and natural forests. Total carbon stocks under different land-use systems varied from 14.4 Mg ha^{-1} in rice–rice rotations to 133.7 Mg ha^{-1} in cashew. However, TOC in cashew was on par with that in areca nut and natural forests (Table 4). Compared to the respective controls, the stock of TOC was significantly higher in areca nut (by 2.3 times), natural forests (by 2.9 times), rice–rice rotations (0.7 times), and rice–pulses rotations (2.1 times). Similarly, the stock of VLC was 3.6 times higher in cashew over the control. The corresponding figures were being 2.3 times higher in coconut, 1.6 times in rice–rice rotations, and 1.9 times in rice–pulses rotations than the respective controls. Stocks of LC also had a similar pattern and increased by 2.2–3.5 times in ALUS and by 1.6–1.9 times in AGLUS, as did in LLC. The corresponding increase over the control was 2.2–3.5 times and 0.2–1.6 times, for NLC in ALUS and AGLUS, respectively. The analogous increase in active and passive pools was the manifestation of different fractions of SOC, which was higher in ALUS and AGLUS than their respective control (Fig. 2). Besides NLC and TOC, other attributes of SOC recorded their highest values in cashew and the lowest in coconut in ALUS. In AGLUS, TOC and NLC were higher in rice–pulses rotations than in rice–rice rotations.

3.2. Influence of land-use system on soil nutrients and biochemical properties

The available nitrogen, phosphorus, and potassium were increased significantly in ALUS and AGLUS over the control (Table 5). Similarly, available boron and zinc also exhibited an increasing trend over the control site in ALUS and AGLUS. MBC and BSR have also followed a similar trend of distribution. The level of dehydrogenase and urease improved in ALUS and AGLUS (Fig 2). In ALUS, the performance of cashew, areca nut, and the forest was on par, whereas in AGLUS, the rice-pulses system has edged over the rice-rice system. Among the physical properties, the bulk density was found higher in the rice-rice and fallow system, and the lowest value was observed in the areca nut system. Significantly higher pH (neutral) was noticed under the areca nut system; remaining all other systems were found acidic.

3.3. Influence land use system on soil quality

Principle components varied in the extent to which they could explain the variability in soil quality: PC1 explained 32.5% of the variability, whereas the extent of variation was 20.4%, 14.9% 12.2%, 8%, and 5.8% in PC2, PC3, PC4, PC5, and PC6, respectively. The cumulative variance was 93.7%. For developing the MDS to assess soil quality, PCs with eigenvalues >1, contributing at least 5% of the variance, were considered. In PC1, only VLC was retained as a part of the MDS, with a loading of 0.976; in PC2, it was only MBC, with a loading of 0.99. pH (0.85), K (0.938), N (0.861), Zn (0.902) were the factors in PC3 to PC6, respectively (Table 6). The non-linear and weighted additive soil quality indexing method was employed to understand the influence of land-use systems on soil quality. In AGLUS, SQI for rice–pulses rotations were higher than rice–rice rotations (Table 7). In contrast, in ALUS, SQI was the highest in areca nut, followed, in decreasing order, by natural forests, cashew, pastures, and coconut (Table 7). Compared to the control, SQI in areca nut was higher by 83% and that in rice–pulses rotations by 17%.

3.4. Correlation

A Pearson's correlation matrix was constructed among the SOC pools and SQI (Table 8). The VLC, LC and TOC were strongly correlated to SQI (p <0.01). Likewise, SQI was greatly influenced by MBC (r = 0.973**, p <0.01). Microbial biomass carbon was significantly correlated to all the four fractions of SOC whereas DHA was correlated significantly only to NLC (r = 0.835**, p <0.01). Neither MBC nor DHA were significantly correlated to the lability index. The correlation coefficient is being high for MBC (r = 0.978**, p <0.01), SQI (r = 0.950**, p <0.01), and AP of carbon (r = 0.871**, p <0.01) (Table 8).

4. DISCUSSION

4.1. Influence of ALUS and AGLUS on soil organic carbon

Soils in the hills are shallow, gravelly, and prone to erosion—a combination known for eroding carbon, particularly in undulating lands (Pandey et al., 2010a; Van Oost et al., 2008). Moreover, these soils cannot sustain conventional agriculture and are better suited to ALUS. This is the reason for predominant cashew plantations, which was managed with minimum or zero tillage. Extensive tillage is known for lowering SOC concentrations and stocks due to increased mineralization, decreased physical protection, and more significant depletion of nutrients and carbon (Lal, 1995; VandenBygaart et al., 2003). Singh et al. (2013) reported high organic carbon build-up under the canopy of cotton, attributed to lower temperatures due to the high leaf area index. This inverse relationship between soil temperature and SOC is well known (Alvarez and Lavado, 1998) due to the decreased oxidation rate (Pandey et al., 2010b). Singh et al. (2011) established a quadratic relationship between soil temperature and SOC concentration and stock involving four climatic conditions, and four land uses in a study executed at the western Himalayas. Based on these arguments, we conclude that ALUS, so long as it leads to a large canopy cover, protects the existing stocks of SOC and adds to them by reducing oxidation, lowering soil temperature, controlling run-off through extensive root systems, and finally bind the soil. Thus, selecting land use to match the SA in alternative agriculture systems (ALUS) benefits the soil in terms of increased concentrations and stocks of SOC in the top layer (0–30 cm).

4.2. Influence of land-use system on the fractions of soil organic carbon

The positive influence of land-use systems with ALUS and AGLUS is apparent in the increased levels of total carbon and its components, namely very labile, labile, less labile, and non-labile carbon, over their respective control plots. The increase can be attributed to the positive influence of reduced erosion, higher canopy cover, and higher biomass returns in ALUS. Comparable levels of TOC in cashew, areca nut, and natural forests indicate that under a well-managed system, stands of horticultural tree crops behave similarly to forests, which are known for their high SOC sequestration potential (Lehtonen et al., 2020; Neill et al., 1995). The observation corroborated with the earlier findings (Francaviglia et al., 2017; Lehtonen et al., 2020). They have reported increased amounts of SOC fractions with the recycling of residues.

Site-specific soil and water conservation measures, the addition of fresh litter, and subsequent decomposition further enhance the capacity of ALUS to check the loss of SOC. In the study area, Areca nut is grown under irrigated conditions. It is well known that the moisture is inversely related to soil temperature (Zhang et al. 2007) and shares a positive polynomial relationship with SOC. Therefore, greater soil moisture underneath the canopy of the areca nut and the consequent lower temperatures probably explain the higher SOC. Areca nut is planted usually on comparatively stable topography supporting deep and nuanced loamy to fine soils known for their higher water holding capacity (Singh et al. 2018). In coconut, the large unprotected open spaces below the palms were probably ineffective in checking erosion and oxidation. Previous studies have shown the SOC potential of forests (Neill et al. 1995) owing to deeper penetration by roots (Sheikh et al. 2009), greater capacity of trees to sequester carbon (Potter et al. 1998), improvement in the microclimate (Ingram & Fernandes 2001), and absence of tillage (Pandey & Chaudhari 2010).

Growing pulses after rice also enhanced VLC and LC in AGLUS compared to their levels in the control plots. The addition of nitrogen through the root nodules of legumes probably stimulated the phosphatase activity (Kathju et al., 2007) and other related biochemical processes such as the formation of MBC and dehydrogenase activity urease (Biederbeck et al., 1998). The coast of Goa is also known for its phosphorus-rich soils. Thus, the mineralization of native phosphorus and nitrogen added by the pulse crop probably increased the mineralization of native SOC. The explanation also covers the higher concentrations of LLC, NLC and TOC stocks in ALUS and rice–pulses rotation under AGLUS. Growing pulses after rice also enhanced VLC and LC in AGLUS compared to their levels in the control plots. The addition of nitrogen through the root nodules of legumes probably stimulated phosphatase activity (Kathju et al., 2007) and other related biochemical processes such as the formation of MBC and the activity of dehydrogenase and urease (Biederbeck et al., 1998). The coast of Goa is known for its phosphorus-rich soils. Thus, the mineralization of native phosphorus and nitrogen added by the pulse crop probably increased the mineralization of native SOC. The explanation also covers the higher concentrations of LLC and NLC stocks and total carbon in ALUS and rice–pulses rotation under AGLUS.

The higher concentration of active carbon pool observed in ALUS is ascribed to higher biomass returns, enlarged canopies, and lower erosion together with better drainage seen on the hills. The synergistic influence of all these factors may have led to the larger active pools seen in ALUS, an observation consistent with Benbi et al. (2015), who found the pool of labile carbon in agroforestry systems is more significant than that in sugarcane, maize-wheat, rice-wheat rotations. In AGLUS, particularly in the case of flooded rice, the physical properties of soil are less optimal, particularly in terms of porosity. In contrast, soil's more suitable physical properties in ALUS probably protected VLC and LC more effectively. Lower bulk density is a characteristic of the better physical condition of soils seen in ALUS. Dhumgond et al. (2012) also noted that the levels of carbon in paddy fields were lower than those in agroforestry systems and coffee plantations. Chacko et al. (2014) also reported lower levels of active SOC in paddy fields than those in coconut plantations.

4.3. Influence of land-use system on soil quality

Increased lability index (LI) in ALUS and AGLUS indicated the positive effects of land-use systems. The positive effects of land-use systems were also evident in ALUS and AGLUS in terms of increased available nitrogen, phosphorus, and potassium compared to the corresponding levels in the controls. The results in ALUS are consistent with the findings of Singh and Sharma (2007). They reported the improvement in the release of nutrients from decomposing litter and reserves of organic matter in land uses based on the poplar trees. Moreover, subsoil layers of red and lateritic soils are richer in nutrients, and deep-rooted trees can exploit those nutrient reserves. The nutrients thus brought to the surface available in that layer after decomposition of litter. The influence of litter and its decomposition may also explain the higher values of such biochemical properties as MBC, BSR, dehydrogenase, and urease activity in ALUS compared to those in the control plots (Fig. 2). The higher levels of SOC probably acted as a stabilizing framework that led to higher values of the relevant biochemical parameters, thereby preventing their further degradation (Trasar-Cepeda et al., 2008). In AGLUS, particularly under the rice–pulses rotation, the mineralization of native SOC due to increased nitrogen and phosphorus may be the reasons for the enhanced biochemical activity. The increased levels of boron and zinc both in ALUS and AGLUS can be attributed to the development of chelating compounds of these two nutrients with SOC fractions (Lindsay, 1979), thereby preventing their loss either through fixation or through leaching. The positive effects of better management practices under various land-use systems were also apparent in terms of reduced bulk density, which is characteristic of soils with physical properties more suitable for cultivation. The reduction in bulk density was probably due to higher SOC levels and enhanced microbial activity. The latter produces compounds that act as a cementing agent to improve soil structure, increase porosity, and reduce soil densification.

4.4. Implications

The study indicated that following better management practices to grow cashew and areca nut in Goa, the stocks of SOC could be increased three to four times over the present level. The increase in SOC stock is expected up to three times with the pastures and coconut. The projected gains in stocks of SOC can be increased 1.72 times over the existing stocks by following better management practices with the rice–pulses rotation in the coasts. The state land records of Goa showed that the state has 13,402 ha of fallow land, the extent of which has been increasing from 2006 to 2020, and the trend is expected to continue in the future because iron ore mining offers higher returns. It was also noted that mining on hills affects the extent of fallows in the coastal plains. In this situation, sustainable agriculture with ALUS has vast potential. It may open new vistas of non-conventional agriculture to support dairy, timber, and ecosystem-based services in the state.

5. CONCLUSIONS

The study concludes that AGLUS, on the coastal plains, and ALUS in the hills, both with the area/site-specific best management practices, are the sustainable land-use options. Rice-pulses rotation in the coastal plains could be intensified using appropriate ameliorating measures depending on the depth of sulphidic material. Vegetables and horticultural crops including coconut, areca nut, and cashew on ridges, rice in low-lying lands, and aquaculture in ponds can increase cropping intensity even further, reducing soil salinity and increasing employment at the same time. Based on these findings, advisories advocating sustainable agriculture with ALUS on the hills and with AGLUS on the coastal plains of Goa may be considered. These strategies can be extended to similar landscapes in the coastal regions of Karnataka, Maharashtra, and Kerala. The present study also demonstrates that Goa can become a carbon hub between the states of Karnataka and Maharashtra by following sustainable agriculture with ALUS and AGLUS.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Competing interests: “The authors declare no conflict of interest.”

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Table 1. Area specific best management practices (BMP) in Goa

Landscapes	Land use systems	Management practices
ALUS	Coconut	Soil water conservation measures: Contour trench, in-situ moisture conservation measures, stone wall with vegetative barrier in the upstream of stone wall; Planting species (*Cocos nucifera* L.)
	Cashew	Soil water conservation measures: Contour trench, stone wall with vegetative barrier in the upstream of stone wall, silt detention trench in bottom of conical hills, in-situ moisture conservation measures, water harvesting structure in the nearby stream; planting species (*Anacardium occidentale*)
	Arecanut	Soil water conservation measures: Contour trench, stone wall with vegetative barrier in the upstream of stone wall, silt detention trench in bottom of conical hills, in-situ moisture conservation measures, water harvesting structure in the nearby stream, Planting species (*Areca catechu*)
	Forest	Soil water conservation measures: Contour trench, stone wall with

		vegetative barrier in the upstream of stone wall; Planting species teak (*Tectona grandis*), *Terminalia crenulata, T. chebula, Adina cordifolia, Alstonia scholaris, Lannea coromandelica, Bombax ceiba, Careya arborea and Dillenia pentagyna* etc.
	Pasture	Soil water conservation measures Contour trench, stone wall with vegetative barriers in the upstream of stone wall, Planting species plantations of *Cynodon doctylon*, *Cenchrus ciliaris, Cyperus rotundus*, Agropyron repens, *Clitoria ternatea, Brachiaria ruziziensis*, etc., controlled grazing
AGLUS	Fallow	Initiative for execution of soil and water conservation measures could not reach
	Rice-Rice	Community embankments to protect rice fields from sea water inundation: puddling, transplantation of rice and recommended dose of fertilizers (100:50:50 kg NPK/ha) together with all the recommended cultural practices
	Rice-Pulses	Community embankments to protect rice fields from sea water inundation; puddling, transplantation of rice and recommended dose of fertilizers (100:50:50 kg NPK/ha) together with all the recommended cultural practices; pulses (cowpea and moong) with minimum/zero tillage under residual moisture conditions
	Rice-Fallow	Upland rice by broadcasting in the first season of cropping, while field are left unattended in the second season

Table 2. Influence of sustainable agriculture on the different fractions of soil organic carbon (g kg^{-1} soil)

Land use system		**VLC**	**LC**	**LLC**	**NLC**	**TC**	**AP**	**PP**	**LI**
AGLUS	Rice-Rice	0.5±0.1d	0.4±0.1d	0.6±0.1d	2.4±0.3d	3.7±0.3c	0.8±0.1d	2.7±0.3e	0.71±0.1b
	Rice-Pulses	0.4±0.1d	1.8±0.4de	3.2±0.6d	4.7±0.5cd	10±1c	2±2.2d	7.6±7.9de	0.75±0.1b
	Rice-Fallow	0.3±0.1d	0.2±0.1e	1.8±0.2d	2.1±0.2d	4.2±0.4c	0.5±0.4d	3.8±3.8e	0.68±0.1b
ALUS	Coconut	0.9±0.1c	4.3±0.4c	7.6±0.7c	5.1±0.8cd	17.6±1.6b	5.1±0.5c	12.6±1.2cd	1.06±0.1a
	Cashew	1.4±0.1a	7.1±0.5a	12.7±0.9a	10.3±1.5ab	31.4±2.7a	8.5±0.6a	22.9±2.2ab	1.01±0.1a
	Arecanut	1.1±0.1bc	5.4±0.5bc	9.7±0.9bc	7.2±0.7bc	23.2±2.1b	6.4±0.6bc	16.8±1.6c	1.02±0.1a
	Forest	1.3±0.2ab	6.7±0.6ab	11.9±1.1ab	12.6±1.2a	32.3±1.6a	7.9±0.7ab	24.4±1.2a	0.89±0.1ab
	Pasture	0.9±0.1c	4.5±0.2c	8±0.4c	9.9±1ab	23.1±1.3b	5.4±0.3c	17.8±1.2bc	0.86±0.1ab
	Fallow	0.4±0.1d	1.9±0.2e	3.4±0.4d	4.4±0.7cd	10±0.8c	2.3±0.3d	7.7±0.7de	0.84±0.1ab

Table 3. Influence of sustainable agriculture on share of active and passive pools in total carbon

Landscapes	Land use systems	% share of pools in TOC	
		Active	Passive
AGLUS	Rice-Rice	22.9	77.1
	Rice-Pulses	20.8	79.2
	Rice-Fallow	11.9	88.1
ALUS	Pasture	29.4	70.6
	Coconut	27.1	72.9
	Cashew	27.7	72.3
	Arecanut	24.5	74.5
	Forest	23.4	76.6
	Fallow	23.2	77.8

Table 4. Influence of sustainable agriculture on different fractions of carbon stock (Mg C ha^{-1})

Land use system		VLC	LC	LLC	NLC	Total C Stock	AP	PP
AGLUS	Rice-Rice	1.7±0.2d	1.4±0.2e	2.1±0.2d	9.4±1.1e	14.4±1.1f	3.1±0.2b	11.4±1.1c
	Rice-Pulses	1.4±0.3d	7.2±1.4d	12.8±2.5cd	19±1.8cd	40.2±4.2ef	5.6±0.2b	26.8±0.9c
	Rice-Fallow	1.1±0.2d	0.9±0.2e	8.1±0.8cd	9.5±0.7e	19.5±1.3ef	2±0.3b	18.1±1.5c
ALUS	Coconut	3.7±0.3c	19.1±1.5c	34.1±2.7b	23.2±3.4cd	80±6.4d	22.8±1.8b	57.2±5b
	Cashew	5.8±0.4a	30.4±1.8a	54.2±3.1a	43.5±6.1ab	133.7±10.4ab	36.1±2.1b	97.6±8.6b
	Arecanut	4.7±0.4b	24.4±1.8a	43.4±3.1ab	32.1±2.5bc	104.4±7.6cd	29±2.1a	75.5±5.5a
	Forest	5.5±0.4a	28.8±2.1a	51.5±3.7a	55.7±6a	141.4±5.9a	34.3±2.5b	107.1±5.2b
	Pasture	4±0.2bc	20.8±0.7bc	37.2±1.1b	46.2±4.6ab	108.1±5.8bc	24.8±0.8b	83.3±5.3b
	Fallow	1.7±0.2d	8.6±0.9d	15.4±1.5c	20.1±3.3cd	45.7±3.2e	10.3±1b	35.5±3b

Table 5. Influence of sustainable agriculture on soil properties attracting management

Land use system		BD (kg m^{-3})	pH	Available N (kg/ha)	Available P (kg/ha)	Available K_2O (kg/ha)	Boron (mg/kg)	Zn (mg/kg)
AGLUS	Rice-Rice	1.49±0.1ab	5.7±0.2b	90.4±4.5e	10.4±0.4d	118.8±8.8d	4.7±0.7abcd	3.2±0.1a
	Rice-Pulses	1.39±0.1c	5.6±0.3	142.2±9.2bc	16.3±0.4bc	155.5±7.3bcd	7.3±1.6a	3.1±0.1a

			b		d			
	Rice-Fallow	1.45±0.1b	5.9±0.3b	95.2±8de	11.7±0.4cd	125.9±4.5cd	6.8±0.7ab	0.2±0.1b
ALUS	Coconut	1.41±0.1bc	5.8±0.2b	102.4±4.9cde	26±3.6ab	241.8±42.9bc	3.2±1bcd	0.5±0.1b
	Cashew	1.49±0.1bc	5.8±0.2b	145.2±6.6b	27.3±4.6a	211.3±26.5bcd	3.5±0.8bcd	0.3±0.1b
	Arecanut	1.35±0.1c	7±0.2a	131±7.9bcd	20.6±1abc	446.2±35.1a	1.4±0.1d	3.6±0.5a
	Forest	1.5±0.1ab	5.8±0.2b	188.3±14.4a	28.2±2.3a	230.4±21.7bcd	3.1±0.6cd	0.3±0.1b
	Pasture	1.40±0.1bc	5.4±0.2b	155.6±10.6ab	25.7±1.1ab	252.1±16.2b	5.4±0.6abc	0.4±0.2b
	Fallow	1.62±0.1a	5.4±0.2b	99.7±3.9cde	11.5±0.7cd	129±27.6cd	3.1±0.6cd	0.3±0.1b

Table 6. Influences of sustainable agriculture on soil quality- principal component analysis

	PC1	PC2	PC3	PC4	PC5	PC6
Eigen value	6.166	3.875	2.827	2.327	1.516	1.097
Variance (%)	32.453	20.394	14.877	12.249	7.979	5.773
Cumulative variance (%)	32.453	52.847	67.725	79.974	87.953	93.725
Factor loading/Eigen value						
pH	-0.217	-0.450	**-0.853**	-0.320	-0.011	0.024
VLC	**0.976**	0.118	0.029	-0.100	0.058	0.104
LC	0.981	0.094	0.031	-0.117	0.056	0.077
LLC	0.979	0.105	0.036	-0.110	0.055	0.081
NLC	0.982	-0.020	0.050	-0.093	0.053	0.112
BD	-0.857	0.190	-0.086	0.154	-0.194	0.365
Nitrogen	0.447	-0.021	0.718	0.280	**0.861**	-0.055
P	-0.447	0.439	-0.395	0.293	0.364	0.415
K	0.263	-0.056	-0.106	**-0.938**	-0.025	-0.160
S	-0.302	-0.006	-0.324	-0.059	-0.590	0.088
Boron	-0.136	0.143	-0.174	0.910	0.049	-0.092
Cu	0.206	-0.308	0.019	0.029	-0.022	-0.097
Zn	0.398	-0.002	-0.072	-0.484	0.713	**0.902**
Fe	0.484	-0.058	0.729	0.409	0.141	0.067
Mn	-0.117	-0.020	-0.363	0.214	-0.241	0.117
MBC	0.048	**0.990**	0.008	0.058	-0.004	-0.085
BSR	0.159	-0.344	0.766	0.226	0.065	0.015
Dehydrogenase	0.048	0.990	0.008	0.059	-0.004	-0.085
Urease	0.048	0.990	0.008	0.059	-0.004	-0.085

Table 7. Influences of sustainable agriculture on soil quality

Land use system		pH	VLC	Nitrogen	K	Zn	MBC	SQI
AGLUS	Rice-Rice	0.07	0.01	0.01	0.01	0.03	0.05	0.18d
	Rice-Pulses	0.07	0.03	0.05	0.02	0.03	0.05	0.25d
	Rice-Fallow	0.08	0.00	0.02	0.00	0.03	0.03	0.16d
	Fallow	0.06	0.01	0.01	0.03	0.01	0.03	0.15d
ALUS	Pasture	0.06	0.24	0.06	0.09	0.03	0.14	0.62b
	Coconut	0.08	0.19	0.02	0.07	0.03	0.06	0.45c
	Cashew	0.08	0.33	0.06	0.05	0.02	0.15	0.69ab
	Forest	0.08	0.31	0.07	0.07	0.01	0.18	0.72ab
	Arecanut	0.13	0.29	0.04	0.13	0.06	0.16	0.8a
	Mean	0.08	0.16	0.04	0.05	0.03	0.09	

Table 8. Correlation co-efficient between fractions of SOC, SELF and SQI

	VLC	LC	LLC	NLC	TC	LI	MBC	DHA	SQI
VLC	1								
LC	0.977**	1							
LLC	0.972**	0.995**	1						
NLC	0.893**	0.913**	0.908**	1					
TOC	0.969**	0.990**	0.989**	0.960**	1				
LI	0.765*	0.814**	0.799**	.540	0.731*	1			
MBC	0.888**	0.883**	0.874**	0.844**	0.885**	0.656	1		
DHA	0.728*	0.729*	0.717*	0.836**	0.776*	0.392	0.927**	1	
SQI	0.928**	0.926**	0.927**	0.853**	0.923**	0.733*	0.973**	0.866**	1

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed)

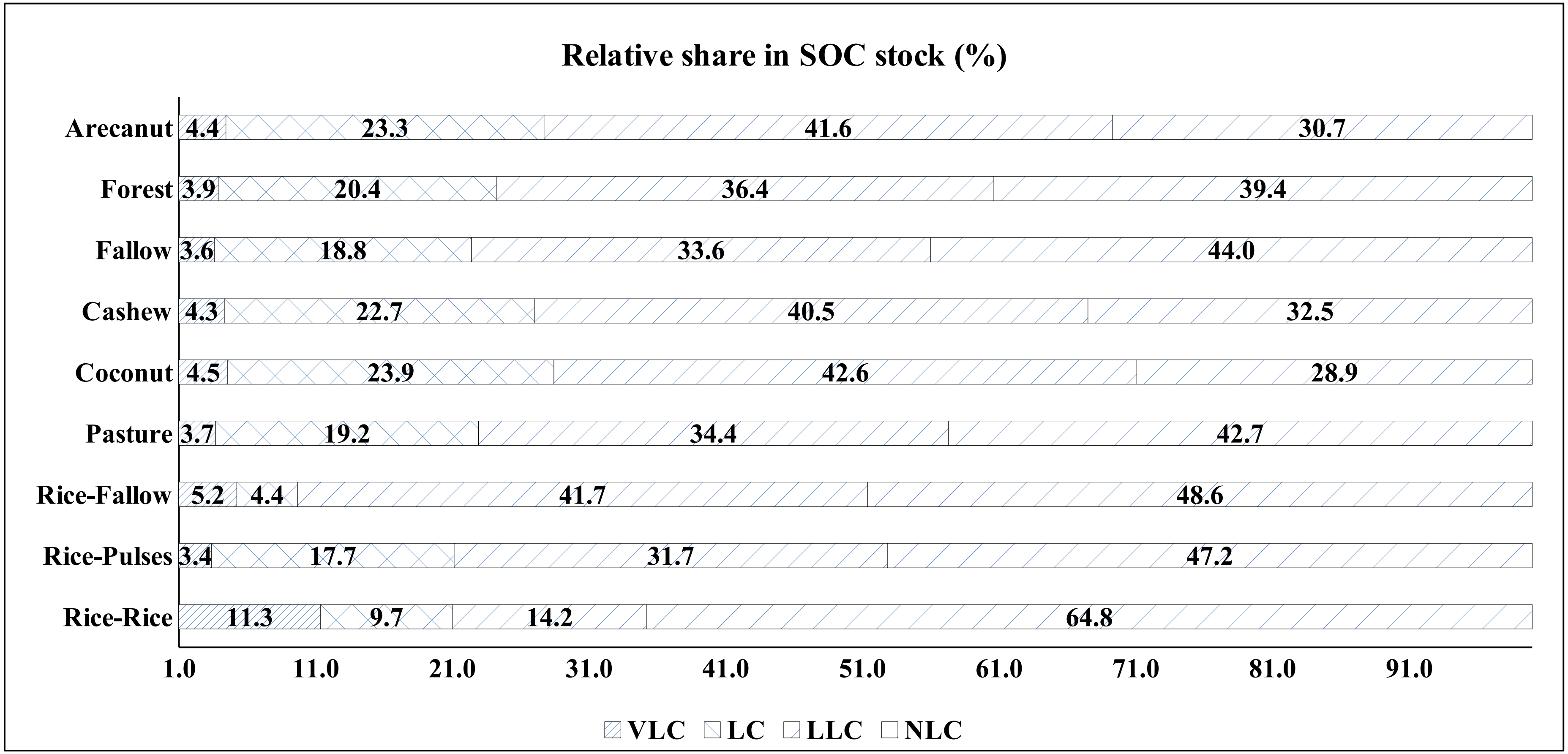

Fig. 1. Influence of sustainable agriculture on the share of different fractions of SOC in total carbon

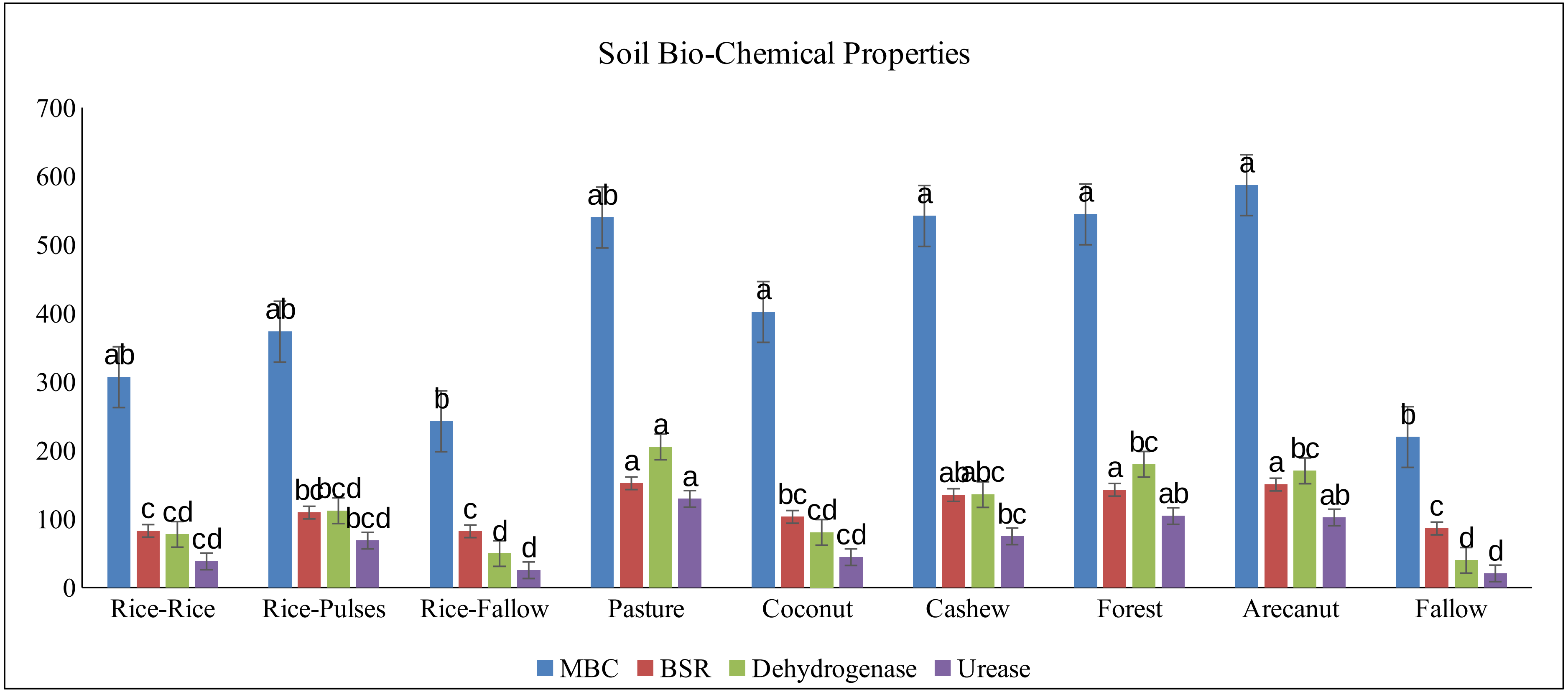

Fig 2. Influence of sustainable agriculture on bio-chemical properties [Note: MBC (μg g^{-1} of soil); BSR (mg CO_2-C g^{-1} day^{-1}); Dehydrogenase (μg TPF g^{-1} day^{-1}); Urease (μg urea g^{-1} h^{-1})]