ASSESSMENT OF SOIL CARBON POOLS IN ACID SULPHATE SOILS OF KUTTANAD

by

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THESIS

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DECLARATION

I, hereby declare that this thesis entitled **"Assessment of soil carbon pools in acid sulphate soils of Kuttanad"** is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or other similar title, of any other University or Society.

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LIST OF ABBREVIATIONS AND SYMBOLS USED

%	Per cent
Hr	Hours
i. e.	That is
Ml	Milli litre
Kg	Kilo gram
min.	Minutes
Mha	Million hectare
Mg	Milli gram
Sl. No.	Serial number
kg^{-1}	Per kilogram
Mg ha^{-1} yr^{-1}	Mega gram per hectare per year
rpm	Revolution per minute
Fig.	Figure
viz.	Namely
pH	Negative logarithm of hydrogen ions
μm	Micron meter
Ppm	parts per million
Pg	Peta gram
Gt	Giga ton
C	Carbon

N	Nitrogen
CO_2	Carbon dioxide
SOC	Soil Organic Carbon
SIC	Soil Inorganic Carbon
WSC	Water Soluble Carbon
LC	Labile Carbon
POC	Particulate Organic Carbon
MC	Minaralizable Carbon
DOM	Dissolved Organic Matter
DOC	Dissolved Organic Carbon
SOM	Soil Organic Matter
BD	Bulk Density
WSA	Water Stable Aggregate
EC	Electrical Conductivity
CEC	Cation Exchange Capacity
MBC	Microbial Biomass Carbon
MRT	Mean Residence Time
PCM	Potential Carbon Mineralisation
mg kg^{-1}	Milligram per kilogram
µg	Microgram
^0C	Degrees Celsius
CD	Critical Difference

et al.	And others
r	Correlation coefficient
FCRD	Factorial Completely Randomized Design
$Ca(OH)_2$	Calcium hydroxide
Al^{3+}	Aluminium ion

Introduction

1. INTRODUCTION

Soil organic carbon is an important attribute of soil quality. It influences soil physical, chemical and biological properties and processes. It regulates energy and nutrients for soil biota, aggregate stability, water retention, hydraulic properties, resistance and resilience to compaction, buffering capacity, cation exchange capacity and formation of soluble and insoluble complexes with metals. The soil organic matter in tropical soils is in a decline and is one of the major constraints to food and nutritional security.

Destruction of natural ecosystem and its conversion through anthropogenic activities are the major cause for the decline in the soil organic carbon pools, and this has a counter effect on the soil and water quality, biomass productivity and has a strong impact on global warming. Studies on soil organic matter and carbon pools are important to find out ways and means to improve soil organic matter and carbon storage which will result in increased agricultural productivity and environmental quality.

Soil is the largest reservoir of terrestrial carbon and its major contribution is from soil organic matter. The global soil carbon (C) pool of 2500 giga ton (Gt) includes almost 1550 Gt of soil organic carbon and 950 Gt of soil inorganic carbon (SIC). The carbon stored in soils is thrice higher than that in above ground biomass and twice higher than that in the atmosphere (Eswaran *et al*., 1993).

Land use history has a strong impact in the SOC pool. There is a dynamic equilibrium between land use and SOC and any land use practice that increases vegetative cover or reduces its removal could have a positive influence on the global carbon budget by increasing the terrestrial carbon sink. Different land use systems have varying ability to store soil organic carbon. The type of land use system decides whether the soil is a net sink or source of CO_2. Wetlands are the effective carbon sinks because of low rate of organic matter decomposition due to standing water conditions. Improving the carbon sequestering capacity of the soil through improved land use and management practices such as minimum tillage, crop residue recycling, integrated nutrient management, agro-forestry system, wise choice of cropping system etc. is the need of the hour. The increase in carbon sequestration have a positive effect in increasing soil fertility, crop productivity, long term sustainability and ultimately in reducing greenhouse effect.

The foremost environmental challenge confronted by the world is the mitigation of global warming. The upsurge in the atmospheric concentration of greenhouse gases specifically CO_2 is the key reason for global warming. The mitigation of global warming through soil carbon sequestration is a subject of scientific interest.

Acid sulphate soils are unique in nature, with continuous chemical degradation due to severe acidification process. They have a pH below 4 that is directly or indirectly caused by sulfuric acid formed by the oxidation of pyrites. The intrinsic property of these soils is the existence of either sulfuric horizon or sulfidic materials (Anda *et al.*, 2009). The extreme acidity is caused by the drainage of sulphitic mud that accumulate in the first place under severely reducing conditions mostly in tidal swamps and in the bottom sediments of brackish lakes. Problems arise whenever the rate of acid production from oxidation of sulphides exceeds the buffering capacity of soil. These soils also contain toxic levels of ions such as iron (Fe^{2+}), sulphates (SO_4^{2-}) and chlorides Cl^- rendering the soils poor in productivity.

In India, around 0.293 Mha of land is under acid sulphate soils (Bhattacharyya *et al.*, 2015) and their distribution is concentrated particularly in two states viz., West Bengal and Kerala. In Kerala, Kuttanad is known to be the "rice bowl of the state". It includes 50,000 ha of rice fields, out of which 15,000 ha belongs to acid sulphate soils (Typic Sulfaquent) (Beena and Thampatti, 2013).

The lower pH of the kari soils of Kuttanad is due to the acid sulphate nature of the soil and the presence of undecomposed organic matter in the form of wood fossils. Morphological and physicochemical properties of these soils show great degree of variation. They are dark brown to black in colour, sticky and plastic, subangular blocky in structure and sandy to clayey in texture, with random deposits of lime shells and humus (Thampatti, 1997). These wetlands are undergoing very fast transformation due to unsustainable agriculture practices, but they serve as a carbon sink due to its specific wetland characteristics.

Rice production in Kuttanad showed a declining trend for the past few decades despite the use of high yielding varieties and modern farming techniques. The major reason attributed is the loss of soil health. It is important to study the soil organic matter status and carbon pools in these soils to identify the key issues responsible for this decline. Although acid sulphate soils of Kuttanad exhibit considerable limitations to agricultural use, it can be made productive through efficient management of soil carbon pools. Improvement of soil organic carbon pool will result in augmentation of soil quality and agronomic productivity per unit area. In addition to the enhancement of food security, soil carbon sequestration will also offset fossil fuel emissions.

Estimation of soil carbon pools in major soil series of Kuttanad under different agricultural land use systems will help to identify the carbon fractions dominant in different land uses and will help to prioritize land use systems for carbon sequestration. It will help to develop suitable management practices to enhance soil organic carbon status and thereby crop productivity in Kuttanad soils. The study of soil carbon dynamics is also important to understand the carbon balance and their response to future global climate change.

Hence the present study on "Assessment of soil carbon pools in acid sulphate soils of Kuttanad" was carried out with the following objectives

1. To study the soil organic and inorganic carbon stocks in different soil series of acid sulphate soils of Kuttanad under different land use systems.

2. To assess the different soil carbon pools in acid sulphate soil series of Kuttanad under different land use systems.

3. To study the influence of land use on soil properties and soil carbon pools.

Review of Literature

2. REVIEW OF LITERATURE

The soil organic carbon (SOC) has been recognized as a significant constituent of soil quality, which influences a wide range of soil physical, chemical and biological properties, processes and functioning. The conservation of SOC in cropland is a major determinant of the productivity and long-term stability of agricultural systems. SOC storage is the most promising measure for mitigating global climate change. Land use change rapidly influence different SOC fraction, such as labile carbon, particulate organic carbon and water soluble carbon rather than total SOC, and serves as a vital indicator of critical soil function. Restoration of soil quality through soil carbon management is the need of the hour because soil organic carbon is extremely reactive, dynamic and a resilient indicator of soil quality.

Acid sulphate soils are highly acidic, saline, high in organic carbon content and contain toxic levels of iron, sulphates and chlorides rendering the soil poor in productivity. Retaining the carbon status of the soils is needed to reduce all these problems. Suitable land use system can help in sequestering carbon in soil and reduce acidity, metal toxicity and greenhouse effect. The research information pertaining to soil carbon pools with particular reference to acid sulphate soil and land use systems are reviewed in this chapter.

2.1 SOIL CARBON POOLS AND DYNAMICS

SOC is the largest terrestrial carbon pool which can store 1500-2000 Pg of carbon in different forms (Neider and Benbi, 2000). Bhattacharyya *et al.* (2000) computed 63 Pg SOC in different physiographic regions of India in first 150 cm soil depth. The soil carbon pool includes both organic and inorganic forms. SOC includes plant, animal and microbial residues in all stages of decomposition. The depth wise distribution of SOC pool in Indian soils is 9.55 Gt and 30 Gt at 0.3 m and 1.5 m depth respectively (Bhattacharyya *et al.*, 2009). The primary carbonate minerals such as calcite, dolomite and gypsum along with secondary carbonates contribute to soil inorganic carbon (SIC) pool. The productivity and sustainability of ecosystems are greatly influenced by soil carbon dynamics, which in turn add substantially to global carbon cycle (Chan *et al*, 2001).

Based on decomposition or turnover rates, three main pools of soil organic matter have been identified. These are active (1-2 years), slow (15-100 years) and passive (500-5000 years) pools. Both active and slow organic matter is biologically active and micro- organisms are continuously decomposing them. Active soil organic matter is not completely decomposed and moves into slow or passive pools. They forms a relatively small portion of total soil organic matter but it plays important roles in maintaining and monitoring soil quality (Weil and Magdoff, 2004).

The different SOC fraction like hot water soluble carbon, dissolved organic carbon and particulate organic C serve as the sensible indicators of land use changes than total SOC (Tan *et al.,* 2007). In addition labile C also functions as a primary indicator of the land use effect on soil quality (Jinbo *et al.,* 2006). Hu *et al.* (1997) recorded the highest labile C in forest soils. In addition, agricultural soils also had a significantly higher proportion of soil organic matter as labile C. The SOC and DOC content in soil decreased after grassland were shifted to forest or cropland, in the sequence of grassland soil> forest soil> cropland soil (Jiao *et al.*, 2009).

The land use changes have elevated the CO_2 concentration in the atmosphere, and have the ability to alter the long term turnover of soil C pools. Land use categories have a significant impact on the magnitude of labile and non-labile C pools (Stecio *et al.*, 2007). The C balance in the soil is also influenced by the microbial communities from diverse environments (Steenwerth, 2003). Soil organic matter turnover is affected by the microbial biomass (Jenkinson, 1990), which constitute 1% of the soil organic carbon (Moore *et al.*, 2000). The microbial biomass is the most labile fraction of SOM and the pool size in rice soils accounts to 2- 4% of total C

(Reichardt *et al.*, 1997). It declined in agricultural soils due to decrease in the addition of organic matter (Doran, 2002).

2.2 CARBON SEQUESTRATION

Lal (2004) stated that carbon sequestration entails removing the atmospheric CO_2 into long lived pools and accumulating it securely so that it is not immediately re-emitted. The important constituent of global carbon cycle is the SOC and it sequesters 1100 to 1600 Pg in soil (Izaurralde *et al.*, 2000). The soil organic carbon sequestration rate varies from 500 to 800 kg/ ha/ year in cold and humid regions and 100 to 300 kg/ ha/ year in dry and warm regions (Lal, 2002). Sustainable land management practices can sequester about 40-80 Pg of carbon in soils over next 50-100 years (Bell and Lawrence, 2009). Different land uses have varying ability for carbon sequestration due to differential SOC and aggregation dynamics (Six *et al.*, 1998). Grasslands sequester about twice the quantity of C in the soil than arable land (Cambardella and Elliot, 1992).

2.3 ORGANIC CARBON DEPLETION IN SOILS

Lal (2004) stated that the agricultural and degraded soils of the world act as a sink for 50 to 66% of the carbon loss of about 42 to 78 giga tons of carbon. The depletion of soil organic carbon (SOC) is mainly attributed to change in land use, increased tillage, crop residue burning, summer fallowing, clean cultivation, inadequate soil management practices etc. The reduction of SOC pool is endorsed to three factors that include mineralization, leaching of dissolved organic carbon (DOC) and soil erosion or runoff. About 60 to 70 % of lost carbon from the soil can be re-sequestered through the adoption of certain soil and crop management practices such as no tillage or minimum tillage, use of cover crops, integrated nutrient management, precision farming etc.

Kotto- Same *et al*. (1997) opined that in the humid forest zone of Cameroon, the forest contained 308 t C ha^{-1} and lost 220 t C ha^{-1}, when these forest lands have been converted to agriculture. The soil and ecosystem processes and past management practices influence SOC concentrations. The current cultivation practices have greatly decreased the carbon contents of agricultural soils, thereby increasing the atmospheric CO_2 concentrations (Collins *et al*., 2000).

2.4 FACTORS INFLUENCING SOIL ORGANIC CARBON STORAGE

Gale and Camberdalla (2000) conveyed that soils have a great potential to store carbon under no till practices. Lal (2004) stated that the factors such as soil texture, structure, rainfall, temperature, farming system and soil management have an influence on organic carbon sequestration. Climate has a great influence on SOC pool.

Adhikari *et al*. (2009) found that the balance between carbon input (organic matter production) and output (decomposition, methanogenisis, etc.) and the resulting storage of carbon in wetlands depend on several factors such as the topography and the geological position of the wetland, the hydrological regime, the type of plant present, the temperature and moisture of the soil, pH and the morphology. The accumulation of soil organic carbon was influenced by rainfall and temperature. In low rainfall zones, SOC decreased with increase in temperature and in high rainfall zones, the SOC increased with increase in temperature. In India, the highest mean SOC accumulation of 8.7 g kg^{-1} was observed in rice fallow system followed by rice-rice, maize- wheat, rice- pulse, soya bean based, rice- wheat and pearl millet based system (Pal and Shurpali, 2006).

The SOC pool to a depth of 1 m varies from 30 tons/ha in arid climatic conditions to 800 tons/ha in cold regions. Land use change from natural to agricultural ecosystem weakens the carbon sequestration to the tune of 60% in soils of temperate regions and 75% in tropics. The outcomes of dimunition of SOC pool are degradation of soil quality, decreased biomass productivity, water quality and ultimately resulting in global warming. There is a positive relationship between total SOC content with precipitation and clay content and an inverse relationship was found between total SOC content and temperature (Jobbagy and Jackson, 2000).

2.5 ACID SULPHATE SOILS AND THEIR PROPERTIES

Beena and Thampatti (2013) reported that the organic carbon content of the acid sulphate soils were high and it varied from 2.73 to 5.35%. For the past few decades, these soils show a declining trend in rice production, which is primarily due to the decrease in productivity, increase in cost of cultivation, loss in soil health and decrease in cropped area (Nath *et al.*, 2016).

Acid sulphate soils are highly acidic when dry with pH ranging from 3 to 4.5 and the total soluble salt concentration as high as 6 dSm^{-1}. During summer months, upon drying, oxidation of sulfur compounds occur and sulfuric acid is formed. All these factors lead to the poor crop production even after the adoption of high yielding varieties (Kurup and Ranjeet, 2002).

2.6 INFLUENCE OF LAND USE ON SOIL CARBON DYNAMICS

There existed a large dissimilarity in the length of time and the rate at which carbon accumulate in the soil, which is correlated to the productivity of the recovering vegetation, physical and chemical conditions in the soil, past history of soil organic carbon inputs and physical disturbances. The type of ecosystem and land use had a great influence on the amount, decomposability and placement of above ground and below ground inputs. There existed a net balance between the rate of soil organic carbon inputs and rate of mineralization, which decides the amount of organic carbon stored in the soil (Post and Kwon, 2000).

The decline in the soil organic matter due to the conversion of natural vegetation to agricultural crop land was chiefly related to the lower fraction of non-soluble matter in the readily decomposed crop residue. After a continuous cultivation for 30 to 50 years, there occured a loss of 50% of SOC and within the top 100 cm, the reduction is around 30% (Post and Kwon, 2000). Soil carbon dynamics and soil properties like aggregation were strongly influenced by land use and management practices (Shrestha *et al.*, 2007). Sreekanth *et al.* (2013) reported that other than the native grassland site, a considerable amount of soil carbon is stored in the conventional cropping site of cardamom.

Don *et al.* (2011) opined that the SOC stocks in the soil are greatly influenced by the type of land use. Land use changes pose a great risk, because they are the second abundant source of human induced greenhouse gas emission, which is chiefly attributed to the deforestation in the tropics and the subtropics. The conversion of primary forest into cropland, perennial crop and grassland leads to the elevated SOC loss of 25%, 30% and 12% respectively. Secondary forests store 9% less SOC than primary forest, which indicate the importance of primary forest in storing carbon. The afforestation of agricultural land and the conversion of cropland into grassland increased SOC by 29% and 26% respectively. SOC storage down to a depth of 60 cm including the humus layer were better at the spruce site (10.3 kg C m^{-2}) as related with the grassland, wheat and maize (7 to 8 C kg m^{-2}). In the mineral soils, agricultural soils have greater carbon stock when compared to the forest soil (John *et al.*, 2005).

Davidson and Janssens (2006) revealed that the wetlands, peatlands and permafrost soils generally contain higher carbon densities than upland mineral soils, and together they make up enormous stocks of carbon globally. Hansen and Nestlerode (2014) estimated that wetlands have the potential to accumulate 11,517 Gg C $year^{-1}$ and efficiently store 34–47 Mg C ha^{-1}. The carbon sequestration rate of undisturbed wetlands was lower (15% for mangrove and 55% for saltmarsh) than disturbed wetlands, but the carbon store was higher for undisturbed wetlands (65% for mangrove and 60% for saltmarsh) (Howe *et al*., 2009).

The percentage storage of SOC in the top 20 cm of the shrublands, grasslands, and forests were 33%, 42% and 50% respectively. The relative distribution of SOC with depth has a sturdy relationship with vegetation than with climate, but was in contrast with the absolute amount of SOC. The percentage of SOC in the top 20 cm relative to the first meter varied from 29% in cold arid shrub lands to 57% in cold humid forests and, for a given climate, was always deepest in shrub lands, intermediate in grasslands, and shallowest in forests (Jobbagy and Jackson, 2000).

Sustainable management practices such as reduced tillage, decreased bare fallow, increased residue input and conversion to perennial vegetation will in turn reduce the atmospheric CO_2 concentrations. The carbon content in soil is usually greater than in the living vegetation. Hence, it is vital to have an idea about the carbon dynamics and its role in terrestrial ecosytem carbon balance and global carbon cycle (Post and Kwon, 2000).

2.7 INFLUENCE OF LAND USE ON SOIL PROPERTIES

2.7.1 Soil Texture

Kong *et al*. (2009) revealed that soil texture has an important role in improving soil carbon concentrations in different land use types under different management intensities. Soils with large proportion of fine particles have greater ability to sequester atmospheric carbon. Telles *et al*. (2003) stated that soil texture especially clay content have a major influence in slowing down the carbon cycle which in turn improves the storage and dynamics of carbon in the tropical forest soils. A greater percentage of total soil C was found in < 2 μm fractions in the cultivated soils (30%) than under natural vegetation (18%), in which the total C was associated with the 2 to 20 μm fractions to a greater extent than in the cultivated soil (Caravaca *et al.*, 1999).

2.7.2 pH

Soil acidity increases due to the increase in the H^+ ion concentration in soil solution, which is due to the presence of carboxylic, phenolic and hydroxyl groups of organic matter (Rao, 1992). Increase in the pH of two slightly acid (pH 5.7 and 5.8) soils using $Ca(OH)_2$, stimulated the mineralization of N and C. Initially, the rate of CO_2 evolution from soils whose pH was raised to 7.3 – 7.4, was 2–3 times higher than the unamended soils. But the rate of CO_2 evolution from $Ca(OH)_2$-treated soil decreased rapidly after about 7–10 days. During the entire 100 days of incubation, $Ca(OH)_2$-treated soils at pH 7.3–7.4 produced 37% and 67% more CO_2 - C than their untreated counterparts. When pH was increased, the release of labile organic matter leads to the increase in CO_2 evolution (Curtin *et al.*, 1998). Datta *et al.* (2015) observed lowest pH at 0- 20 cm depth under litchi and jamun plantation compared to mango and guava and attributed it to the production of organic acids during the decomposition of leaf litter as well as the quantity of litter input because the chemical composition of the litter may also vary among the land uses.

2.7.3 Electrical Conductivity

Thampatti and Jose (2000) revealed that the soils of Kuttanad are mildly saline and a decline in EC is observed during the post barrage period. Both the surface and subsurface layers show higher values of EC due to the accumulation of salts. Mathew *et al.* (2001) found that the EC of these soils are as high as 6 dS m^{-1} and the EC of the surface soils never reached high values due to the drainage practices followed by the farmers.

2.7.4 Exchangeable Acidity

Thampatti (1997) stated that the values of exchangeable acidity were greater during summer months, while potential and hydrolytic acidity were greater during rainy season. The exchangeable acidity was chiefly contributed by exchangeable H^+ and exchangeable Al^{3+}. The exchangeable acidity of acid sulphate soils varied from 1.78 cmol kg^{-1} to 9.83 cmol kg^{-1} while the exchangeable Al^{3+} content varied from 0.67 cmol kg^{-1} to 6.64 cmol kg^{-1} (Beena and Thampatti, 2013).

2.7.5 Bulk Density

The organic matter content greatly influence the bulk density of soil, which is chiefly attributed to enhancement of aggregation of soil particles (Ladd, 1996). Soil compaction increases bulk density and this result in poor aeration and root growth thereby resulting in low carbon accumulation (Smith and Doran, 1996). Soil bulk density has been found to be negatively correlated to SOC (Shrestha *et al*., 2004). Bhattacharyya *et al*. (2007) reported that in black soils the bulk density decreases as the SOC content increases in first 30 cm depth of soil. Gajri and Majumdar (2002) observed low bulk density in forest system due to no disturbance to soil which might have contributed to retention of organic matter.

2.7.6 Cation Exchange Capacity

There was a trivial effect of interaction between clay minerals and organic matter on the soil CEC (Parfitt *et al*., 1995). Soils with high quantity of biomass derived black carbon have a huge cation exchange capacity than adjacent soils with low black carbon content. The high surface charge density and specific surface area of the black carbon is responsible for the improved cation exchange capacity of the soils rich in black carbon (Liang *et al*., 2006). The organic matter have found to increase the CEC of soils and the soil carbon pools were positively correlated with CEC (Papini, 2011).

2.8 INFLUENCE OF LAND USE ON SOIL CARBON POOLS

2.8.1 Total Organic Carbon

The maximum soil organic carbon content of 7.39 per cent was observed in abandoned paddy field and it is nearly 89 per cent higher than the minimum value recorded from the homestead soil. The soils of coconut plantation performed as a better sink for carbon and were low in methane emissions (Chacko *et al.*, 2014).

Gulde *et al.* (2008) reported that increase in soil organic input does not always linearly increase the soil organic carbon, and acts as a constraint for the rate and efficiency of carbon stabilization in soil. In the mineral soil as well as the small macroaggregates (250–2000 μm), microaggregates (53–250 μm), and the silt plus clay fraction (<53 μm), an improvement was witnessed in SOC contents with an increase in manure application rate to 120 Mg ha^{-1} yr^{-1}. But, no additional C was sequestered when the manure application rate was increased to 180 Mg ha^{-1} yr^{-1}, which indicates C saturation in these SOC pools. Although the C input increases, there is a saturation limit for the soil and the additional carbon input will accumulate as labile fractions. The elevation of soil carbon pool by 1 ton will increase the crop yield to an extent of 20 to 40 kg/ha for wheat, 10 to 20 kg/ha for maize and 0.5 to 1 kg/ha for cowpea. In addition to augmenting food security, carbon sequestration also counterbalance fossil fuel emission at the rate of 0.4 to 1.2 giga tons of carbon per year or 5 to 15% of the global fossil fuel emissions (Lal, 2004). The amount and rate of loss of SOC is greatly influenced by land use and management practices (Guggenberger *et al.*, 1994).

2.8.2 Soil Inorganic Carbon

Lal (2004) stated that the SIC sequestration is very low (5 to 150 kg/ha) as compared to SOC sequestration. This may be due to the biogenic processes and leaching of carbonates into the ground water especially in soils irrigated with water containing low carbonates. Land use has a significant influence on SIC levels in cultivated soils. Human activity has a great impact on SIC as well as SOC pools (Wu *et al.*, 2009).

Mi *et al.* (2008) revealed that the amount and vertical distribution of SIC is connected to climate and land cover type. Content of SIC in each incremental horizon was positively correlated with mean annual temperature and negatively correlated with mean annual precipitation. The SIC storage pattern across land cover types are as follows desert, grassland > shrubland, cropland > marsh, forest and meadow. Densities of SIC augmented generally with depth in all ecosystem types with the exclusion of deserts and marshes where it was highest in intermediate layers.

2.8.3 Water Soluble Carbon

Water soluble carbon (WSC) or the dissolve organic carbon (DOC) is the most vigorously cycling soil organic carbon pools and they are easily decomposed by micro-organisms and serve as an energy source. Chantigny (2003) revealed that the change in management practices have a short term influence on dissolved organic matter and water extractable organic matter, while the vegetation type and amount of litter returned to the soil have a long term effect.

Zsolnay (1996) indicated that DOM concentration is larger in forest than in agricultural soils. In forest soil, DOC concentration ranges from 5 to 440 mg L^{-1}, whereas WEOC content ranges from 1000 to 3000 mg L^{-1}. In agricultural soils, the value varies from 0 to 70 mg L^{-1} for DOC and from 5 to 900 mg L^{-1} for WEOC. Christ and David (1996) suggested that the DOC production was relatively quick in the first 2 days of incubation, and then declined to almost 90 µg g^{-1} $week^{-1}$. But under warmer conditions, production rates in the first 2 days of incubation were higher.

2.8.4 Labile Carbon

The more susceptible indicators of soil organic carbon change resulting from forest transition are the labile fractions. They are the active carbon pools, which can be easily altered by the microbial activities. Conversion of native forest to intensively-managed plantations would decline labile organic C, which may be due to a combination of factors including amount of litter materials, activity of micro-organisms and management practices, which would vary greatly with the forest conversion (Yang *et al.*, 2009).

Labile C served as a vital indicator of soil quality. The land use has a promising influence on the labile C fractions in the top soil (0-20 cm). The labile fraction organic C contents decreased considerably with increasing soil depth in wetlands. But, the upland forest, abandoned cultivated, and cultivated soils showed a minute decrease in labile fraction organic C contents with increasing soil depth (Jinbo *et al.*, 2006).

2.8.5 Particulate Organic Carbon

Particulate organic matter is the coarser fraction and transient pool of organic matter, which is comparatively the more stable carbon pool. They are the intermediate fraction of SOC between active and slow fractions and they vary greatly over time due to change in management practices. These fractions are more than 53 µm and function as an indicator of soil quality. POC contributed to 42 to 74% of TOC and they were enormous under pasture and more conservative management than traditional cropping regimes. Changes in POC contributed for 81.2% of the changes in TOC, which is due to the effect of change in land use and management. Thus, POC serves as a more susceptible indicator of change caused by land use and management practices than TOC (Chan, 2001). Franzluebbers and Arshad (1997) opined that clay have a vital role in sequestering POC by sheltering its decomposition. There was a significant loss of soil and particulate organic carbon because of change in land use.

John *et al.* (2005) revealed that the POM accounts for 52% of the total organic carbon content in the A horizon of the spruce stand. At the maize site the percentage of maize-derived C was slight in the fraction <53 µm with 24% and progressively strengthened with increasing aggregate size to 47% in the fraction >1000 µm. But at the grassland, maize and wheat site, about 86-91% of the SOC was associated with the heavy mineral fractions. The type of land use has a great influence on the distribution pattern of litter carbon to functionally different SOM pools and an increasing SOC concentration were correlated with the development of macro aggregates.

2.8.6 Mineralizable Carbon

Soil C mineralization is an important display of soil functional quality (Mutuo *et al.*, 2006). Rey *et al.* (2005) opined that the carbon mineralization rate of the top soil is almost 12 times faster than the bottom layers. The sensitivity of carbon mineralization to varying soil moisture is reliant on temperature. A sudden variation in soil moisture increased carbon mineralization during dry summer.

Giardina *et al.* (2001) stated that there is a decline in C and N mineralization rate with increase in clay content. Litter quality also has an influence on the mineralization rate. Aspen litter quality is superior than pine litter quality, but pine soils released an average of 238 g C kg^{-1} soil C compared with 103 g C kg^{-1} soil C for aspen soils. Higher microbial biomass under pine also indicates that pine soil C was of higher quality than aspen soil C.

2.8.7 Microbial Biomass Carbon

Soil microbial biomass carbon contributes a substantial portion of labile carbon pool which along with climate controls the turnover rate of labile carbon. Prabha *et al.* (2013) found that in wetland rice soils, application of biochar in appropriate proportion has a significant influence over the soil carbon dynamics by increasing the major soil carbon sequestration parameters like soil organic carbon, particulate organic carbon and microbial biomass carbon and has the ability to combat global warming without affecting the rice productivity. The pool size of microbial biomass carbon in rice soils accounts for only 2 - 4% of total carbon that represents an important and most labile fraction of SOM and this pool is turned over very rapidly (Reichardt *et al.*, 1997). Soil microbial biomass carbon regulates SOM decomposition and nutrient cycling. Thus it plays a key role in maintaining function and sustainability of terrestrial ecosystem. Benbi *et al.* (2012) reported that the microbial biomass carbon in selected bench mark soil series of Punjab varied between 125 and 249 $\mu g\ C\ g^{-1}$ soil, which contributed 1.7 to 4.1% of SOC. The ratio of MBC to SOC is a possible indicator for degree of disturbance of soil C cycling. A low ratio indicates a reduced pool of available C in soil (Klose *et al.*, 2004).

2.8.8 Oxidizable Organic Carbon Fractions

About 3 to 8% of SOC constituted the active pool with the average field mean residence time (MRT) of 100 days. Slow pools constituted 50% of the SOC in the surface and 65% in the subsurface, which had field MRTs from 12–28 y for C_4-C and 40–80 y for C_3-derived C depending on soil type and location. The field MRT of C_3-derived C increased 10-15 years under no till management system compared to conventional tillage. The resistant pool dwindled from an average of 50% at the surface to 30% at depth. The SOC dynamics were reliant on features such as soil heritage, texture, cultivation, parent material and depositional characteristics (Collins *et al.*, 2000). C fluxes were largely controlled by the small but highly bio- reactive, labile pools in terrestrial soils, while long term C storage was determined by the long lived recalcitrant fractions. Highest labile as well as recalcitrant pool was observed in 0- 5 cm when compared to 5- 15 cm depth (Veni *et al.*, 2014). Datta *et al.* (2015) reported an increased content of passive carbon pool with depth in guava and mango plantation due to the increase in silt and clay content, where as active carbon pool decreased with depth.

2.8.9 Soil Organic Matter Fractions

Change in soil organic matter fractions indicates change in land use than change in soil organic matter. Humic substances represent 40 – 60% of soil organic matter and include three different fractions according to different stability under acid hydrolysis and permanganate oxidation. The distributions of the soil organic matter fractions varied in the ranges 12–32.5% (fulvic acids), 12–34.5% (humic acids), and 40–69.5% (humin) (Guimaraes *et al.*, 2013).

2.9 SOIL CARBON STOCK AND INDICES

The organic carbon stock in soil ranged from 101.5 to 127.4 Mg ha^{-1}. The broadleaf tree plantations placed into prior native forest or pasture did not influence soil carbon stocks, whereas pine plantations decreased soil carbon stocks by 12-15%. Land use changes have turned down the carbon stocks from pasture to plantation (-10%), native forest to plantation (-13%), native forest to crop (-42%) and pasture to crop (-59%). Soil carbon stocks perked up after land use changes from native forest to pasture (+8%), crop to pasture (+19%), crop to plantation (+18%) and crop to secondary forest (+53%) (Guo and Gifford, 2002). Datta *et al.* (2015) reported that the total organic carbon stock significantly decreased with increase in depth. Among the land uses, the TOC stock at the surface soil (0- 20 cm) in descending order with guava (28.80 Mg C ha^{-1}) > Jamun (27.30 Mg C ha^{-1}) > litchi (25.70 Mg C ha^{-1}) and mango (19.20 Mg C ha^{-1}) and in sub surface soil (40- 60 cm) 13.9, 8.1, 9.6 and 9.0 Mg C ha^{-1} respectively.

Chacko *et al.* (2014) reported that presence of high value of POC/ SOC ratio (0.98) in paddy soil is an indicator demanding proper management activity and the lower ratio (0.18) in teak plantation was due to intense land disturbance, where the loss of POC was more. The high value of carbon turnover which is the ratio of potential carbon mineralization (PCM) to SOC represented under paddy soil (3.20) shows the result of disturbance and possibility of shifting it from source to sink. The PCM/ SOC ratio narrowed considerably in coconut plantation shows the increased sink capacity of soil thereby the chance of losing the stored carbon in the form of CO_2 is less.

Materials and Methods

3. MATERIALS AND METHODS

Soil carbon signifies the largest carbon pool of terrestrial ecosystems, and has been approximated to have one of the largest potentials to sequester carbon worldwide. The present study entitled "Assessment of soil carbon pools in acid sulphate soils of Kuttanad" was envisaged to characterise the different soil series of acid sulphate soils of Kuttanad under different land use systems based on the different physical and physico – chemical parameters and dynamics of carbon. The methodology adopted for the present study is detailed in this chapter.

3.1 SELECTION OF STUDY AREA

Kuttanad is known to be the "rice bowl of Kerala". It is a distinctive agricultural tract, which lies at 0.6 to 2.2 m below MSL. It extends between $9^0 8'$ and $9^0 52'$ N latitudes and $76^0 19'$ and $76^0 44'$ E longitudes spread over the districts of Alappuzha, Kottayam and Pathanamthitta. It is a unique ecosystem due to its location near equator, equitable temperature regime, high rainfall and high solar radiation throughout the year. It experiences humid tropical climate, with the temperature ranging from 21 °C to 36 °C and annual rainfall of 3000 mm. The total geographic area of the region is 854 km^2. The soils of Kuttanad are typical water logged soils and generally fall under the acid saline group, where about 15,000 ha belongs to acid sulphate soils. The six acid sulphate soil series delineated from Kuttanad (Beena, 2005) and three agricultural land use systems selected for the study are given below

Soil series

1. Ambalapuzha series
2. Purakkad series
3. Thakazhi series
4. Thuravur series
5. Thottapalli series
6. Kallara series

Agricultural land use systems

1. Rice
2. Coconut
3. Rice – fish

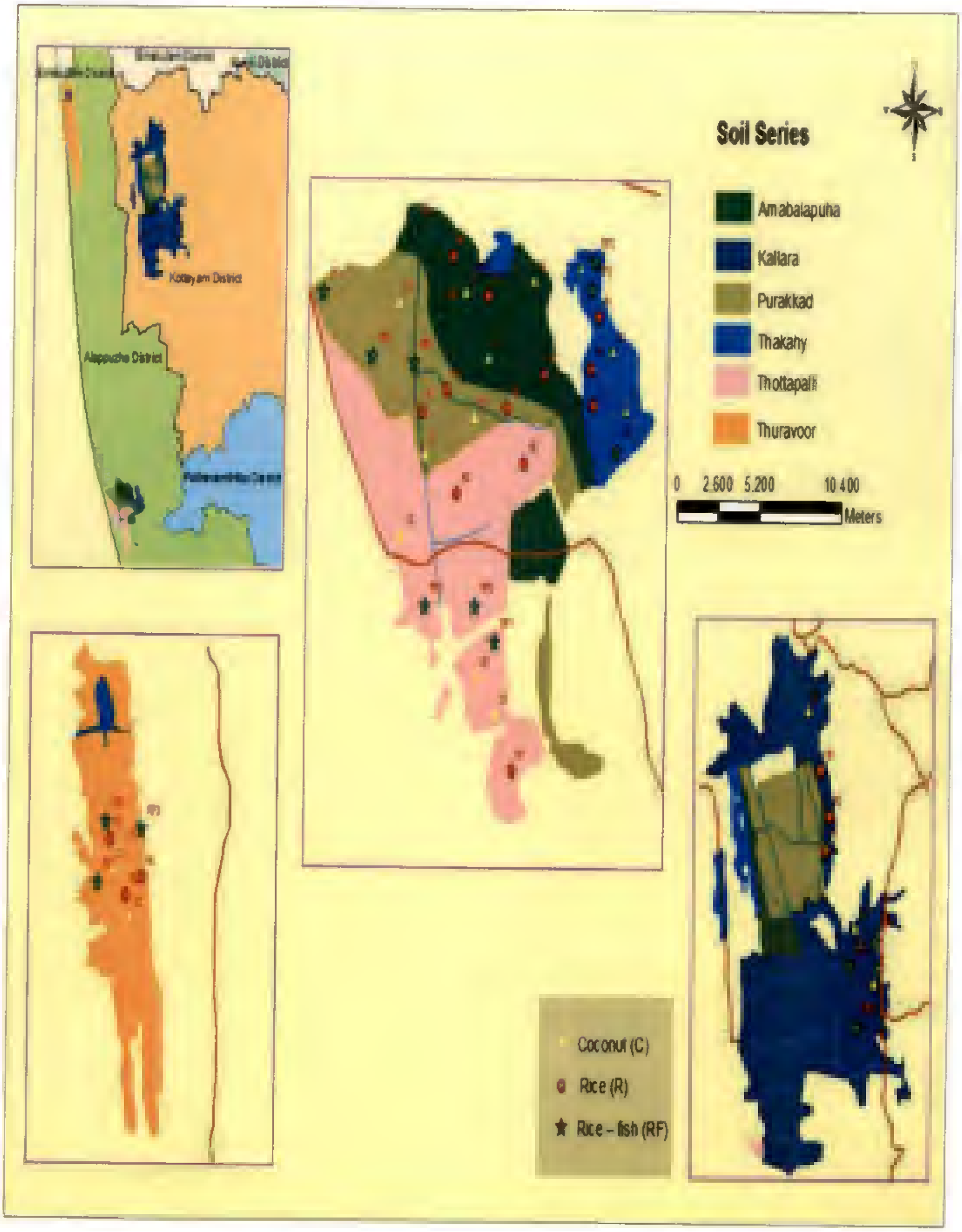


Fig. 1. Location map of study area

3.2 SOIL SAMPLE COLLECTION

Soil samples were collected from three locations each under the three agricultural land use systems from all the six soil series studied. Samples were collected during the month of May. Surface samples were collected using an auger at a depth of 0 – 15 cm from different locations and the samples were pooled, from which representative samples were drawn. Core samples were also collected from each sampling site. The soil samples were shade dried and powdered with a wooden mallet and sieved through a 2 mm sieve prior to laboratory analysis.

3.3 SOIL ANALYSIS

3.3.1 Physical and Physico-chemical Properties

3.3.1.1 Soil Texture

Soil texture was determined using International pipette method as described by Piper (1966). Sand, silt and clay fractions were found out and expressed as per cent. Soil textural name was found from soil textural triangle given by USDA.

3.3.1.2 pH

The soil pH was determined in 1: 2.5 soil - water suspension using combined glass - calomel electrode in a digital pH meter (Jackson, 1973).

3.3.1.3 Electrical Conductivity

The electrical conductivity of the soil was measured in 1: 2.5 soil - water suspension using a conductivity meter and results were expressed in dS m^{-1} at 25 °C (Jackson, 1973).

3.3.1.4 Exchangeable Acidity

Exchangeable acidity was determined by extraction of the samples with 1 M KCl as described by Page *et al.* (1982).

3.3.1.5 Bulk Density

Bulk density of soil was analysed by core sampler method (Black, 1965) by collecting core samples from field. Soil mass was determined from the oven dry weight of the core samples and the volume was calculated from the core dimensions. Bulk density was determined by dividing soil mass by volume and expressed in Mg m^{-3}.

3.3.1.6 Cation Exchange Capacity

Cation exchange capacity was measured by extraction using neutral normal ammonium acetate followed by distillation as explained by Jackson (1973) and expressed in cmol kg^{-1} soil.

3.3.2 Soil Carbon Pools

3.3.2.1 Soil Inorganic Carbon

Soil inorganic carbon was determined by the method of Puri (1949) and expressed as per cent.

3.3.2.2. Total Organic Carbon

Total organic carbon content in the samples was determined by Walkley and Black (1934) wet oxidation method.

3.3.2.3 Water Soluble Carbon

Water soluble carbon was determined as per the method given by McGill *et al.* (1986) by extracting with water followed by wet oxidation method. Ten g of air dried soil was taken in a centrifuge tube, mixed with 20 ml of distilled water and shaken in a horizontal shaker for an hour, followed by centrifugation at 6000 rpm for 5-10 minutes to clear the supernatant. Ten ml of the supernatant was taken in a conical flask followed by the addition of 2 ml of 0.1 N $K_2Cr_2O_7$ and subsequently 10 ml of concentrated sulfuric acid was added and kept on the water bath at 100°C for half an hour and titrated against 0.01 N ferrous ammonium sulphate (FAS) using ferroin as an indicator

3.3.2.4 Labile Carbon

Labile carbon was determined by potassium permanganate oxidation method as described by Blair *et al.* (1995). Five g of air dried sample was weighed in a centrifuge tube and 20 ml of 0.02 M $KMnO_4$ was added into it and shaken for 2 minutes and centrifuged at 5000 rpm to clear the supernatant. Two ml of supernatant was taken and made up to 50 ml and the absorbance read at 550 nm.

3.3.2.5 Particulate Organic Carbon

Particulate organic carbon was determined by sodium hexa meta phosphate dissolution method as described by Camberdella and Elliott (1992). Ten g of air dried sample was weighed in a conical flask and 30 ml of 0.5% sodium hexa meta phosphate solution was added and shaken for 15 hours on a reciprocal shaker and rinsed thoroughly with water to remove silt and clay fractions. The particulate organic matter plus sand retained on the 53 µm sieve was analysed for carbon content by following Walkley and Black wet oxidation method.

3.3.2.6 Mineralizable Carbon

Mineralizable carbon was determined by CO_2 evolution method following laboratory incubation study for 50 days as described by Ladd *et al.* (1995) in aerobic condition. The CO_2 measurement was made on alternate days during the initial period and the interval was fixed based on the evolution and the estimation was continued up to 50 days until a steady emission was observed. Hundred g of soil was weighed in a conical flask and moisture maintained at 60% of field capacity. The CO_2 evolved were trapped in vials containing 0.1 N NaOH, which were hung inside the conical flask using a thread and the flask was sealed tightly using a rubber stopper to prevent any CO_2 loss. The vials with alkali were regularly replaced by fresh ones. The CO_2 absorbed by NaOH was precipitated using $BaCl_2$ and estimated by titrating against 0.1 N HCl using phenolphthalein as indicator.

3.3.2.7 Microbial Biomass Carbon

Soil microbial biomass carbon was estimated by fumigation - incubation technique as outlined by Jenkinson and Ladd (1981).

3.3.2.8 Oxidizable Organic Carbon Fractions

The different pools of oxidizable organic carbon was apportioned by modified Walkley and Black titration method as described by Chan *et al.* (2001) into the following pools

Very labile pool = organic carbon oxidizable by 12 N H_2SO_4

Labile pool = difference in organic carbon oxidizable by 18 N H_2SO_4 and 12 N H_2SO_4

Less labile = difference in organic carbon oxidizable by 24 N H_2SO_4 and 18 N H_2SO_4

Non-labile pool = difference between total organic carbon and organic carbon oxidizable by 24 N H_2SO_4

Active pool = very labile pool + labile pool

Passive pool = less labile pool + non labile pool

3.3.2.9 Soil Organic Matter Fractions

Humic acid and fulvic acid content of the soil samples were determined using the procedure as stated by Tan (1996).

3.4 Soil Carbon Stock and Indices

3.4.1 Soil Organic Carbon Stock

Soil organic carbon stock was calculated by the equation given by Batjes (1996) and expressed in Mg ha^{-1}

Soil organic carbon stock = soil organic carbon (%) × bulk density (Mg m^{-3}) × soil depth (m) × 100

3.4.2 Carbon Indices

Various carbon indices were worked out as follows (Blair *et al.* 1995)

Carbon Pool Index (CPI) = TOC in sample soil/ TOC in reference soil

Carbon Lability Index (CLI) = Lability of carbon in sample soil/ Lability of carbon in reference soil

Carbon Management Index (CMI) = CPI × CLI

3.4.3 Carbon Proportion and Turnover

Carbon proportion and turnover was worked out by the method given by Chacko *et al.* (2014). The carbon proportion was computed by the ratio of particulate organic carbon (POC)/ soil organic carbon (SOC) which represents the contribution of POC to SOC. Carbon turnover was computed by the ratio of C mineralization (MC)/ C storage (SOC).

3.4.4 Land Quality Index

Land quality index was calculated based on soil organic carbon stock as per the criteria stated by Shalimadevi (2006).

SOC stock (kg m^{-2})	Land quality index
< 3	Very low
3 – 6	Low
6 – 9	Medium
9 – 12	Moderate
12 – 15	High
> 15	Very high

3.5 STATISTICAL ANALYSIS

The data generated were subjected to statistical analysis as per Factorial Completely Randomized Design (FCRD) using statistical analysis software (SAS) package. The relationship among soil properties and soil carbon pools were studied by simple correlation and regression analysis.

Results

4. RESULTS

A study was carried out to assess the soil carbon pools in the acid sulphate soils of Kuttanad and to evaluate the influence of land use systems on them. The soil samples collected from six soil series and three land use systems were analyzed for soil properties such as soil texture, pH, EC, exchangeable acidity, bulk density and cation exchange capacity and soil carbon pools such as soil inorganic carbon, total organic carbon, water soluble carbon, labile carbon, particulate organic carbon, mineralizable carbon and microbial biomass carbon and the results obtained are reported in this chapter.

4.1 PHYSICAL AND PHYSICO - CHEMICAL PROPERTIES OF SOIL

4.1.1 Soil Texture

The results of soil textural analysis are given in table 1. The results indicated that Ambalapuzha series belongs to the textural class sandy clay loam with sand content of 40.46 to 49.93%, silt 23.50 to 31.18% and clay 25.25 to 28.05%. The percentage of sand, silt and clay fractions in Purakkad series ranged from 20.35 to 36.52%, 18.25 to 31.18% and 42.53 to 46.30% respectively and the textural class is clay. The soils of Thakazhi series is silty clay to clay loam with sand, silt and clay fractions of 12.60 to 42.52%, 17.05 to 43.05% and 38.16 to 42.06% respectively under different land use system. Thuravur series showed higher clay content (40.15 - 46.54%) compared to sand (27.25 – 31.50%) and silt (14.10 – 20.67%). The soils of Thottapalli series is sandy loam to sandy clay, while Kallara series comes under the textural class clay.

Table 1. Soil texture of acid sulphate soils of Kuttanad under different agricultural land use systems

Soil series (S)	Soil textural fractions and class	Agricultural land use systems		
		L_1 - Rice	L_2 - Coconut	L_3 - Rice – fish
S_1 - Ambalapuzha	Sand (%)	40.46	49.93	49.86
	Silt (%)	31.18	23.50	23.50
	Clay (%)	28.05	25.25	25.50
	Class	Sandy clay loam	Sandy clay loam	Sandy clay loam
S_2 - Purakkad	Sand (%)	36.52	22.35	20.35
	Silt (%)	18.25	28.47	31.38
	Clay (%)	42.53	46.30	46.15
	Class	Clay	Clay	Clay
S_3 – Thakazhi	Sand (%)	42.52	12.60	41.50
	Silt (%)	17.05	43.05	19.52
	Clay (%)	38.53	42.06	38.16
	Class	Clay loam	Silty clay	Clay loam
S_4 – Thuravur	Sand (%)	31.50	29.87	27.25
	Silt (%)	20.26	14.10	20.67
	Clay (%)	40.15	43.25	46.54
	Class	Clay	Clay	Clay
S_5 – Thottapalli	Sand (%)	38.25	69.56	37.25
	Silt (%)	5.10	10.05	6.10
	Clay (%)	54.32	17.50	52.67
	Class	Sandy clay	Sandy loam	Sandy clay
S_6 - Kallara	Sand (%)	26.70	26.52	23.02
	Silt (%)	21.50	24.50	22.56
	Clay (%)	48.56	45.04	51.46
	Class	Clay	Clay	Clay

4.1.2 pH

The pH of acid sulphate soils of Kuttanad under different agricultural land use systems are presented in table 2. The pH showed a significant difference among the different soil series, with the highest value of 4.58 in Thuravur series which was on par with Thakazhi series (4.36) and the lowest pH was observed in Ambalapuzha series (3.26). The different land use systems under study also showed a significant variation in pH with the highest value of 4.34 in coconut based system which was on par with rice – fish (4.07) and the lowest from rice (3.54). The interactions between soil series and land use was also found to be significant with the highest pH of 5.48 being recorded from Thakazhi series under rice – fish land use system (S_3L_3) which was on par with S_4L_2, S_4L_3 and the lowest pH of 2.98 from rice – fish in Ambalapuzha series (S_1L_3).

Table 2. pH of acid sulphate soils of Kuttanad under different agricultural land use systems

Soil series (S)	Agricultural land use systems (L)			Mean
	L_1 – Rice	L_2 – Coconut	L_3 - Rice – fish	
S_1 – Ambalapuzha	3.07	3.73	2.98	3.26
S_2 – Purakkad	3.78	4.47	3.10	3.78
S_3 – Thakazhi	3.61	4.01	5.48	4.36
S_4 – Thuravur	3.64	4.97	5.14	4.58
S_5 – Thottapalli	3.70	4.60	3.66	3.98
S_6 – Kallara	3.46	4.28	4.08	3.94
Mean	3.54	4.34	4.07	
	S	L	S × L	
S.E (m)	0.207	0.147	0.360	
CD (0.05)	0.421	0.298	0.729	

4.1.3 Electrical Conductivity

The electrical conductivity of acid sulphate soils of Kuttanad ranged from 0.08 to 3.15 dS m^{-1} (Table 3). The highest value was recorded from Thuravur series under rice (S_4L_1) which was on par with S_1L_3, S_2L_3, S_4L_2, S_4L_3 and the lowest from Thakazhi series under coconut (S_3L_2). The different soil series of Kuttanad varied significantly with respect to EC of soil. Thuravur series recorded the highest value of 2.61 dS m^{-1} which was significantly higher than all other series, followed by Ambalapuzha series which was on par with Kallara, Purakkad and Thottapalli series. The agricultural land use systems also significantly influenced the EC of soil. It was the highest in rice - fish system (1.80 dS m^{-1}) which was followed by rice (1.21 dS m^{-1}) and coconut (0.77 dS m^{-1}).

Table 3. Electrical conductivity of acid sulphate soils of Kuttanad under different agricultural land use systems, dS m^{-1}

Soil series (S)	Agricultural land use systems (L)			Mean
	L_1 – Rice	L_2 - Coconut	L_3 - Rice – fish	
S_1 – Ambalapuzha	0.69	0.18	2.79	1.22
S_2 – Purakkad	0.88	0.24	2.17	1.10
S_3 – Thakazhi	0.85	0.08	1.38	0.77
S_4 – Thuravur	3.15	2.20	2.47	2.61
S_5 – Thottapalli	0.46	0.29	1.10	0.62
S_6 – Kallara	1.19	1.63	0.90	1.24
Mean	1.21	0.77	1.80	
	S	L	S × L	
S.E (m)	0.308	0.218	0.533	
CD (0.05)	0.624	0.441	1.081	

4.1.4 Exchangeable Acidity

The results of excahangeable acidity of soil presented in table 4 indicated that there was a significant difference among the different soil series and land use systems. The highest value was recorded in Ambalapuzha series (5.98 cmol kg^{-1}) and the lowest in Thuravur series (0.88 cmol kg^{-1}) which was on par with Thottapalli series (1.09 cmol kg^{-1}). Rice – fish land use system recorded the highest exchangeable acidity of 3.74 cmol kg^{-1} which was significantly higher than rice (2.74 cmol kg^{-1}) and coconut (1.91 cmol kg^{-1}). The interaction between soil series and agricultural land use system was also found to be significant. Rice – fish in Purakkad series recorded the highest exchangeable acidity of 9.38 cmol kg^{-1} while coconut in Thuravur series recorded the lowest (0.16 cmol kg^{-1}).

Table 4. Exchangeable acidity of acid sulphate soils of Kuttanad under different agricultural land use systems, cmol kg^{-1}

Soil series (S)	Agricultural land use systems (L)			Mean
	L_1 – Rice	L_2 - Coconut	L_3 - Rice – fish	
S_1 – Ambalapuzha	3.65	5.31	8.98	5.98
S_2 – Purakkad	2.05	1.09	9.38	4.17
S_3 – Thakazhi	4.26	2.05	0.26	2.19
S_4 – Thuravur	1.48	0.16	0.99	0.88
S_5 – Thottapalli	1.3	0.95	1.01	1.09
S_6 – Kallara	3.71	1.92	1.8	2.47
Mean	2.74	1.91	3.74	
	S	L	S × L	
S.E (m)	0.390	0.276	0.675	
CD (0.05)	0.791	0.560	1.370	

4.1.5 Bulk Density

The highest bulk density of 1.03 Mg m^{-3} was noted from Ambalapuzha series which was on par with Purakkad series (0.99 Mg m^{-3}) and the lowest value of 0.70 Mg m^{-3} was recorded from Thuravur series which was on par with Kallara series (0.72 Mg m^{-3}). With respect to the different land use systems, there existed a significant difference and the mean values ranged between 0.79 and 0.99 Mg m^{-3} with the highest value from coconut based system and the lowest value from rice – fish which was on par with rice (0.85 Mg m^{-3}). Among the interactions, the highest value of bulk density (1.21 Mg m^{-3}) was registered from the coconut based system in Ambalapuzha series (S_1L_2) and the lowest (0.68 Mg m^{-3}) from rice – fish in Kallara series (S_6L_3), which was found to be on par with S_1L_3, S_3L_1, S_3L_3, S_4L_1, S_4L_2, S_4L_3, S_6L_1 and S_6L_2.

Table 5. Bulk density of acid sulphate soils of Kuttanad under different agricultural land use systems, Mg m^{-3}

Soil series (S)	Agricultural land use systems (L)			Mean
	L_1 – Rice	L_2 - Coconut	L_3 - Rice – fish	
S_1 – Ambalapuzha	1.07	1.21	0.81	1.03
S_2 – Purakkad	0.99	1.08	0.89	0.99
S_3 – Thakazhi	0.74	1.11	0.78	0.88
S_4 – Thuravur	0.71	0.68	0.72	0.7
S_5 – Thottapalli	0.88	1.05	0.85	0.93
S_6 – Kallara	0.69	0.78	0.68	0.72
Mean	0.85	0.99	0.79	
	S	L	S × L	
S.E (m)	0.045	0.032	0.079	
CD (0.05)	0.092	0.065	0.159	

4.1.6 Cation Exchange Capacity

The cation exchange capacity of acid sulphate soils of Kuttanad under different agricultural land use systems are given in table 6. The results indicated that the different locations had significant influence on cation exchange capacity. Kallara series showed the highest cation exchange capacity of 43.16 cmol kg^{-1} and Purakkad series showed the lowest cation exchange capacity of 17.80 cmol kg^{-1} which was on par with Thottapalli series (19.34 cmol kg^{-1}). Among the land uses, the highest value of cation exchange capacity of 26.19 cmol kg^{-1} was observed in coconut land use system which was on par with rice (24.78 cmol kg^{-1}) and the lowest value of 23.38 cmol kg^{-1} was observed in rice - fish which was also on par with rice. Among the interactions, Kallara series under rice – fish (S_6L_3) land use system showed the maximum CEC of 45.50 cmol kg^{-1} which was found to be on par with S_6L_1, S_6L_2 and the minimum value of 14.60 cmol kg^{-1} was recorded from rice – fish in Purakkad series (S_2L_3).

Table 6. CEC of acid sulphate soils of Kuttanad under different agricultural land use systems, cmol kg^{-1}

Soil series (S)	Agricultural land use systems (L)			Mean
	L_1 – Rice	L_2 - Coconut	L_3 - Rice – fish	
S_1 – Ambalapuzha	22.62	28.74	21.12	24.16
S_2 – Purakkad	14.95	23.87	14.60	17.80
S_3 – Thakazhi	23.38	23.10	21.23	22.57
S_4 – Thuravur	23.8	20.87	20.33	21.67
S_5 – Thottapalli	22.24	18.29	17.50	19.34
S_6 – Kallara	41.74	42.25	45.50	43.16
Mean	24.79	26.19	23.38	
	S	L	S × L	
S.E (m)	1.205	0.852	2.087	
CD (0.05)	2.444	1.728	4.233	

4.2 SOIL CARBON POOLS

4.2.1 Soil Inorganic Carbon

The results of soil inorganic carbon in acid sulphate soils of Kuttanad under different land use systems have confirmed the absence of calcium carbonate in the surface horizons.

4.2.2 Total Organic Carbon

The results with respect to total organic carbon in soil are presented in table 7.

Table 7. Total organic carbon content of acid sulphate soils of Kuttanad under different agricultural land use systems, %

Soil series (S)	Agricultural land use systems (L)			Mean
	L_1 – Rice	L_2 - Coconut	L_3 - Rice – fish	
S_1 – Ambalapuzha	3.34	3.17	3.51	3.34
S_2 – Purakkad	2.84	3.47	3.23	3.18
S_3 – Thakazhi	3.44	2.89	6.21	4.18
S_4 – Thuravur	6.58	2.50	2.11	3.73
S_5 – Thottapalli	2.59	1.97	2.80	2.46
S_6 – Kallara	9.38	8.67	8.61	8.89
Mean	4.69	3.78	4.41	
	S	L	S × L	
S.E (m)	0.283	0.200	0.490	
CD (0.05)	0.574	0.406	0.994	

The highest total organic carbon was observed in Kallara series (8.89%) and the lowest in Thottapalli series (2.46%). Among the various land use systems, rice land use system registered the highest value of 4.69% which was on par with rice - fish (4.41%). The lowest value was recorded from coconut land use system

(3.78%). The interaction effect of soil series and land use system revealed that the highest total organic carbon of 9.38% was observed in Kallara series under rice land use system and the lowest in Thottapalli series under coconut (1.97%). The influence of land use system on total organic carbon content was found to be significant in Thakazhi and Thuravur series while it was not significant in Ambalpuzha, Purakkad, Thottapalli and Kallara series.

4.2.3 Water Soluble Carbon

Table 8 shows the results of water soluble carbon content in soil which ranged between 44.38 (Thottapalli series, Coconut) and 208.68 mg kg^{-1} (Kallara series, Rice).

Table 8. Water soluble carbon of acid sulphate soils of Kuttanad under different agricultural land use systems, mg kg^{-1}

Soil series (S)	Agricultural land use systems (L)			Mean
	L_1 – Rice	L_2 – Coconut	L_3 - Rice – fish	
S_1 – Ambalapuzha	72.19	59.15	117.77	83.04
S_2 – Purakkad	56.57	56.57	86.05	66.40
S_3 – Thakazhi	51.81	62.09	104.12	72.67
S_4 – Thuravur	201.9	126.98	179.47	169.45
S_5 – Thottapalli	49.52	44.38	60.24	51.38
S_6 – Kallara	208.68	202.60	146.25	185.84
Mean	106.78	91.96	115.65	
	S	L	S × L	
S.E (m)	9.904	7.003	17.154	
CD (0.05)	20.089	14.205	34.794	

There was a significant difference between different soil series with respect to water soluble carbon content of soil. The highest mean value was observed in Kallara series (185.84 mg kg^{-1}) which was on par with Thuravur series (169.45 mg kg^{-1}). The lowest value was observed in Thottapalli series (51.38 mg kg^{-1}) which was on par with Purakkad series (66.40 mg kg^{-1}). Rice – fish (115.65 mg kg^{-1}) and rice (106.78 mg kg^{-1}) land use systems recorded on par results for water soluble carbon which were significantly higher than coconut (91.96 mg kg^{-1}). The influence of land use system on water soluble carbon was significant in all the soil series except Thottapalli series.

4.2.4 Labile Carbon

The results of the labile carbon content of acid sulphate soils of Kuttanad under different agricultural land use systems are given in table 9.

Table 9. Labile carbon of acid sulphate soils of Kuttanad under different agricultural land use systems, mg g^{-1}

Soil series (S)	Agricultural land use systems (L)			Mean
	L_1 – Rice	L_2 – Coconut	L_3 - Rice – fish	
S_1 - Ambalapuzha	5.60	4.64	7.94	6.06
S_2 - Purakkad	5.33	4.76	8.62	6.24
S_3 - Thakazhi	9.70	9.59	5.85	8.38
S_4 - Thuravur	11.24	10.19	9.05	10.16
S_5 - Thottapalli	4.89	5.05	4.36	4.77
S_6 – Kallara	13.06	12.55	11.09	12.23
Mean	8.30	7.80	7.82	
	S	L	S × L	
S.E (m)	0.253	0.179	0.438	
CD (0.05)	0.512	0.362	0.888	

All the locations vary significantly with respect to labile carbon with the mean values ranging from 4.77 (Thottapalli series) to 12.23 mg g^{-1} (Kallara series). The mean values of labile carbon among the different land use system ranged from 7.8 to 8.3 mg g^{-1}. The highest value was recorded from rice and the lowest value from coconut which was on par with rice – fish (7.82 mg g^{-1}). There existed a significant difference among the interactions, where the highest value recorded was 13.06 mg g^{-1} (Kallara series, rice) and the lowest value recorded was 4.36 mg g^{-1} (Thottapalli series, rice-fish) which was on par with S_1L_2, S_2L_2, S_5L_1 and S_5L_2. Agricultural land use systems influenced the soil labile carbon in all the series except Thottapalli series.

4.2.5 Particulate Organic Carbon

The particulate organic carbon of the acid sulphate soils of Kuttanad under different agricultural land use systems are given in table 10.

Table 10. Particulate organic carbon content of acid sulphate soils of Kuttanad under different agricultural land use systems, %

Soil series (S)	Agricultural land use systems (L)			Mean
	L_1 – Rice	L_2 – Coconut	L_3 - Rice – fish	
S_1 – Ambalapuzha	1.54	0.61	1.37	1.17
S_2 – Purakkad	1.72	0.11	2.05	1.29
S_3 – Thakazhi	2.83	1.37	0.62	1.61
S_4 – Thuravur	1.21	1.74	0.30	1.09
S_5 – Thottapalli	0.85	0.47	0.55	0.62
S_6 – Kallara	7.23	4.57	4.81	5.54
Mean	2.56	1.48	1.62	
	S	L	S × L	
S.E (m)	0.335	0.237	0.580	
CD (0.05)	0.680	0.480	1.177	

The results clearly depicts that the locations had a significant influence on the POC with the mean values ranging from 0.62 to 5.54%, with the highest value from Kallara series and the lowest from Thottapalli series which was on par with Ambalapuzha, Purakkad and Thuravur series. The highest mean value of POC of 2.56% was registerd from rice based system and the lowest value of 1.48% from coconut which was on par with rice – fish (1.62%). There existed a significant difference among the interactions with the highest value of 7.23% from rice based system in Kallara and the lowest of 0.11% from coconut in Purakkad series. The influence of agricultural land use systems on POC was found to be significant in Purakkad, Thakazhi, Thuravur and Kallara series.

4.2.6 Percentage contribution of WSC, LC and POC to TOC

The results shown in table 11 indicated that the percentage contribution of water soluble carbon to total organic carbon was very less and it ranged from 0.17 (Thakazhi) to 0.45% (Thuravur).

Table 11. Percentage contribution of water soluble, labile and particulate organic carbon to total organic carbon.

Soil series/ Land use	WSC as % of TOC	LC as % of TOC	POC as % of TOC
Soil series			
S_1 – Ambalapuzha	0.25	18.14	35.03
S_2 – Purakkad	0.21	19.62	40.57
S_3 – Thakazhi	0.17	20.05	38.52
S_4 – Thuravur	0.45	27.24	29.22
S_5 – Thottapalli	0.21	19.39	25.20
S_6 – Kallara	0.21	13.76	62.32
Land use			
L_1 – Rice	0.23	17.69	54.58
L_2 – Coconut	0.24	20.63	39.15
L_3 - Rice – fish	0.26	17.73	36.73

With respect to the percentage contribution of labile carbon to total organic carbon, the values ranged between 13.76 and 27.24% and the highest contribution was observed from Thuravur series. The particulate organic carbon significantly contributed towards total organic carbon and the value ranged from

25.20 to 62.32% and the highest contribution was noticed from Kallara series. Among the different land uses, the contribution of WSC to TOC was found to be high in rice- fish, LC to TOC in coconut and POC to TOC in rice.

4.2.7 Mineralizable Carbon

The results of cumulative amount of carbon mineralized in 50 days of incubation are given in table 12.

Table 12. Mineralizable carbon content of acid sulphate soils of Kuttanad under different agricultural land use systems for 50 days, mg g^{-1}

Soil series (S)	Agricultural land use systems (L)			Mean
	L_1 – Rice	L_2 - Coconut	L_3 - Rice – fish	
S_1 – Ambalapuzha	2.60	2.80	2.81	2.74
S_2 – Purakkad	2.70	2.72	2.64	2.69
S_3 – Thakazhi	2.58	2.68	2.62	2.62
S_4 – Thuravur	2.17	2.46	2.58	2.40
S_5 – Thottapalli	2.85	2.76	2.91	2.84
S_6 – Kallara	2.36	2.46	2.35	2.39
Mean	2.54	2.65	2.65	
	S	L	S × L	
S.E (m)	0.056	0.039	0.097	
CD (0.05)	0.113	0.080	NS	

The mineralizable carbon content varied betweeen 2.17 to 2.91 mg g^{-1}. Among the different soil series, the highest value was recorded from Thottapalli series (2.84 mg g^{-1}) which was on par with Ambalapuzha series (2.74 mg g^{-1}) and the lowest values was recorded from Kallara series (2.39 mg g^{-1}) which was on par with Thuravur series (2.40 mg g^{-1}). With respect to different land uses, the maximum value of 2.65 mg g^{-1} was registered from coconut and rice - fish land use system while the minimum value of 2.54 mg g^{-1} was recorded from rice. The interaction between the soil series and the land use systems did not influence the mineralizable carbon content of the soil.

4.2.8 Microbial Biomass Carbon

The microbial biomass content of acid sulphate soils of Kuttanad varied between 71 mg kg^{-1} and 488 mg kg^{-1} (Table 13). There existed a significant difference in the mean values of microbial biomass carbon in the different soil series and land use systems. Among the different soil series, the highest value of 394 mg kg^{-1} was noted from Kallara series and the lowest value of 125 mg kg^{-1} from Ambalapuzha series which was on par with Thakazhi series (184 mg kg^{-1}). With respect to the different land use systems studied, the maximum value of 315 mg kg^{-1} was observed from rice – fish based system and the minimum value of 225 mg kg^{-1} from coconut which was on par with rice (252 mg kg^{-1}). The interactions did not significantly influence the microbial biomass carbon content of the soil.

Table 13. Microbial biomass carbon content of acid sulphate soils of Kuttanad under different agricultural land use systems, mg kg^{-1}

Soil series (S)	Agricultural land use systems (L)			Mean
	L_1 – Rice	L_2 - Coconut	L_3 - Rice – fish	
S_1 - Ambalapuzha	116	71	186	125
S_2 – Purakkad	283	276	347	302
S_3 – Thakazhi	205	204	143	184
S_4 – Thuravur	445	266	275	329
S_5 – Thottapalli	72	231	449	251
S_6 – Kallara	391	303	488	394
Mean	252	225	315	
	S	L	S × L	
S.E (m)	36.54	25.84	63.29	
CD (0.05)	74.12	52.41	NS	

4.2.9 Oxidizable Organic Carbon Fractions

4.2.9.1 Very Labile Pool

The very labile pool of carbon in acid sulphate soils of Kuttanad are shown in table 14. The highest value of 1.27% was registered from Kallara series and the lowest value of 0.34% from Thuravur series which was on par with Thakazhi series (0.36%). There existed a significant difference among the land use systems with the highest value of 0.72% in coconut based system and the lowest value of 0.67% in rice – fish which was on par with rice (0.67%). The highest value of 1.47% was recorded from coconut based system in Kallara series (S_6L_2) and the lowest value of 0.06% from rice – fish in Thuravur series (S_4L_3) which was on par with S_1L_1 and S_3L_3.

Table 14. Very labile pool of carbon in acid sulphate soils of Kuttanad under different agricultural land use systems, %

Soil series (S)	Agricultural land use systems (L)			Mean
	L_1 – Rice	L_2 - Coconut	L_3 - Rice – fish	
S_1 – Ambalapuzha	0.12	0.71	0.58	0.47
S_2 – Purakkad	0.64	0.94	0.81	0.80
S_3 – Thakazhi	0.69	0.27	0.13	0.36
S_4 – Thuravur	0.78	0.17	0.06	0.34
S_5 – Thottapalli	0.88	0.73	0.97	0.86
S_6 – Kallara	0.92	1.47	1.45	1.27
Mean	0.67	0.72	0.67	
	S	L	S × L	
S.E (m)	0.016	0.012	0.028	
CD (0.05)	0.033	0.023	0.057	

4.2.9.2 Labile Pool

The soil series and land use systems have a significant impact on the labile pool of carbon (Table 15). The highest labile pool of carbon was registered from Purakkad series (0.73%) which was on par with Kallara series (0.72%) and the lowest value was registered from Thottapalli series (0.10%). The different land use systems also have a major influence on the labile pool of carbon with the maximum value of 0.51% in rice based system which was on par with coconut (0.51%) and the lowest value of 0.46% in rice – fish. Kallara series under coconut based system (S_6L_2) recorded the maximum value of 0.83% which was on par with S_2L_2 (0.79%), S_6L_3 (0.81%) and the minimum value of 0.08% was observed from rice – fish in Thottapalli series (S_5L_3). The influence of agricultural land use systems on labile pool of carbon was significant in all the soil series studied except Thottapalli series.

Table 15. Labile pool of carbon in acid sulphate soils of Kuttanad under different agricultural land use systems, %

Soil series (S)	Agricultural land use systems (L)			Mean
	L_1 – Rice	L_2 – Coconut	L_3 - Rice – fish	
S_1 - Ambalapuzha	0.74	0.62	0.68	0.68
S_2 – Purakkad	0.64	0.79	0.76	0.73
S_3 – Thakazhi	0.51	0.44	0.24	0.40
S_4 – Thuravur	0.53	0.28	0.16	0.32
S_5 – Thottapalli	0.12	0.09	0.08	0.10
S_6 – Kallara	0.50	0.83	0.81	0.72
Mean	0.51	0.51	0.46	
	S	L	S × L	
S.E (m)	0.015	0.011	0.027	
CD (0.05)	0.031	0.022	0.054	

4.2.9.3 Less Labile Pool

The mean values of less labile pool of carbon in the various soil series of acid sulphate soils of Kuttanad are presented in table 16. The soil series and land use systems significantly influenced the less labile pool of carbon. The highest value was noted in Thuravur series (0.45%) and the lowest value from Thottapalli series (0.21%) which was on par with Purakkad series (0.23%). Among the land use systems, the maximum value of 0.41% was recorded from the land use system rice and the minimum value of 0.23% from coconut which was on par with rice – fish (0.25%). On taking into account the different interactions, the maximum value of 0.82% was recorded from rice based system in Thuravur (S_4L_1) and the minimum value of 0.10% from rice – fish in Thottapalli (S_5L_3). The land use systems significantly influenced less labile pool of carbon in all the soil series studied.

Table 16. Less labile pool of carbon in acid sulphate soils of Kuttanad under different agricultural land use systems, %

Soil series (S)	Agricultural land use systems (L)			Mean
	L_1 – Rice	L_2 - Coconut	L_3 - Rice – fish	
S_1 – Ambalapuzha	0.32	0.13	0.33	0.26
S_2 – Purakkad	0.19	0.16	0.34	0.23
S_3 – Thakazhi	0.37	0.41	0.31	0.37
S_4 – Thuravur	0.82	0.35	0.19	0.45
S_5 – Thottapalli	0.38	0.15	0.10	0.21
S_6 – Kallara	0.35	0.19	0.24	0.26
Mean	0.41	0.23	0.25	
	S	L	S × L	
S.E (m)	0.020	0.014	0.034	
CD (0.05)	0.040	0.028	0.070	

4.2.9.4 Non Labile Pool

Critical appraisal of the data in table 17 revealed that the soil series had a significant influence on the content of non-labile pool of carbon with the maximum value of 5.90% in Kallara series and the minimum value of 1.30% in Thottapalli series which was on par with Purakkad series (1.42%). Regarding the different land use systems, rice recorded the highest value of 2.91% which was on par with rice – fish and coconut registered the lowest value of 2.32%. A significant difference was also observed among the interactions where the maximum value of 6.44% was recorded from rice in Kallara series which was on par with S_3L_3 (5.49%), S_6L_2 (6.17%) and the minimum value of 1.00% was obtained from coconut in Thottapalli series (S_5L_2) which was found to be on par with S_1L_2, S_1L_3, S_2L_1, S_2L_2, S_2L_3, S_3L_1, S_3L_2, S_4L_2, S_4L_3, S_5L_1 and S_5L_3. Significant variations in non-labile carbon pool among the agricultural land use systems were obtained in Thakazhi and Kallara series.

Table 17. Non labile pool of carbon in acid sulphate soils of Kuttanad under different agricultural land use systems, %

Soil series (S)	Agricultural land use systems (L)			Mean
	L_1 – Rice	L_2 - Coconut	L_3 - Rice – fish	
S_1 – Ambalapuzha	2.15	1.71	1.92	1.93
S_2 – Purakkad	1.36	1.57	1.31	1.42
S_3 – Thakazhi	1.87	1.76	5.49	3.04
S_4 – Thuravur	4.45	1.70	1.72	2.62
S_5 – Thottapalli	1.21	1.00	1.68	1.30
S_6 – Kallara	6.44	6.17	5.09	5.90
Mean	2.91	2.32	2.87	
	S	L	S × L	
S.E (m)	0.289	0.205	0.502	
CD (0.05)	0.587	0.415	1.017	

4.2.9.5 Active Carbon Pool

The soil series and agricultural land use systems had a significant influence on the active pool of carbon in acid sulphate soils of Kuttanad and the results are presented in table 18. Kallara series recorded the maximum value (1.99%) and Thuravur series the minimum value (0.66%). Among the land use systems, the highest value of 1.23% was recorded from coconut based system and the lowest value of 1.12% from rice – fish. With respect to the different interactions, the highest value of 2.30% was noted from coconut based system in Kallara and the lowest value of 0.23% from rice – fish in Thuravur. The influence of agricultural land use system on active carbon pool was found to be significant in all the six soil series.

Table 18. Active carbon pool in acid sulphate soils of Kuttanad under different agricultural land use systems, %

Soil series (S)	Agricultural land use systems (L)			Mean
	L_1 – Rice	L_2 - Coconut	L_3 - Rice – fish	
S_1 - Ambalapuzha	0.86	1.33	1.26	1.15
S_2 - Purakkad	1.29	1.73	1.57	1.53
S_3 - Thakazhi	1.20	0.72	0.36	0.76
S_4 - Thuravur	1.32	0.45	0.23	0.66
S_5 - Thottapalli	1.01	0.82	1.05	0.96
S_6 – Kallara	1.42	2.30	2.26	1.99
Mean	1.18	1.23	1.12	
	S	L	S × L	
S.E (m)	0.025	0.018	0.043	
CD (0.05)	0.051	0.036	0.089	

4.2.9.6 Passive Carbon Pool

Soil series and land use system significantly influenced the passive pool of carbon (Table 19). The highest value of 6.16% was noted from Kallara series and the lowest value of 1.51% from Thottapalli series which was on par with Purakkad series (1.64%). Rice based system showed the highest value of 3.31% and it was on par with rice – fish (3.12%) and the lowest value of 2.55% was noted from Coconut. Among the interactions, the maximum value of 6.79% was observed from rice in Kallara series which was on par with S_3L_3, S_6L_2 and the minimum value of 1.15% was recorded from coconut in Thottapalli series (S_5L_2) which was found to be on par with S_1L_2, S_2L_1, S_2L_2, S_2L_3, S_4L_2, S_4L_3, S_5L_1, S_5L_2 and S_5L_3. The agricultural land use systems significantly influenced passive carbon pool in Thakazhi, Thuravur and Kallara series.

Table 19. Passive carbon pool in acid sulphate soils of Kuttanad under different agricultural land use systems, %

Soil series (S)	Agricultural land use systems (L)			Mean
	L_1 – Rice	L_2 - Coconut	L_3 - Rice – fish	
S_1 - Ambalapuzha	2.47	1.84	2.25	2.19
S_2 – Purakkad	1.55	1.73	1.65	1.64
S_3 – Thakazhi	2.24	2.17	5.83	3.42
S_4 – Thuravur	5.27	2.05	1.91	3.07
S_5 - Thottapalli	1.59	1.15	1.78	1.51
S_6 – Kallara	6.79	6.36	5.34	6.16
Mean	3.31	2.55	3.12	
	S	L	S × L	
S.E (m)	0.289	0.204	0.500	
CD (0.05)	0.586	0.414	1.014	

4.2.10 Soil Organic Matter Fractions

4.2.10.1 Humic Acid

The content of humic acid fraction in acid sulphate soils of Kuttanad are given in table 20. Thuravur series registered the highest humic acid content of 3.10% which was on par with Purakkad (2.93%) and the lowest value of 1.58%

was registered from Thottapalli series. Concerning the different land use systems, there existed a significant difference and the mean values ranged between 1.83 and 2.72% where the highest value was from coconut based system which was on par with rice (2.6%) and the lowest value was from rice – fish. The interactions have significantly influenced the humic acid content with the highest value of 6.09% in the rice based system in Thuravur series and the lowest value of 0.20% from rice – fish in Thakazhi series.

Table 20. Humic acid fraction in acid sulphate soils of Kuttanad under different agricultural land use systems, %

Soil series (S)	Agricultural land use systems (L)			Mean
	L_1 – Rice	L_2 - Coconut	L_3 - Rice – fish	
S_1 – Ambalapuzha	1.77	2.83	1.91	2.17
S_2 – Purakkad	1.49	3.33	3.96	2.93
S_3 – Thakazhi	3.11	2.46	0.20	1.92
S_4 – Thuravur	6.09	1.70	1.51	3.10
S_5 – Thottapalli	1.32	2.60	0.81	1.58
S_6 – Kallara	1.79	3.43	2.56	2.59
Mean	2.6	2.72	1.83	
	S	L	S × L	
S.E (m)	0.102	0.072	0.177	
CD (0.05)	0.208	0.147	0.359	

4.2.10.2 Fulvic Acid

The different soil series and land use systems showed significant impact on the fulvic acid fraction in acid sulphate soils of Kuttanad as shown in table 21. The highest value of 20.10% was recorded from coconut based system in Ambalapuzha series and the lowest value of 0.09% was noticed from rice – fish based system in Purakkad series. Among the different series, the highest value was recorded from Ambalapuzha series (9.70%) which was on par with Thuravur series (9.37%) and the lowest value was recorded from Kallara series (2.67%). The different land use systems had significant influence on the fulvic acid content and the maximum value recorded was 9.34% (Coconut) and the minimum value noted was 5.38% (Rice – fish).

Table 21. Fulvic acid fraction in acid sulphate soils of Kuttanad under different agricultural land use systems, %

Soil series (S)	Agricultural land use systems (L)			Mean
	L_1 – Rice	L_2 - Coconut	L_3 - Rice – fish	
S_1 - Ambalapuzha	1.35	20.10	7.66	9.70
S_2 - Purakkad	10.38	5.62	0.09	5.36
S_3 - Thakazhi	5.15	13.78	0.15	6.36
S_4 - Thuravur	8.17	5.63	14.31	9.37
S_5 - Thottapalli	9.05	9.26	7.65	8.65
S_6 – Kallara	3.93	1.66	2.43	2.67
Mean	6.34	9.34	5.38	
	S	L	S × L	
S.E (m)	0.291	0.206	0.505	
CD (0.05)	0.591	0.418	1.024	

4.2.11 Soil Organic Carbon Stock

The soil series and the different land use systems significantly influenced the soil organic carbon (SOC) stock as presented in table 22. The highest SOC stock of 115.96 Mg ha^{-1} was observed from Kallara series and the lowest of 32.06 Mg ha^{-1} from Thottapalli series. Rice land use system registered the maximum soil organic carbon stock of 61.28 Mg ha^{-1} which was on par with rice-fish (57.57 Mg ha^{-1}). The organic carbon stock was the lowest in coconut based land use system (49.32 Mg ha^{-1}). The interactions also imposed significant influence on the soil organic carbon stock where in the highest value registered was 122.37 Mg ha^{-1} (Kallara series, Rice) which was on par with S_6L_2 (113.14 Mg ha^{-1}), S_6L_3

(112.36 Mg ha^{-1}) and the lowest value registered was 25.75 Mg ha^{-1} (Thottapalli series, Coconut).

Table 22. Soil organic carbon stock in acid sulphate soils of Kuttanad under different agricultural land use systems, Mg ha^{-1}

Soil series (S)	Agricultural land use systems (L)			Mean
	L_1 – Rice	L_2 - Coconut	L_3 - Rice – fish	
S_1 - Ambalapuzha	43.59	41.32	45.85	43.59
S_2 – Purakkad	37.01	45.29	42.11	41.47
S_3 – Thakazhi	45.02	37.72	81.00	54.58
S_4 – Thuravur	85.82	32.67	27.54	48.67
S_5 – Thottapalli	33.84	25.75	36.58	32.06
S_6 – Kallara	122.37	113.14	112.36	115.96
Mean	61.28	49.32	57.57	
	S	L	S × L	
S.E (m)	3.693	2.611	6.397	
CD (0.05)	7.491	5.297	12.974	

4.2.12 Carbon Indices

4.2.12.1 Carbon Pool Index

The various soil series and land use systems showed significant influence on the carbon pool index as given in table 23. The highest value observed was 2.10 (Kallara series) and the lowest value was 0.58 (Thottapalli series). Rice land use system registered the maximum carbon pool index of 1.10 which was on par with rice-fish (1.05). The lowest value of 0.90 was registered from coconut. Kallara series under rice land use system (S_6L_1) registered the highest value of 2.19 which was on par with S_6L_2 and S_6L_3 while Thottapalli series under coconut land use system registered the lowest value of 0.47.

Table 23. Carbon pool index in acid sulphate soils of Kuttanad under different agricultural land use systems

Soil series (S)	Agricultural land use systems (L)			Mean
	L_1 – Rice	L_2 - Coconut	L_3 - Rice – fish	
S_1 - Ambalapuzha	0.78	0.75	0.83	0.79
S_2 – Purakkad	0.66	0.82	0.77	0.75
S_3 – Thakazhi	0.80	0.69	1.47	0.99
S_4 – Thuravur	1.54	0.59	0.50	0.88
S_5 - Thottapalli	0.61	0.47	0.66	0.58
S_6 – Kallara	2.19	2.06	2.04	2.10
Mean	1.10	0.90	1.05	
	S	L	S × L	
S.E (m)	0.066	0.046	0.114	
CD (0.05)	0.133	0.094	0.231	

4.2.12.2 Carbon Lability Index

The soil series and the land use had a significant influence on the carbon lability index (Table 24). The mean values of carbon lability index among the different soil series ranged from 0.60 to 1.53 with the highest value from Kallara series and the lowest value from Thottapalli series. Rice based system recorded the highest value of 1.04 which was found to be superior than the other two systems which recorded the same carbon lability index of 0.98. The interactions had significant influence on the carbon lability index value where in the highest value registered was 1.64 (Kallara series, Rice) which was on par with S_6L_2, S_6L_3 and the lowest value obtained was 0.55 (Thottapalli series, Rice-fish).

Table 24. Carbon lability index in acid sulphate soils of Kuttanad under different agricultural land use systems

Soil series (S)	Agricultural land use systems (L)			Mean
	L_1 – Rice	L_2 - Coconut	L_3 - Rice – fish	
S_1 – Ambalapuzha	0.70	0.58	1.00	0.76
S_2 – Purakkad	0.67	0.60	1.08	0.78
S_3 – Thakazhi	1.22	1.20	0.74	1.05
S_4 – Thuravur	1.41	1.28	1.14	1.27
S_5 – Thottapalli	0.61	0.63	0.55	0.60
S_6 – Kallara	1.64	1.57	1.39	1.53
Mean	1.04	0.98	0.98	
	S	L	S × L	
S.E (m)	0.032	0.022	0.054	
CD (0.05)	0.064	0.045	0.110	

4.2.12.3 Carbon Management Index

The carbon management index of acid sulphate soils of Kuttanad are shown in table 25. Kallara series recorded the maximum carbon management index of 3.22 and the minimum value of 0.35 was registered from Thottapalli series. The highest value of 1.29 was registered from rice based system which was significantly higher than rice – fish (1.08) and coconut (1.01). With respect to interactions, Kallara series under rice land use system recorded the highest carbon management index of 3.58 and the Thottapalli series under coconut based system recorded the lowest index of 0.29.

Table 25. Carbon management index in acid sulphate soils of Kuttanad under different agricultural land use systems

Soil series (S)	Agricultural land use systems (L)			Mean
	L_1 – Rice	L_2 - Coconut	L_3 - Rice – fish	
S_1 – Ambalapuzha	0.55	0.44	0.82	0.60
S_2 – Purakkad	0.44	0.49	0.82	0.58
S_3 – Thakazhi	0.98	0.82	1.09	0.96
S_4 – Thuravur	1.83	0.75	0.57	1.05
S_5 – Thottapalli	0.38	0.29	0.36	0.35
S_6 – Kallara	3.58	3.23	2.85	3.22
Mean	1.29	1.01	1.08	
	S	L	S × L	
S.E (m)	0.099	0.070	0.172	
CD (0.05)	0.200	0.142	0.348	

4.2.13 Carbon Proportion and Turn Over

The carbon proportions and turnover in acid sulphate soils of Kuttanad under different agricultural land use systems are given in table 26. The carbon proportion (POC/ SOC) was found to be the highest in Kallara series (0.62) and rice land use system (0.54), while the lowest in Thottapalli series (0.25) and rice – fish land use system (0.36). It is evident that the soil series and the land use system has influenced the carbon turnover rate (MC/ SOC) with the maximum value of 1.15 in Thottapalli series and the minimum value of 0.27 in Kallara series. Coconut based land use system recorded the highest carbon turnover rate of 0.70 while rice based system the lowest of 0.54.

Table 26. Carbon proportion and turn over in acid sulphate soils of Kuttanad under different agricultural land use systems

Soil series/Land use	Carbon proportion (POC/SOC)	Carbon turn over (MC/SOC)
Soil series		
S_1 – Ambalapuzha	0.35	0.82
S_2 – Purakkad	0.40	0.85
S_3 – Thakazhi	0.38	0.63
S_4 – Thuravur	0.29	0.64
S_5 – Thottapalli	0.25	1.15
S_6 – Kallara	0.62	0.27
Land use		
L_1 – Rice	0.54	0.54
L_2 – Coconut	0.39	0.70
L_3 - Rice – fish	0.36	0.60

4.2.14 Land Quality Index

The land quality index of acid sulphate soils of Kuttanad under different agricultural land use systems based on soil organic carbon stock in kg m^{-2} are given in table 27. Among the soil series, Kallara is the best and it is rated moderate land quality index. Comparing the different land use systems, rice was the best registering medium land quality index, while other two were of low category.

Table 27. Land quality index of acid sulphate soils of Kuttanad under different agricultural land use systems

Soil series (S)	Agricultural land use systems (L)			Mean
	L_1 – Rice	L_2 – Coconut	L_3 - Rice – fish	
S_1 – Ambalapuzha	Low (4.36)	Low (4.13)	Low (4.59)	Low (4.36)
S_2 – Purakkad	Low (3.70)	Low (4.53)	Low (4.21)	Low (4.15)
S_3 – Thakazhi	Low (4.50)	Low (3.77)	Medium (8.10)	Low (5.46)
S_4 – Thuravur	Medium (8.58)	Low (3.27)	Very Low (2.75)	Low (4.87)
S_5 – Thottapalli	Low (3.38)	Very low (2.58)	Low (3.66)	Low (3.21)
S_6 – Kallara	Moderate (12.24)	Moderate (11.31)	Moderate (11.24)	Moderate (11.60)
Mean	Medium (6.13)	Low (4.93)	Low (5.76)	

( ) – soil organic carbon stock in kg m^{-2}

Discussion

5. DISCUSSION

A study was conducted to assess the influence of various land use systems on the soil carbon storage as different soil carbon pools in acid sulphate soils of Kuttanad. The physical and physic - chemical properties and different carbon fractions of the six soil series *viz.*, Ambalapuzha, Purakkad, Thakazhi, Thuravur, Thottapalli and Kallara under three agricultural land use systems namely rice, coconut and rice – fish were studied and the results are discussed in this chapter.

5.1 SOIL PROPERTIES

5.1.1 Soil Texture

The soil texture of the acid sulphate soils of Kuttanad varied from sandy loam to clay. The soil series namely Kallara, Thuravur and Purakkad comes under the textural class clay. The wide variation in soil texture seen among the various soil series of Kuttanad can be attributed to the annual fluvial and lacustrine deposits received in these soils. Soils with large proportion of fine particles have greater ability to sequester carbon as reported by Kong *et al.* (2009). Particle size distribution greatly influences the soil chemical properties. Soil texture has a significant impact over accumulation and mineralization of soil organic matter (Hamkalo and Bedernichek, 2014). These soils series have also recorded the higher carbon content with the Kallara series having a total organic carbon content of 8.89%.

5.1.2 pH

The present investigation revealed that the mean values of pH of the acid sulphate soils of Kuttanad varied from 2.98 to 5.48 (Fig. 2). There existed a significant difference in the pH among the soil series which may be due to the inherent soil properties, presence of pyrite layer, hydrology of the area and cultivation practices. Among the different soil series, the lowest pH of 3.26 was recorded from Ambalapuzha series, which can be attributed to the frequent exposure of the iron pyrite layer and the oxidation of sulfur compounds upon drying resulting in the formation of sulfuric acid (Kurup and Ranjeet, 2002).

Among the different land uses, rice recorded the lowest pH of 3.54. The frequent cultivation activities in the rice ecosystem which brings the iron sulphides to the surface and soil drying before harvest have aggravated the development of acidity due to the oxidation of pyrites. Similar results were also reported by Thampatti and Jose (2000). The highest pH of 4.34 was recorded from the coconut land use system which is on par with rice – fish which has a pH of 4.07. The higher pH in coconut land use system can be attributed to the contribution of sand and silt added to the coconut basins from outside. On the other hand, soils in rice and rice – fish land use systems have developed from acid sulphate soils itself and this reflects in the low pH of these soils. The fish culture in rice field has a positive effect in reducing the acidity in the rice field and maintaining the pH. Thus, the integration of rice and fish will help in decreasing the cost of fertilization, will maintain soil fertility and prevent the accumulation of toxic substances as validated by Kurup and Ranjeet (2002).

5.1.3 Electrical Conductivity

The EC of acid sulphate soils of Kuttanad under different agricultural land use systems varied from 0.08 to 3.15 dS m^{-1} (Fig. 3). This variation in soil electrical conductivity may be due to the tidal and fluvial effects which varied due to the influence of climate The highest EC values were observed from the Thuravur series. Similar results were reported by Nath *et al.* (2016). Among the different land use systems, coconut showed the lowest EC value of 0.77 dS m^{-1} when compared to other land uses. The deterrence of saline water entry may have decreased the electrical conductivity of these soils. Thampatti and Jose (2000) have also reported similar findings.

5.1.4 Exchangeable Acidity

The low pH and high CEC of the soils of Kuttanad have resulted in increased exchangeable acidity with the highest value of 5.98 cmol kg^{-1} in Ambalapuzha series (Fig. 4) which showed the lowest pH of 3.26. Similarily, Thuravur series recorded the lowest exchangeable acidity of 0.88 cmol kg^{-1} and the highest pH of 4.58. On comparing the different land use systems, coconut recorded the lowest exchangeable acidity and the highest pH. Thus the soil pH

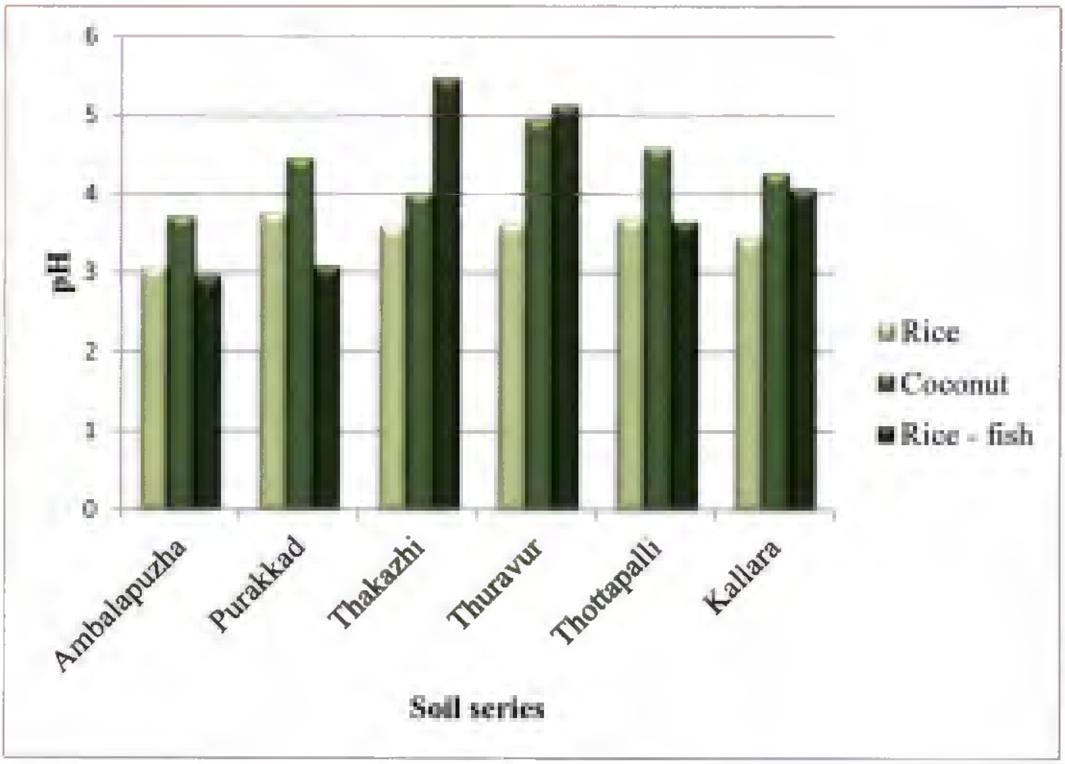


Fig. 2. pH of acid sulphate soils of Kuttanad under different agricultural land use systems

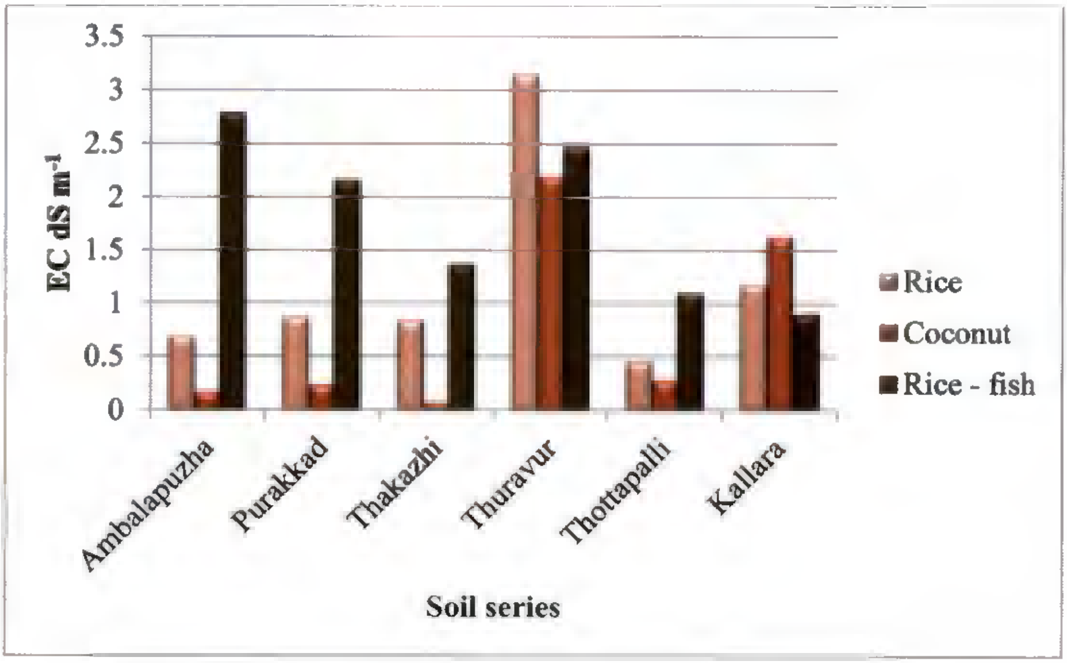


Fig. 3. Electrical conductivity of acid sulphate soils of Kuttanad under different agricultural land use systems, dS m^{-1}

was inversely related with exchangeable acidity. The high amount of exchangeable aluminium generally seen in acid sulphate soils would have contributed to the higher exchangeable acidity in these soils. The production of organic acids through the decomposition of organic matter has also intensified the exchangeable acidity. The results are in line with the finding of Beena and Thampatti (2013).

5.1.5 Bulk Density

There existed a significant difference in the values of bulk density among the soil series, which may be due to the difference in the hydrology, cultivation practices and organic additions in the different soil series. Kallara and Thuravur series recorded the lowest bulk density values. They also have comparatively higher total organic carbon content. Kallara soil series is present in the lower most elevations of Kuttanad at the mouth of the Meenachil river. The organic deposits brought in by the Meenachil river would have resulted in the high organic carbon content and low bulk density of these soils. The bulk density and the total organic carbon content are inversely correlated (Shrestha *et al.*, 2007). Among the different land use systems, coconut recorded the highest bulk density of 0.99 Mg m^{-3} (Fig. 5) and the lowest organic carbon content of 3.78%. The type of ecosystem and land use have a great influence on the amount, decomposability and placement of above ground and below ground inputs and also have an influence on different soil properties as stated by Post and Kwon (2000).

5.1.6 Cation Exchange Capacity

The CEC of the soils under different land use systems varied from 14.60 to 45.50 cmol kg^{-1} (Fig. 6). Kallara series recorded the highest CEC of 43.16 cmol kg^{-1}, which can be attributed to the increased clay and organic carbon content of this soil series. There also exist a positive correlation between total organic carbon and CEC of the soil ($r = 0.85$). Similar findings were also reported by Parfitt *et al.* (1995). The land use systems have significantly influenced the soil CEC which may be due to the difference in the organic addition to the soil. Rice – fish in Kallara series has registered the highest CEC of 45.50 cmol kg^{-1} and the highest total organic carbon content of 8.61%.

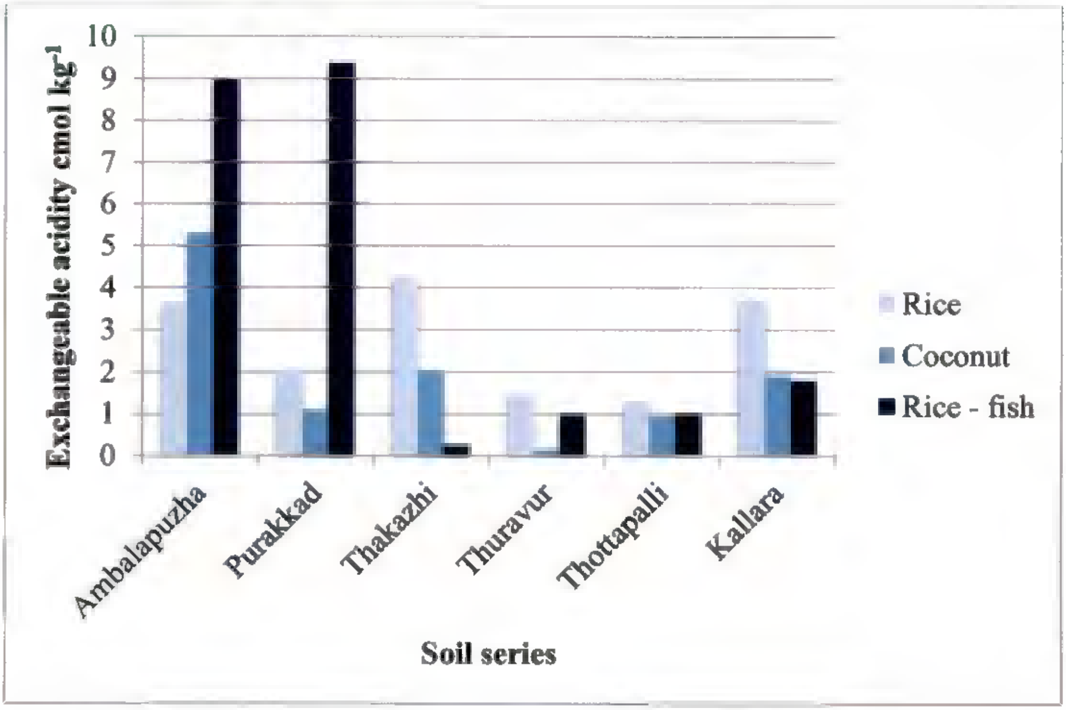


Fig. 4. Exchangeable acidity of acid sulphate soils of Kuttanad under different agricultural land use systems, cmol kg^{-1}

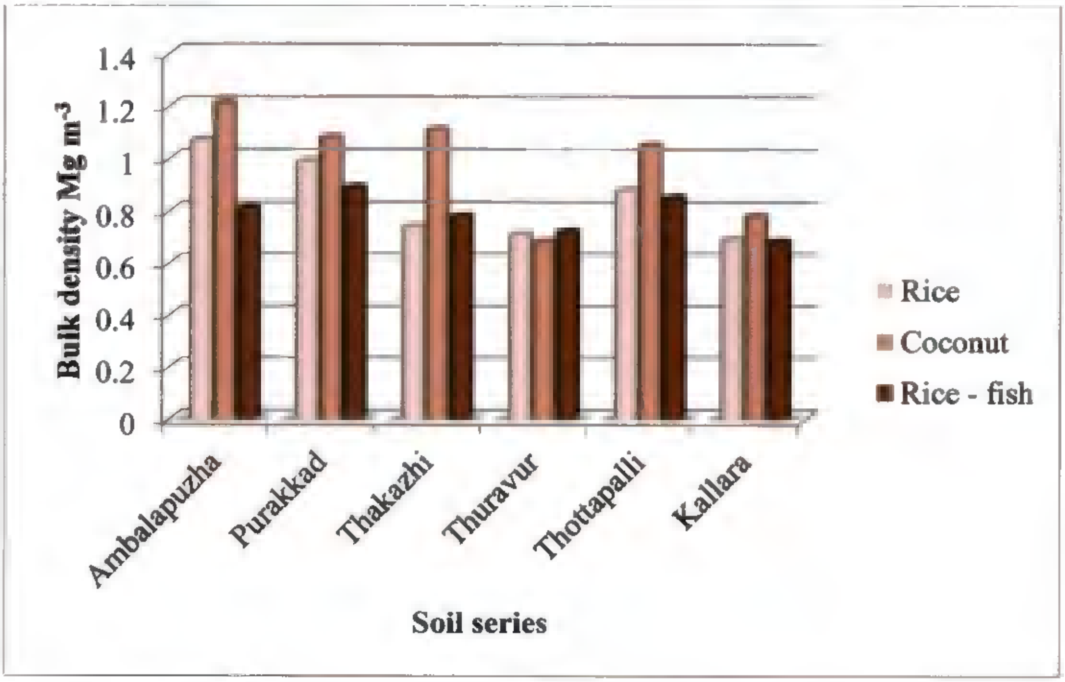


Fig. 5. Bulk density of acid sulphate soils of Kuttanad under different agricultural land use systems, Mg m^{-3}

5.2 SOIL CARBON POOLS

5.2.1 Soil Inorganic Carbon

Soil inorganic carbon was not found in the surface horizons in any of the soil series across the different land use systems. The heavy annual precipitation may have leached out the carbonates from the surface horizon. The sequestration of inorganic carbon in the soil is very low as compared to organic carbon as stated by Lal (2004). The results are in line with the findings of Mi *et al*. (2008) who reported that the content of soil inorganic carbon in each horizon is inversely correlated to annual precipitation which may due to the leaching of carbonates.

5.2.2 Total Organic Carbon

The different soil series exhibited a wide difference in the total organic carbon content. Kallara series recorded the highest carbon content of 8.89% (Fig. 7). Similar results were also reported by Nath *et al*. (2016). Carbon accumulation in soil is highly correlated to the productivity of the recovering vegetation, physical and chemical conditions in the soil, past history of soil organic carbon inputs and physical disturbances. This may have contributed to the variation in carbon content among the soil series (Post and Kwon, 2000). It can also be attributed to the topography and geological position of the wetland in low altitude as stated by Adhikari *et al.* (2009). The different land use system had also significantly influenced the soil carbon accumulation with the highest carbon content reported from rice and rice-fish land use system followed by coconut. In India, the highest SOC accumulation was reported from rice fallow system (Pal and Shurpali, 2006). In paddy soil, the organic amendments and rice residues (stubbles and roots) are the main carbon sources. The presence of this decomposable organic matter under submerged condition might have resulted in the increase in soil organic carbon in paddy soil. These results are also in conformity with the findings of Shrestha *et al*. (2007) who reported that carbon dynamics is greatly influenced by land use and management practices.

5.2.3 Water Soluble Carbon

Water soluble carbon is the mobile and reactive soil carbon source and it is the sensible indicator of soil organic matter quality. The percentage contribution

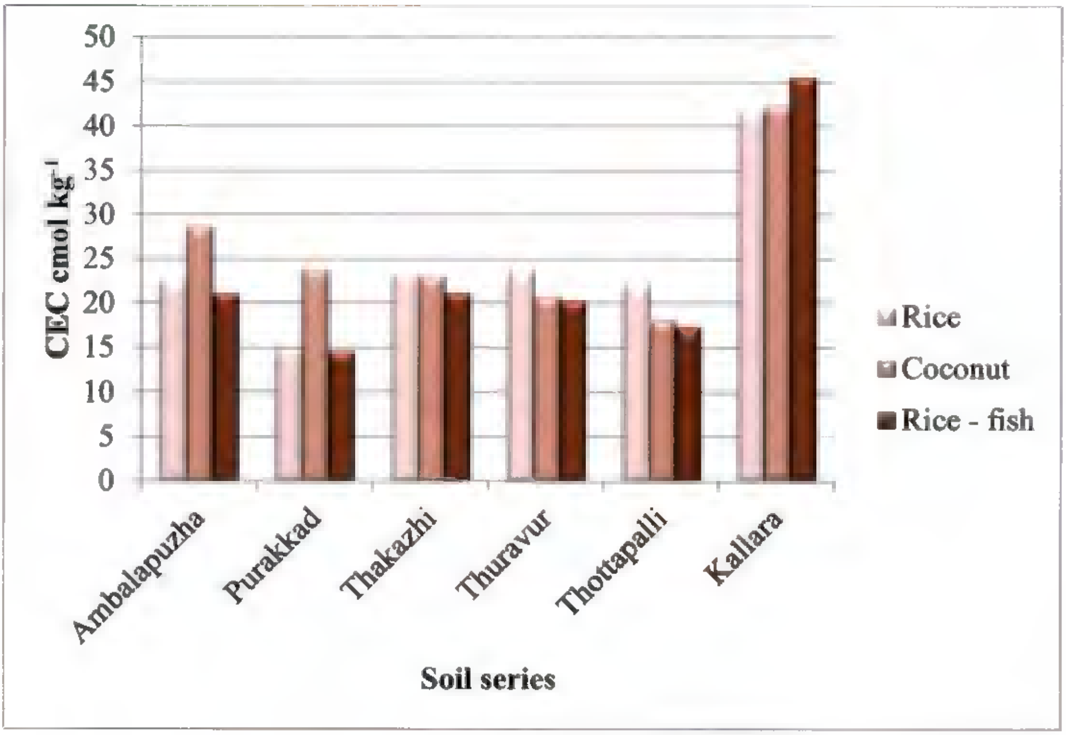


Fig. 6. CEC of acid sulphate soils of Kuttanad under different agricultural land use systems, cmol kg^{-1}

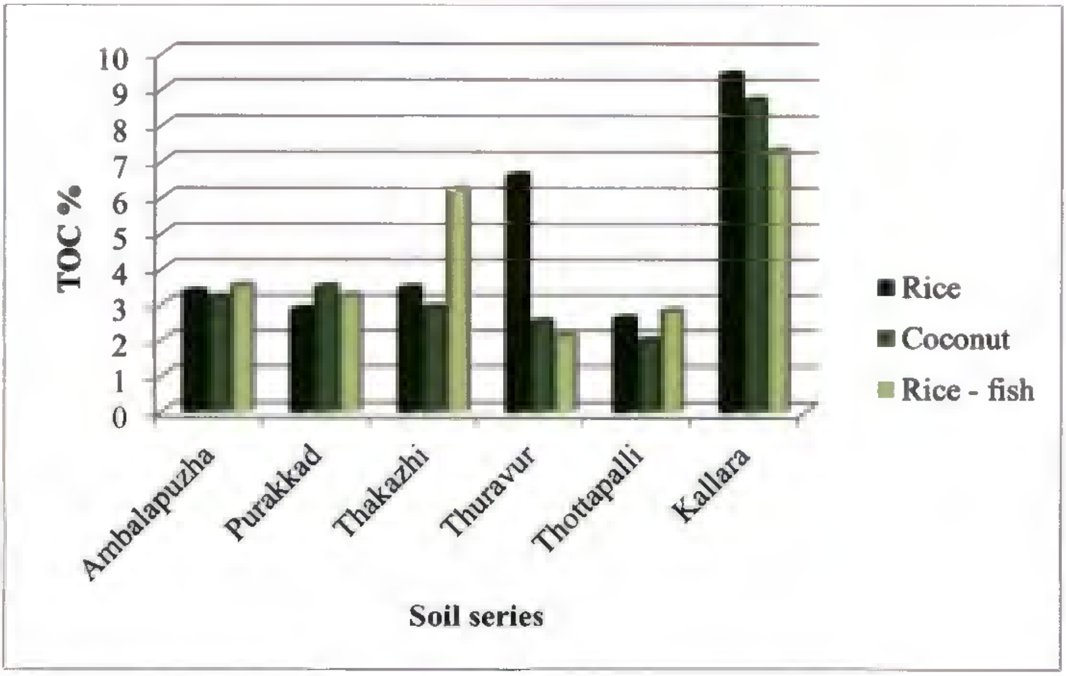


Fig. 7. Total organic carbon content of acid sulphate soils of Kuttanad under different agricultural land use systems, %

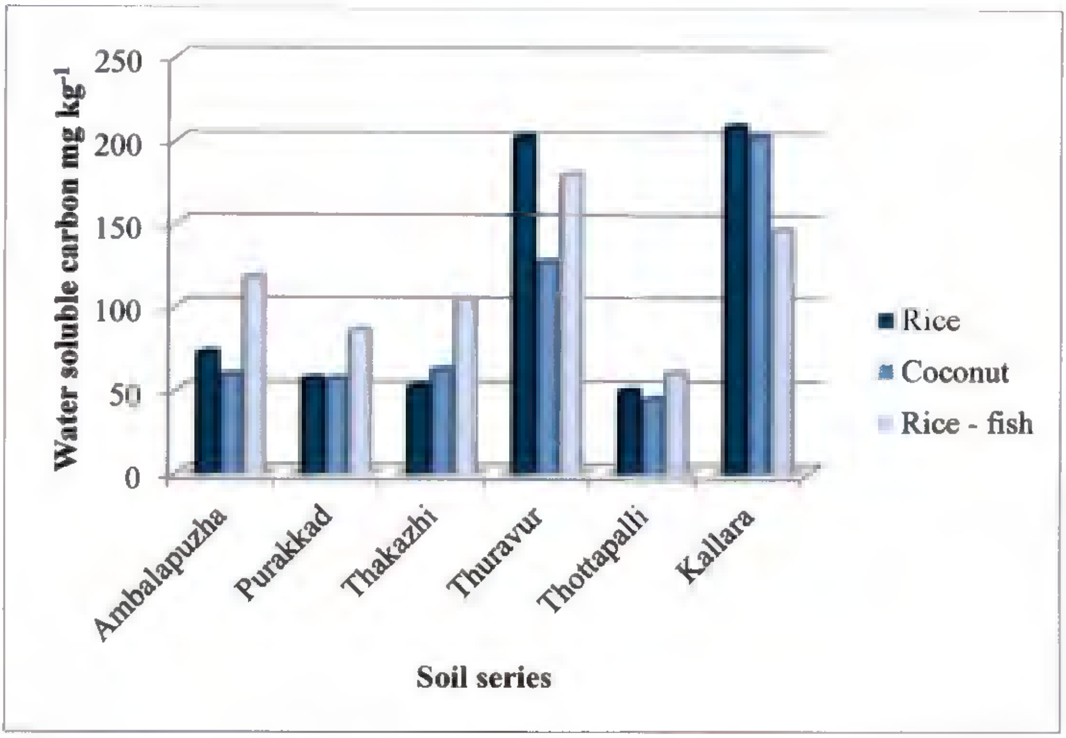


Fig. 8. Water soluble carbon in acid sulphate soils of Kuttanad under different agricultural land use systems, mg kg^{-1}

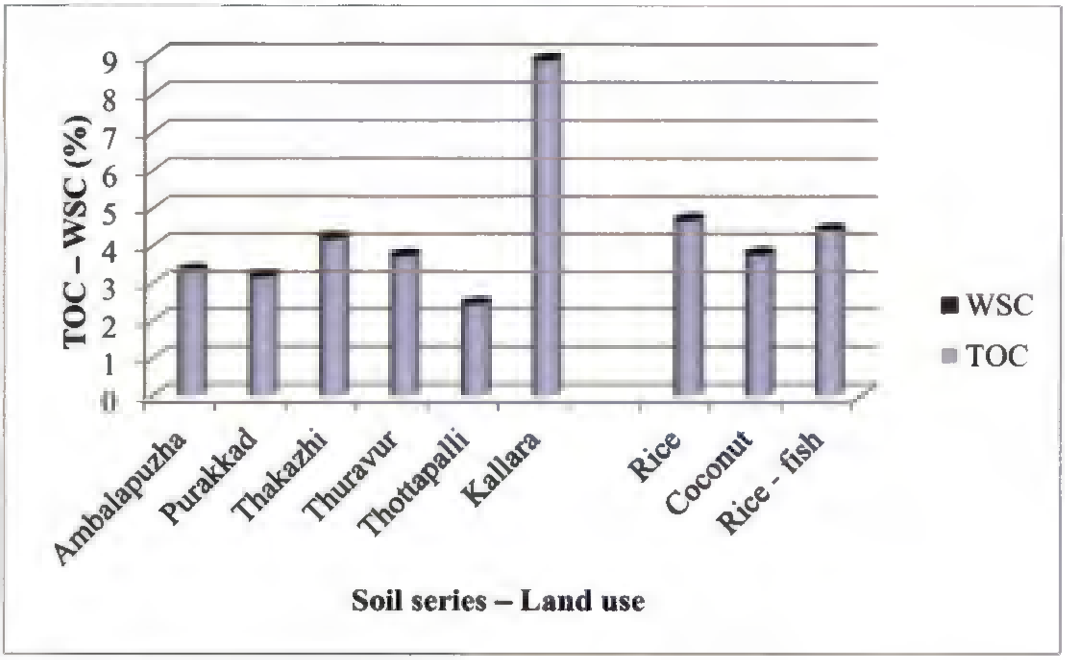


Fig. 9. Percentage contribution of water soluble carbon to total organic carbon in acid sulphate soils of Kuttanad under different agricultural land use systems

of water soluble carbon to the total organic carbon was very insignificant and it ranged from 0.17 to 0.45% (Fig. 9). These pools are vigorously cycled and easily decomposed by micro-organisms and serves as energy source. The highest contribution of water soluble carbon towards the total organic carbon was observed from Thuravur series and from rice-fish land use system. This is attributed to the mobile and reactive nature of water soluble carbon in aquatic ecosystems as stated by Ghani *et al.* (1999). The water soluble carbon is also found to be positively correlated with total organic carbon ($r = 0.72$), labile carbon ($r = 0.81$) and particulate organic carbon ($r = 0.57$) (Fig. 23 & 24). Similar findings were also reported by Zsolnay (1996). The soil series and the land use systems have substantially affected the content of water soluble carbon. The highest water soluble carbon content of 185.84 mg kg^{-1} and 115.65 mg kg^{-1} were noted from Kallara series and rice – fish land use system respectively (Fig. 8). Kallara series and rice – fish land use system have comparatively higher clay and total organic carbon content. Small sized soil particles have higher sorptive potential. Hence, soils rich in clay content have higher water soluble carbon, because the carbon fractions that eluted down the soil profile may be sorbed on the clay surface as stated by Hamkalo and Bedernichek (2014).

5.2.4 Labile Carbon

Labile carbon fractions are the active carbon pools and they contribute significantly towards total organic carbon and the value ranged from 13 to 27% (Fig. 10 & 11). The highest contribution was noticed from Thuravur series and from coconut land use system. Higher level of labile carbon indicates greater turnover rate of organic matter and higher availability of nutrients. Labile carbon is also found to be positively correlated with total organic carbon ($r = 0.67$), water soluble carbon ($r = 0.81$) and particulate organic carbon (0.75) (Fig. 23 & 24). Labile carbon pool is readily decomposable, easily oxidizable and is sensitive to attack by micro-organisms and is more prone to management induced changes in soil organic carbon. It plays an important role in nutrient cycling in soil and thereby influences soil quality and productivity. Similar results were reported by Yang *et al.* (2009).

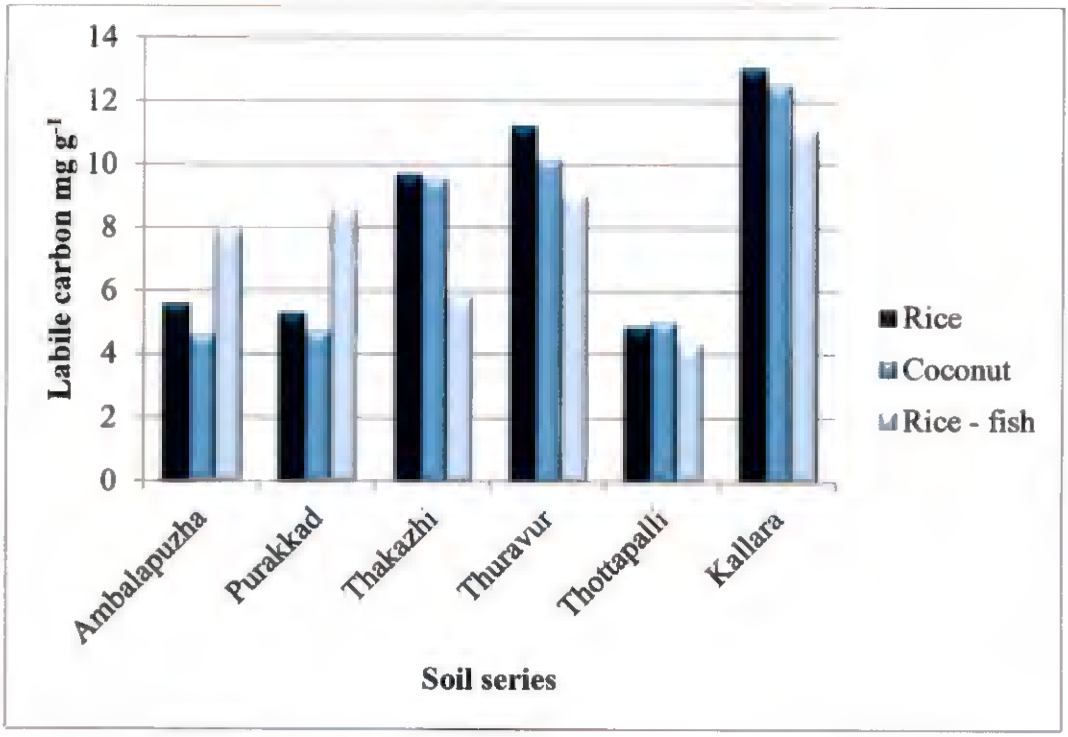


Fig. 10. Labile carbon in acid sulphate soils of Kuttanad under different agricultural land use systems, mg g^{-1}

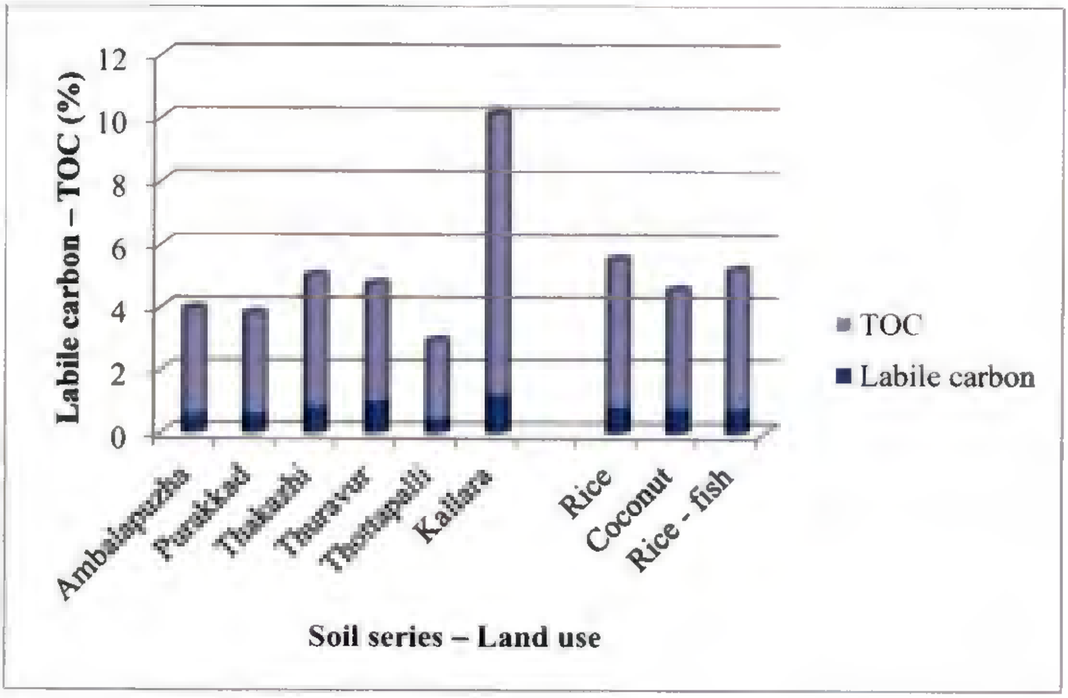


Fig. 11. Percentage contribution of Labile carbon to total organic carbon in acid sulphate soils of Kuttanad under different agricultural land use systems

5.2.5 Particulate Organic Carbon

Particulate organic carbon fractions are the stable carbon pools and they are the more sensitive indicators of change due to land use and management. POC contribute significantly towards total organic carbon and the value ranged from 25 to 62% (Fig. 13) and the highest contribution towards total organic carbon was observed from Kallara series and rice land use system, which also recorded the highest total organic carbon content. POC contribution of 42 to 74% towards total organic carbon was also observed by Chan (2001). Rice land use system in Kallara recorded the highest particulate organic carbon content of 7.23% (Fig. 12). A similar finding of POC content of 6.12% in paddy fields was obtained by Chacko *et al.* (2014). Land use changes affect the soil organic carbon due to the changes in the particulate organic carbon fractions, which confirm the role of this fraction in soil carbon sequestration (Figueiredo *et al.*, 2010). Kallara series have a higher clay content and clay has a higher ability to sequester POC as reported by Franzluebbers and Arshad (1997). Intensive agricultural actiivties may promote the loss of POC due to the destruction of macro-aggregates thus enabling its decomposition by soil micro-organisms (Six *et al.*, 2002).

5.2.6 Mineralisable Carbon

The maximum mineralisable carbon content was noticed from Thottapalli series and from coconut land use system (Fig. 14 & 15), however it recorded the lowest total organic carbon and soil carbon storage. Kallara series and rice land use system recorded the minimum mineralisable carbon, the highest total organic carbon and the maximum storage of soil organic carbon. Thus, mineralisable carbon is inversely correlated with total organic carbon. A negative correlation was also observed between mineralisable carbon and labile carbon ($r = -0.82$), particulate organic carbon ($r = -0.58$) and water soluble carbon ($r = -0.78$) (Fig. 25). The land use system substantially influenced the mineralisable carbon content in the different soil series of Kuttanad. These results are in line with the findings of Chacko *et al.* (2014) who reported that soil carbon mineralization influences the CO_2 production potential and global warming and hence different land use systems have varying ability to store and release carbon. Inspection of the soil

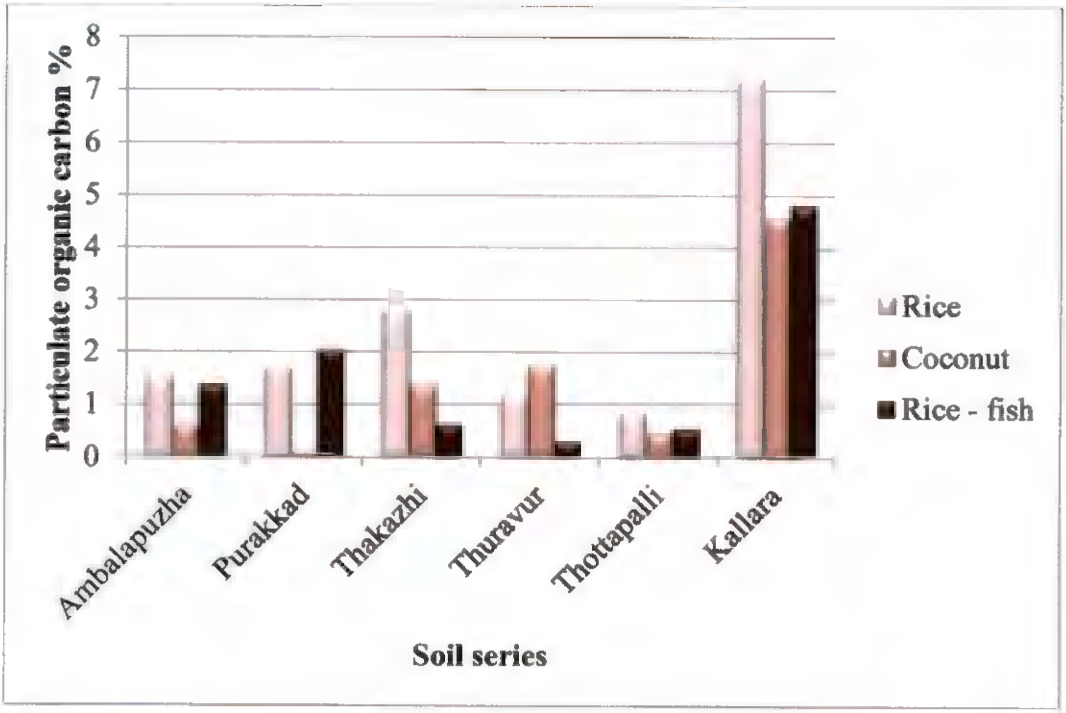


Fig. 12. Particulate organic carbon content of acid sulphate soils of Kuttanad under different agricultural land use systems, %

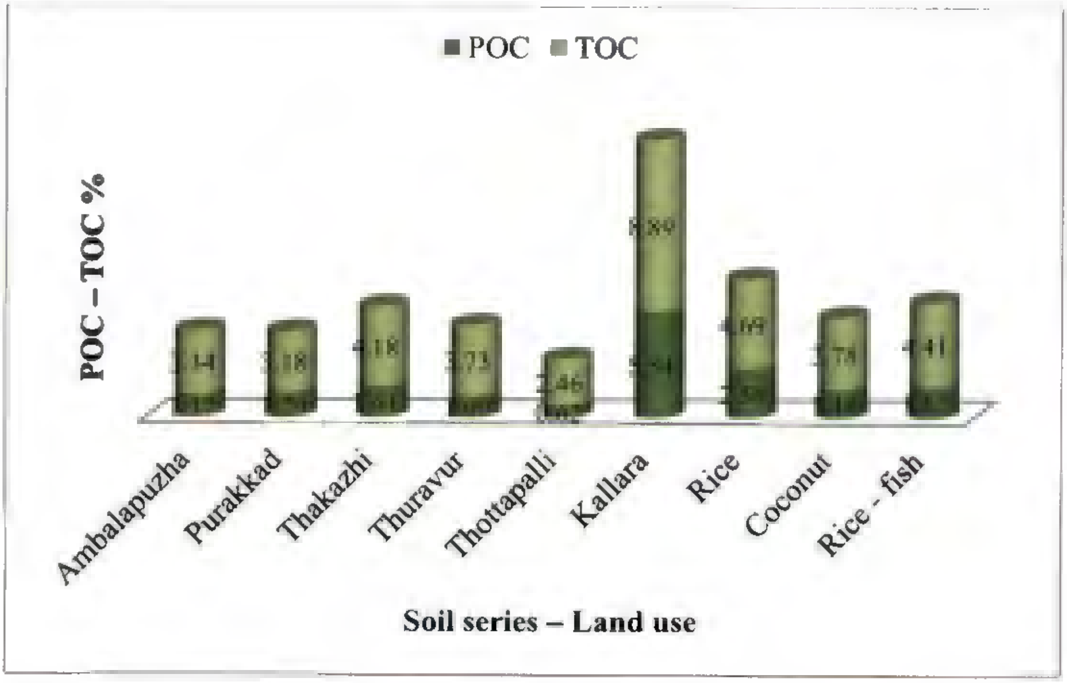


Fig. 13. Percentage contribution of Particulate organic carbon to total organic carbon in acid sulphate soils of Kuttanad under different agricultural land use systems

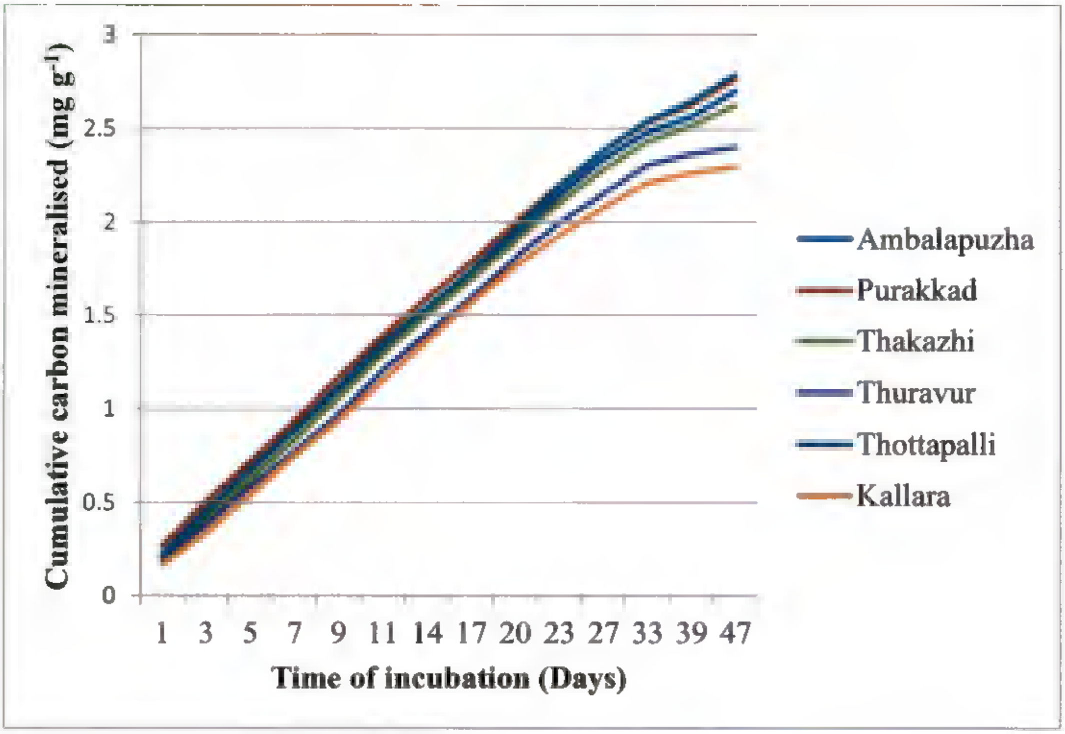


Fig. 14. Mineralizable carbon content in different series of acid sulphate soils of Kuttanad

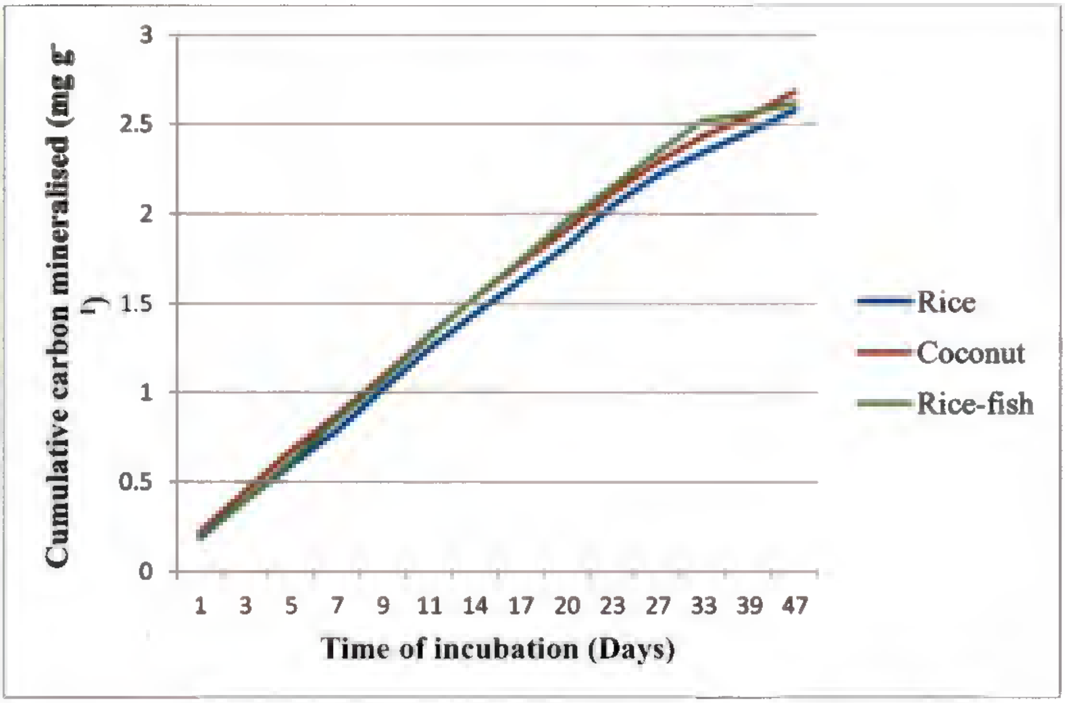


Fig. 15. Mineralizable carbon content in different land use systems of acid sulphate soils of Kuttanad

series and land use have revealed that the cumulative carbon mineralized increased from 0 to 50th day of incubation (Fig. 14 & 15).

5.2.7 Microbial Biomass Carbon

The bio chemical properties of soil serve as an indicator of soil quality. The soil series and land use system had substantially influenced the microbial biomass carbon in the acid sulphate soils of Kuttanad. The microbial biomass carbon content was found to be the highest in kallara series and rice – fish land use system. The microbial biomass carbon is also found to be positively correlated with total organic carbon. Similar results were reported by Velmourougane *et al.* (2013). The soil series and the land use system that recorded the highest microbial biomass carbon have also registered the highest total organic carbon content. Since microbial biomass carbon is the labile pool of soil organic matter, Kallara series had also registered the highest labile carbon while rice – fish land use system had registered the highest water soluble carbon. These findings are in line with those reported by Reichardt *et al.* (1997).

5.2.8 Oxidizable Organic Carbon Fractions

There existed a significant difference in the soil series and land use system with respect to the fractions of organic carbon extracted under a gradient of oxidizing conditions. Very labile pool and labile pool constitute the easily oxidizable fractions. Significantly higher carbon concentration was observed in non-labile pool compared to other fractions. This is because the labile C pool has a greater turnover rate therefore it is much smaller in size than non- labile C pool. Thus oxidizable carbon fractions serve as a more vital indicator of soil quality compared to total organic carbon. Similar findings were reported by Chan (2001). Active pool contributes 17 to 48% towards the total organic carbon and the highest contribution was observed in Purkkad series and coconut land use system (Fig. 16 & 17). The contribution of passive carbon pool towards total organic carbon varied from 51 to 82% (Fig. 18 & 19). The soil series, Kallara, Thakazhi and Thuravur series and land use systems rice and rice – fish contributed more passive pool of carbon towards total organic carbon (Fig. 20). The source of organic matter in rice and rice – fish land use system is mainly the stubbles left

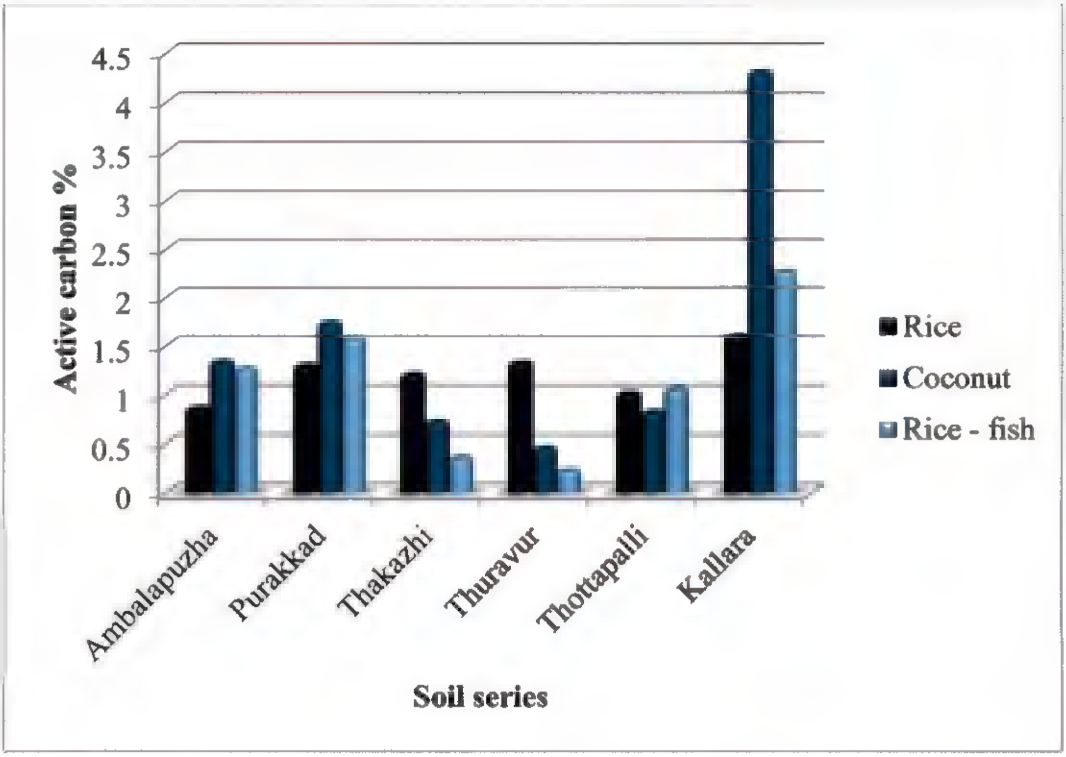


Fig. 16. Active pool of carbon in acid sulphate soils of Kuttanad under different agricultural land use systems, %

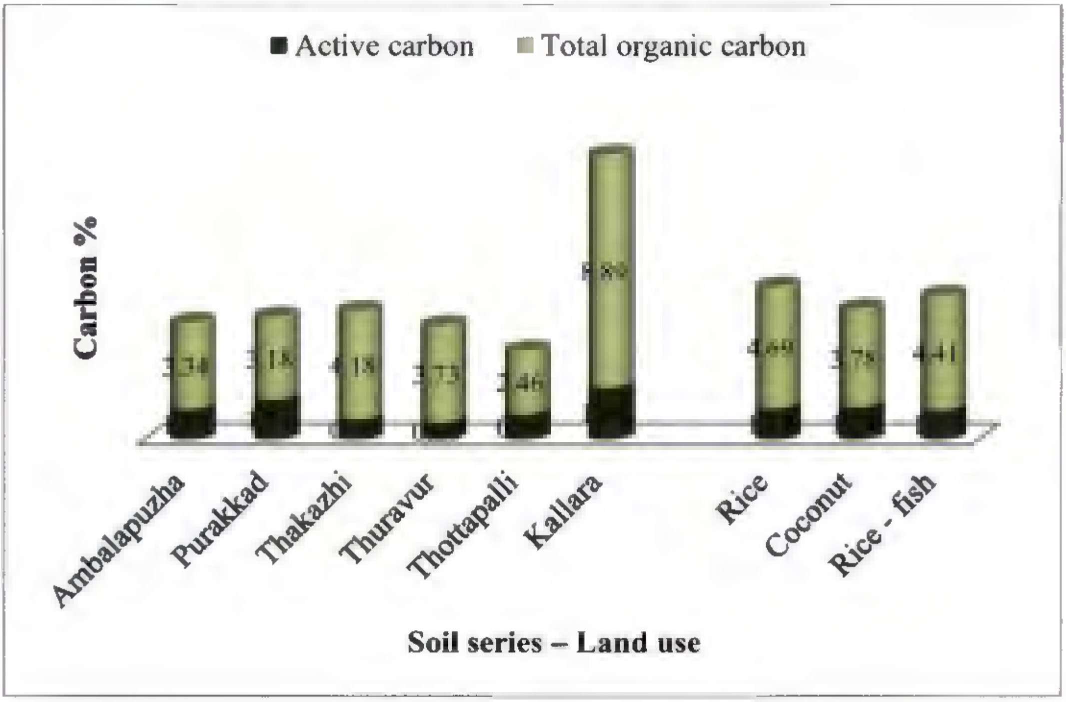


Fig. 17. Contribution of active carbon pools to total organic carbon in acid sulphate soils of Kuttanad under different agricultural land use systems

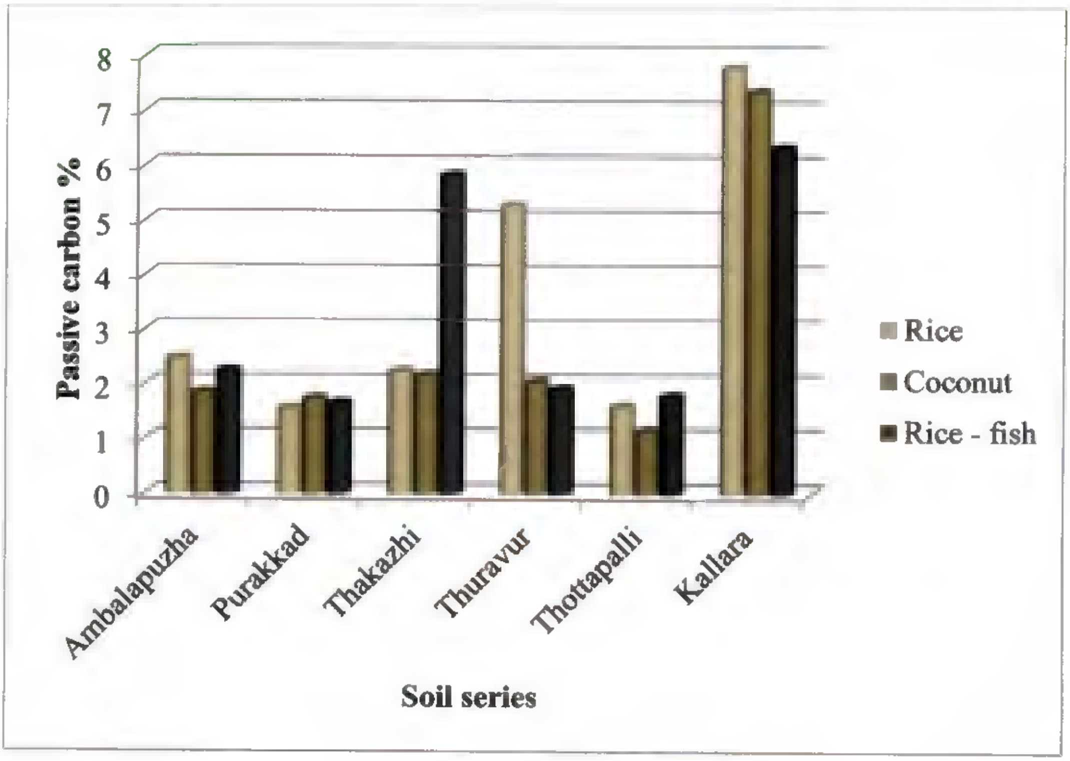


Fig. 18. Passive pool of carbon in acid sulphate soils of Kuttanad under different agricultural land use systems, %

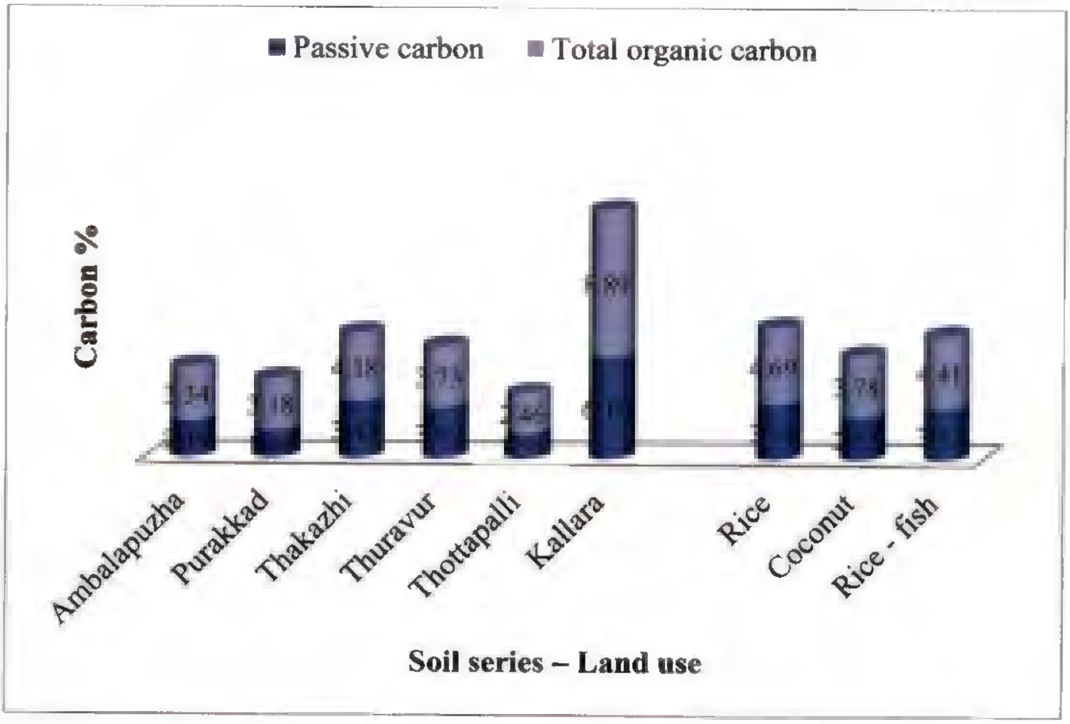


Fig. 19. Contribution of passive carbon pools to total organic carbon in acid sulphate soils of Kuttanad under different agricultural land use systems

over after the harvest of the paddy crop. This would have contributed to the higher passive pool of carbon. Carbon in the passive pool is inert with a turnover time of 2000 years and hence has a better soil carbon storage. Kallara series and rice land use system recorded the highest passive pool of carbon and hence contribute substantially towards soil carbon storage. Similar results were also reported by Collins *et al.* (2000) and Datta *et al.* (2015).

5.2.9 Soil Organic Matter Fractions

Humic acid content was the highest in Thuravur series and coconut land use system which was similar to rice (Fig. 21). The highest fulvic acid content was witnessed in Ambalapuzha series and coconut land use system (Fig. 22). The fulvic acid concentration is generally higher than humic acid. The ratio of humic acid to fulvic acid varies from 0.11 to 2.06. This ratio was less than 1 in most of the locations and it confirms the predominance of fulvic acid compared to humic acid which indicates the slow rate of decomposition of organic matter or frequent organic addition to the soil (Guimaraes *et al.*, 2013). The slow rate of organic matter decomposition in these soils may be as a result of the extremely low pH due to pyrite oxidation and the salinity due to the tidal effect which would have affected the micro-organisms responsible for the mineralization of organic matter. The concentrations of soil organic matter fractions might have varied as a result of different land use and management activities. The type of land use influenced the organic matter fractions, which may be due to the micro climate, vegetative canopy and litter input. The results are in confirmity to the findings of Yao *et al.* (2010).

5.2.10 Soil Organic Carbon Stock

Critical analysis of the data had revealed that soil organic carbon stock was found to be the maximum in Kallara series and rice land use system, which also recorded the highest total organic carbon content. Land use change had significantly influenced the soil organic carbon stock as stated by Guo and Gifford (2002). Rainfall and clay content are the major factors that influence soil organic carbon stock under different land uses. The higher clay content contributed to the higher carbon stock in these soils. Slow rate of decomposition of soil organic

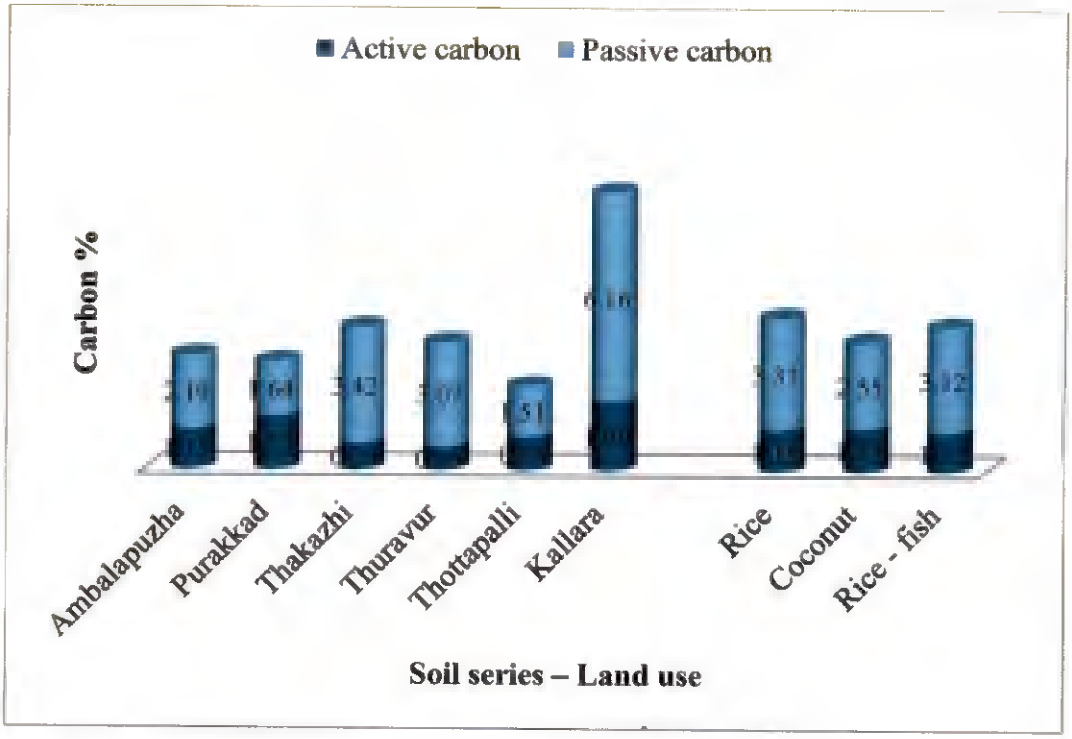


Fig. 20. Distribution of total carbon between active and passive pools in acid sulphate soils of Kuttanad under different agricultural land use systems

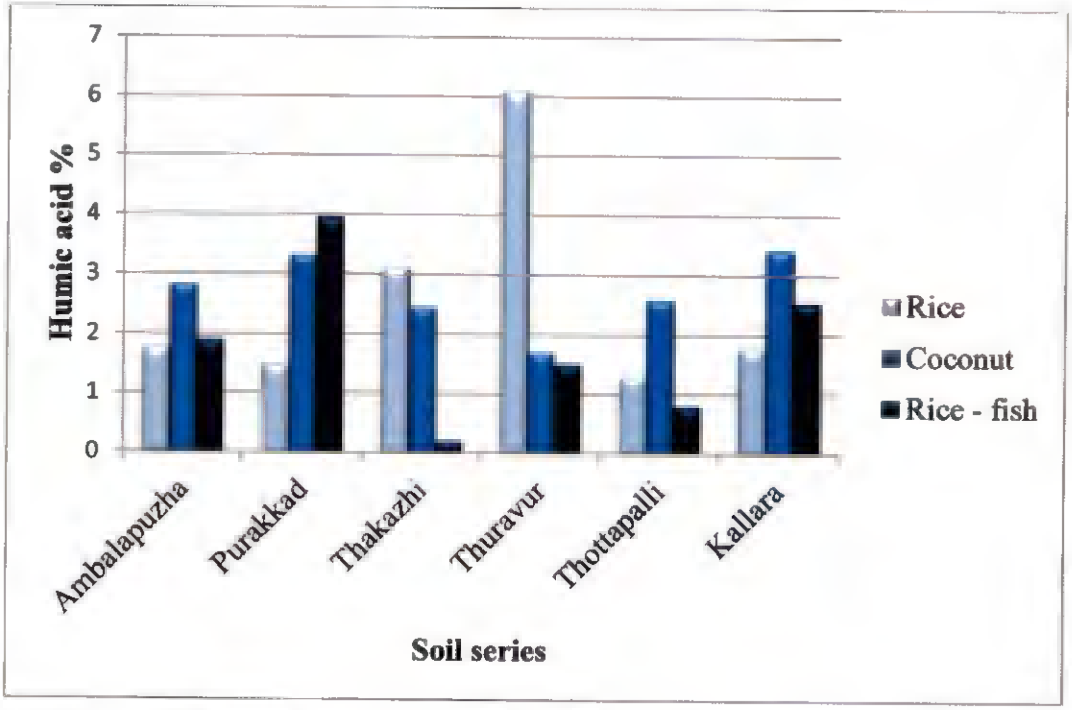


Fig. 21. Humic acid fraction in acid sulphate soils of Kuttanad under different agricultural land use systems, %

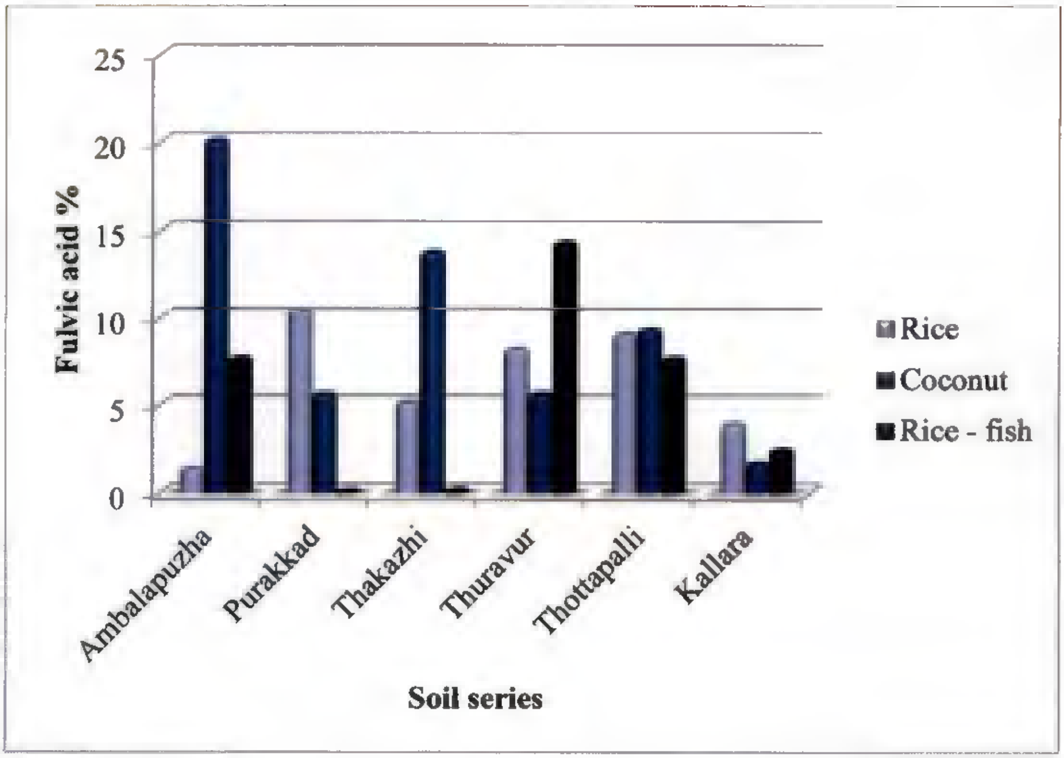
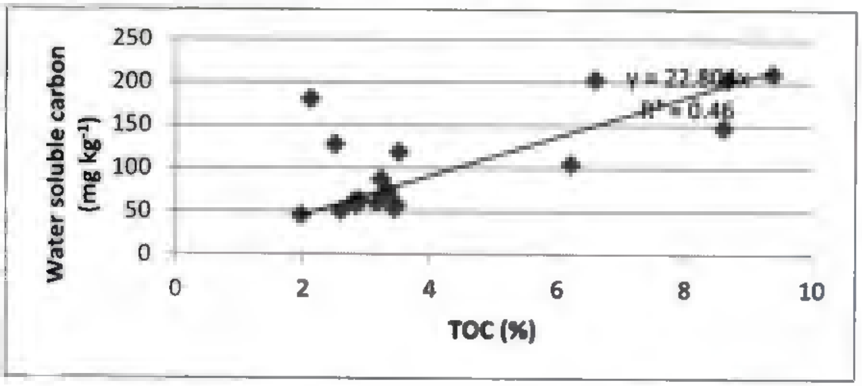


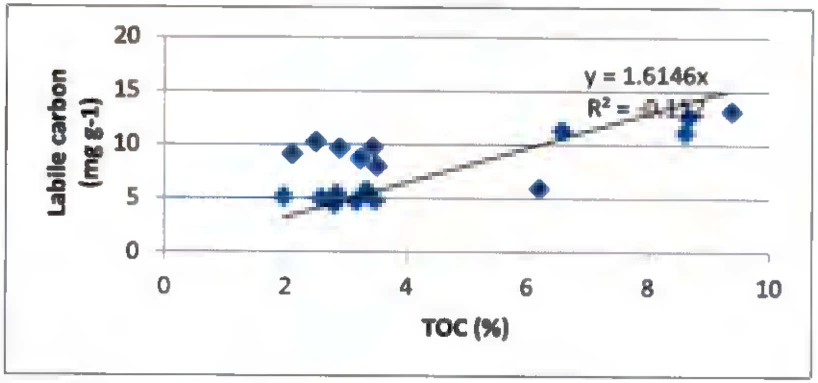
Fig. 22. Fulvic acid fraction in acid sulphate soils of Kuttanad under different agricultural land use systems, %

Fig. 23. Relationship of total organic carbon with water soluble carbon, labile carbon and particulate organic carbon in acid sulphate soils of Kuttanad

r=0.72, Significant at 5% level



r=0.67, Significant at 5% level



r=0.80, Significant at 5% level

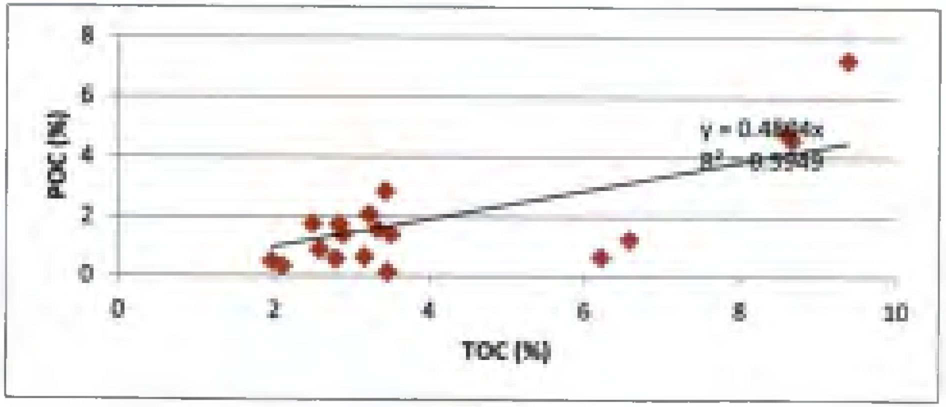
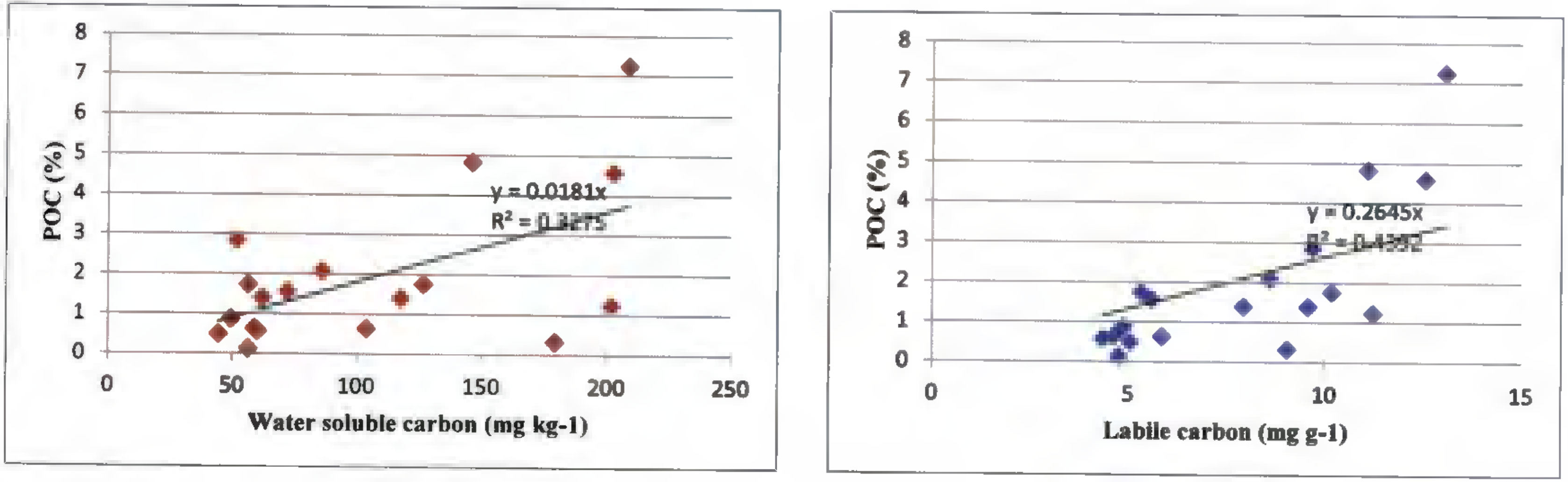


Fig. 24. Relationship of particulate organic carbon with water soluble carbon and labile carbon in acid sulphate soils of Kuttanad

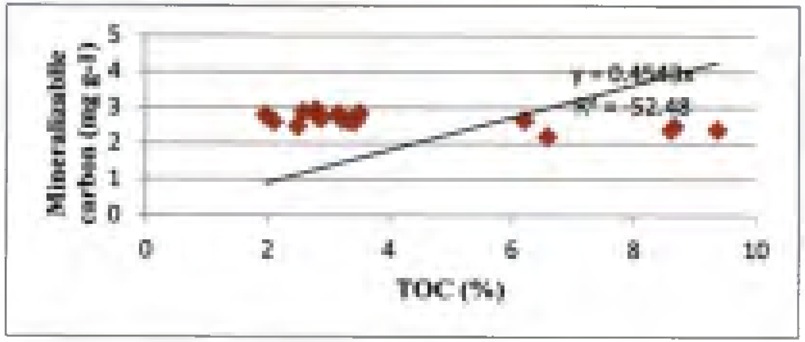


r=0.57, Significant at 5% level

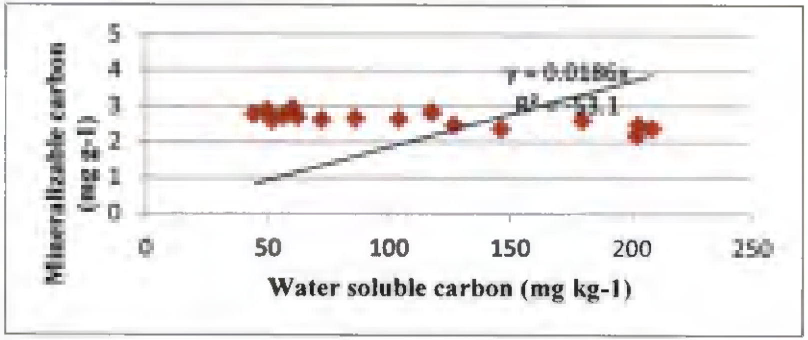
r=0.75, Significant at 5% level

Fig. 25. Relationship of mineralizable carbon with total organic carbon, water soluble carbon, labile carbon and particulate organic carbon in acid sulphate soils of Kuttanad

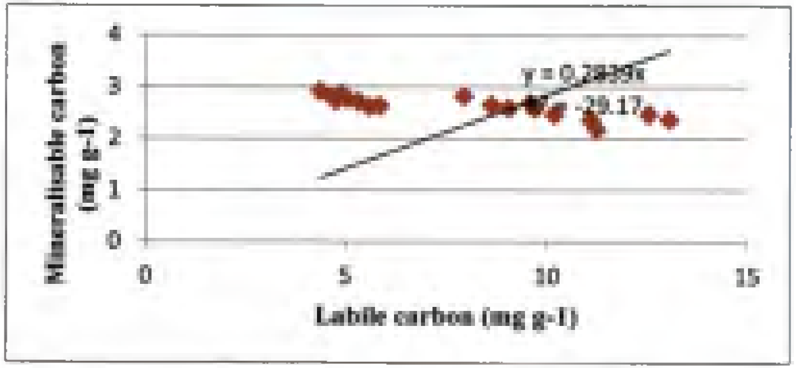
r=-0.70, Significant at 5% level



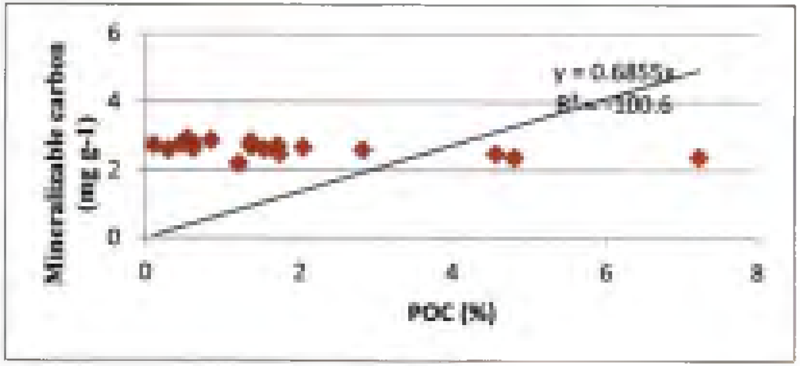
r=-0.78, Significant at 5% level



r=-0.82, Significant at 5% level



r=-0.58, Significant at 5% level



matter and decreased microbial activity may have resulted in increased carbon stock in these soils. In addition, increased micro aggregate fraction in these soils also provide protection to soil organic matter and decrease carbon loss and thereby augment the soil organic carbon stock (Girma and Wolde-Meskel, 2013).

5.2.11 Carbon Indices

The carbon indices like carbon pool index, carbon lability index and carbon management index are worked out for evaluating the impact of agriculture or land use on C dynamics. The carbon pool index of the soils varied from 0.47 to 2.19. The loss of carbon from a soil of small carbon pool is of greater consequence when compared to the loss of same amount of carbon from the soil of large pool size (Jha *et al.*, 2012). The value of carbon lability index varied from 0.55 to 1.64. The loss of labile carbon is of great consequence than the loss of non - labile carbon. The carbon management index varied from 0.29 to 3.58. Kallara series and rice land use system recorded the highest value for all the indices. Among the three indices carbon management index serve as a better indicator for soil health in terms of soil quality. A high carbon management index indicates an impact in the quality and quantity of SOC stock and hence improvement in the quality and sustainability of the system (Jha *et al.*, 2012).

5.2.12 Carbon Proportions and Turn Over

The mineralisable fraction of carbon in the soil denotes carbon turn over. Highest carbon turnover was observed from Thottapalli series and coconut land use system, while the lowest carbon turnover was recorded from Kallara series and rice land use system which also recorded the highest POC/SOC ratio. Chacko *et al.* (2014) had also witnessed the highest POC/SOC ratio from paddy soils. The sink capacity of a soil is determined by the POC/SOC ratio and soil carbon storage, while potential carbon mineralization and carbon turn over indicates the carbon source. The higher POC/ SOC ratio was observed in Kallara series and rice land use system indicating it as a potential carbon sink. The higher carbon turnover rate was observed in Thottapalli series and coconut land use system indicating it as potential carbon source. These findings are also in line with those reported by Chacko *et al.* (2014).

5.2.13 Land Quality Index

The highest soil organic carbon stock and better land quality index was observed in Kallara series and rice land use system. All the other series and land uses were categorized as low land quality index due to low soil organic carbon stock. The soil organic carbon is the most differentiating and reliable land quality indicator that could corroborate with the land use (Kumar *et al.*, 2015)

Summary

6. SUMMARY

Soils form the largest store house of terrestrial organic carbon. Land use is the most vital factor that influences soil carbon pools and fluxes. In order to estimate the carbon sequestration capacity of the soil, it is important to evaluate the carbon pools under existing land uses and their distribution in the soil. Hence, the present study was carried out with the specific objective to assess the soil carbon storage as different soil carbon pools in major soil series of acid sulphate soils of Kuttanad under different land use systems. Soil samples were collected from three agricultural land use systems namely rice, coconut and rice – fish from six soil series namely Ambalapuzha, Purakkad, Thakazhi, Thuravur, Thottapalli and Kallara series. The samples were analyzed for different soil physical and physico- chemical properties such as soil texture, pH, EC, exchangeable acidity, bulk density, cation exchange capacity and for various soil carbon pools such as soil inorganic carbon, total organic carbon, water soluble carbon, labile carbon, particulate organic carbon, mineralizable carbon, microbial biomass carbon, oxdizable organic carbon fractions and soil organic matter fractions. Various carbon indices and soil carbon stocks were also worked out as per standard procedures. The conclusions drawn from the results are summarized in this chapter.

The soils studied belong to the textural class sandy loam to clay. The mean values of the pH varied from 2.98 to 5.48 with the highest in Thakazhi series under rice – fish land use system and the lowest in rice – fish in Ambalapuzha series. The highest EC of 3.15 dS m^{-1} was observed from Thuravur series under rice land use system and the lowest value of 0.08 dS m^{-1} was registered from coconut in Thakazhi series. The mean values of exchangeable acidity ranged from 0.16 cmol kg^{-1} to 9.38 cmol kg^{-1} and the maximum value was recorded from Purakkad series with rice – fish based system and the minimum value in Thuravur series with coconut based system. Coconut in Ambalapuzha series registered the highest bulk density of 1.21 Mg m^{-3} and rice – fish in Kallara series recorded the lowest value of 0.68 Mg m^{-3}. Kallara series with rice – fish land use system showed the highest CEC of 45.50 cmol kg^{-1}, while the lowest value of 14.60 cmol kg^{-1} was recorded from rice – fish in Purakkad series.

A significant difference was observed among the mean values of total organic carbon with the maximum value of 9.38% for rice in Kallara series and the minimum value of 1.97% for coconut in Thottapalli series. The highest value of water soluble carbon content of 208.68 mg kg^{-1} was observed from rice in Kallara series and the lowest value of 44.38 mg kg^{-1} was recorded from coconut in Thottapalli series. With respect to labile carbon, the highest value of 13.06 mg g^{-1} was noted from rice based system in Kallara series and the lowest value of 4.36 mg g^{-1} was recorded from rice - fish in Thottapalli series. The mean values of particulate organic carbon ranged between 0.11 and 7.23% with the highest in Kallara series under rice and the lowest in Purakkad series under coconut. The mineralizable carbon values ranged between 2.17 and 2.91 mg g^{-1} with the highest value in Thottapalli series (Rice - fish) and the lowest in Thuravur series (Rice).

The highest microbial biomass carbon recorded was 488 mg kg^{-1} (Kallara series, Rice-fish) and the lowest value recorded was 71 mg kg^{-1} (Ambalapuzha series, Coconut). The highest value of very labile carbon pool of 1.47% was registered from coconut based system in Kallara series and the lowest value of 0.06% was obtained from rice – fish in Thuravur series. Kallara series with coconut based system documented the maximum value for labile carbon pool of 0.83% and the minimum value of 0.08% was documented from rice – fish in Thottapalli series. The less labile carbon pool was found to be the highest in Thuravur under rice based system (0.82%) and the lowest value of 0.10% was noticed from rice – fish in Thottapalli. A significant difference had occurred in the non-labile carbon pool among the interactions with the maximum value of 6.44% from rice in Kallara series and the minimum value of 1.00% from coconut in Thottapalli series.

The highest active carbon pool of 2.30% was noted from coconut based system in Kallara and the lowest value of 0.23% was recorded from rice – fish in

Thuravur. The maximum value of 6.79% for passive carbon pool was observed from rice in Kallara series and the minimum value of 1.15% was recorded from coconut in Thottapalli series. The different land uses had significantly influenced the humic acid content with the highest value of 6.09% from rice based system in Thuravur series and the lowest value of 0.20% from rice – fish in Thakazhi series. The highest fulvic acid content of 20.10% was recorded from coconut based system in Ambalapuzha series and the lowest value of 0.09% was noticed from rice – fish based system in Purakkad series.

The different soil series and land uses had a significant influence on the soil organic carbon stock and the highest value registered was 122.37 Mg ha^{-1} (Kallara series, Rice) and the lowest value was 25.75 Mg ha^{-1} (Thottapalli series, Coconut). Kallara series with rice land use system recorded the maximum carbon pool index value of 2.19 and Thottapalli series under coconut land use system showed the minimum value of 0.47. The highest carbon lability index value registered was 1.64 (Kallara series, Rice) and the lowest value registered was 0.55 (Thottapalli series, Rice-fish). Kallara series with rice land use system recorded the highest carbon management index of 3.58 and the Thottapalli series with coconut based system registered the lowest index of 0.29. The POC/ SOC ratio was found to be the highest in Kallara series (0.62) and rice land use system (0.54) indicating it as a potential carbon sink. It is evident that the soil series and the land use system have significantly affected the carbon turnover rate with the minimum value in Kallara series (0.27) and rice land use system (0.54). The highest carbon turnover rate was observed in Thottapalli series and coconut land use indicating it as a potential carbon source. The land quality index was rated as moderate for Kallara series and medium for rice land use system, but low for all the other series and land use system

The organic carbon stock and the carbon pools were the highest in Kallara series followed by Thakazhi series. Among the different land uses, rice and rice-fish contributed to maximum soil organic carbon stock and carbon pools showing the prevalence of conducive environment in these ecosystems for the buildup of organic carbon. This emphasizes the need to conserve the wetland ecosystems of Kuttanad to sequester more carbon into the soil.

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ASSESSMENT OF SOIL CARBON POOLS IN ACID SULPHATE SOILS OF KUTTANAD

by

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ABSTRACT

The study entitled “Assessment of soil carbon pools in acid sulphate soils of Kuttanad” was carried out to assess the soil carbon storage as different soil carbon pools in acid sulphate soils of Kuttanad under different land use systems. The study was conducted by collecting surface soil samples (0 – 15 cm) from three agricultural land use systems namely rice, coconut and rice-fish from six acid sulphate soil series namely Ambalapuzha, Purakkad, Thakazhi, Thuravur, Thottapalli and Kallara. The soil samples were analysed for physical, physico-chemical properties and carbon pools and the results were statistically analysed in FCRD with three replications.

The soils studied belong to the textural class sandy loam to clay. The results of the various soil parameters revealed that soil pH varied from 2.98 (Ambalapuzha series, Rice-fish) to 5.48 (Thakazhi series, Rice-fish). The highest EC of 3.15 dS m^{-1} was recorded from Thuravur series under rice land use system while the lowest from Thakazhi series under coconut land use system (0.08 dS m^{-1}). The exchangeable acidity was the highest in Purakkad series under rice-fish (9.38 cmol kg^{-1}) and it was the lowest in Thuravur series under coconut land use (0.16 cmol kg^{-1}). The bulk density of soils ranged from 0.68 Mg m^{-3} (Kallara series, Rice-fish) to 1.21 Mg m^{-3} (Ambalapuzha series, Coconut). Kallara series under rice-fish recorded the highest CEC (45.50 cmol kg^{-1}).

The results of soil carbon pools revealed that soil inorganic carbon was not present in any of the soil series. The total organic carbon content was significantly influenced by different land uses in all the series with the highest value of 9.38% in Kallara series under rice and the lowest value of 1.97% in Thottapalli series under coconut. A similar trend was observed for water soluble carbon which ranged from 44.38 to 208.68 mg kg^{-1}. Labile carbon in various soil series under different land uses varied form 4.36 mg g^{-1} (Thottapalli series, Rice-fish) to 13.06 mg g^{-1} (Kallara series, Rice). Particulate organic carbon was the highest in rice land use in Kallara series (7.23%) while it was the lowest in Purakkad series

under coconut (0.11%). The mineralised carbon values ranged from 2.17 to 2.91 mg g^{-1} with the highest value in Thottapalli series (Rice-fish) and the lowest in Thuravur series (Rice).

The active and passive carbon pools and their contribution to total soil carbon pool was the highest in Kallara series. Among the different land uses, coconut had the highest active pool, while rice land use recorded the highest passive pool of carbon. The humic acid content varied from 0.20% (Thakazhi series, Rice-fish) to 6.09% (Thuravur seires, Rice) and the fulvic acid content ranged from 0.09% (Purakkad series, Rice-fish) to 20.10% (Ambalapuzha series, Coconut). The soil organic carbon stock and carbon pool indices were the highest in Kallara series under rice land use and the lowest in Thottapalli series under coconut. The proportion of POC to SOC was the highest in Kallara series under rice land use indicating it as a potential carbon sink. The carbon turnover rate was found to be the highest in Thottapalli series under coconut land use indicating it as a potential carbon source.

The organic carbon stock and the carbon pools were the highest in Kallara series followed by Thakazhi series. Among the different land uses, rice and rice-fish contributed to maximum soil organic carbon stock and carbon pools showing the prevalence of conducive environment in these ecosystems for the buildup of organic carbon. This emphasizes the need to conserve the wetland ecosystems of Kuttanad to sequester more carbon into the soil.

Appendices

APPENDIX 1

GPS READINGS

Soil series	Agricultural land use	Replication	Latitude (N)	Longitude (E)
Ambalapuzha	Rice	R1	9°22'80.0" N	76°23'09.3" E
		R2	9°22'54.1" N	76°23'28.3" E
		R3	9°23'09.3" N	76°22'21.8" E
	Coconut	R1	9°22'80.2 N	76°23'09.3" E
		R2	9°22'50.0" N	76°23'15.4" E
		R3	9°22'46.9 N	76°23'71.4" E
	Rice- fish	R1	9°22'80.2 N	76°23'09.3" E
		R2	9°22'27.6" N	76°21'39.5" E
		R3	9°22'34.5" N	76°21'34.6" E
Purakkad	Rice	R1	9°20'08.6" N	76°22'57.6 " E
		R2	9°20'20.6" N	76°22'83.3" E
		R3	9°21'18.8" N	76°22'33.7" E
	Coconut	R1	9°20'08.6" N	76°22'57.6" E
		R2	9°20'20.6" N	76°22'83.3" E
		R3	9°21'25.7" N	76°22'13.0" E
	Rice- fish	R1	9°22'04.5" N	76°21'59.9" E
		R2	9°21'22.4" N	76°22'01.0" E
		R3	9°21'22.4" N	76°22'19.9" E
Thakazhi	Rice	R1	9°22'46.2" N	76°24'96.9" E
		R2	9°22'57.0" N	76°26'56.1" E
		R3	9°22'51.3" N	76°26'42.0" E
	Coconut	R1	9°22'39.9" N	76°24'39.8" E
		R2	9°22'27.4" N	76°24'34.6" E
		R3	9°22'32.2" N	76°24'54.5" E
		R1	9°22'24.9" N	76°24'43.6" E

	Rice- fish	R2	9°22'34.6" N	76°24'53.2" E
		R3	9°22'35.8" N	76°24'44.9" E
Thuravur	Rice	R1	9°47'02.2" N	76°18'45.1" E
		R2	9°46'42.6" N	76°18'56.8" E
		R3	9°46'48.7" N	76°18'58.9" E
	Coconut	R1	9°47'07.3" N	76°18'55.4" E
		R2	9°46'29.8" N	76°18'48.6" E
		R3	9°47'00.8" N	76°18'46.9" E
	Rice- fish	R1	9°46'34.4" N	76°18'25.6" E
		R2	9°47'10.9" N	76°18'38.4" E
		R3	9°47'07.7" N	76°18'56.6" E
Thottapalli	Rice	R1	9°18'47.5" N	76°24'36.5" E
		R2	9°19'54.0" N	76°22'59.1" E
		R3	9°19'49.5" N	76°22'37.7" E
	Coconut	R1	9°18'54.0" N	76°24'38.9 "E
		R2	9°19'17.5" N	76°24'27.4" E
		R3	9°19'45.9" N	76°22'30.5" E
	Rice- fish	R1	9°19'42.9" N	76°24'64.8 E
		R2	9°19'39.3" N	76°22'59.4" E
		R3	9°19'40.0" N	76°22'38.3" E
Kallara	Rice	R1	9°42'32.4" N	76°28'39.6" E
		R2	9°42'38.5" N	76°28'35.8" E
		R3	9°42'45.4" N	76°28'39.5" E
	Coconut	R1	9°43'24.2" N	76°28'21.0" E
		R2	9°40'58.5" N	76°30'09.6" E
		R3	9°41'33.8" N	76°29'29.6" E
	Rice- fish	R1	9°41'16.9" N	76°30'10.0" E
		R2	9°41'17.7" N	76°30'00.8" E
		R3	9°40'59.0" N	76°29'57.5" E

APPENDIX II

CORRELATION STUDY

Correlation between various soil properties and soil carbon pools in acid sulfate soils of Kuttanad under different agricultural land use systems

	pH	EC	EA	BD	CEC	TOC	WSC	LC	POC	MC
pH	1									
EC	-0.016	1								
EA	-0.719	0.238	1							
BD	-0.179	-0.674	0.124	1						
CEC	-0.008	-0.100	-0.087	-0.317	1					
TOC	-0.019	0.173	-0.057	-0.500	0.850*	1				
WSC	0.133	0.663	-0.070	-0.697	0.587	0.722*	1			
LC	-0.022	0.474	0.071	-0.669	0.619	0.670	0.808*	1		
POC	-0.249	0.051	0.148	-0.480	0.793	0.797	0.572	0.753*	1	
MC	-0.104	-0.454	0.173	0.602	-0.539	-0.696	-0.783	-0.816	-0.582*	1

* significant at P = 0.05 level

EC = Electrical Conductivity, EA = Exchangeable Acidity, BD = Bulk density, CEC = Cation Exchange Capacity, TOC = Total Organic Carbon, WSC = Water Soluble Carbon, LC = Labile carbon, POC = Particulate organic carbon, MC = Mineralizable carbon.