EVALUATING SOIL CARBON SATURATION IN DIFFERENT AGRO ECOLOGICAL ZONES OF KERALA

by

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THESIS

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DECLARATION

I, Smrithy, M. G. (2016-20-017) hereby declare that this thesis entitled **"EVALUATING SOIL CARBON SATURATION IN DIFFERENT AGRO ECOLOGICAL ZONES OF KERALA"** 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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TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

SYMBOLS AND ABBREVATIONS

AEU	Agroecological Unit
AEZ	Agroecological Zone
C	Carbon
C_{sat}	Carbon saturation
$C_{sat-def}$	Carbon saturation deficit
DMS	Degree minute seconds
GHG	Greenhouse gas
IDW	Inverse Distance Weighted
MRT	Mean Residency Time
OC	Organic carbon
OM	Organic matter
POM	Particulate organic matter
SOC	Soil organic carbon
SOC_{cur}	Current soil organic carbon
UNFCCC	United Nations Framework Convention on Climate Change

CHAPTER 1

INTRODUCTION

One of the main issues faced in this century is the unprecedented changes in climate, a phenomenon known as global climate change. Soil is one of the eminent factors that has been widely recognized to mitigate climate change. Soil can act as a sink as well as a source for carbon. For climatic regulations, the soil should be utilized as a sink instead of a source. Maintaining and improving soil carbon through sensible use would help to mitigate climate. For example, certain soil conditions help carbon sequestration by reducing soil carbon decomposition rate and storing more carbon in the soil and every small change in soil carbon can influence the global climate.

Carbon levels in the soil is influenced by climate interaction and soil properties. The addition of organic materials also influences the carbon level in soil. Land use, land management practices, soil aggregation and microbial activity are some other factors that contribute to carbon storage potential in soils. A positive interaction among these soil factors would develop an enabling environment for carbon stabilization wherein the soil act as a sink and helps in the mitigation process.

The carbon cycle has been dramatically affected by anthropogenic activities such as the combustion of fossil fuels, deforestation, and other land use activities. As a result, the atmosphere now contains around 35% more carbon dioxide than it had before the industrial revolution began. The degree to which the atmosphere traps incoming solar energy increases as carbon dioxide content rises, which further heats the planet. As per the Paris Accord, countries have to restrict their temperature under 2˚ C, preferably 1.5˚ C above pre-industrial levels along with maintaining and improving sinks and reservoirs of GHGs. The solutions like capturing and storing carbon from different sources and afforestation to sequester carbon are large scale processes that might help reduce atmospheric carbon levels to acceptable limits.

Soil is considered to be the best terrestrial source which helps in minimizing future climatic problems. Soils has the ability to sequester more carbon than other sources. Processes such as degraded soil restoration and beneficial soil management practices are being practiced worldwide to achieve long-term soil carbon storage in terrestrial systems.

Protective capacity or the highest limit of a soil's ability to protect SOC by carbon retention i.e., soil's current capacity to protect SOC is determined by how much of the protective potential has previously been used. Carbon in soil is protected by different mechanisms such as chemical (silt + clay) physical (micro-aggregates) biochemical (non-hydrolysable carbon) and unprotected fractions (POM in sand fraction). In soil, the mean residency time (MRT) of each of these fractions might range from a few seconds to several millennia. Only a SOC with a long MRT can help to prevent climate change. The MRT is influenced by environmental and biological factors rather than molecular structural features (recalcitrance) of carbon alone. Selective recalcitrance, spatial inaccessibility, and organo-mineral interactions can all help to keep organic matter stable in soils. The connection of organic matter with soil minerals, which is mostly controlled by soil texture, results in organo-mineral complexes. Because organic carbon (OC) stored in fine soil particles has a longer turnover time and accounts for a considerable fraction of total SOC, this carbon pool is of particular significance in the context of the global C cycle. The amount of OC associated with fine soil particles is usually proportional to their mass in bulk soil and is influenced by soil mineral types and the composition of organic carbon inputs.

The relationship between carbon inputs and soil organic carbon plays a critical role in the atmosphere's carbon balance, and it may be studied using carbon saturation. Soil organic carbon (SOC) is said to be a balance between carbon inputs through photosynthesis and deposition and carbon losses through respiration, erosion, and leaching. As carbon input increases soil shows an increase in carbon accumulation. This storage capacity has a limit know as soil carbon saturation. The soil carbon saturation idea proposes that there is a limit to whole soil organic carbon accumulation and only a small portion of the carbon accumulated can be considered stable as a result of the saturation process (Di *et al*.,2017). According to certain models, the further a soil is from saturation (i.e., the higher the saturation deficit), the more efficient it is at more carbon. When soil reaches saturation, it absorbs less SOC, at a slower rate and with less efficiency. With increased organic carbon inputs, the soil carbon saturation theory hypotheses that SOC storage efficiency diminishes as soils approach their carbon saturation points. Changes in SOC storage are known to be influenced by organic carbon inputs and SOM stability. Further, soil carbon storage delays carbon dioxide removal into the atmosphere which also improves soil quality and productivity.

In order to prevent the excess loss of carbon through the atmosphere, it is imperative that we identify their maximum storage capacity. Soil carbon saturation deficit in different areas can be analyzed using certain established models. Models like Rothamstead C model and different abiotic models are used for analyzing carbon deficit or saturation in soil. However, the most popular model used for the calculation of soil carbon saturation is a simple regression equation developed by Hassink (Hassink *et al*., 1997; Stewart *et al*., 2008a). The input variables required for these models are based on their objective and are used mainly for identifying the relations of carbon with soil colloidal surfaces.

The objective of the present study was to estimate soil carbon saturation and deficiency in the different agroecological zones and units of Kerala. The study focused to identify soil carbon deficit zones and identifying such areas would help design management practices to improve their carbon sink capacities.

CHAPTER 2

REVIEW OF LITERATURE

2.1 SOIL HAS THE POTENTIAL TO ACT AS A CARBON SINK

Soil carbon is acknowledged as the greatest carbon reservoir on the planet. In comparison to carbon pools in the atmosphere and plants, it has a far bigger storing capacity on a global scale. After the oceanic and geologic pools, the soil is the third largest C pool. The 3150 Pg carbon global soil carbon pool contains 450 Pg C in wetlands, 400 Pg carbon in permafrost soils, and 2300 Pg C in upland soils, which is further partitioned into 1500 Pg carbon in the top 1 meter and 800 Pg carbon in the deeper layers up to 3 meters. Soil is an important part of the carbon (C) and nitrogen (N) biogeochemical cycles, and hence plays an important role in climate regulation, either by emitting GHGs or by sequestering carbon.

It is easier for soils to lose carbon than it is to gain carbon. Soil C stock changes occur where there had been a change in land use or management (Smith, 2014). According to Hu *et al*. (2019), the ability of soil to store carbon varies with human activity and causes an impact on atmospheric C concentrations, quality of soil, and productivity. The implementation of agricultural management activities (conventional tillage, organic manure, effective fertilizer, irrigation, cover crop, crop rotation, etc.) plays an essential role in improving soil carbon stock and quality. Improving soil's ability to act as a carbon sink can help offset CO_2 emissions while also reducing the negative effects of global climate change and enhancing crop yields.

The goal of the 68th United Nations General Assembly's "International Year of Soils" (2015) is to promote full recognition of soils' significant contributions to food security, climate change, adaptation and mitigation, essential ecosystem services, poverty alleviation, and sustainable development, as well as to promote effective policies and actions for the long-term management and protection of soil resources. The role of soil in the ecosystem has the capacity of reducing the concentration of CO_2 in the atmosphere and releasing this CO_2 back into the atmosphere (Chen *et al*., 2019). For declining CO_2 emission, we had to adopt certain strategies. One of such is soil organic C sequestration. Lal *et al*., (2015) stated that carbon sequestration is the process of capturing and storing carbon, as well as extending its mean residence time (MRT) and reducing re-emission sinks. minimizing the net rise in CO_2 concentration in the atmosphere, increasing the concentration (and pool) of soil organic C (SOC) over the 1.5–2.0 percent threshold, and developing climate-smart soils and agroecosystems.

In recent years soil had lost quantity of carbon as a result of anthropogenic activities (Abdullahi *et al*., 2018). It is important to maintain lost carbon as well as CO_2 remains in the atmosphere. According to COP21 (UNFCCC), the official launch of the "4 per thousand" initiative, which is intended to foster food security and reduce atmospheric CO_2 concentration by increasing the SOC at an annual rate of 0.4% (Chen *et al*., 2019).

The significance of soil organic carbon (SOC) in sustaining soil as a carbon sink is critical. SOC is the balance between carbon input (Fertilization, irrigation, organic amendments, crop rotation) and carbon output (decomposition and erosion). Mullen *et al*. (1999) cited by Hu *et al*. (2019) said that one percent increase in soil organic carbon (SOC) can reduce CO_2 levels by 5 mg/m^3 in the atmosphere. The carbon content of the SOC pool is three times that of the atmosphere (about upper 1m soil). Temperature, precipitation, and the physical and chemical features of the soil all contribute to SOC balance. While SOC concentrations in surface soils are often higher than those at deeper depths, SOC saturation in subsoil may be very low (Lal *et al*., 2015).

2.2 IMPORTANCE OF SOIL SINK

Soil is the largest source of carbon and methane, and it plays a significant role in carbon dioxide regulation in the atmosphere. Soils with more organic matter, no tillage, manure application, and fertilization are ideal for acting as a carbon sink and nitrogen reservoir for soil biota (Chung *et al*., 2014).

The carbon and methane sink in soil play an essential role in regulating atmospheric climate. Carbon and methane fluxes from soil contribute significantly to the terrestrial carbon budget and the global carbon cycle. For example, coastal soils, emit CH_4 in addition to CO_2 due to oxidation-reduction reactions caused by regular tidal effects (Khan *et al*., 2005). Emissions from these sinks are also influenced by soil properties. i.e., carbon dioxide is created in both oxic and anoxic soils, whereas methane is formed in anaerobic conditions as a result of CO_2 reduction. The mechanisms that influence CH_4 and CO_2 emissions are obviously complex and interconnected.

Soil carbon was depleted day by day due to microbial decomposition of soil organic matter as a result of soil temperature changes and the absence of continuous carbon input. Thus, perpetuating the carbon sink in soil by enhancing SOC is very effective in mitigating climate change while also improving soil, water quality, and food production.

2.3 SOIL CARBON STABILIZATION

SOC is a crucial component of soil that has a significant impact on the functioning of terrestrial ecosystems. SOC is stored as a result of interactions between the dynamic ecological processes of photosynthesis, decomposition, and soil respiration. Future warming and rising CO_2, historical land use patterns, and land management practices, as well as the physical variety of landscapes, are all likely to lead to complex patterns of SOC capacity in soil. Crop rotation, residue management, and manure application are examples of agricultural management methods that influence the quantity of carbon (C) entering an agroecosystem and, as a result, alter SOC stabilization and soil fertility (Stewart *et al*., 2008). Soil carbon stabilization was defined by Mol, R.P *et al*. (2019) as the process of preserving carbon stock by reducing the potential loss of SOC due to microbial decomposition, respiration, erosion, and leaching. The stabilization process is influenced by factors like carbon input, soil texture, land use, and the presence of clay minerals. Stabilization mechanisms are present in physical, chemical, biological processes and unprotected (Mayzelle *et al*., 2014).

Physical stabilization: Through the interaction of SOC with the soil mineral matrix, strong chemical bonds are formed. Soil decomposition is hampered due to physical protection. It depends on the soil texture; for example, clay soils protect more carbon than sandy soils under similar conditions (Lal *et al*., 2015; Goh, 2014).

Chemical stabilization: The presence of reactive mineral surfaces, climate, water availability, soil acidity, soil redox status, and soil microbial community all influence the persistence of SOC. Mineral association aids in SOC stabilization due to inherent recalcitrance and occlusion in aggregates. These mechanisms produce biologically inert black carbon, binding of carbon through the formation of soil carbonates is an effective stabilization mechanism (Mol, R.P *et al*., 2019; Goh, 2014; Lal *et al*., 2015)

Biological stabilization: Biologically stabilized SOC depends on the chemical structure of organic residue as well as soil mineral phase. Stabilization occurs through the occlusion of SOC by the formation of stable micro-aggregates and non-hydrolyzable compounds (Lal *et al*., 2015; Goh, 2014). The Organo-mineral complexes contribute far too much to C stability in the soil. The Organo-mineral complexes are the complexes generated by a particular association between organic and mineral materials (Mol, R.P *et al*., 2019). Secondary organo-mineral complexes are formed by the association of organic matter.

Unprotected pool: All SOM less than 2 mm that remains outside micro aggregates and unbound to silt and clay is classified as an unprotected pool.

2.4 CONCEPT OF SOIL CARBON SATURATION

Several agricultural management practices like no tillage, crop residue, cover crop, nitrogen fertilization, straw retention show an increase in carbon accumulation in the soil due to reduced SOM oxidation (Khandakar *et al*., 2017; Stewart *et al*.,2008; Chung *et al*., 2014; Di *et al*., 2018 and Di *et al*., 2017). Increments in soil carbon have a positive effect on reducing atmospheric carbon until the limit is reached. Increases in SOC usually follow a linear pattern, i.e., as carbon input rises, SOC stock also increases (Stewart *et al*.,2008; Vicente *et al*., 2017). The Potential for sequester carbon depends on certain environmental factors like climate, soil physical and chemical properties, and land management. Changes in these factors cause fluctuation in the SOC (West *et al*., 2006). Changes in these factors show a decrease in stabilization efficiency when C inputs are added. The efficiency of additional organic carbon in stabilizing soil organic carbon content has been explicitly examined throughout time, resulting in a new soil organic carbon steady state (Stewart *et al*.,2008).

According to West *et al*., (2006), due to changes in land use, the soil enters a new steady state in which soil C inputs approximate soil C outputs. The new steady state will fluctuate with seasonal changes, land productivity, and changes in mean annual temperature and precipitation. Interval between the old steady state and the new steady state is represented as soil C sequestration duration. When saturation occurs, additional carbon input and land management activities do not enhance carbon intake. If it's no saturation, multiple new steady states emerge until the saturation is reached.

The stabilization capacity of soil is finite unit it ceases active accumulation and reaches a new equilibrium state called soil carbon saturation. "Soil carbon saturation" is defined as threshold soil organic carbon accumulation determined by inherent physio chemical characteristics of soil carbon pool (physical, chemical, biological) (Stewart *et al*.,2007). Saturation models often predict that SOC rises as carbon input rises, but that the incremental increase in SOC decreases as carbon input rises. As a result, soil storage efficiency falls to zero, and soil carbon levels approach saturation. Saturation capacity mostly depends on climatic conditions, quality and quantity of carbon input controlled by land use, and land management (Khandakar *et al*., 2017).

Silt + clay fractions can be used to estimate a soil's capacity to saturate carbon. Increases in carbon input do not result in an increase in carbon association with silt + clay particles (Di *et al*., 2018). The capacity of silt + clay falls to zero (carbon saturation), as OM stabilization effectiveness declines, a higher proportion of OM inputs accumulate in the readily mineralizable POM fraction (Castellano *et al*., 2012). The carbon saturation level of Silt + clay and physical protection pools can be determined by soil texture, cation availability, and mineralogy. For non-protected pools, it is the balance between C input and decomposition rate. While it comes to biologically protected pools, they are mostly controlled by the type of carbon inputs (Stewart *et al*., 2008a).

Some soils, particularly forest soil, are oversaturated. Soils with a significant carbon intake but little human activity are said to be carbon oversaturated (eg: forest, pastures). Hydro pedological features and climatic conditions may play important role in carbon storage above the theoretical saturation level (Khandakar et al., 2017).

Chung *et al*. have a good explanation for carbon saturation evidence (2010). Chung *et al*. (2010) claimed in their study that adding more carbon to the system did not result in carbon build-up. Temperate soils, for example, have more organic matter than tropical soils, which limits increased carbon storage. Although soil C saturation has crucial consequences for SOM management, it is not usually visible. Soil carbon inputs usually have a linear relationship with SOC concentration in soils that have been depleted due to long-term farming. Management practices show no significance in carbon stabilization indicate the presence of carbon saturation. Due to high SOC decomposition rates, agroecosystems subjected to soil disturbance from cultivation may never reach absolute carbon saturation but will achieve a maximum carbon sequestration level under a certain management regime. Soil carbon saturation is effective for managing soils as carbon sinks because soils close to maximum carbon storage capacity will sequester carbon less effectively.

Carbon saturation might lead to high productivity, according to Parvia *et al*., (2019). As the saturation theory claims mineral soils have limited capacity for stabilization. Due to increasing carbon intake and less mineralization as the soil approaches saturation, the storage level drops to zero. Soil carbon turnover rises under these conditions, resulting in increased nitrogen mineralization. This technique has the potential to create a positive feedback loop between plant production and N supply. Because of the constant availability of nitrogen, saturation enhances crop production.

The significance of soil carbon saturation is to identify areas with greater carbon storage capacity, as well as the rate at which carbon accumulates and the time takes for the soil to become saturated (Feng *et al*., 2012). It is critical to analyze soil carbon saturation during different studies as an increase in carbon input led to maximal SOC stock and further SOC accumulation will decline. As a result, if carbon saturation is not taken into account, SOC model simulations or SOC potential predictions have a high degree of uncertainty (Di *et al*., 2017;2018).

2.5 CARBON SATURATION DEFICIT

SOC stabilization is determined by silt and clay contents in soil. The maximum limit of C inputs to clay and silt fractions was reached, increasing the C inputs did not lead to any further increase in C associated with a fine fraction (Di et al., 2018). The ability of soil silt and clay particles to store more organic carbon is carbon saturation deficit or it is the difference between threshold saturation level and actual carbon content (carbon saturation deficit = soil carbon saturation – SOC_{cur}) (Stewart *et al*.,2008a; Di *et al*., 2018). Carbon saturation deficits are different for different land use systems. At the geographic scale, climate (temperature and precipitation), soil physicochemical parameters, and terrain were found to have a significant impact on soil C saturation deficiency.

Saturation deficit theory implying that if the soils may have a higher saturation deficit with low carbon content it has the potential to store additional carbon when managed appropriately. Such soils could be considered as soil sink. Conversely, soils with high carbon and less saturation deficit are said to be carbon sources they have less potential to store carbon (Khandakar *et al*., 2017; Stewart *et al*.,2008a).

Various management practices led to different decomposition rates, affect the SOC stabilization, and thus influence stable soil C saturation deficit in agricultural systems. It is necessary to investigate the stable carbon saturation deficit in soils under a variety of conditions (climate, soil characteristics, carbon input quality and quantity, and physiography). In their investigations, Di *et al*., (2018) found that elements such as soil characteristics, carbon intake, and climate all contribute to a stable soil carbon saturation deficit, and that temperature is a key determinant in determining carbon saturation deficit.

2.6 SATURATION MODELS

Interaction between clay and SOM led to the formation of micro aggregate these render biodegradation in soil. In clay soil, the rate of decomposition slows down (Hassink, 1997). At the same conditions, fine textured soil has a higher carbon storage capacity than coarse textured soil (Hassink, 1996;1997). Complexes formed by SOM are largely controlled by soil texture (Feng et al.,2013). Organic carbon associated with these fine particles has a longer turnover time and generates a C pool. These organic complexes formed are greatly affected by soil minerals and carbon input (Hassink, 1997; Feng *et al*.,2013). Hassink and Whitmore (1997) claimed that accumulation of SOC in excess silt + clay protective capacity would be prone to higher rates of decomposition, and soils' potential to prevent carbon was based mostly on silt + clay protective capacity.

Hassink and Whitmore (1997) used an adsorption mechanism to describe silt plus clay protective capacity. He used to identify the influence of soil texture with a rate of SOC accumulation with the help of specific models. Later in the investigation, it was discovered that C accumulation was not always dependent on soil texture (Stewart *et al*.,2008a;2008b). The Protective capacity of soil is the maximum amount of carbon associated with silt + clay particles. The degree to which a soil's protective capacity is saturated with organic matter has an impact on the retention of freshly supplied carbon residues (Hassink, 1997). Hassink (1996) added the quantity of carbon in soil derived from the decomposition of residue was more closely related to the degree of saturation of a soil's protective capacity than its clay. Hassink (1995) derived a formula for calculating protective capacity. The soil is said to be saturated if it has the maximum amount of silt and clay associated with carbon concentration as anticipated by the equation. It is assumed that soil with a lesser proportion of silt and clay linked with carbon content is unsaturated.

Hassink's approach simply took into account physical capacity., Baldock and Skjemstad (2000) in Stewart *et al*., (2008b) each mineral matrix had a unique capacity to stabilize organic carbon based on the chemical composition of the soil mineral fraction rather than physical capabilities. Carter (2002) in Stewart *et al*., (2008b) developed a conceptual model that combines carbon input, aggregate stability, and macro-organic matter, as well as protective capability. He added SOC increases it attains protective capacity further accumulation occurred in aggregate structures and macro-organic matter function of soil type and carbon inputs. According to six *et al*., (2002) carbon saturation is defined as the chemical association of silt and clay particles, physical protection within micro aggregates, biochemical complexity of the organic compound, and the unprotected carbon pool. Physical, chemical, biological, and unprotected pools, as well as silt + clay, protected pools, are all included in his model (White *et al*., 2014). For analyzing saturation, Feng *et al* (2013) identify limitations in the least square regression method of Hassink (1995). He employed organic carbon loadings and boundary line analysis to identify maximum carbon stabilization (Beare *et al*., 2014; Fujisaki *et al*., 2018).

2.7 CARBON STORAGE POTENTIAL QUANTIFICATION USING THE CARBON SATURATION DEFICIT

Studies show that Carbon saturation deficit can be used to predict soils' ability to hold more SOC (Barre *et al*., 2017). Increases in the stock of soil organic carbon (SOC) can help to reduce anthropogenic carbon emissions. Several agricultural strategies have been used to increase carbon stock. During management practice, the majority of the queries revolved around the soil's storage capacity. The maximum amount of carbon soil that can store over time by applying changes in land management is defined as carbon storage potential. This potential varies depending on pedoclimatic conditions. We quantify soil carbon saturation associated with fine soil particles, which is only a portion of total SOC, using the

Hassink equation in most cases. A considerable and variable fraction of total SOC stock is found in coarse-sized POM associated with sand-sized particles. This indicates the difference between actual carbon storage and carbon saturation deficit. Hence fine soil fraction's carbon saturation deficit alone is not conceptually acceptable for estimating the whole-soil carbon storage potential (Barre *et al*., 2017; Feng *et al*., 2014; Angers *et al*., 2011). When compared to OC in bulk soil, OC of fine soil has a longer residence time. Evaluating the fine soil fraction's carbon saturation deficiency may thus provide information on the potential of increasing the SOC stock with a long residence time.

SOC stock increases primarily as a result of various farming activities that serve to build carbon stock and slow decomposition. It has a deleterious effect in some circumstances. OC contained in a sand-sized particle, for example, has a lower residential value and is hence more vulnerable to carbon leakage. Non-sustainable farming methods typically result in carbon loss from the soil. The contribution of soils to climate change mitigation is limited in this way (Barre *et al*., 2017). SOC stock and saturation distribution can be determined at the national and state levels. It will aid in the knowledge of the agronomic, climatic, topographic, and pedological aspects that control the potential for carbon sequestration in soils, as well as the implementation of better strategies and policies for climate mitigation and productivity methods (Angers *et al*., 2011).

2.8 SOIL CARBON MITIGATION

Enhancing SOC stock is an efficient strategy to prevent climate change. When it comes to mitigation, SOC stability might be a major concern. In this case, management to increase SOC stock should be adopted. Fine-textured soil has more SOC than coarse-textured soil. sandy soils have a short turn-over period, it does not store a large quantity of carbon. In such soil, increasing carbon inputs and improving such management efforts are a waste of time. It increases the pace of decomposition, resulting in the release of carbon dioxide into the atmosphere. If carbon inputs were given to clayey soils rather than sandy soils, they would be more advantageous for carbon storage.

SOC may be enhanced for lower emissions, according to Kirschbaum *et al*., (2019), by simply moving available SOC from regions with low soil protective capacity to areas with high soil protective capacity. When both carbon losses from sandy soils and carbon gains from clayey soils are added together, this might result in a tiny but useful net increase in SOC storage across both soils (Kirschbaum *et al*., 2019).

CHAPTER 3

MATERIALS AND METHODS

The present investigation entitled "Evaluating soil carbon saturation in different Argo ecological zones of Kerala" was carried out during 2020-2021. The data was collected from different published sources such as scientific papers, research articles and thesis. The details of the study area and methodology followed in the study are described below.

3.1 STUDY AREA

The five AEZs and 23 agroecological units in Kerala (AEU) were considered in the present study. The AEZ of Kerala was prepared by integrating climate, geomorphology, land use and soil variability. The five agroecological zones in Kerala have been further subdivided into twenty-three agroecological units, and ninety-eight agroecological subunits. Figures 1 - 2 given below depicts the spatial distribution of the AEZ and AEU in Kerala.

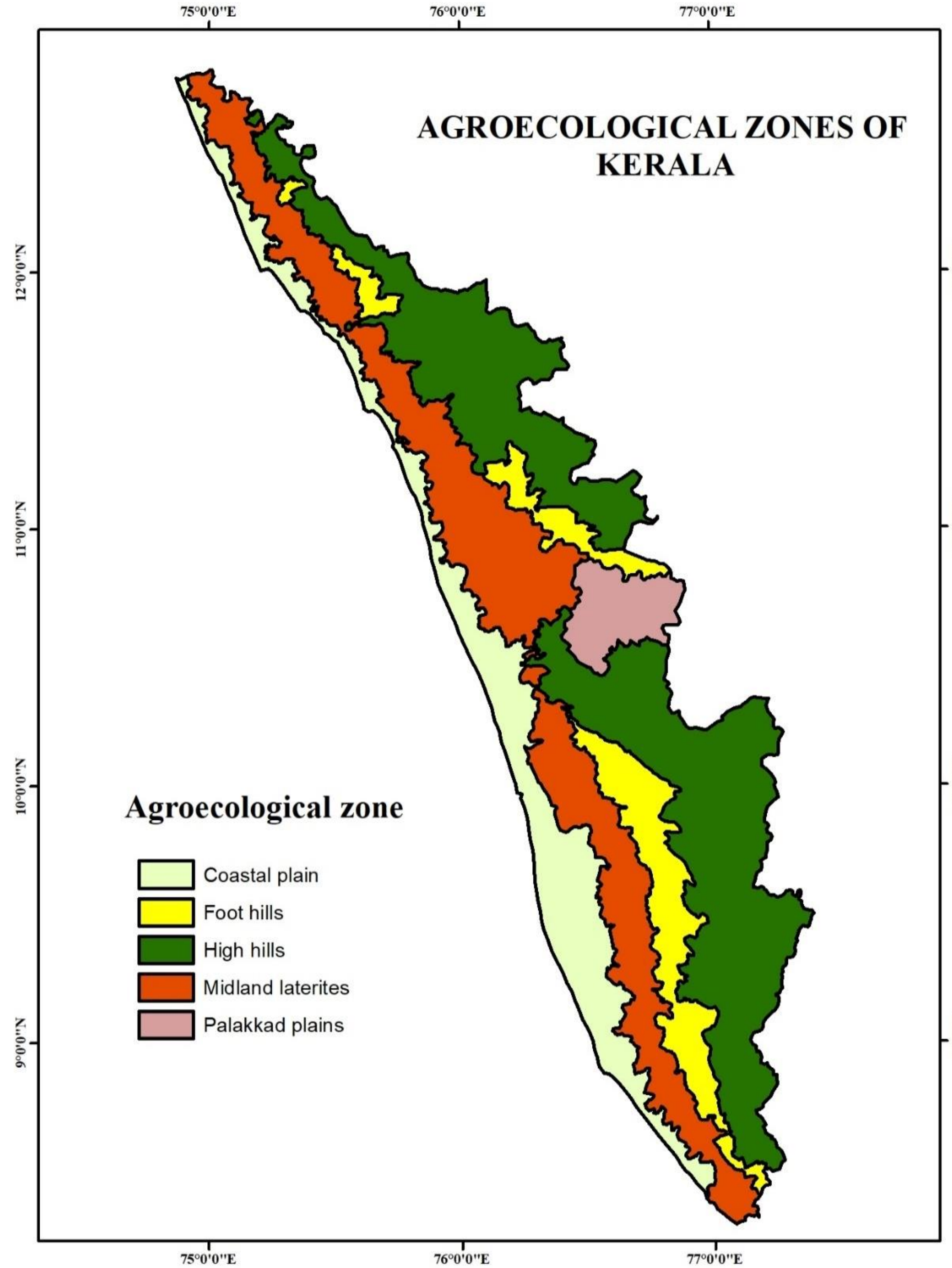

Figure 1: Map depicting the AEZs in Kerala

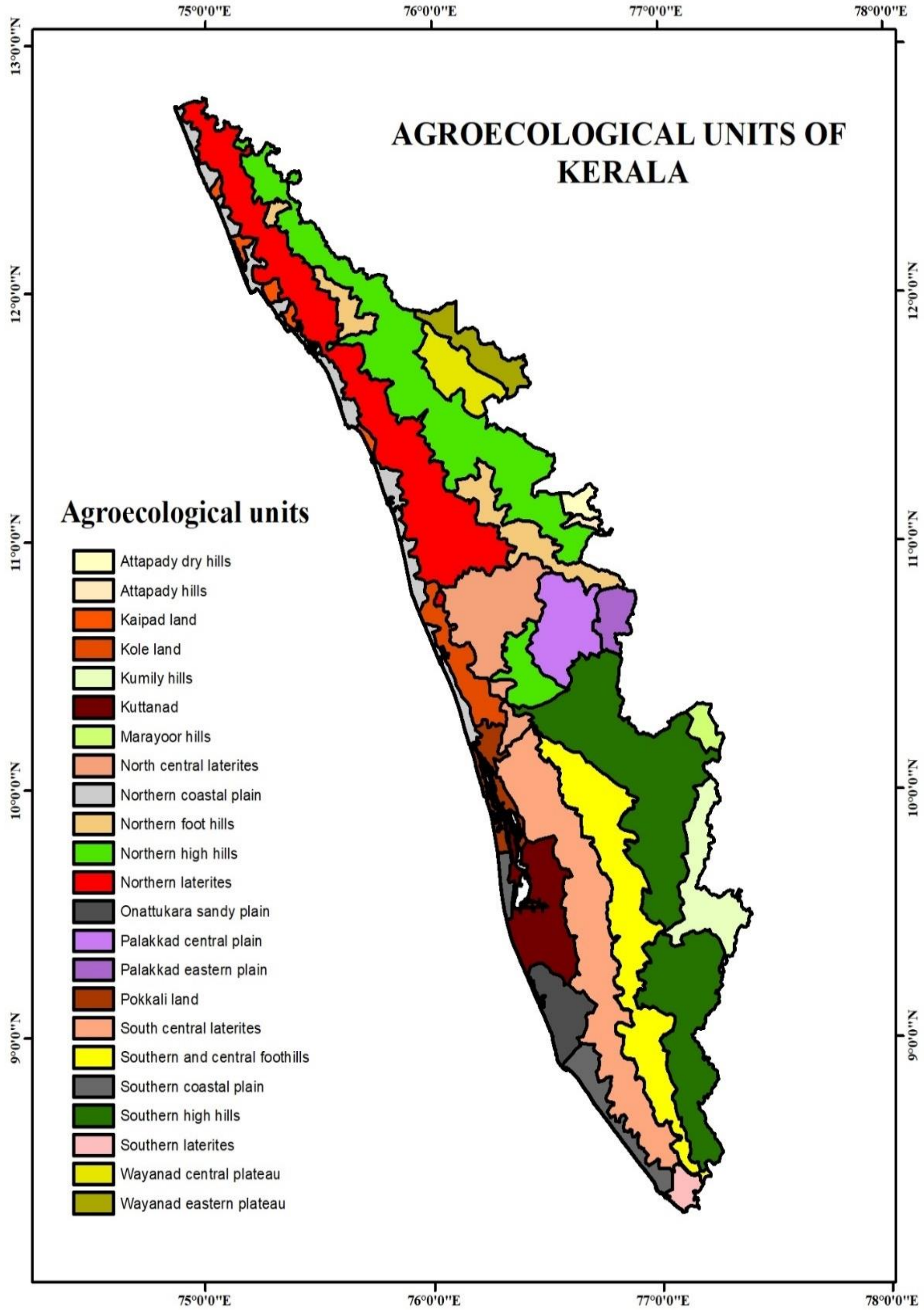

Figure 2 : Map depicting the AEU in Kerala

3.2 DATA COLLECTION

The data was gathered from secondary sources like research papers, research thesis, scientific reports, and from soil survey reports by Govt. of Kerala. About 450 research papers, 4331 data points were analyzed for data collection. The information gathered was processed in excel. Location, SOC (%), land use, particle size, mineral composition, soil depth, and organic matter were the data collected. Soil data are taken for top soils (0 -20 cm) only. The location details was entered using Google earth and a spatial database was created. The database was customized according to Hassink equation. The units were converted to same for calculating Hassink equation. Appendix.1 shows the outline of database.

3.3 ESTIMATION OF CARBON SATURATION OF SOILS

The protective capacity of a soil, also known as carbon saturation, is defined as the capacity of a soil to physically retain organic C by its association with clay and silt particles, and was estimated using the linear regression equation:

$$C_{sat}\ (g\ C/kg) = 4.09 + 0.37(\%\ particles < 20\ \mu m)$$

Where C sat represents carbon saturation in g C/Kg, and particle percentage is calculated as silt + clay = 100 – sand, represented as a percentage or g/100g (Hassink, 1997; Kettler *et al*., 2001; Feng *et al*., 2014a; Stewart *et al*., 2008b; Wiesmeier *et al*., 2014; Meyer *et al*., 2017; Barre *et al*.,2017). Carbon accumulation is identified by the slope of Hassink equation. Here, 0.37 represent slope and 4.09 represent the intersect of linear regression line

The soil carbon saturation estimated using the Hassink equation was used to assess the carbon deficit in different AEZ and AEU as difference between the present SOC content and saturation values for that particular soil.

$$C_{sat\text{-}def} = C_{sat} - SOC$$

Where $C_{sat\text{-}def}$ is carbon saturation deficit, C_{sat} is carbon saturation calculated using Hassink equation in percentage and SOC is actual soil organic carbon of that area.

The estimated carbon saturation deficits were divided into four categories: no deficit (value less than zero), low deficit (between 1 and 0.75), medium deficit (0.75 – 1.5), and high deficit (greater than 1.5). Based on these categories, carbon saturation maps were developed for each district, and the percentage of deficient regions were calculated for both AEZ and AEU.

3.4 DEVELOPMENT OF SOIL CARBON SATURATION DEFICIT MAP

Carbon Saturation map provides a visual representation of the regional distribution of carbon storage potential, which may be used to audit carbon sinks. ArcGIS software (ArcMap 10.8) was used for mapping.

3.4.1 Georeferencing

AEU and AEZ maps were scanned and converted to raster data (.tif) format for georeferencing. Georeferencing of the image was done and the latitude and longitude points were inserted in Coordinate DMS (Degree minute seconds) with the help of the control point tool.

3.4.2 Digitization

Digitization is the process of creating an electronic replica of a real-world item or event that can be saved, displayed, and modified on a computer, as well as broadcast through networks (Manjula *et al*., 2010). The georeferenced raster data was digitized to vector data in shapefile format and was projected with WGS1984 datum. On screen visual digitization of the map was done with the editor tool in ArcMap and the attribute table was created and details of the spatial data was updated.

3.4.3 Interpolation

Interpolation is a technique for predicting values of cells using a small number of sample data points. In the present study, the carbon saturation deficit range within the district was identified with the help of the IDW (Inverse Distance Weighted) tool. IDW is an interpolation method that estimates cell values by averaging the values of sample data points in the nearby processing cell.

CHAPTER 4

RESULTS

4.1 CARBON SATURATION IN AGROECOLOGICAL ZONES OF KERALA

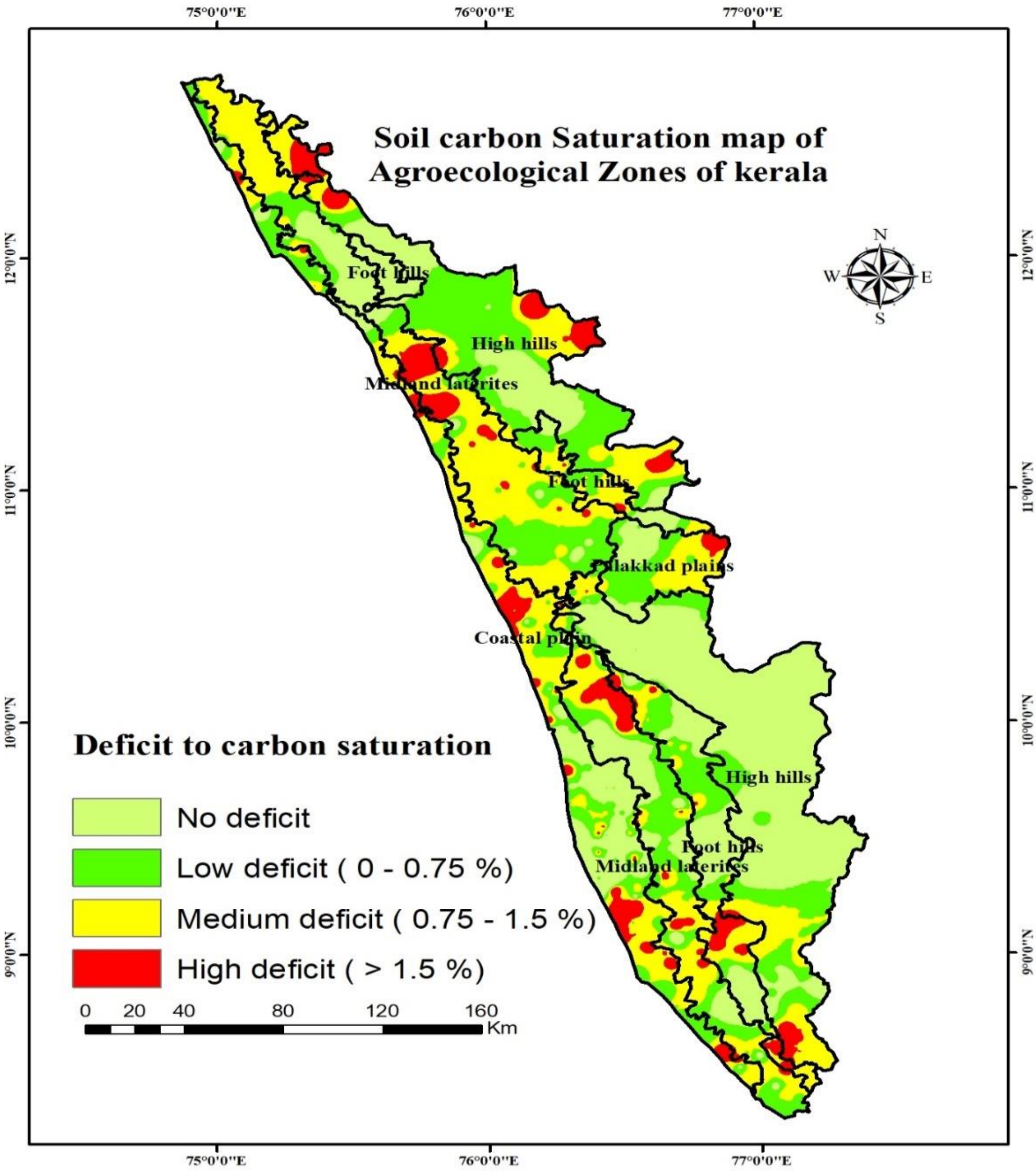

Figure 3: Soil carbon Saturation map in agroecological zones of Kerala

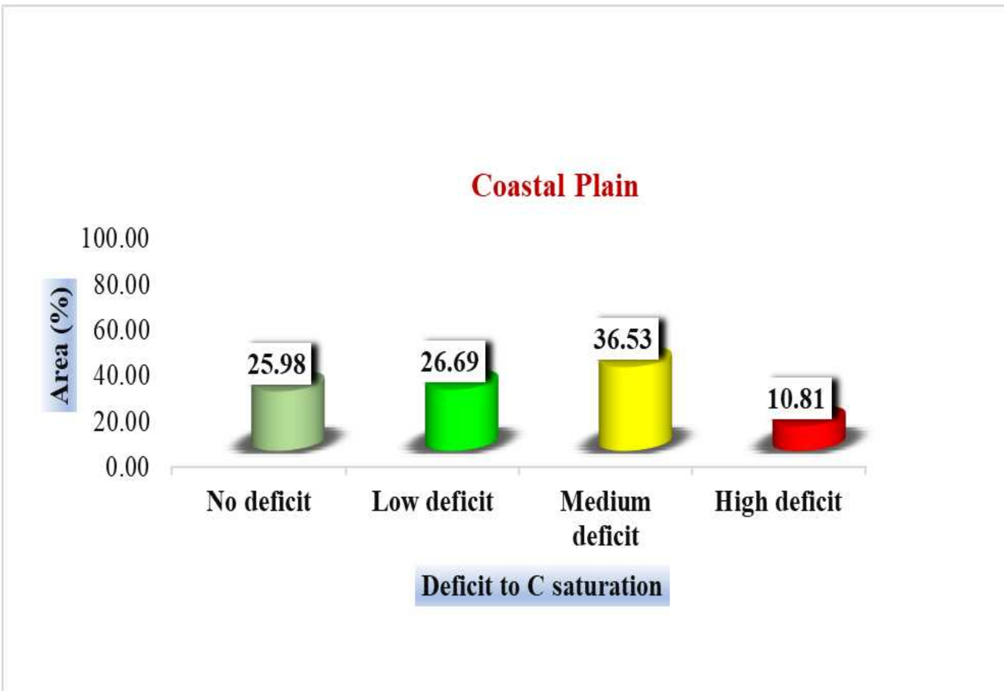
Coastal Plain
100.00
80.00
60.00
40.00
20.00
0.00
Area (%)
25.98
26.69
36.53
10.81
No deficit
Low deficit
Medium deficit
High deficit
Deficit to C saturation

Fig: (4a)

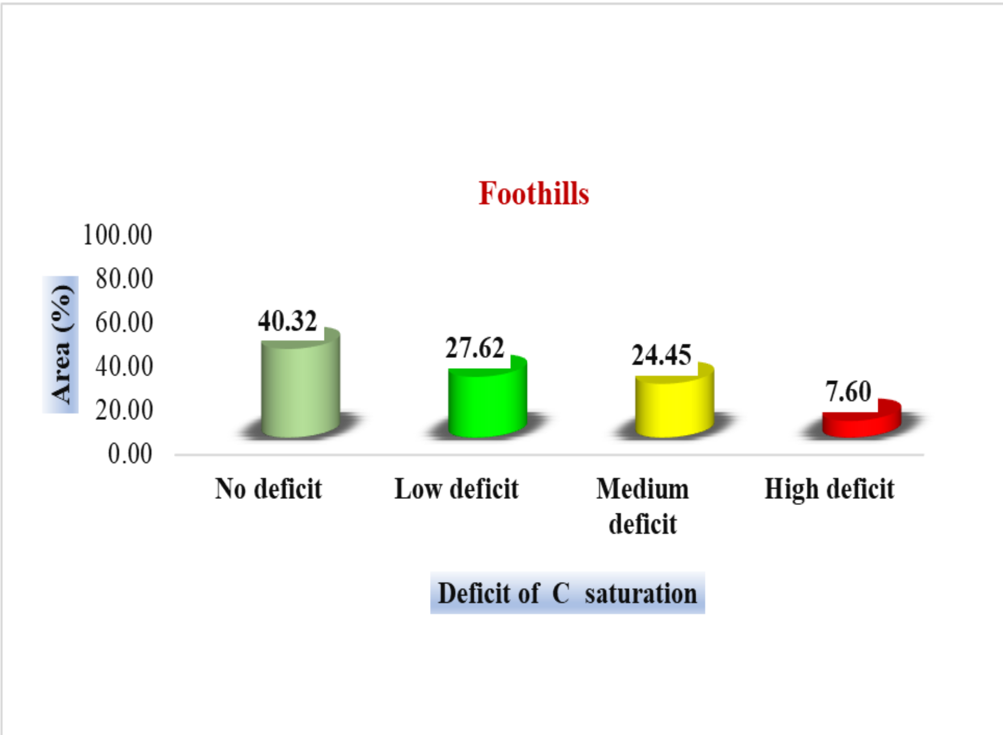
Foothills
100.00
80.00
60.00
40.00
20.00
0.00
Area (%)
40.32
27.62
24.45
7.60
No deficit
Low deficit
Medium deficit
High deficit
Deficit of C saturation

Fig: (4b)

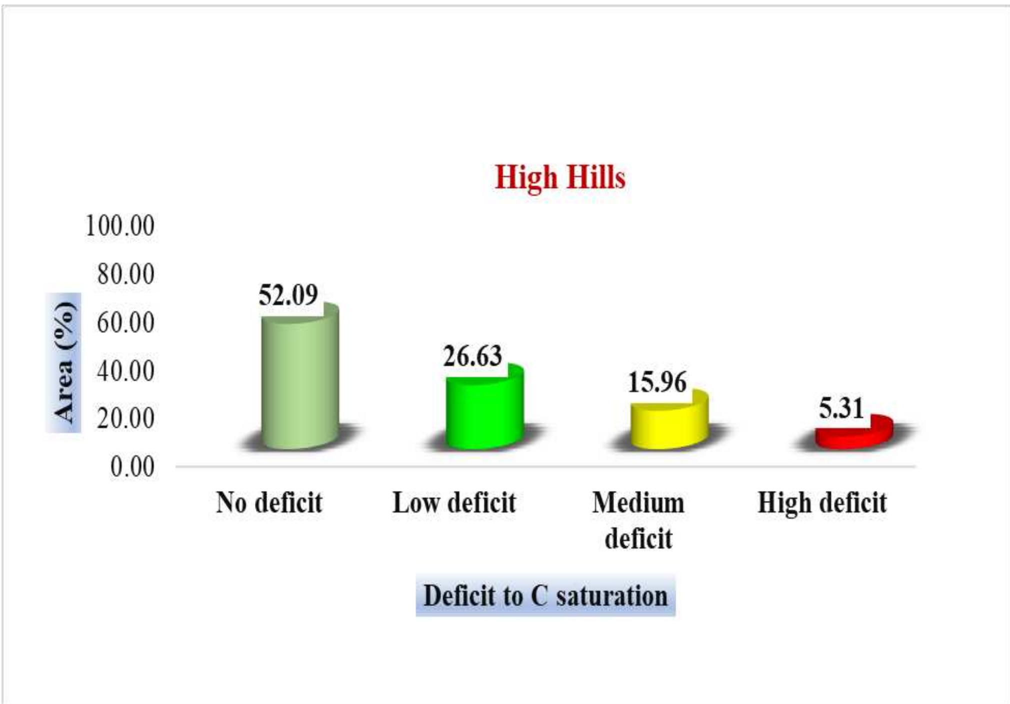
High Hills
100.00
80.00
60.00
40.00
20.00
0.00
Area (%)
52.09
26.63
15.96
5.31
No deficit
Low deficit
Medium deficit
High deficit
Deficit to C saturation

Fig: (4c)

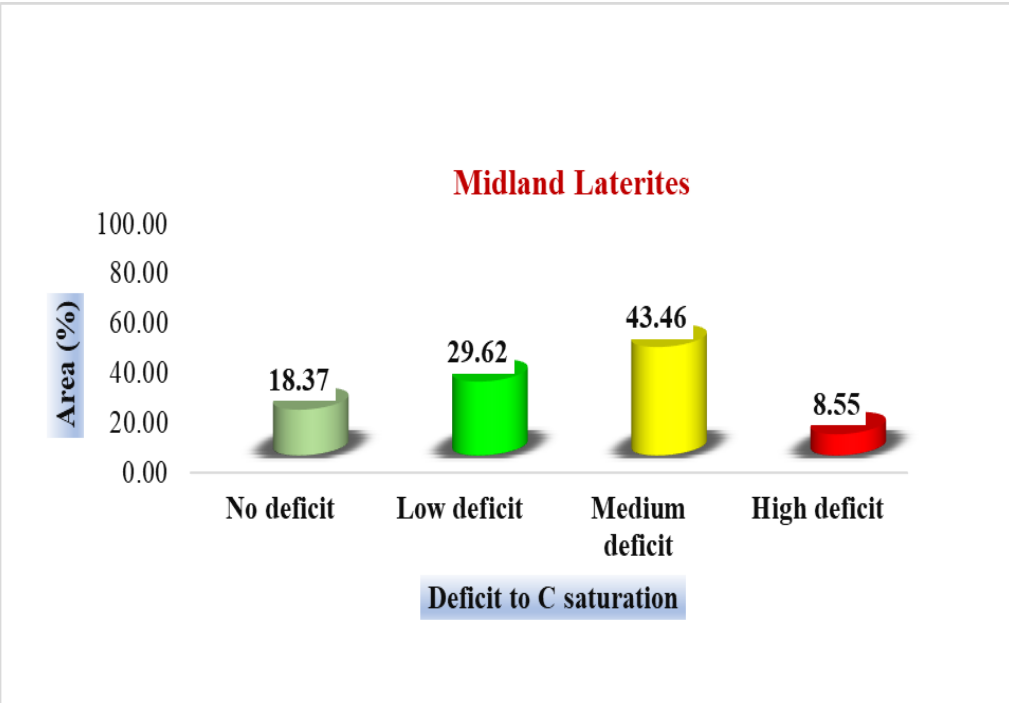
Midland Laterites
100.00
80.00
60.00
40.00
20.00
0.00
Area (%)
18.37
29.62
43.46
8.55
No deficit
Low deficit
Medium deficit
High deficit
Deficit to C saturation

Fig: (4d)

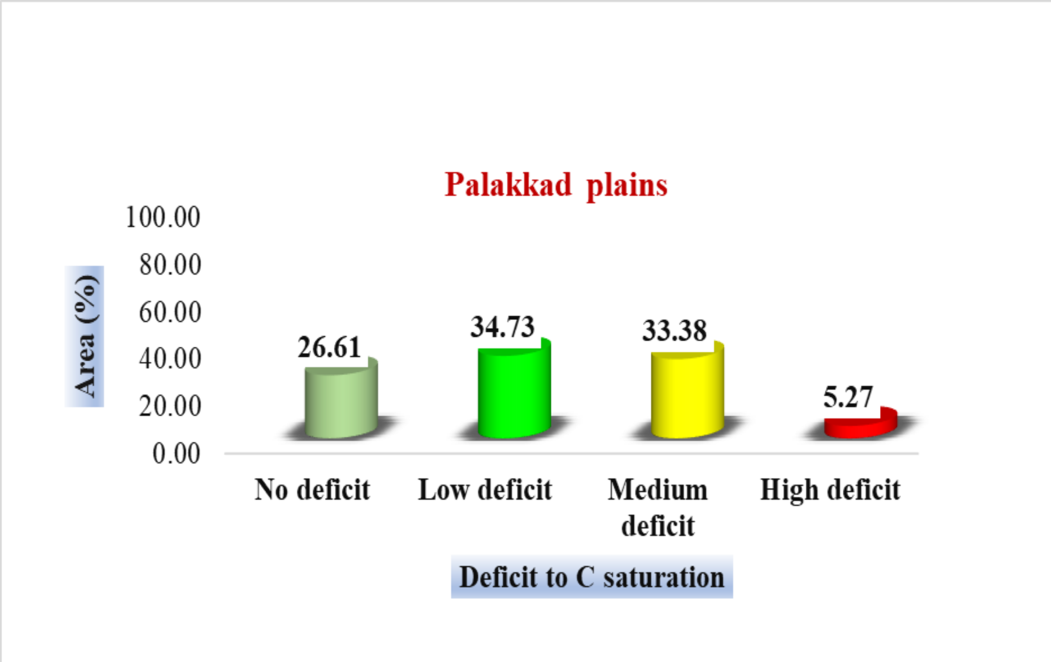

Fig: (4e)

Figures 4a, 4b, 4c, 4d, 4e: Graphs representing soil carbon saturation range in different AEZs of Kerala

Kerala state is divided into five agroecological zones: Coastal Plain, Midland Laterites, Foothills, High Hills, and Palakkad Plain. The Coastal Plain AEZ is a gently slopy land lying between the sea and midlands. This zone covers nearly 13.10% of the total geographical area. Soil carbon saturation deficit in Coastal Plain was almost equally distributed between the medium carbon deficit (36.53%) soil, low carbon deficit (26.69%) and no carbon deficit (25.98%) categories. High carbon deficit category of soils ranged to about 10.81% of the total area under this zone.

Midland laterites are the narrow valleys between the coastal plain on the west and foothills and hills on the east, extending from the southern end to the northern end of the state. It covers about 27.18% of the total geographical area of the state. This AEZ was found to have majority of the area under medium carbon deficit (43.46%) followed by low carbon deficit areas (29.62%). No carbon deficit (18.37%) and high carbon deficit (8.55%) zones were relatively less in this zone.

Low hills between the midland laterite on the west and high hills on the eastern side constitute the Foothills agroecological zone. It covers about 11.84% of the geographical area of the state. Nearly 78% of the area under this zone was found to be in the no or low carbon deficit categories. Only 7.60% of the total area under this AEZ was found to be under high carbon deficit that demands intensive carbon management.

High hills are the hilly region comprising the Western Ghats and plateaus extending from south to north. The Western Ghats comprise Central Sahyadri, the Nilgiris, and South Sahyadri. This zone covers about 39.97% of the total geographical area of Kerala. Most of the are in the High hills AEZ was carbon was rich (no carbon deficit - 52.09%; low carbon deficit - 26.63%). Only 5.31% of the area was under high carbon deficit category in this AEZ.

Palakkad plains are the gently sloping lands of Palakkad, east of Kuthiran hills, bound on the south and north by Nelliyampathy hills and Attappady hills, respectively, and merging with Tamil Nadu uplands through the gap in the Western Ghats. This zone covers 4.12% of the state. Here low carbon deficit (34.73%), medium carbon deficit (33.38%), and no carbon deficit (26.61%) categories are approximately equally distributed. High carbon deficit (5.27%) category is very minimal in this zone.

Among the five AEZ, soils of high carbon deficits are relatively very low, whereas most of the soils fall in the medium, low and no carbon deficit categories. Relatively more carbon deficit can be found in coastal plain compared to other AEZs. Generally, it can be concluded that majority of soils in Kerala shows a low to medium carbon saturation deficits. Vast tracts of soils have attained their carbon saturation and further additions of carbon inputs without sound soil carbon stabilization strategies may encourage carbon emissions from these soils.

The AEZ have been further subdivided into 23 AEUs (Table 1). The mean of carbon deficit categories indicates that 61.22% of the total area in all AEUs of Kerala fall under low and medium carbon deficit categories. Maximum area of

AEU with high carbon deficit were observed in Onattukkara sandy plains (AEU 3), Attapady hills (AEU 18), Attapady dry hills (AEU 19), Wayanad eastern plateau (AEU 21) and Palakkad eastern plains (AEU 23). Nearly all area in the AEUs Kumily hills (AEU 16) and Marayoor hills (AEU 17) were found to be fully carbon saturated or had no carbon deficit.

Table1: Soil carbon saturation deficit area coverage in each AEUs of Kerala

Agroecological units of Kerala (23)	Area (%)			
	No deficit	Low deficit	Medium deficit	High deficit
Southern coastal plain	8.39	40.63	40.52	10.46
Northern coastal plain	13.99	29.43	48.67	7.91
Onattukara sandy plain	2.67	13.52	51.55	32.26
Kuttanad	67.58	24.24	7.40	0.78
Pokkali land	31.16	17.99	43.21	7.64
Kole land	6.37	31.12	43.73	18.77
Kaipad land	13.55	39.76	34.65	12.05
Southern laterites	3.37	55.28	40.45	0.90
South central laterites	28.82	31.62	28.69	10.87
North central laterites	6.16	48.67	42.10	3.08
Northern laterites	16.61	18.47	55.11	9.81
Southern and central foothills	43.11	29.34	19.92	7.63
Northern foothills	38.83	23.92	32.53	4.72
Southern high hills	67.76	18.32	11.88	2.04
Northern high hills	35.29	39.67	19.24	5.81
Kumily hills	99.74	0.26	0.00	0.00
Marayoor hills	100.00	0.00	0.00	0.00
Attappady hills	0.00	18.49	51.78	29.74
Attappady dry hills	0.00	0.00	63.59	36.41
Wayanad central plateau	7.80	61.72	28.67	1.81
Wayanad eastern plateau	0.00	26.81	34.00	39.19
Palakkad central plain	37.94	44.04	18.02	0.00
Palakkad eastern plain	0.00	3.03	76.13	20.84

4.2 ANALYSIS Of DISTRICT WISE SOIL CARBON SATURATION

4.2.1 Carbon Saturation in Agroecological Units of Trivandrum District

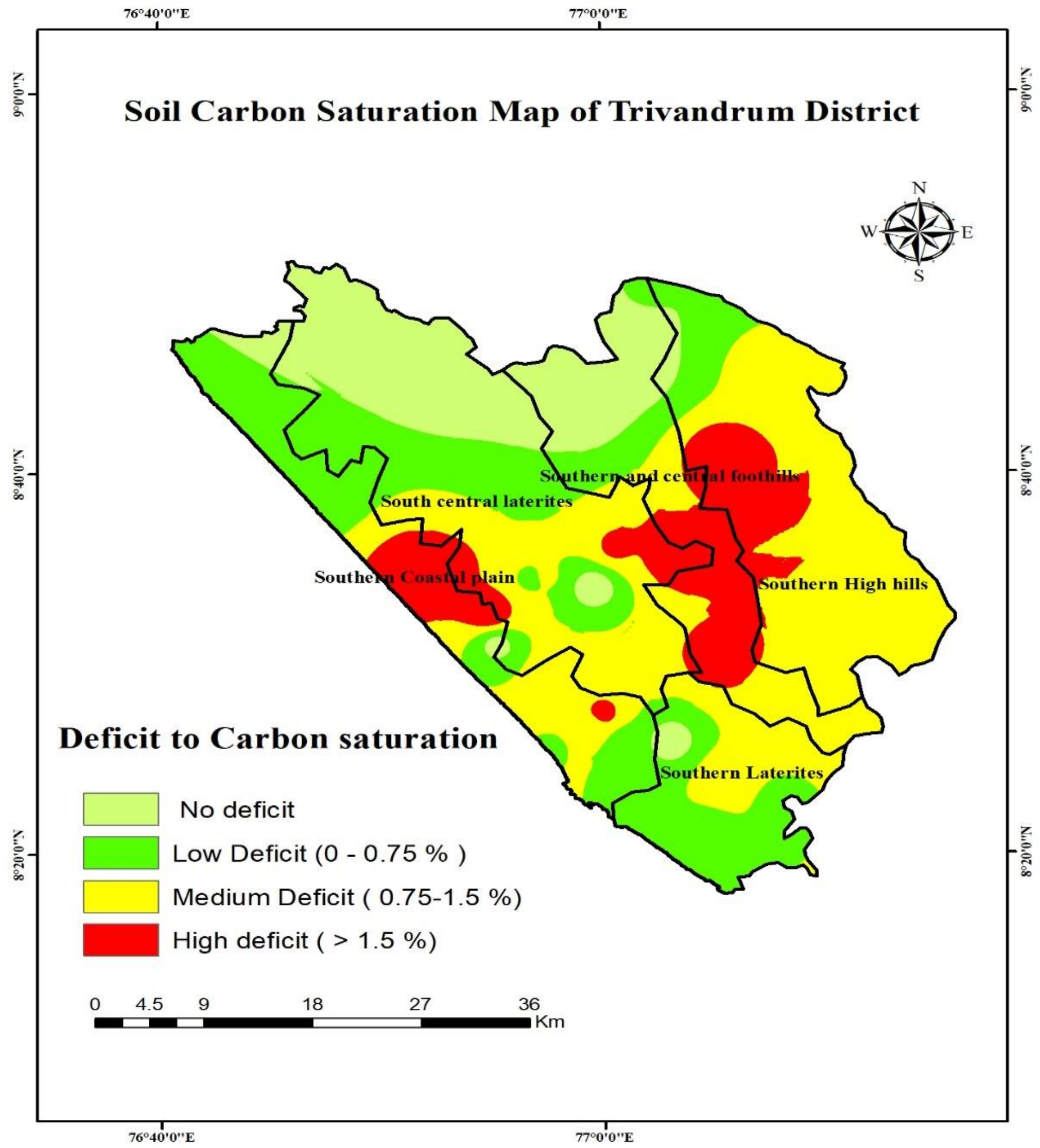

Figure 5: Soil carbon Saturation map in agroecological units of Trivandrum district

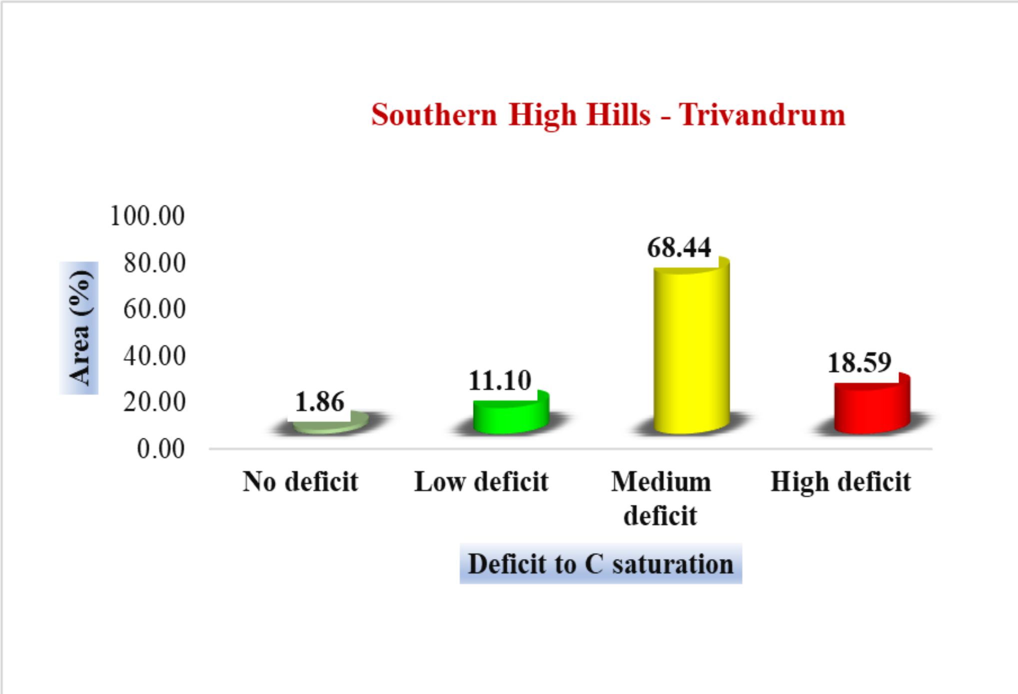
Southern High Hills - Trivandrum
Area (%)
100.00
80.00
60.00
40.00
20.00
0.00
1.86
11.10
68.44
18.59
No deficit
Low deficit
Medium deficit
High deficit
Deficit to C saturation

Fig:(6a)

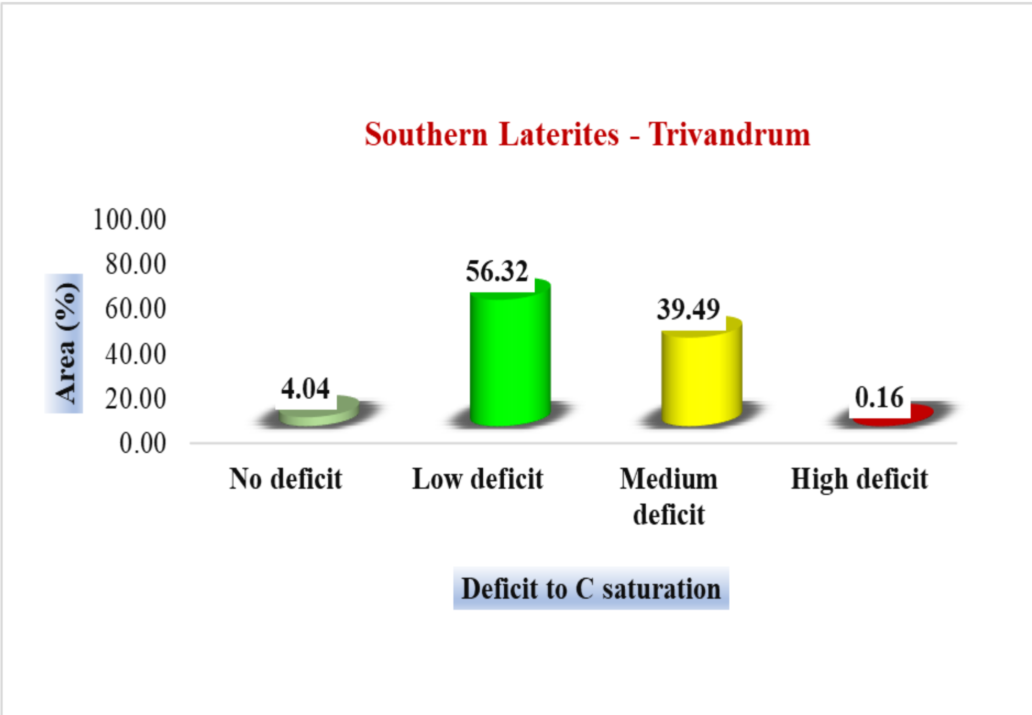
Southern Laterites - Trivandrum
Area (%)
100.00
80.00
60.00
40.00
20.00
0.00
4.04
56.32
39.49
0.16
No deficit
Low deficit
Medium deficit
High deficit
Deficit to C saturation

Fig: (6b)

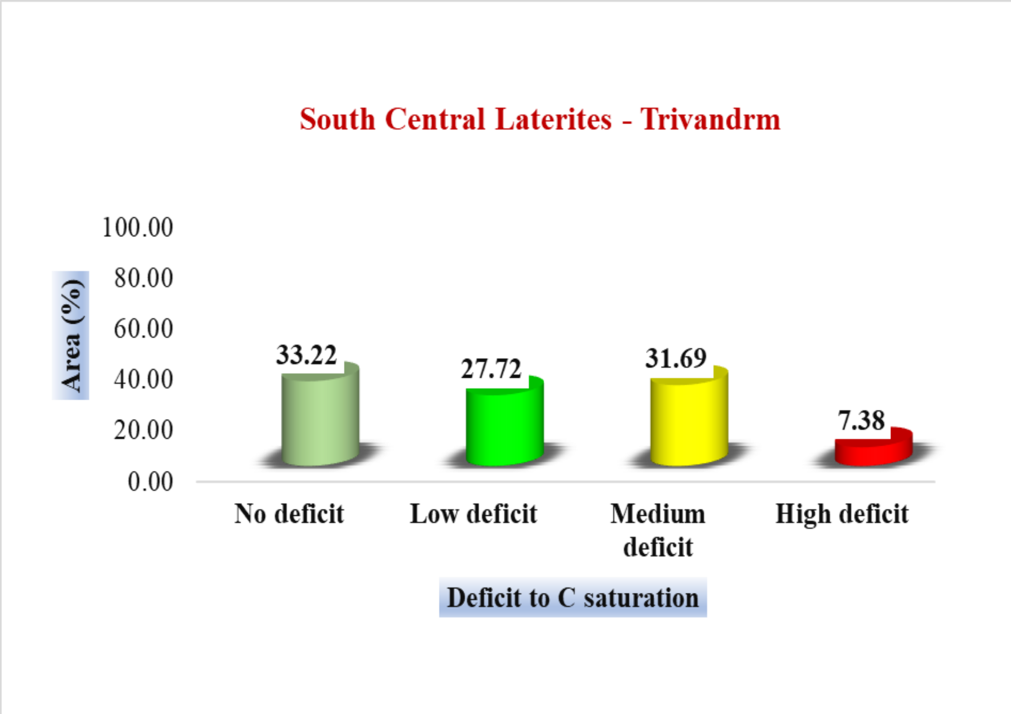
South Central Laterites - Trivandrm
Area (%)
100.00
80.00
60.00
40.00
20.00
0.00
33.22
27.72
31.69
7.38
No deficit
Low deficit
Medium deficit
High deficit
Deficit to C saturation

Fig: (6c)

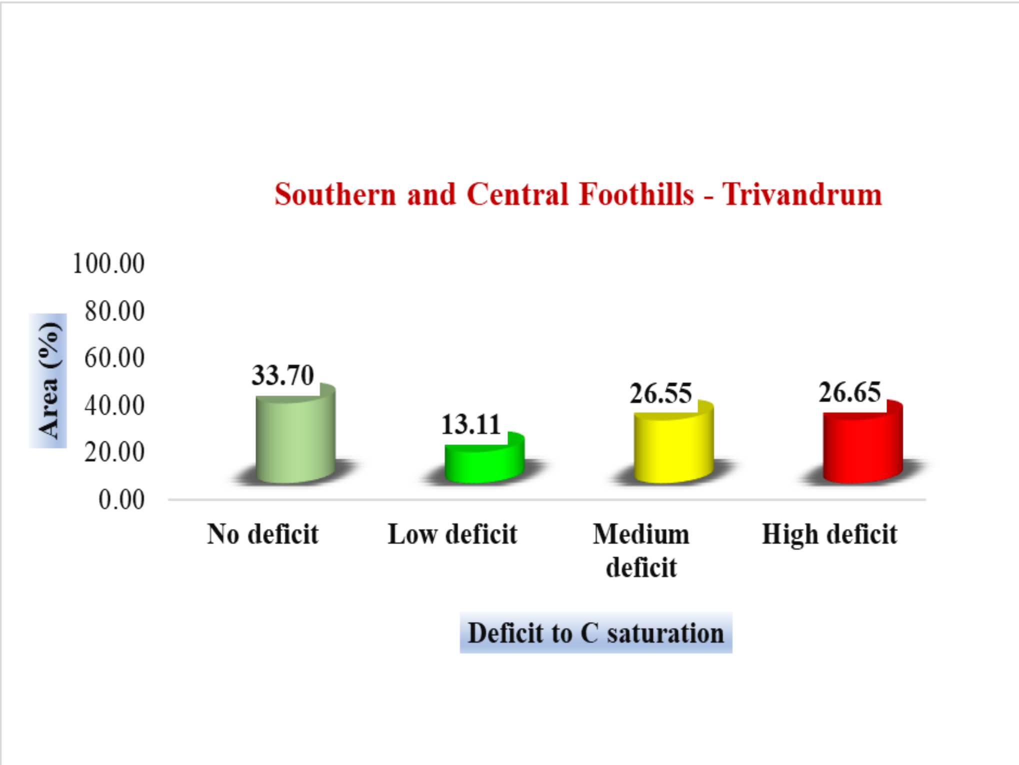
Southern and Central Foothills - Trivandrum
Area (%)
100.00
80.00
60.00
40.00
20.00
0.00
33.70
13.11
26.55
26.65
No deficit
Low deficit
Medium deficit
High deficit
Deficit to C saturation

Fig: (6d)

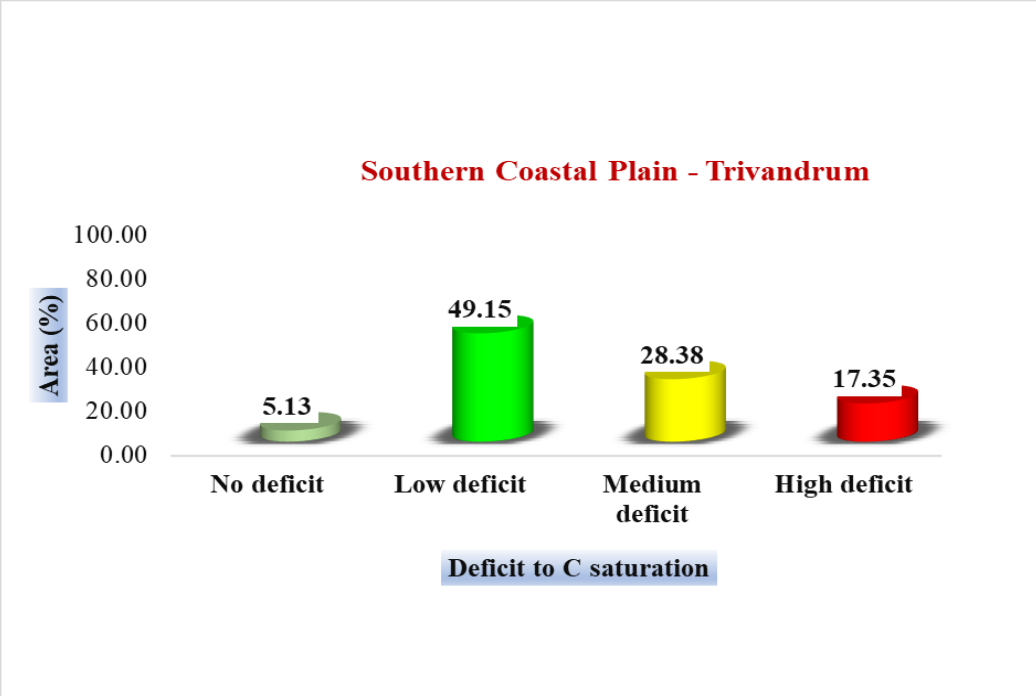

Fig: (6e)

Figures 6a, 6b, 6c, 6d, 6e: Graphs representing soil carbon range in different AEUs of Trivandrum

Southern high hills, southern laterites, south central laterites, southern and central foothills, and southern coastal plains were the five agroecological units that comes under. Trivandrum district. In Trivandrum district, Southern High Hills had maximum area under medium C deficit (68.44%). In the AEU Southern Laterites 95.81% of the soils were found to be in low and medium carbon deficit category. In South Central laterites, the soils had nearly equal proportions of soil area under no carbon deficit (33.22%), low carbon deficit (27.72 %) and medium carbon deficit (31.69 %). In Southern and Central Foothills more than 50% of the soils were in medium to high carbon deficit categories. In southern coastal, only 5.13 % of the soils were found to be with no carbon deficit. In no deficiency zones, carbon inputs should be rationalized as these areas doesn't hold much potential to retain additional carbon inputs.

4.2.2 Carbon Saturation in Agroecological Units of Kollam District

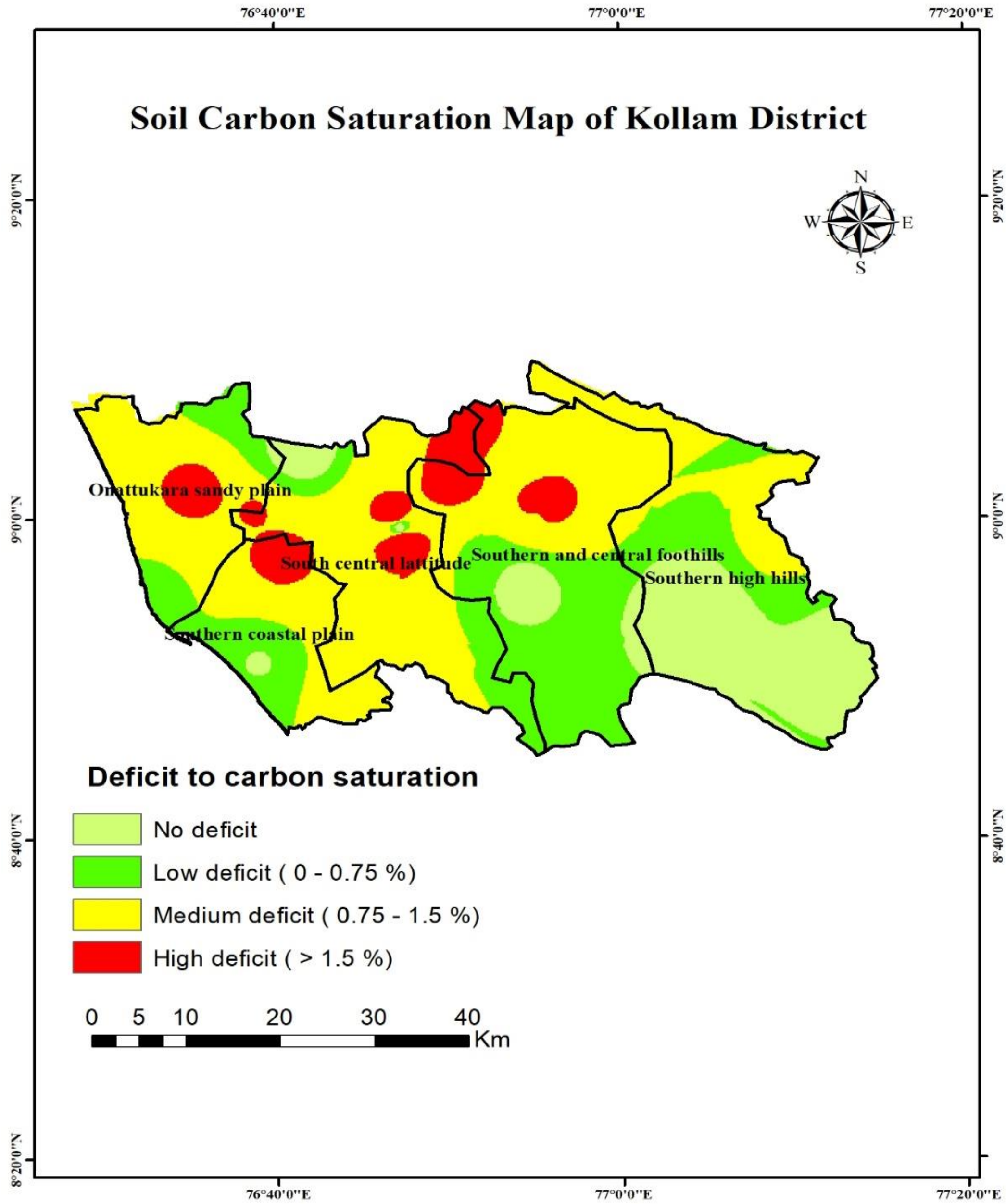

Figure 7: Soil carbon Saturation map in agroecological units of Kollam district

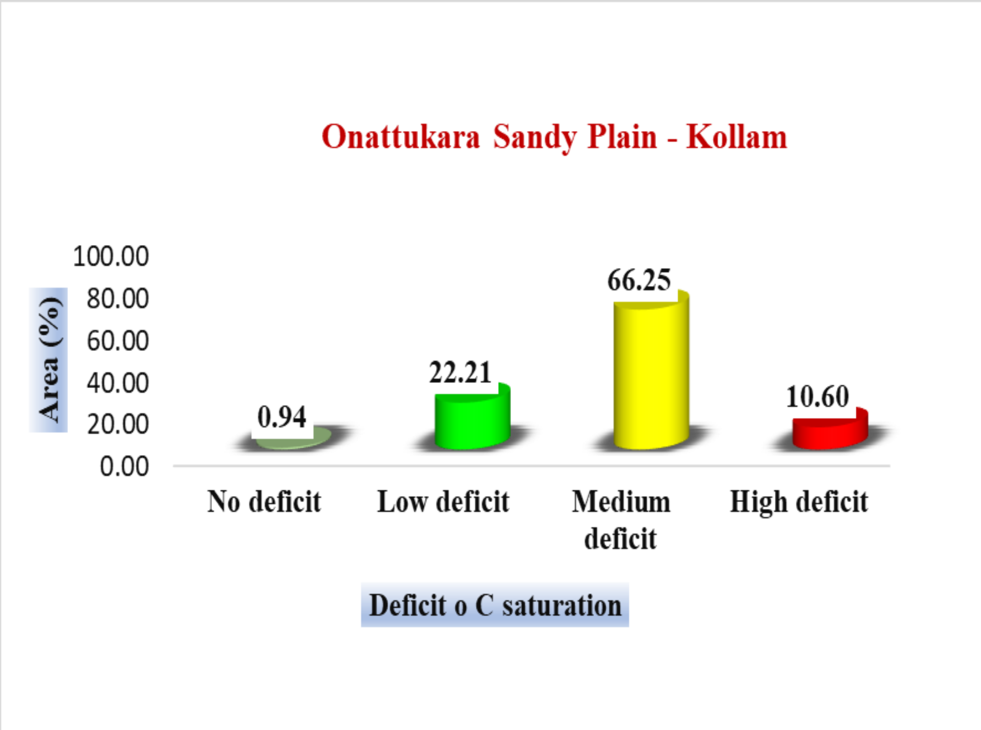
Onattukara Sandy Plain - Kollam
Area (%)
100.00
80.00
60.00
40.00
20.00
0.00
0.94
22.21
66.25
10.60
No deficit
Low deficit
Medium deficit
High deficit
Deficit o C saturation

Fig: (8a)

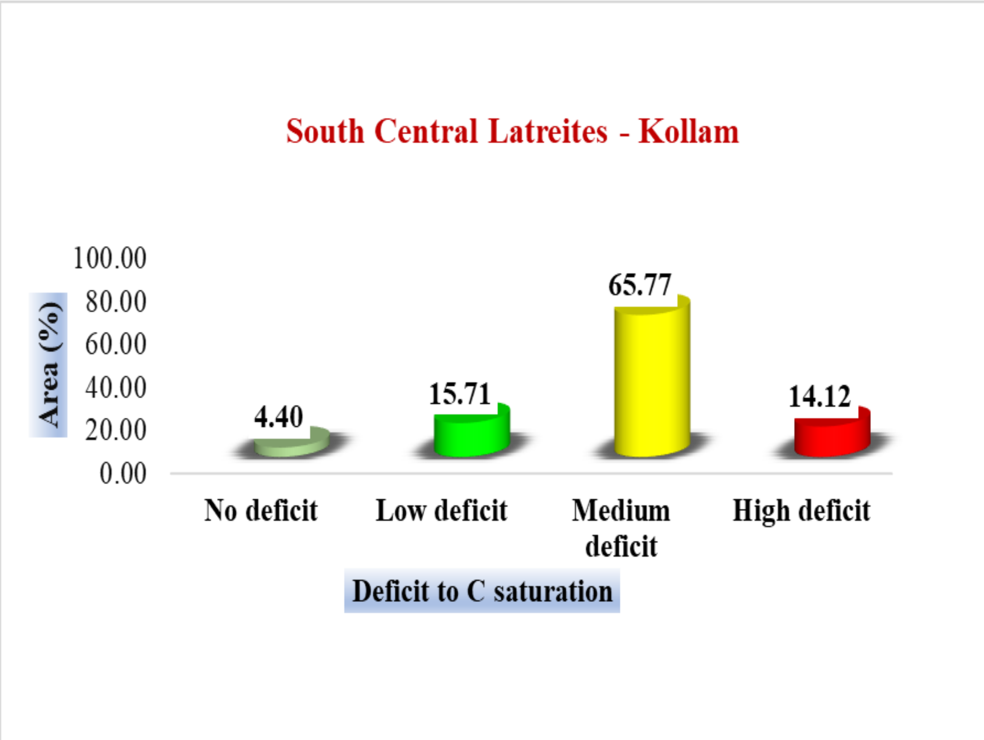
South Central Latreites - Kollam
Area (%)
100.00
80.00
60.00
40.00
20.00
0.00
4.40
15.71
65.77
14.12
No deficit
Low deficit
Medium deficit
High deficit
Deficit to C saturation

Fig: (8b)

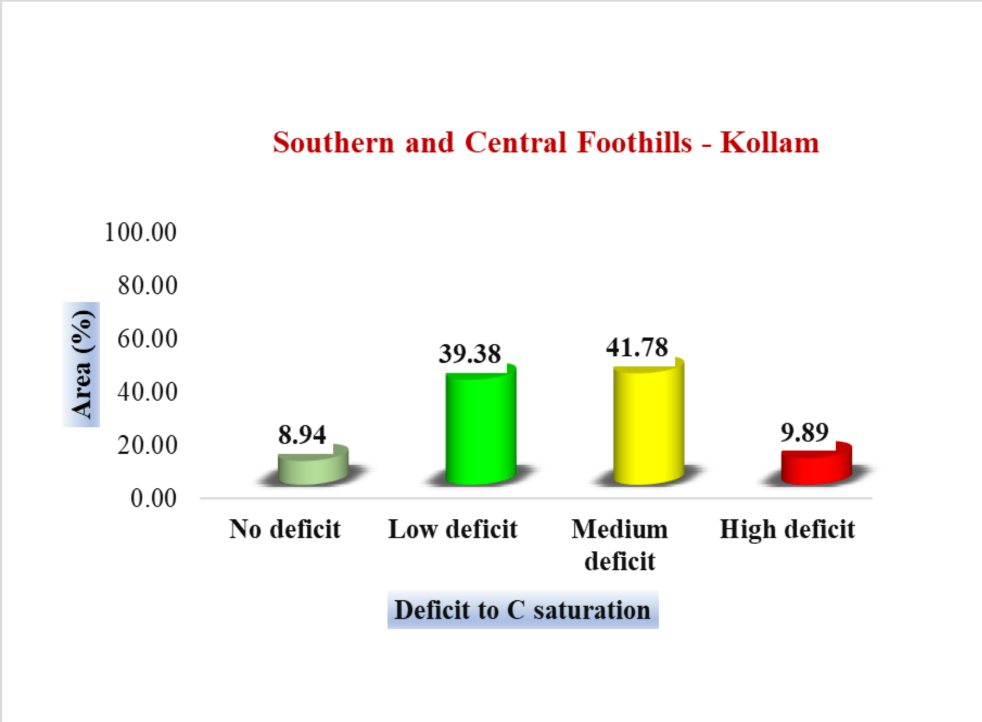
Southern and Central Foothills - Kollam
100.00
80.00
60.00
40.00
20.00
0.00
Area (%)
8.94
39.38
41.78
9.89
No deficit
Low deficit
Medium deficit
High deficit
Deficit to C saturation

Fig: (8c)

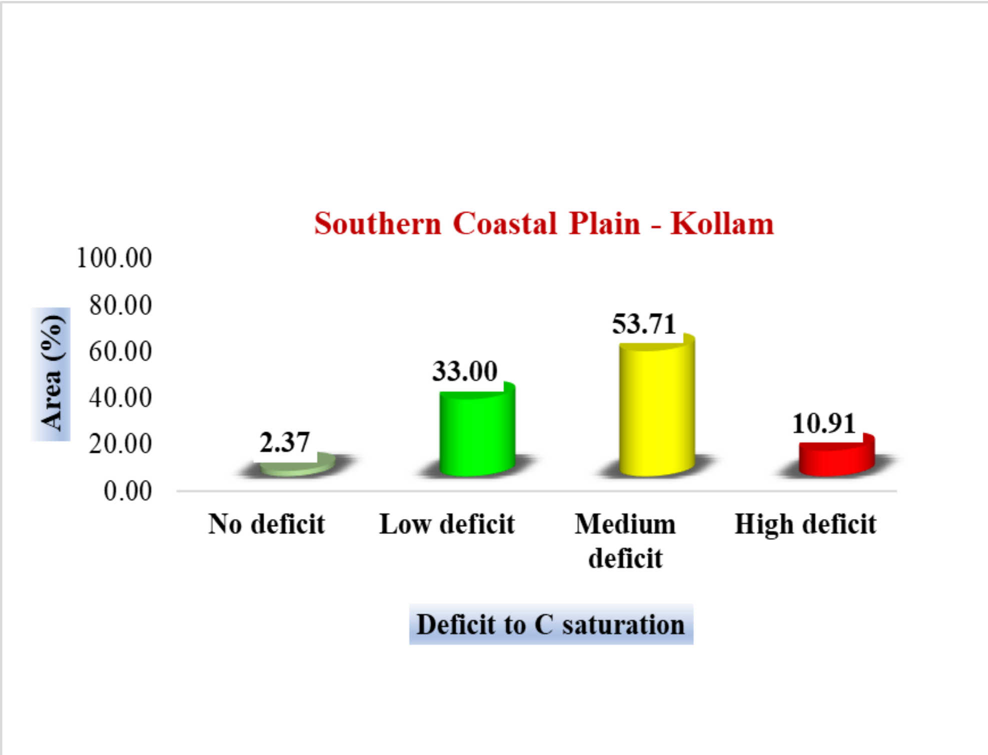
Southern Coastal Plain - Kollam
100.00
80.00
60.00
40.00
20.00
0.00
Area (%)
2.37
33.00
53.71
10.91
No deficit
Low deficit
Medium deficit
High deficit
Deficit to C saturation

Fig: (8d)

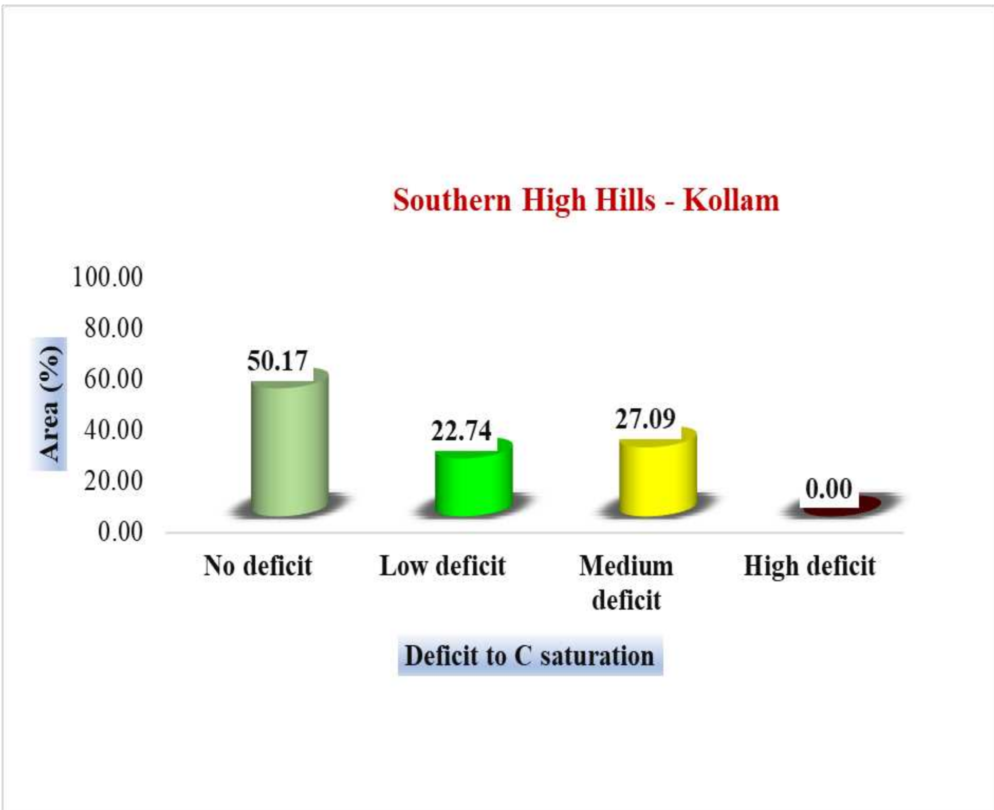

Fig: (8e)

Figures 8a, 8b, 8c, 8d, 8e: Graphs representing soil carbon range in different AEUs of Kollam

There were five AEUs in the Kollam area. The Onattukara sandy plain, which distributed in the districts of Kollam and Alappuzha, were found to have large tracts under medium carbon deficiency (66.25 %). The southern and central foothills had maximum area under medium carbon deficiency (41.78%), whereas soils with high carbon deficits was nil in southern high hills. In Southern High Hills maximum area was found to be with no carbon deficit (50.17%), whereas in southern coastal plain such soils were found to be at a minimum (2.37%). Low deficit carbon soils were mainly distributed in southern and central foothills (39.38%) of Kollam district. In general, soils in Kollam district were found to fall mainly in the medium deficit category.

4.2.3 Carbon Saturation in Agroecological Units of Alappuzha District

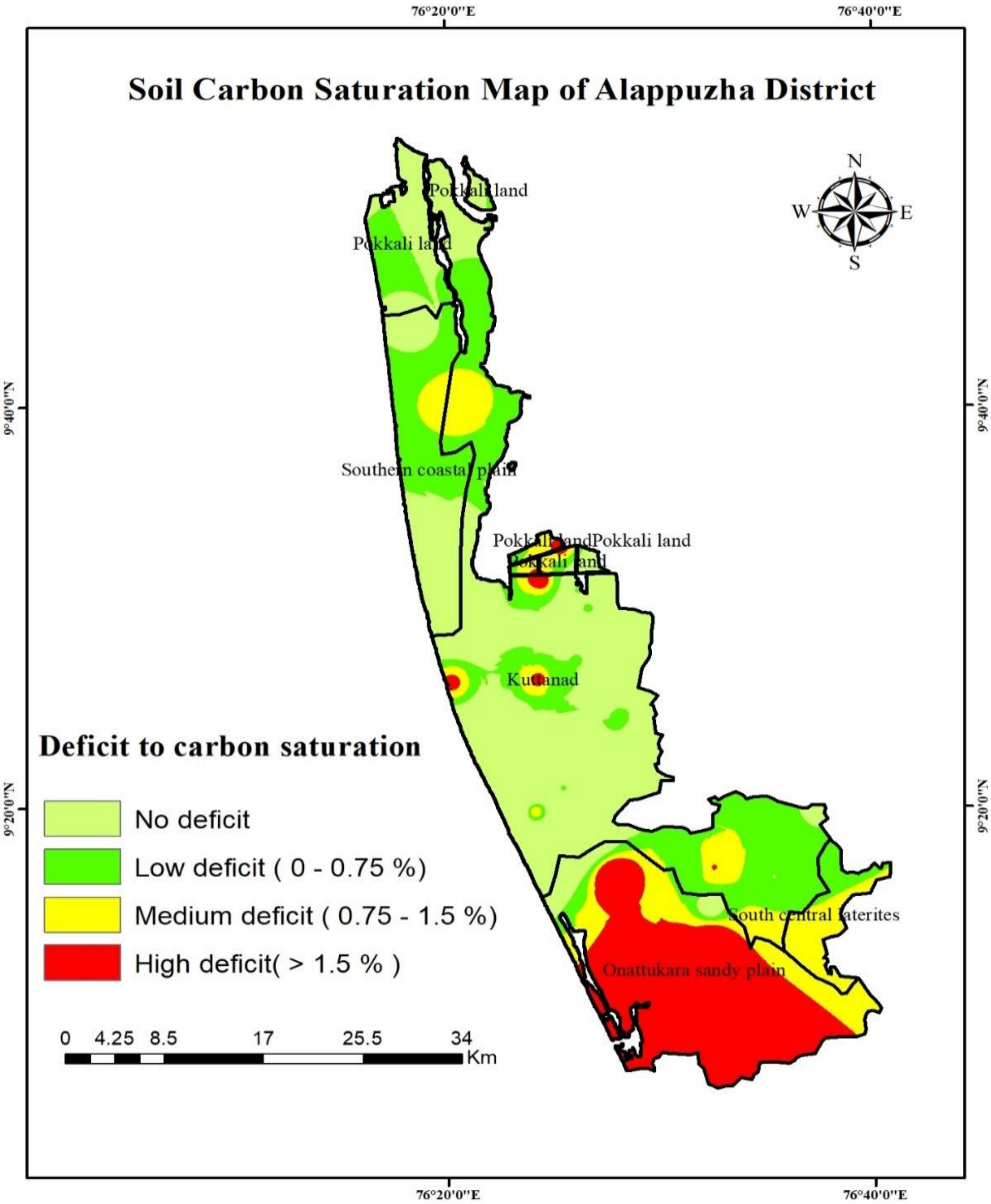

Figure 9: Soil carbon Saturation map in agroecological units of Alappuzha district

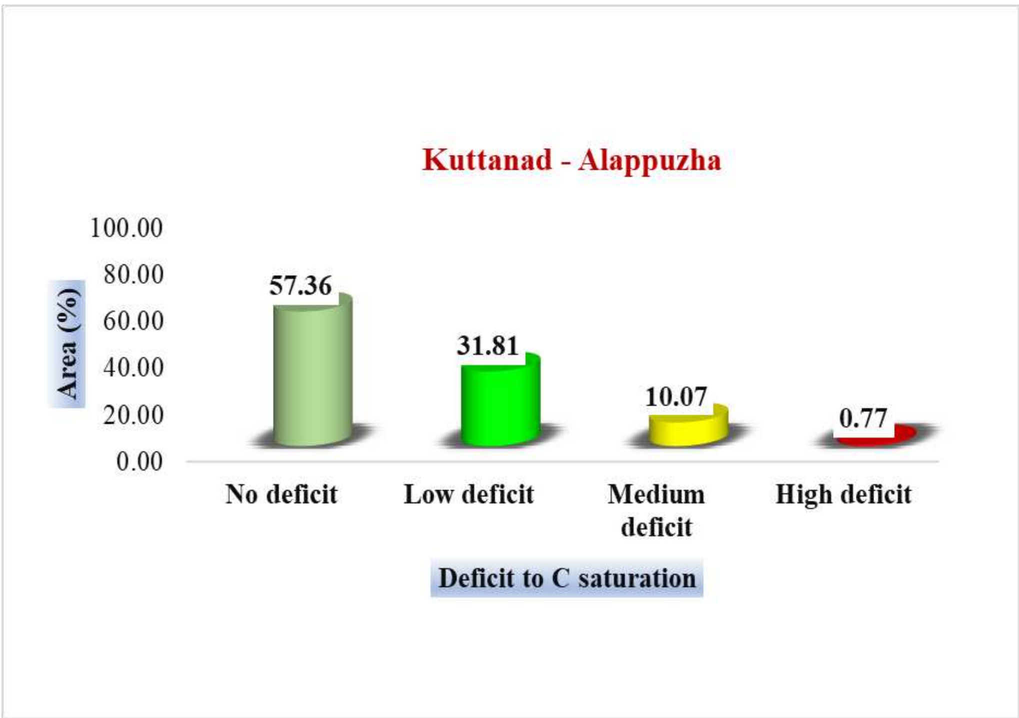

Fig: (10a)

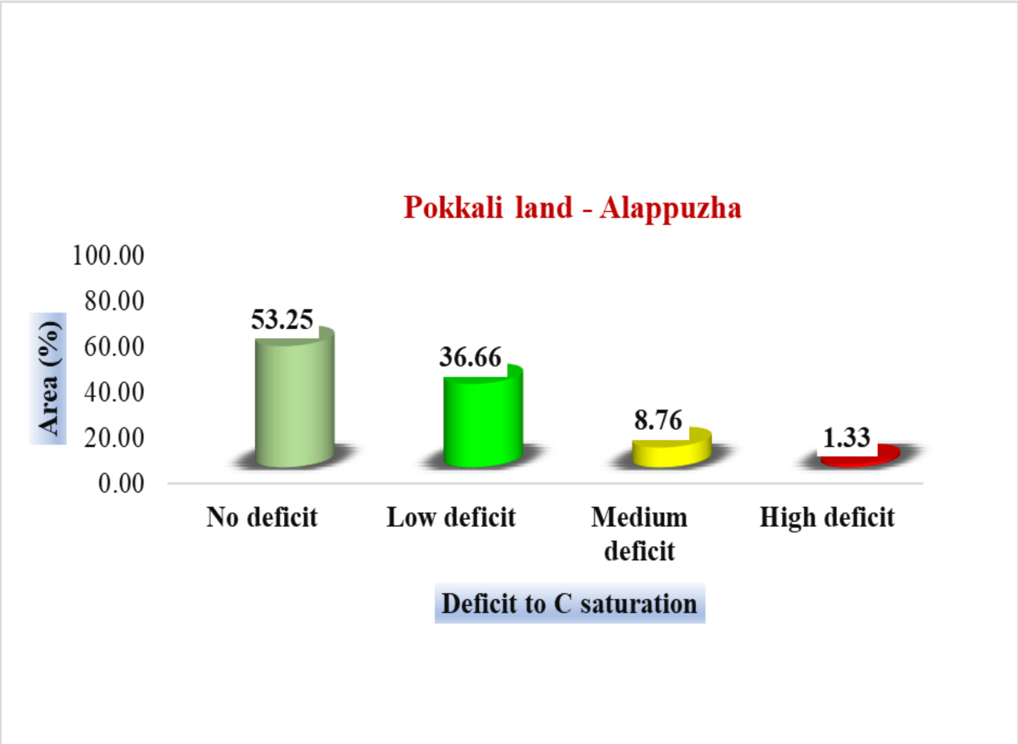

Fig: (10b)

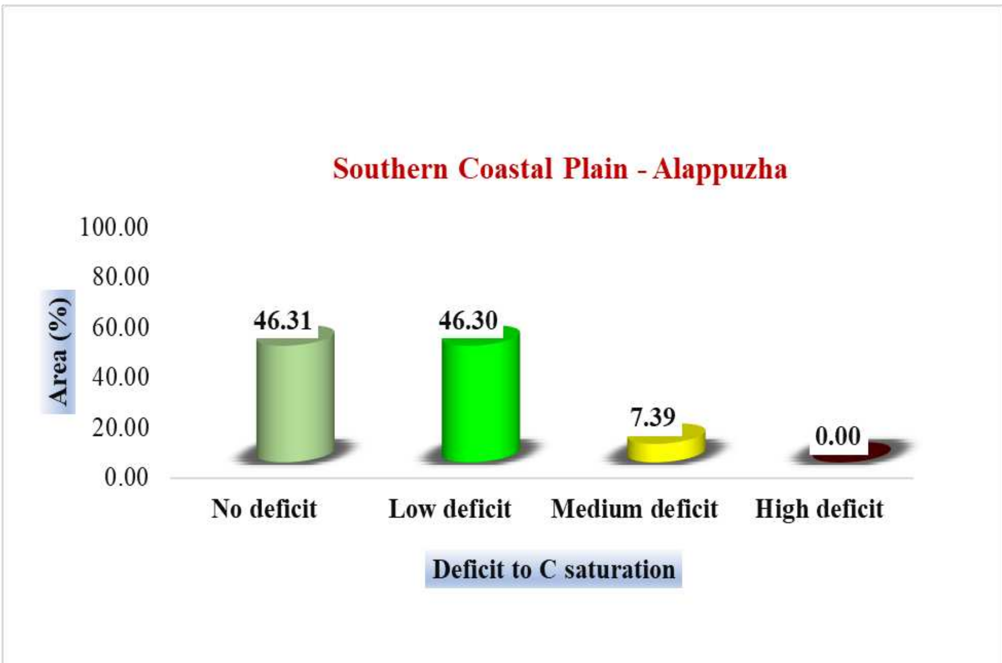

Fig: (10c)

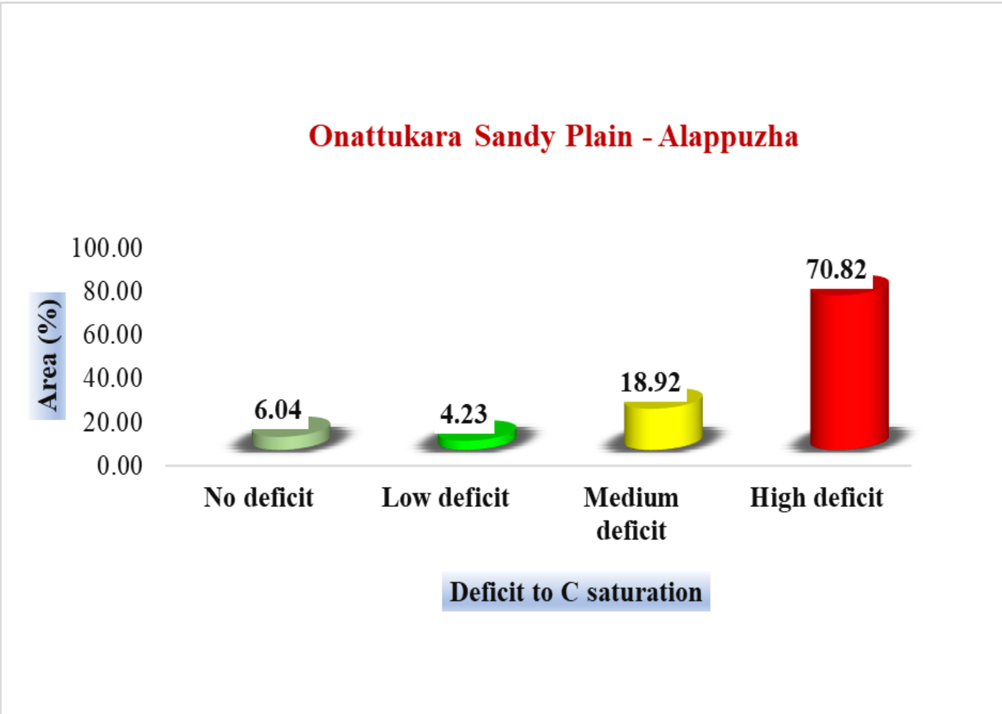

Fig: (10d)

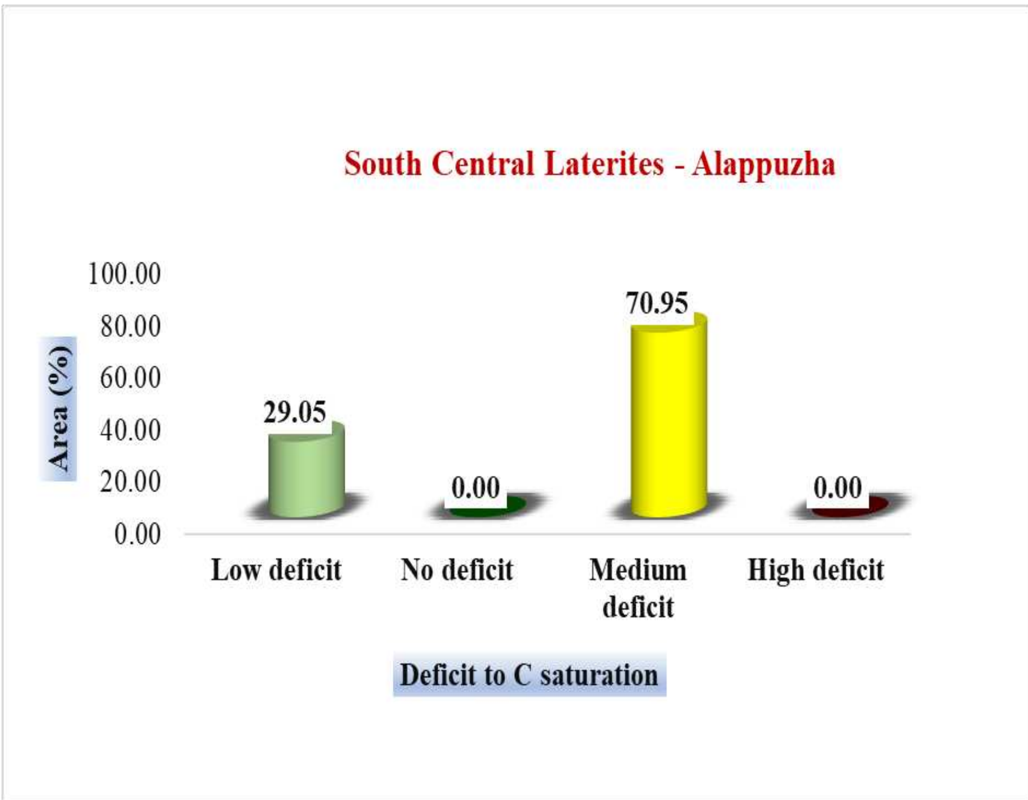

Fig: (10e)

Figures 10a, 10b, 10c, 10d, 10e: Graphs representing soil carbon range in different AEUs of Alappuzha

A major portion of the soils in Kuttanad, Pokkali and Southern coastal plains of Alappuzha district were found to be under no carbon deficit category. Among the five AEUs in Alappuzha, Onattukara sandy plains was found to have 70.82% under high carbon deficit category and 70.95 % of South-Central laterites under medium carbon deficits. Thus, Onattukara Sandy Plains and South-Central laterites in Alappuzha district, require special organic carbon management strategies. Kuttanad is a unique agroecological unit that encompasses waterlogged areas in the districts of Alappuzha, Kottayam, and Pathanamthitta. Approximately, 57.36 % of the soil in Kuttanad is carbon saturated or in the no deficit zone and only 0.77 % of the soil require carbon management. Kuttanad soils are inherently high in organic matter enabling it to be classified as Histosols (Suganya *et al*., 2015; Neenu *et al*.,

2020) and the water-logged areas protect the inherent high OM without much decomposition. The saline hydromorphic soils of Pokkali also exhibit a similar pattern and process of organic carbon retention. On the other hand, the no carbon deficit areas in the southern coastal plains of Kuttanad need not be due to an inherently high organic carbon content rather this is due to the soils texture (high sand contents) and their inability to retain higher amounts of carbon (Neenu *et al*., 2020). As such the carbon saturation points are low in these soils and would easily get saturated with even low carbon levels.

4.2.4 Carbon Saturation in Agroecological Units of Kottayam District

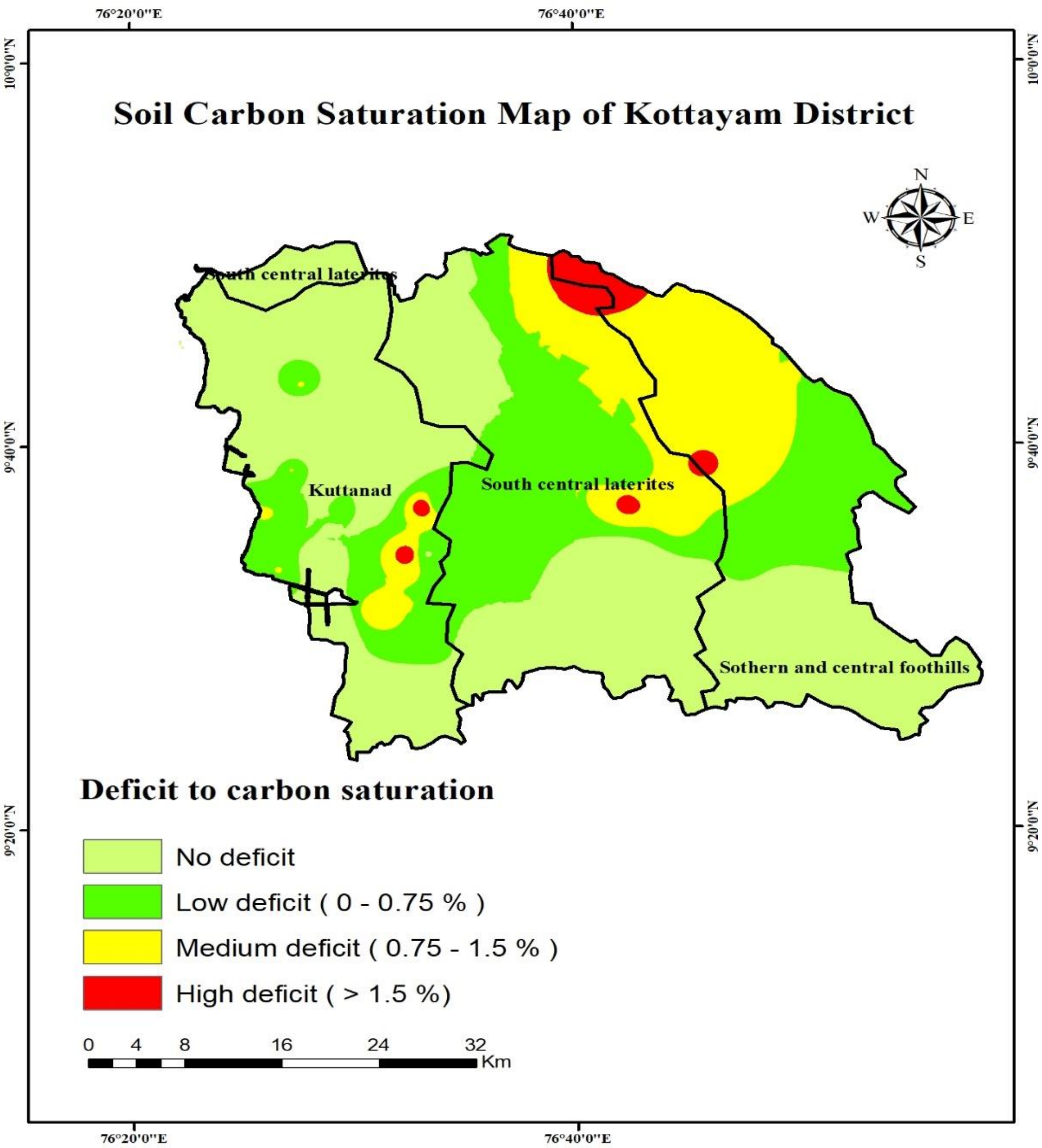

Figure 11: Soil carbon Saturation map in agroecological units of Kottayam district

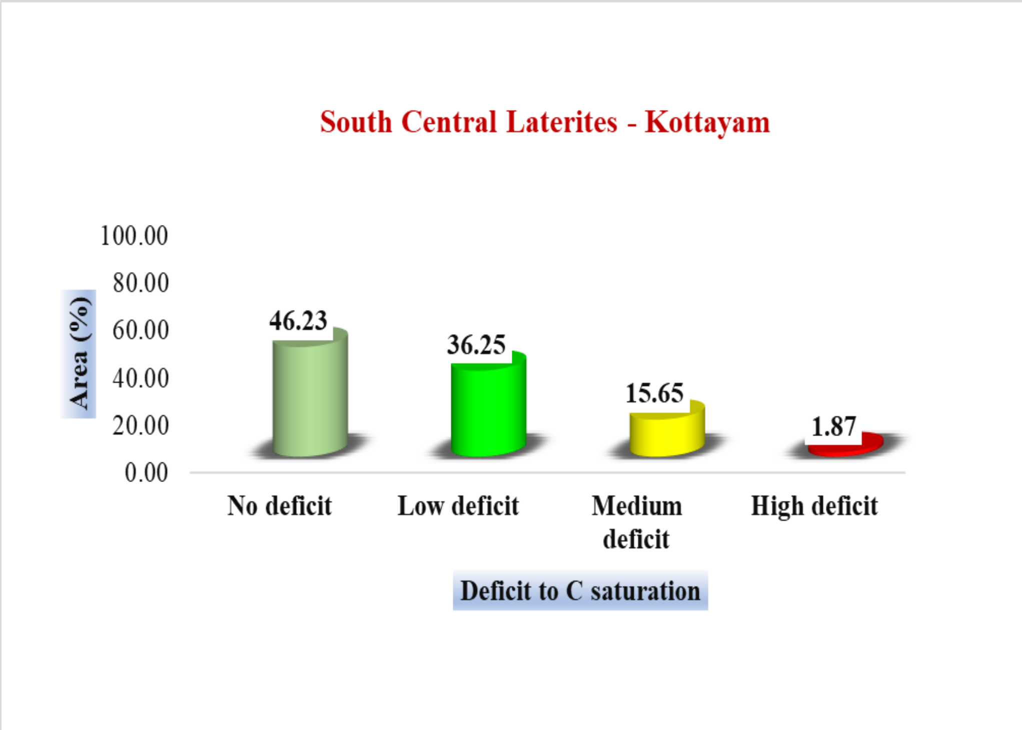

Fig: (12a)

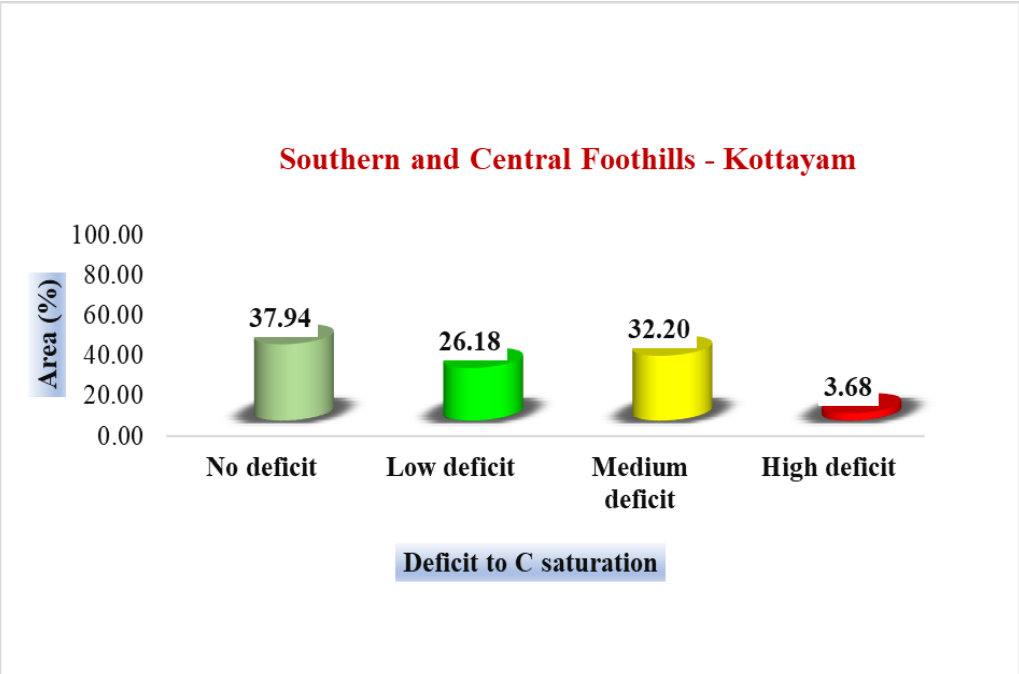

Fig: (12b)

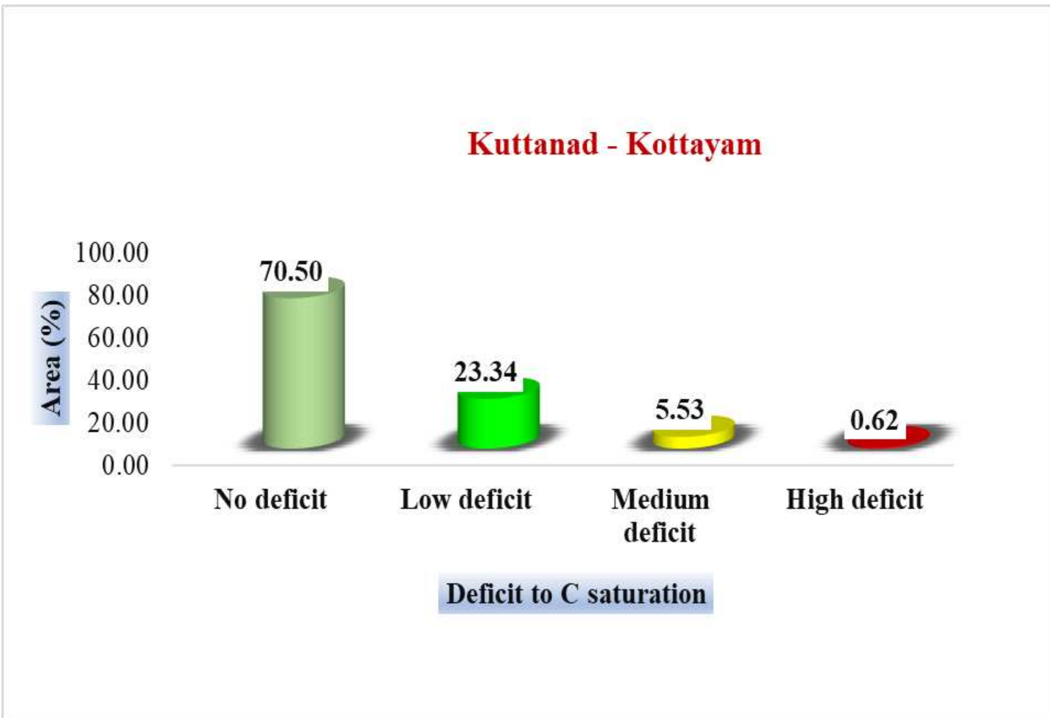

Fig: (12c)

Figures 12a, 12b, 12c: Graphs representing soil carbon range in different AEUs of Kottayam

In the Kottayam district, majority of soils in all AEUs were in the no carbon deficit followed by low carbon deficits category. Similar to Alappuzha, the AEU of Kuttanad had 70.50% under no carbon deficit. In different AEUs of Kottayam, highly carbon deficit soils varied from 0.62 % in Kuttanad to 3.65 % in Southern and central foothills.

4.1.5 Carbon Saturation in Agroecological Units of Pathanamthitta District

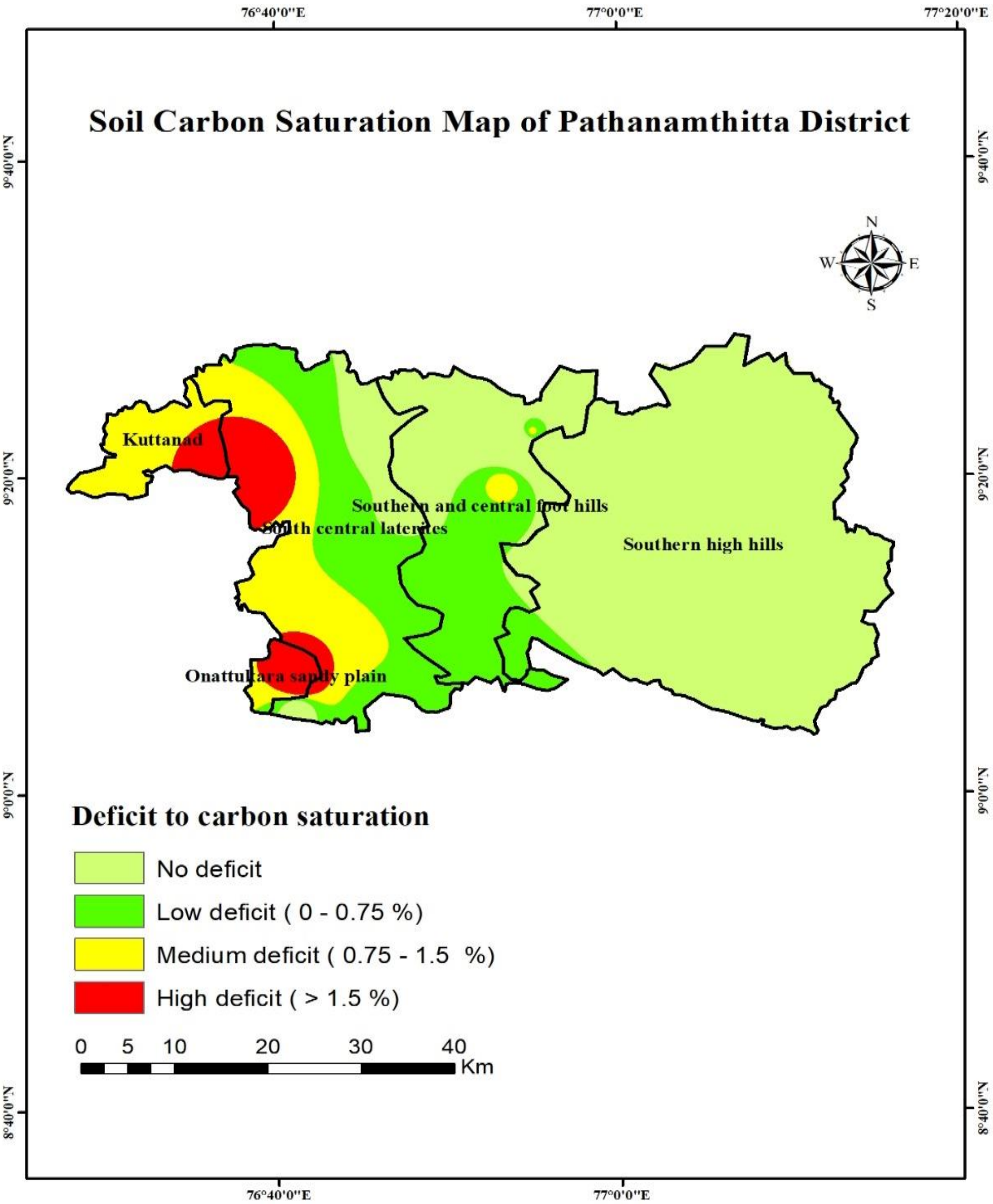

Figure 13: Soil carbon Saturation map in agroecological units of Pathanamthitta District

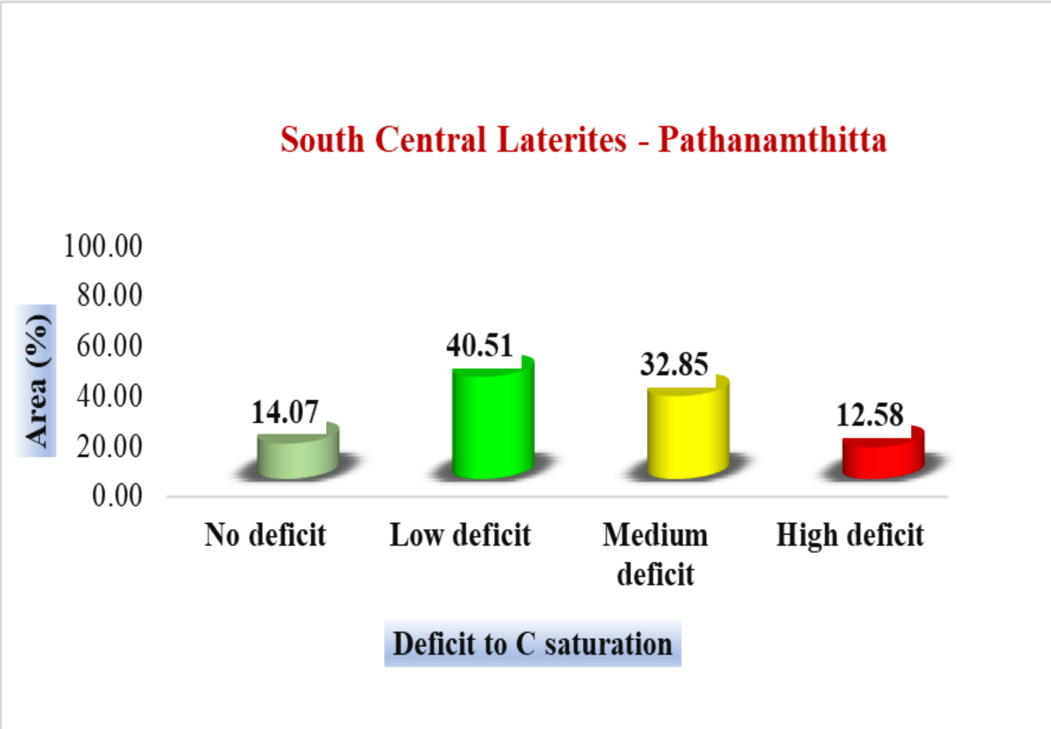

Fig: (14a)

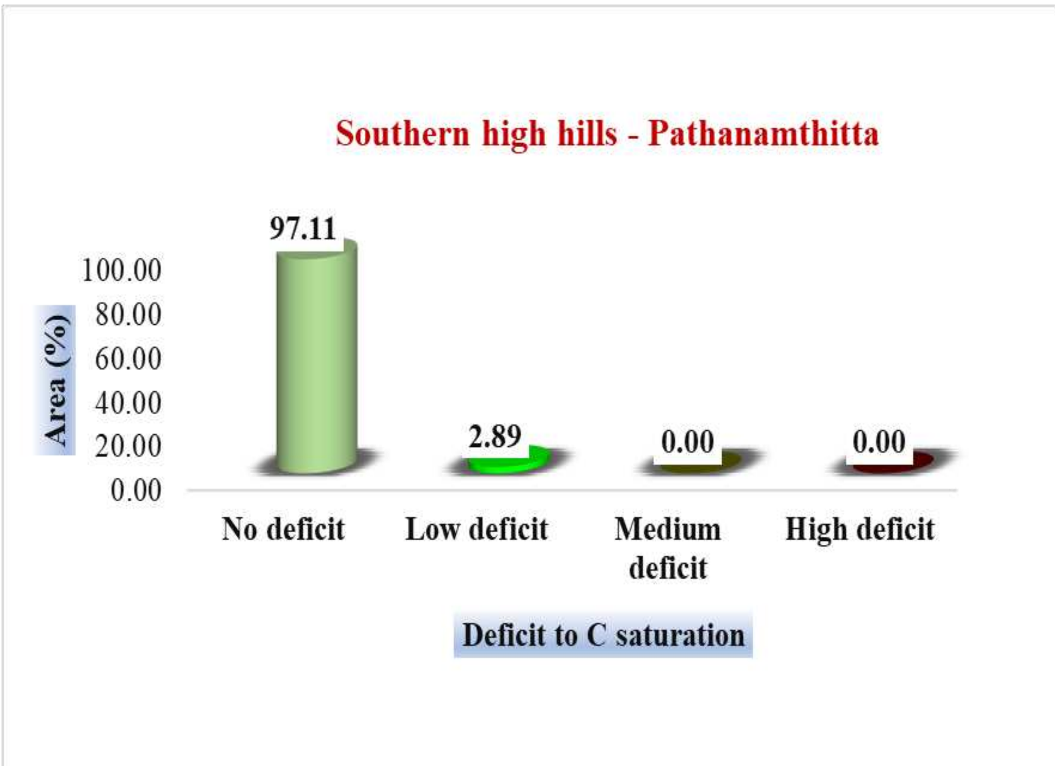

Fig: (14b)

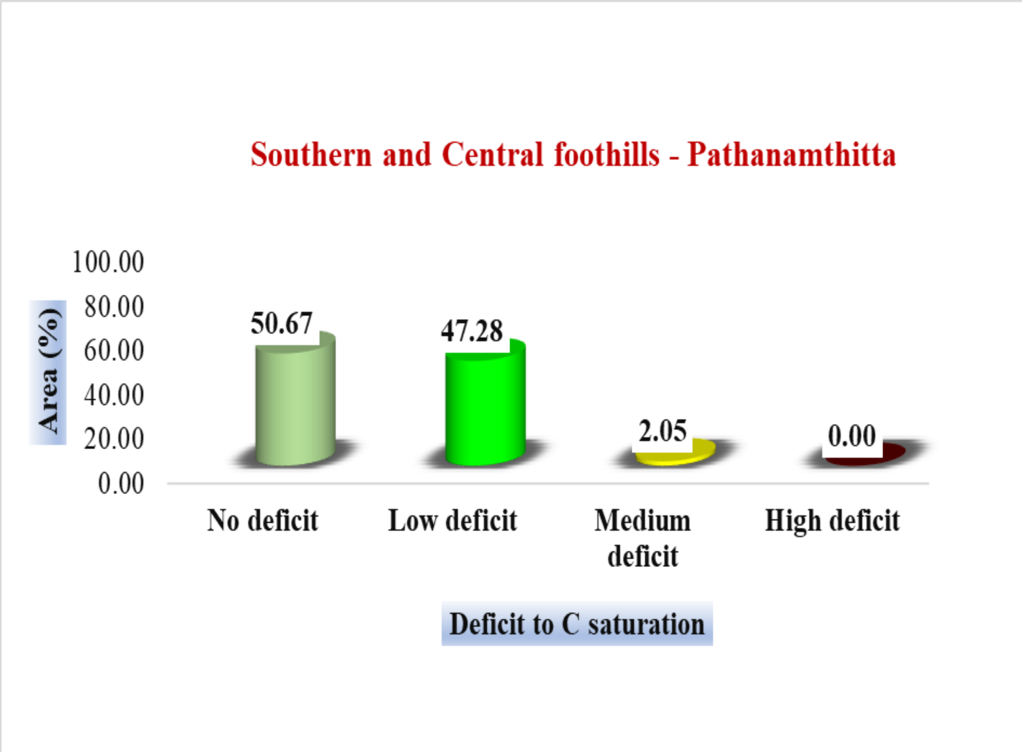

Fig: (14c)

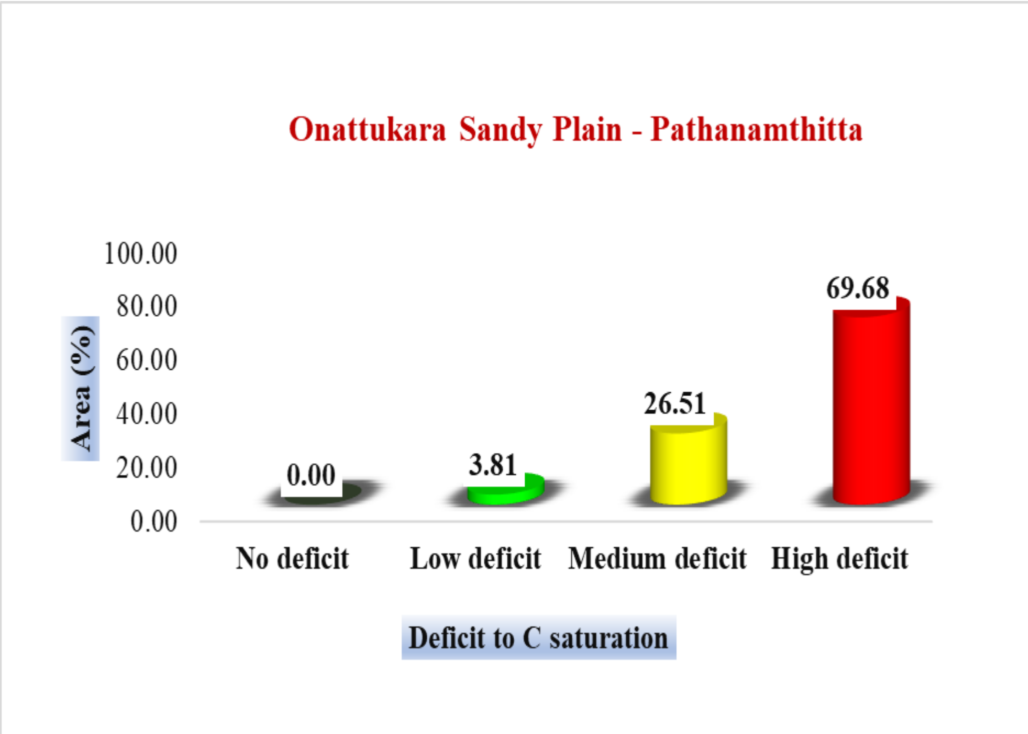

Fig: (14d)

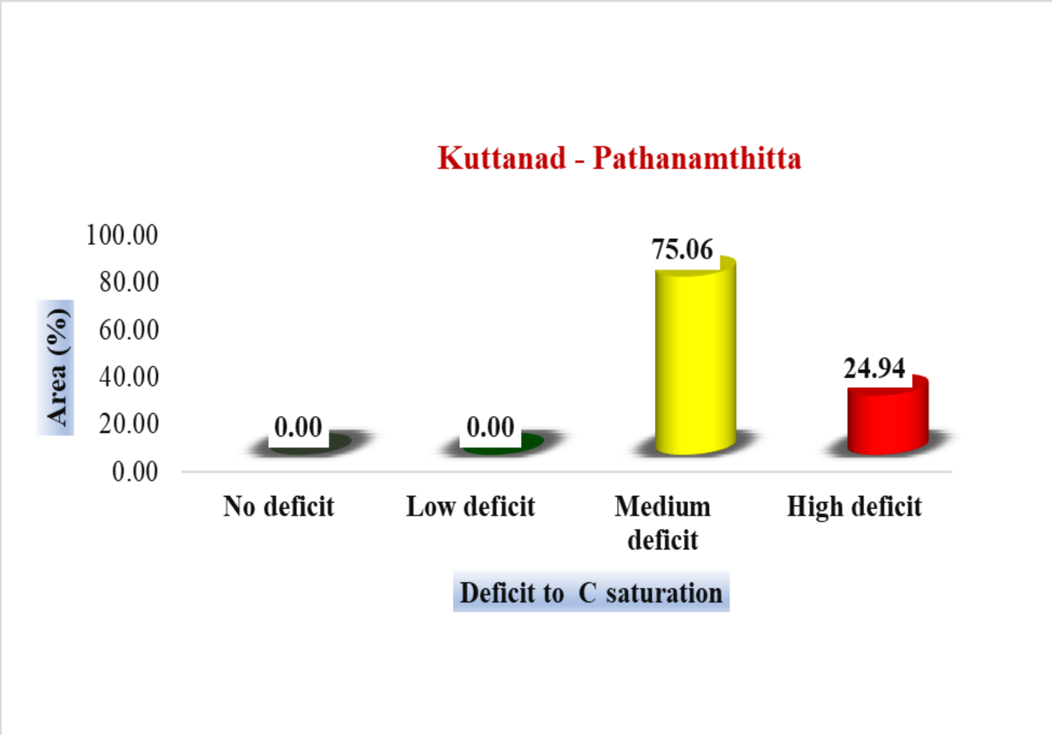

Fig: (14e)

Figures 14a, 14b, 14c, 14d, 14e: Graphs representing soil carbon range in different AEUs of Pathanamthitta

Among the five AEUs of Pathanamthitta district the soils with higher carbon content were found to be more in southern high hills and absent in both Onattukara sandy plain and Kuttanad units. South central laterites have a greater percentage of low carbon deficit soil (40.51%) followed by medium deficit soil (32.85%) and no carbon deficit soil (12.58 %). In the southern and central foothills, 2.05 % of soils were under the medium carbon deficiency category and large tracts were under no carbon deficit (50.67 percent) and low carbon deficit (47.28 percent) categories. Onattukara sandy plain had large areas under high carbon deficit (69.68%) soil i.e., these soils have greater potential to store more carbon. No deficit soil is absent in this AEU and a small amount of low deficit (3.81%). Both no deficiency and low carbon deficit soil are absent in the Kuttanad region, with a larger percentage of medium deficit (75.06) and 24.94 percent of area under high deficit soil. Generally, Pathanamthitta district had large areas with soils near their saturation potential.

4.2.6 Carbon Saturation in Agroecological Units of Idukki District

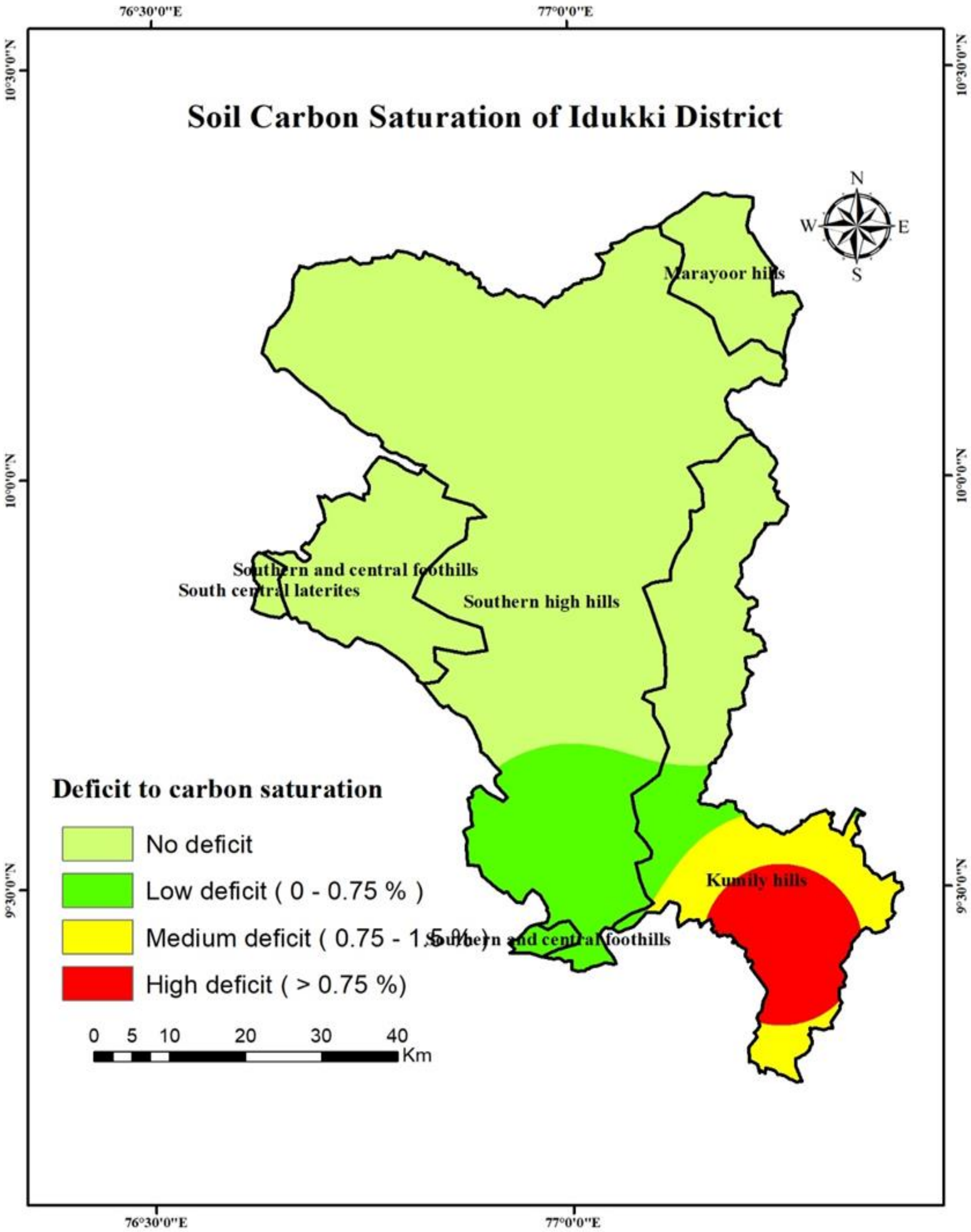

Figure 15: Soil carbon Saturation map in agroecological units of Idukki District

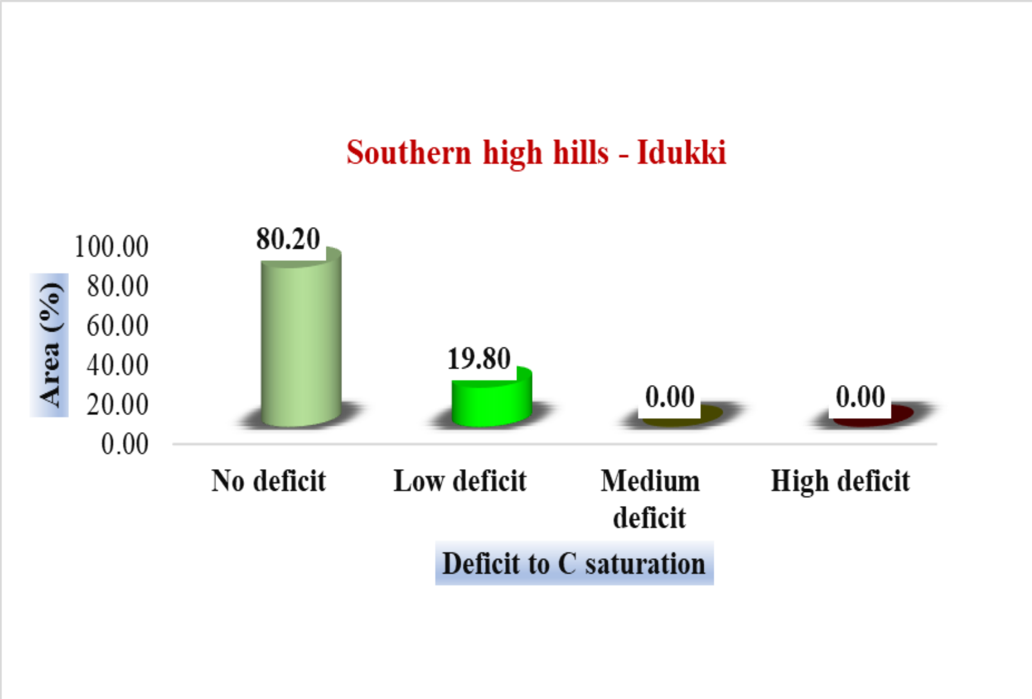

Fig: (16a)

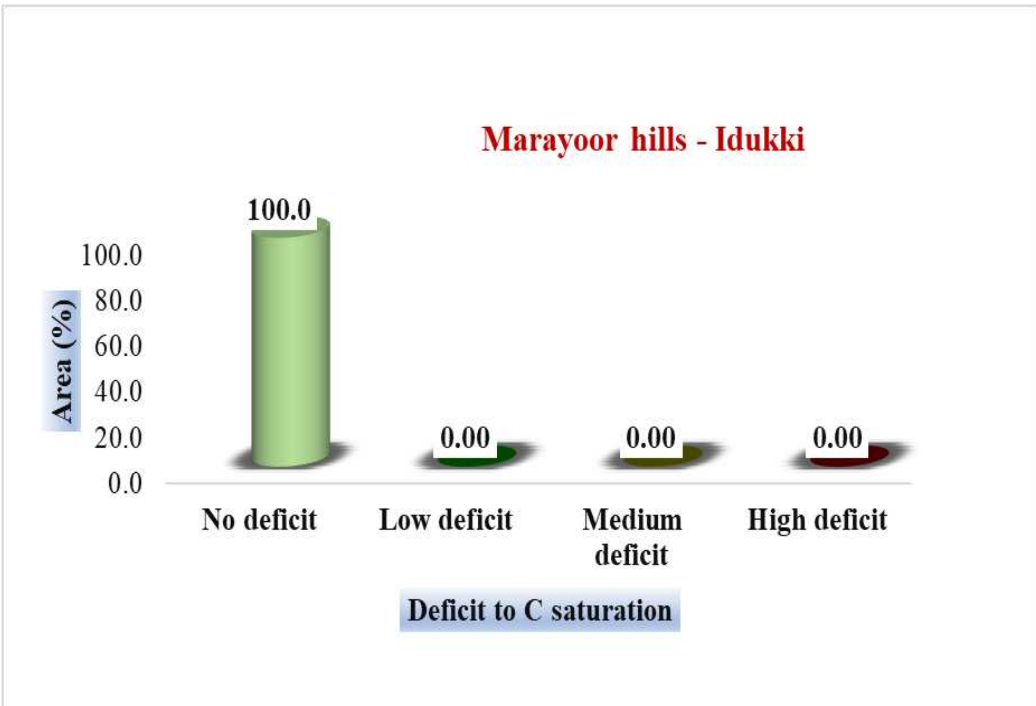

Fig: (16b)

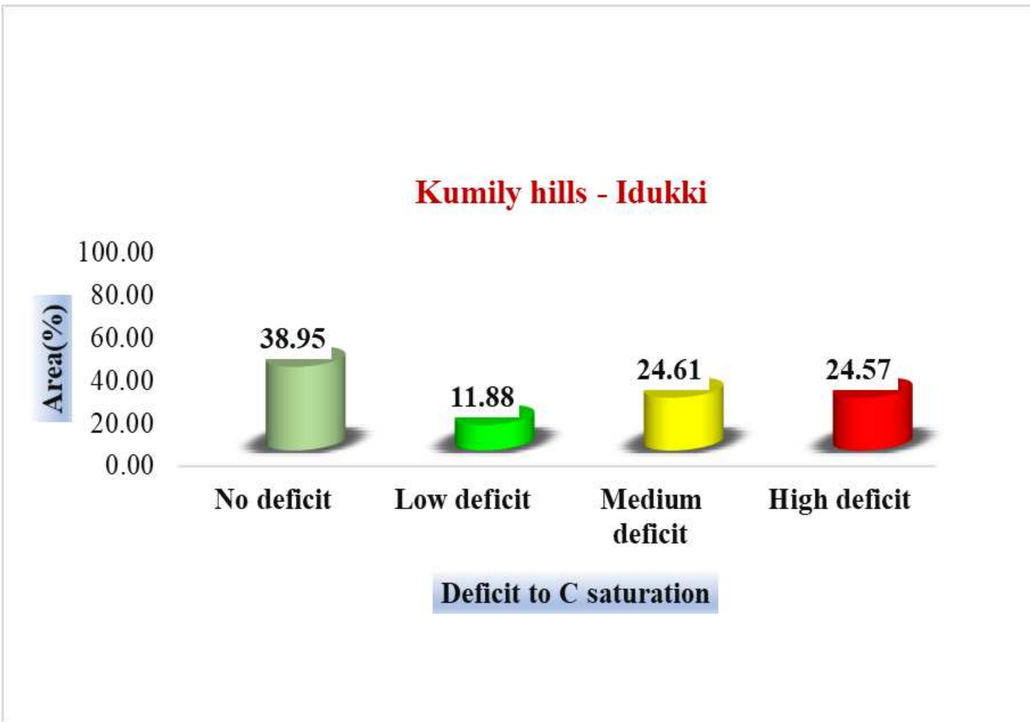

Fig: (16c)

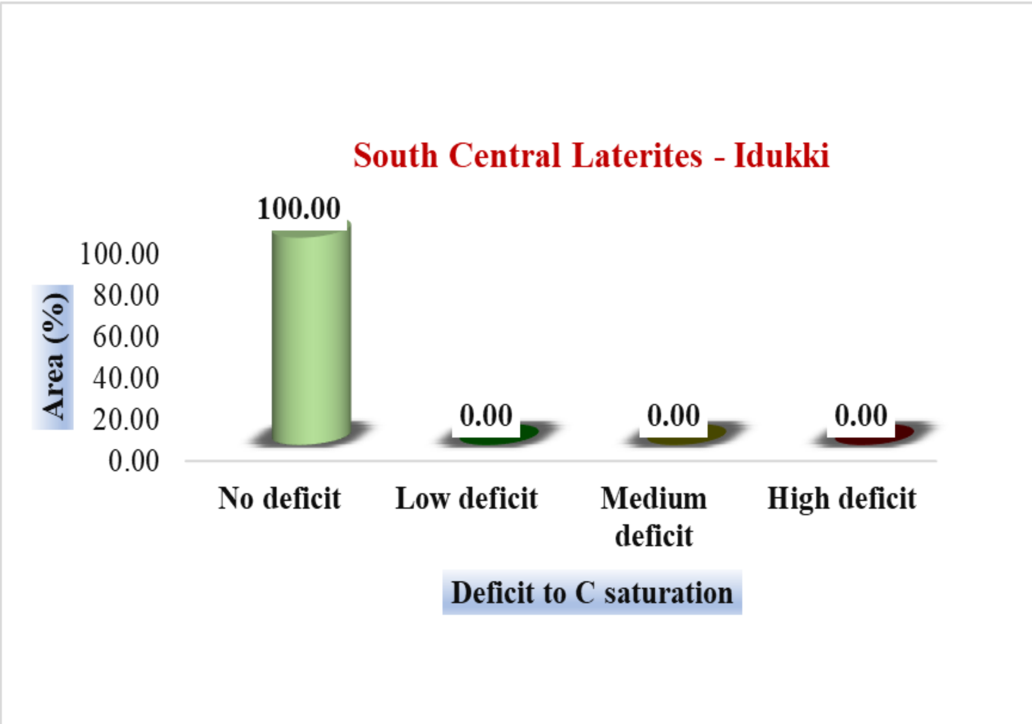

Fig: (16d)

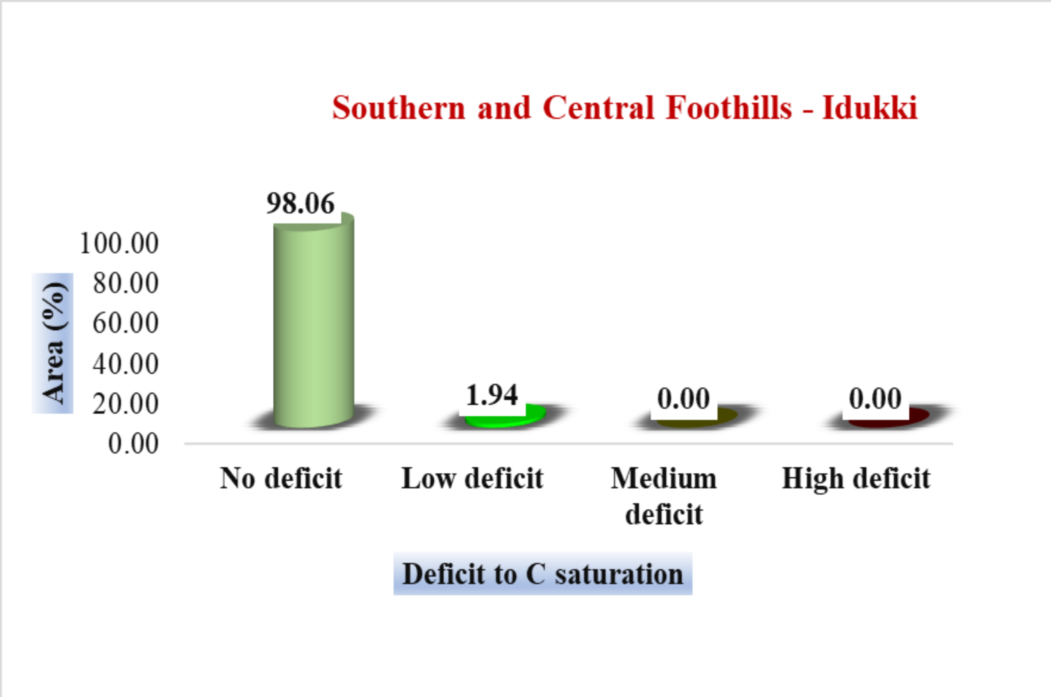

Fig: (16e)

Figures 16a, 16b, 16c, 16d, 16e: Graphs representing soil carbon range in different AEUs of Idukki

Among the five AEUs of Idukki, Kumily hills were the only AEU with one – fourth of the area with high carbon deficit. All the other AEUs had no carbon deficit zone as the main category

4.2.7 Carbon Saturation in Agroecological Units of Ernakulam District

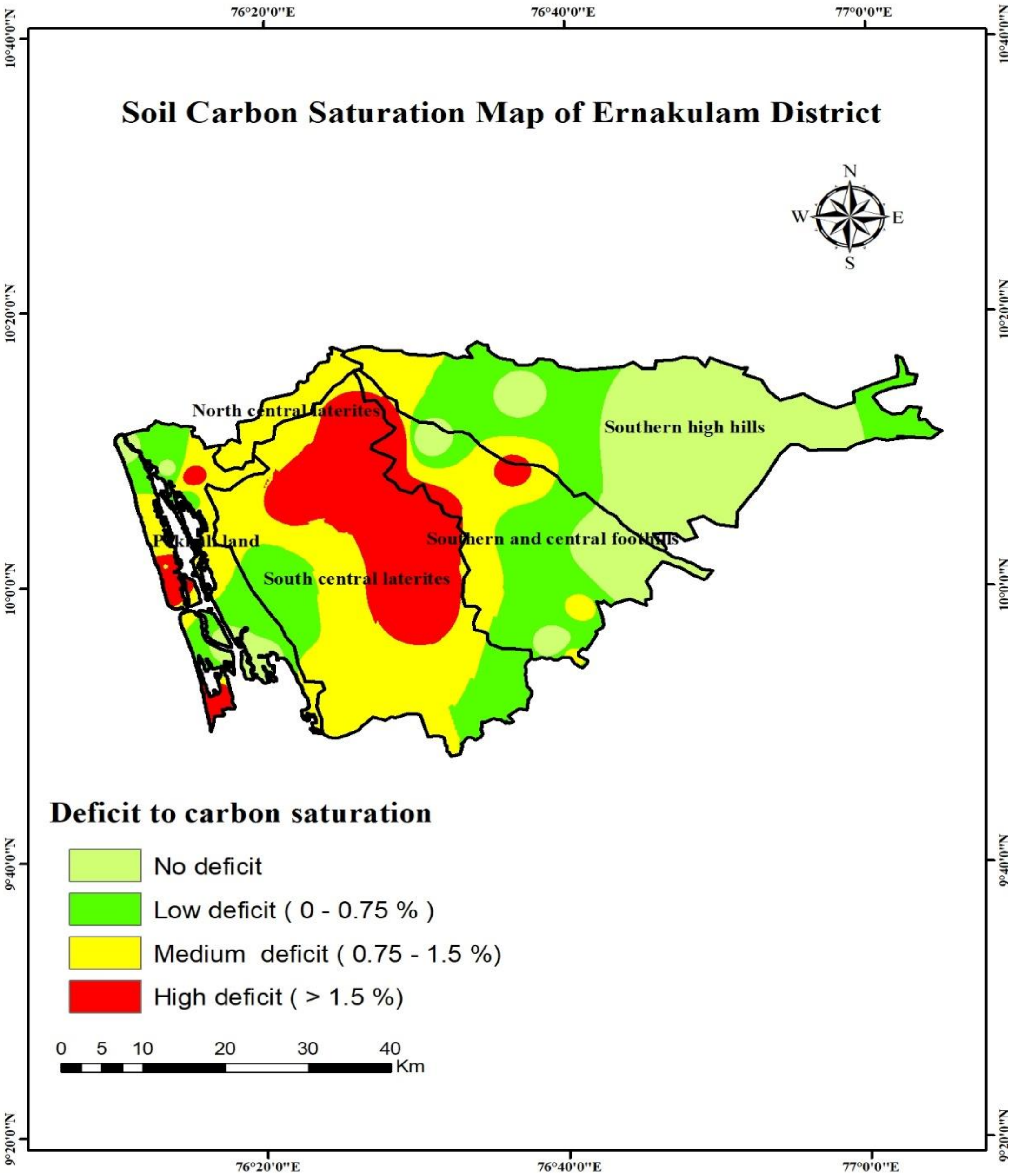

Figure 17: Soil carbon Saturation map in agroecological units of Ernakulam District

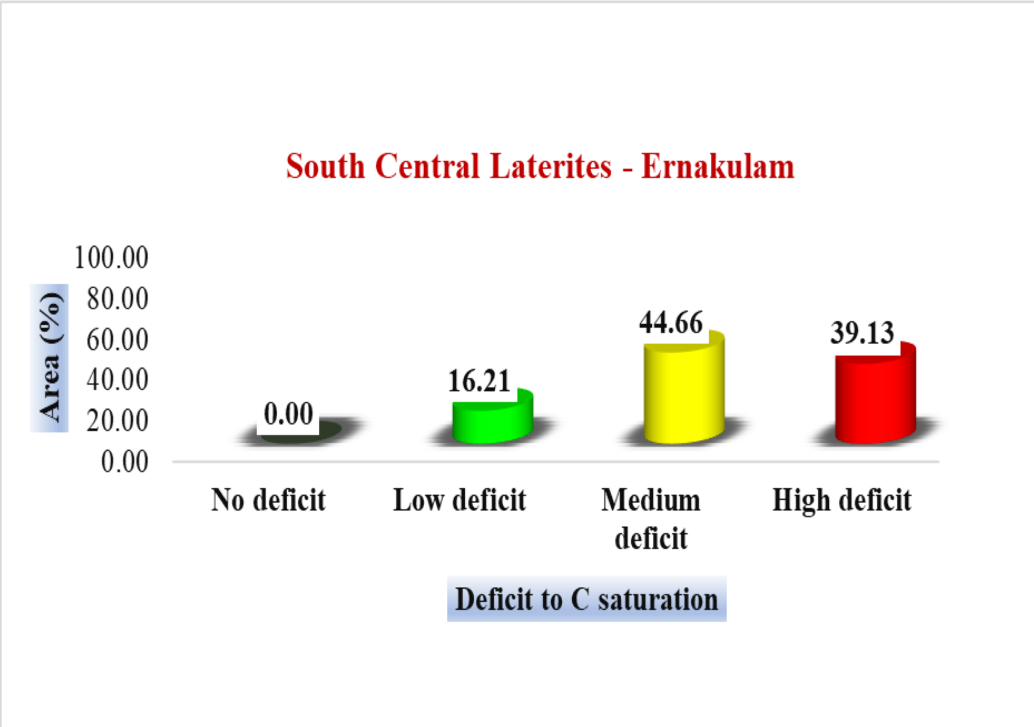

Fig: (18a)

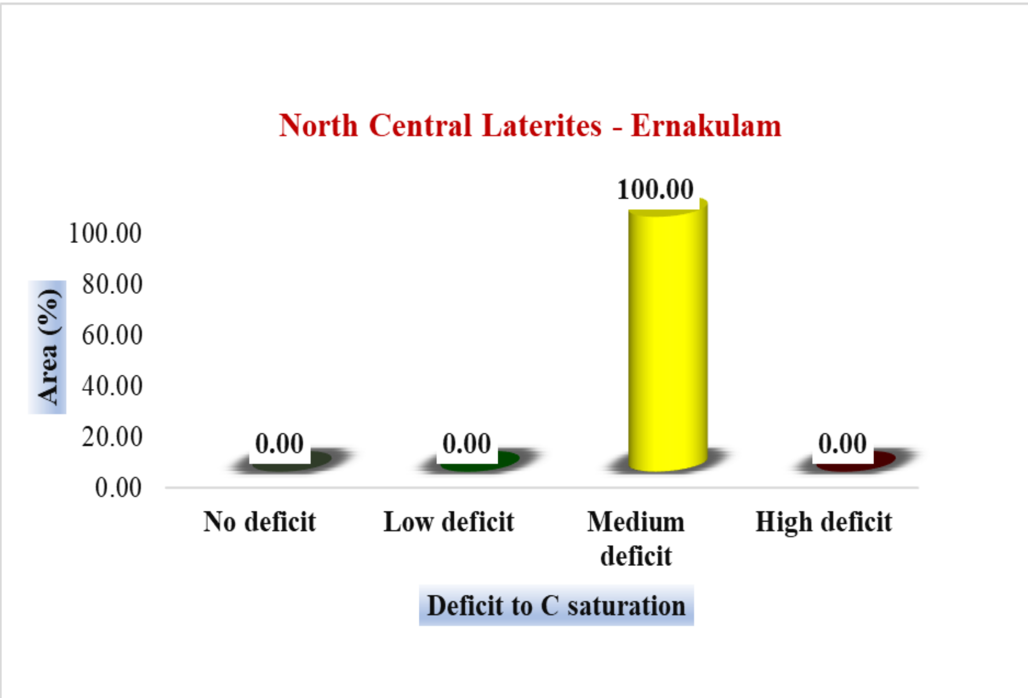

Fig: (18b)

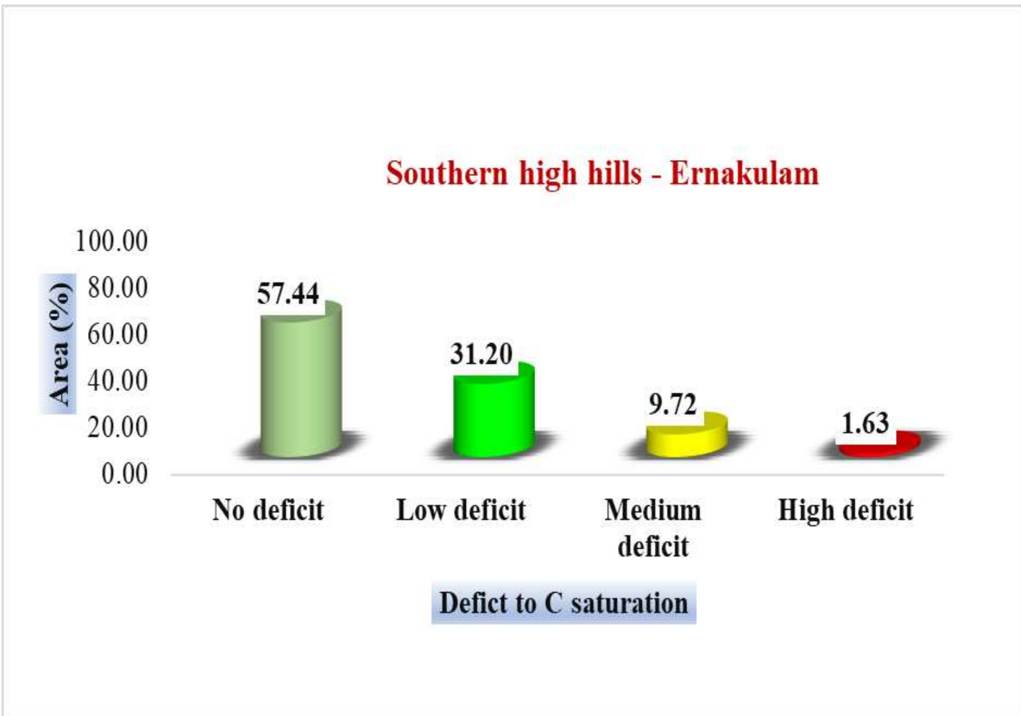

Fig: (18c)

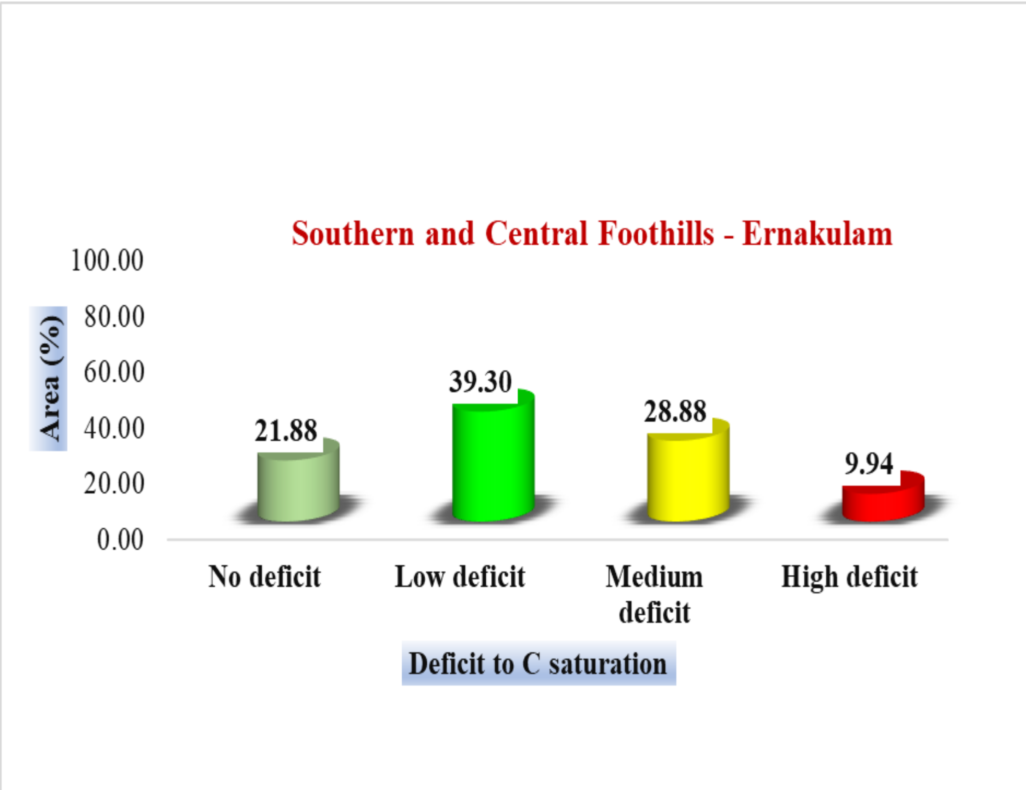

Fig: (18d)

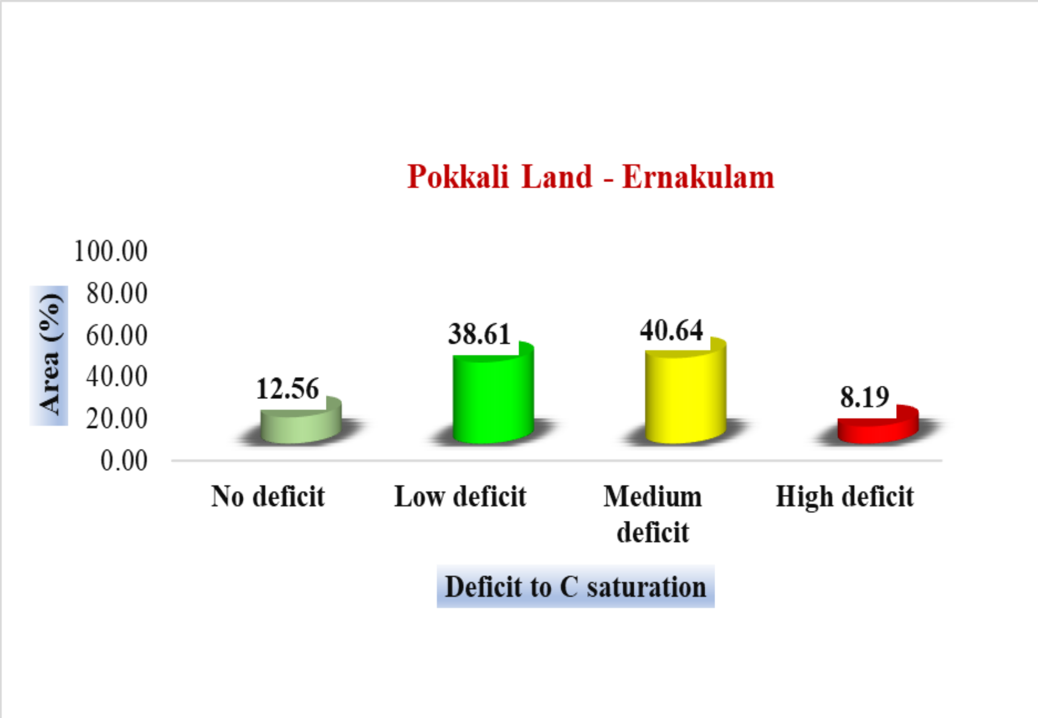

Fig: (18e)

Figures 18a, 18b, 18c, 18d, 18e: Graphs representing soil carbon range in different AEUs of Ernakulam

In the Ernakulam district, the four categories of soil carbon deficit were found to be evenly distributed. North Central Laterites were abundant with medium carbon deficit soil category, while South central laterites had nearly equal areas under medium carbon deficit (44.66%) and high carbon deficit (39.13 %) soil. No carbon deficit soils were rich in Southern High Hills and high carbon deficit soils were rich in South Central Laterites. In the Pokkali region, 12.56 percent of area had no carbon deficit, 38.61 percent had a low carbon deficit, 40.64 percent had a medium carbon deficit, and 8.19 percent had a high carbon deficit. In the southern high hills, no carbon deficit soils were found abundant, whereas high deficit soils were abundant in the south-central laterites.

4.2.8 Carbon Saturation in Agroecological Units of Thrissur District

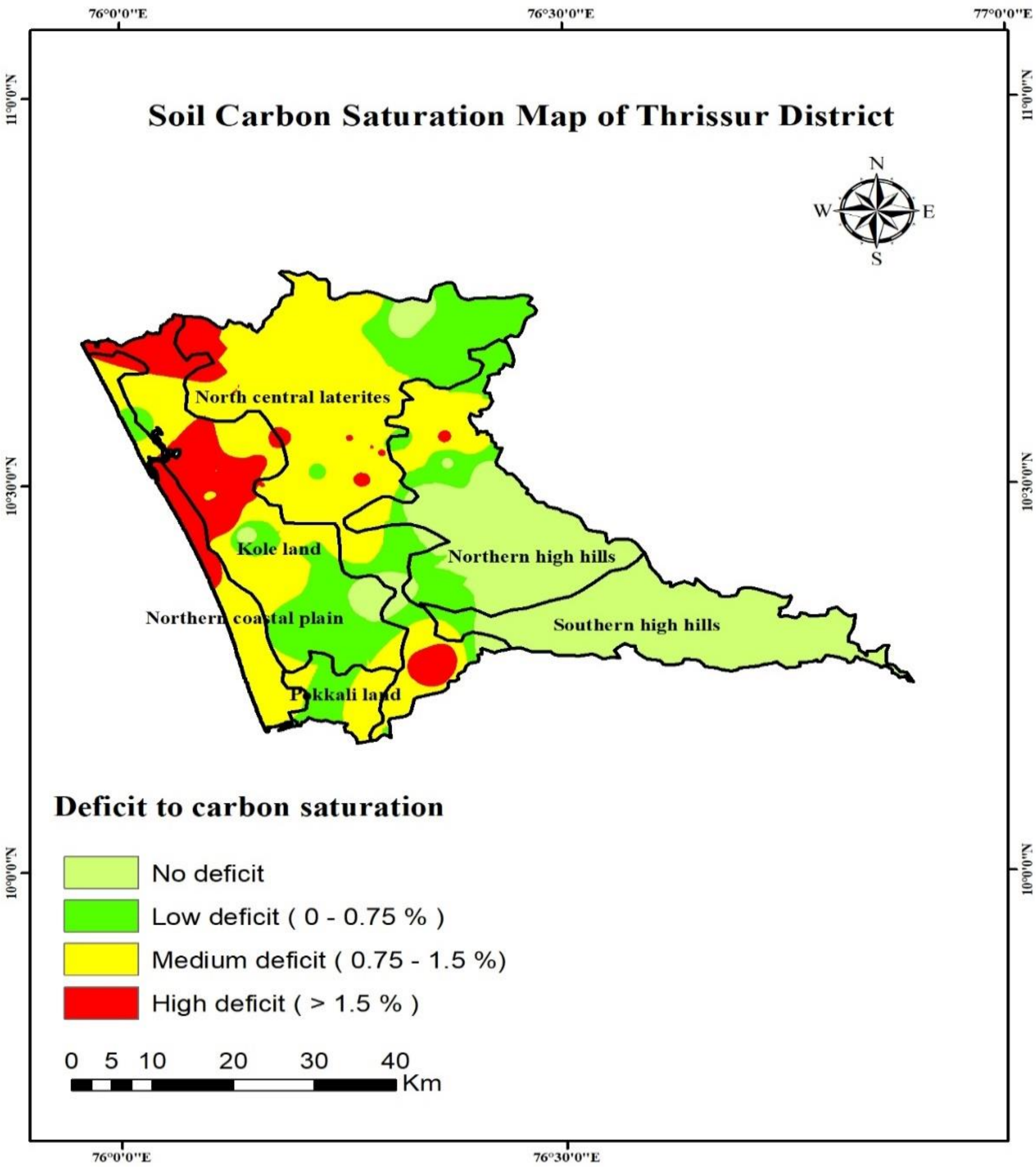

Figure 19: Soil carbon Saturation map in agroecological units of Thrissur District

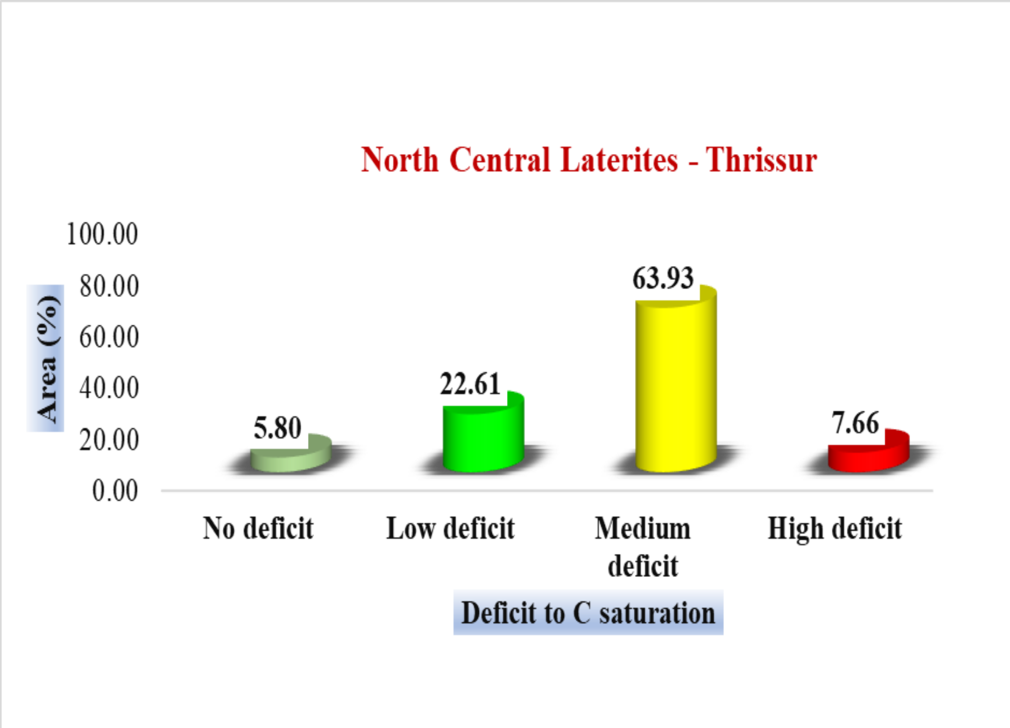

Fig: (20a)

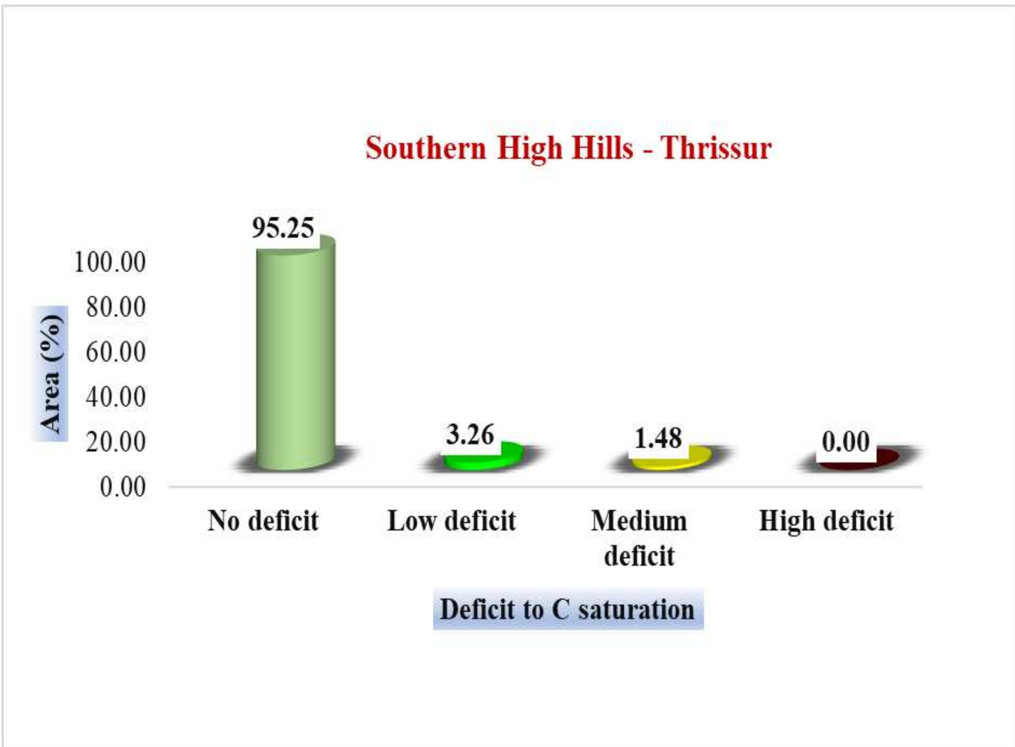

Fig: (20b)

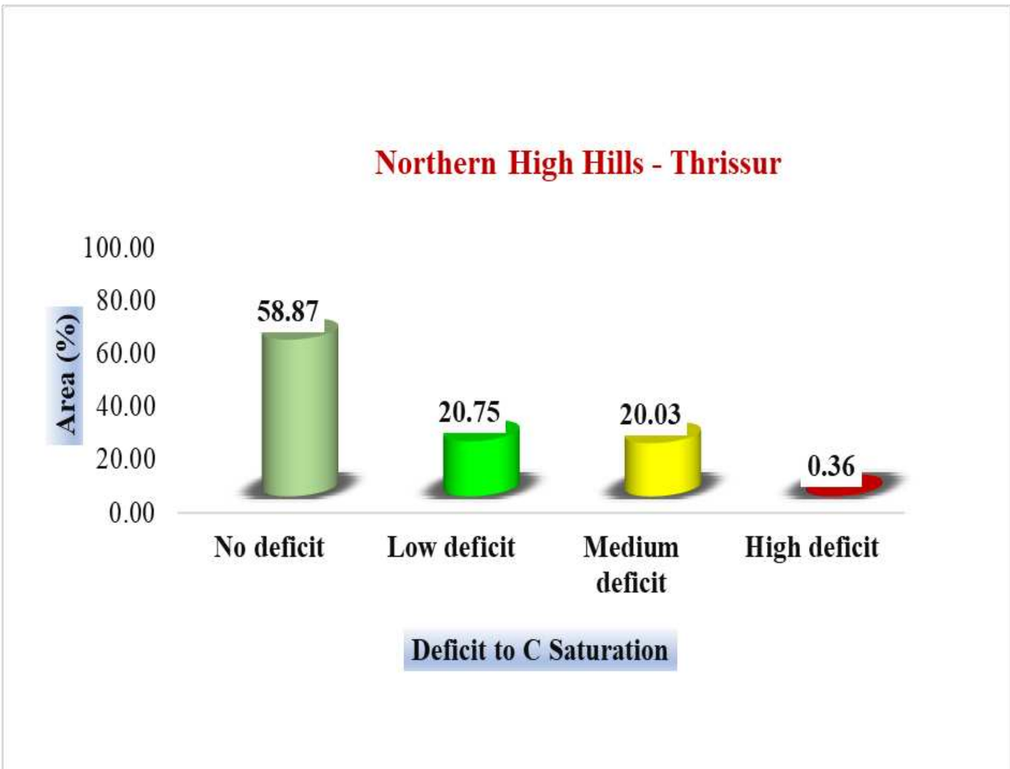

Fig: (20c)

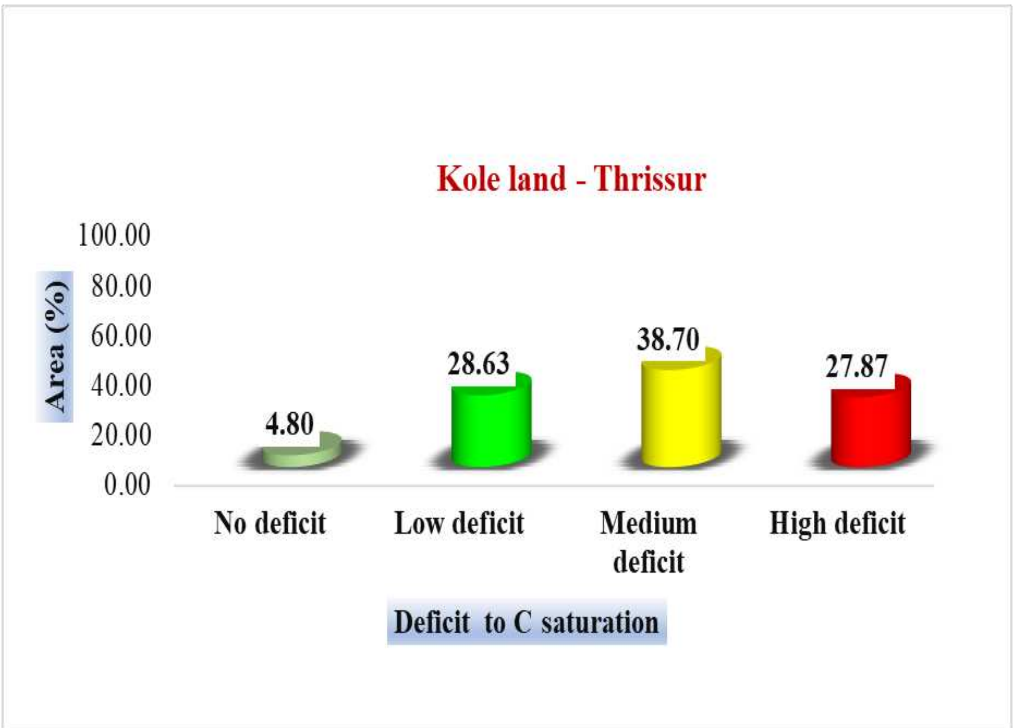

Fig: (20d)

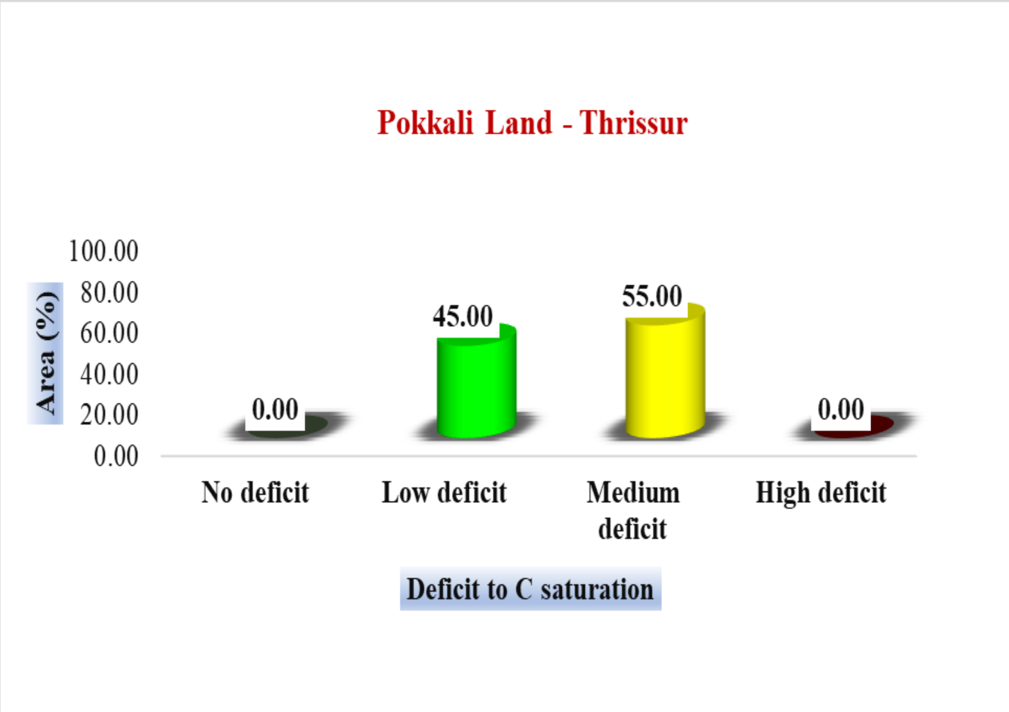

Fig: (20e)

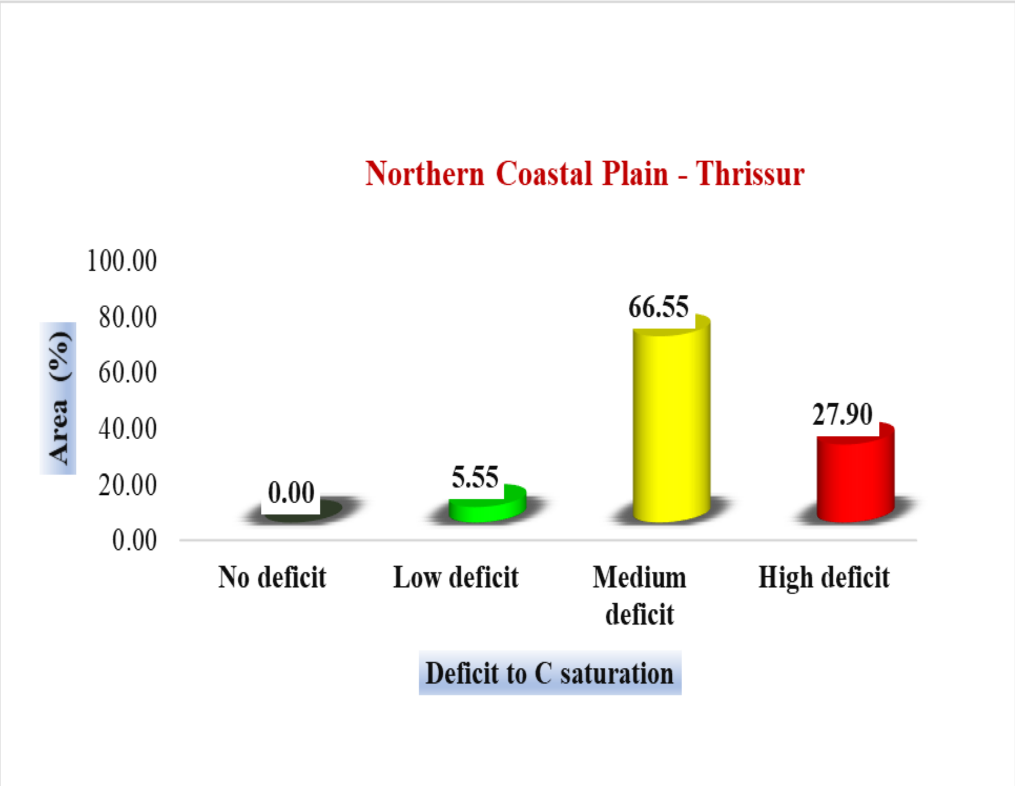

Fig: (20f)

Figures 20a, 20b, 20c, 20d, 20e, 20f: Graphs representing soil carbon range in different AEUs of Thrissur

In Thrissur district maximum area was under medium carbon deficit than other category. AEUs like North Central laterite, Northern Coastal plain, Pokkali land and Kole land were rich with medium carbon deficit soils. Southern High hills and Northern High Hills had relatively more area under no carbon deficit.

4.1.9 Carbon Saturation in Agroecological Units of Palakkad District

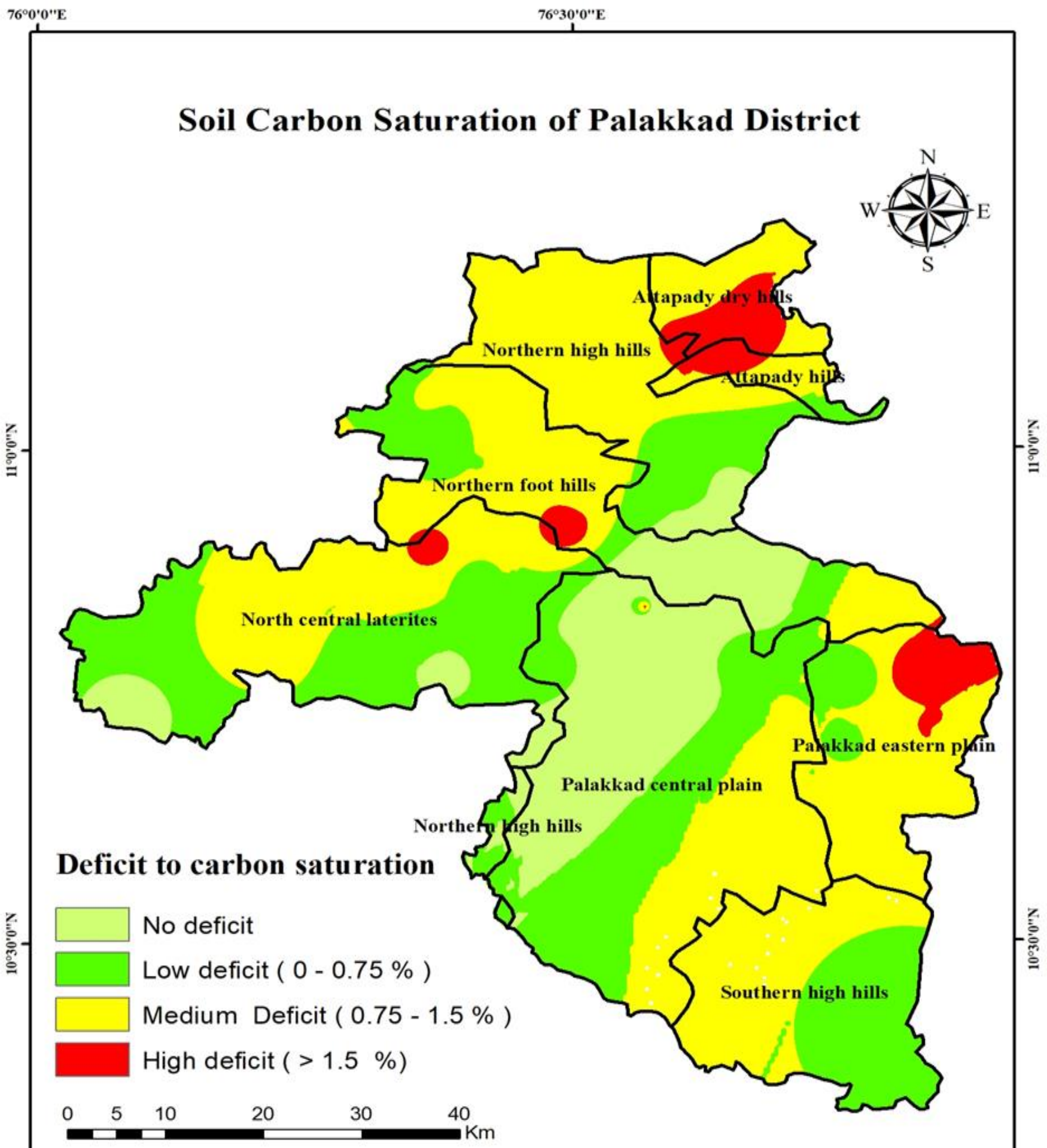

Figure 21: Soil carbon Saturation map in agroecological units of Palakkad District

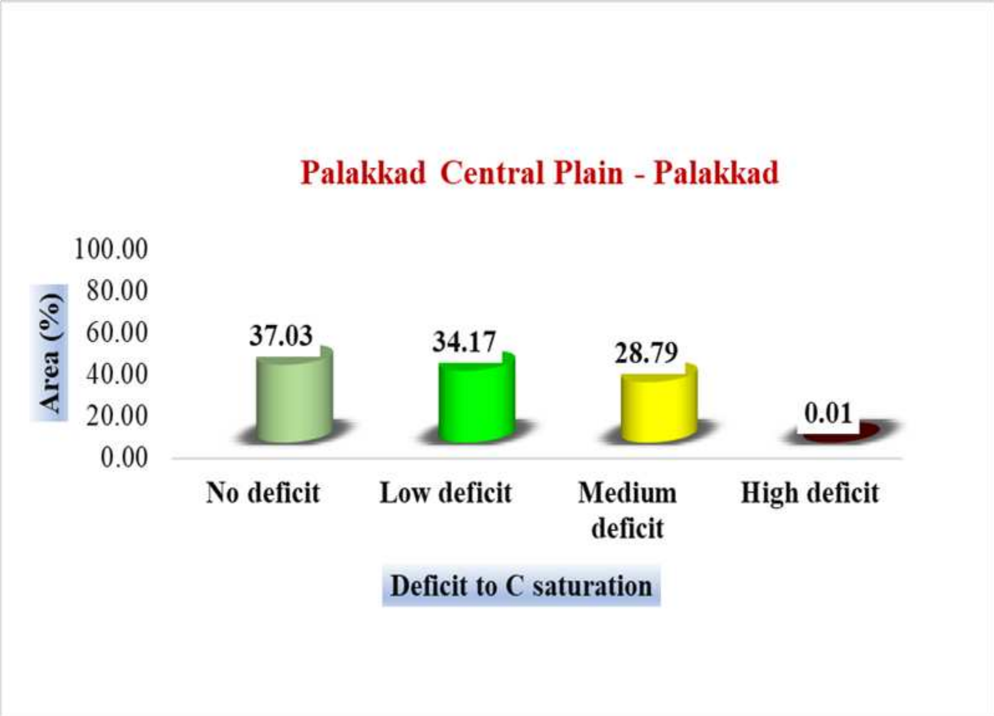

Fig: (22a)

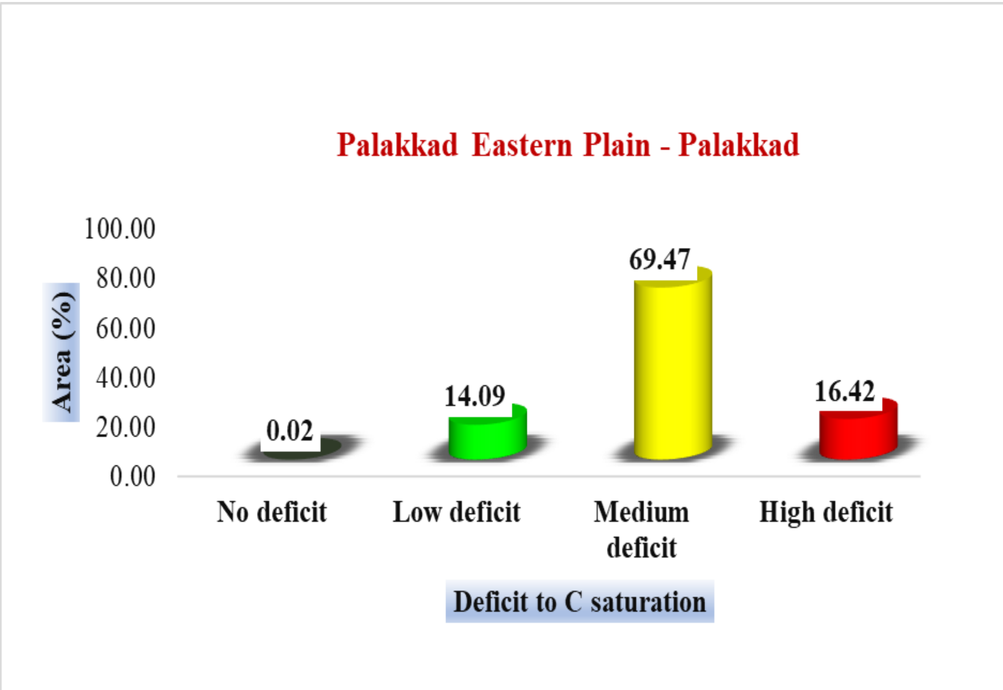

Fig: (22b)

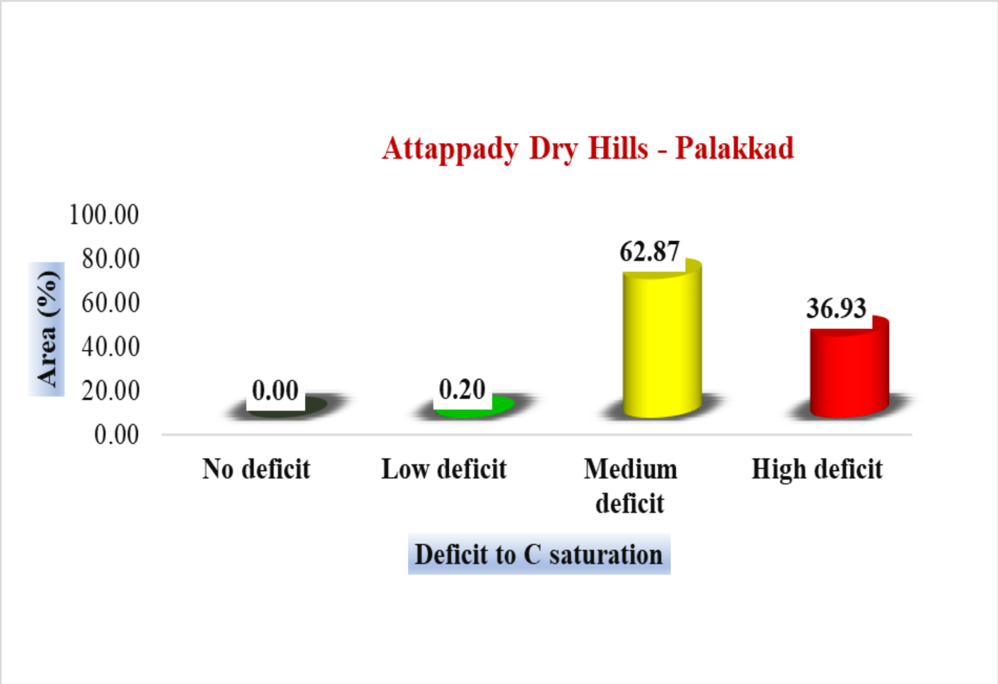

Fig: (22c)

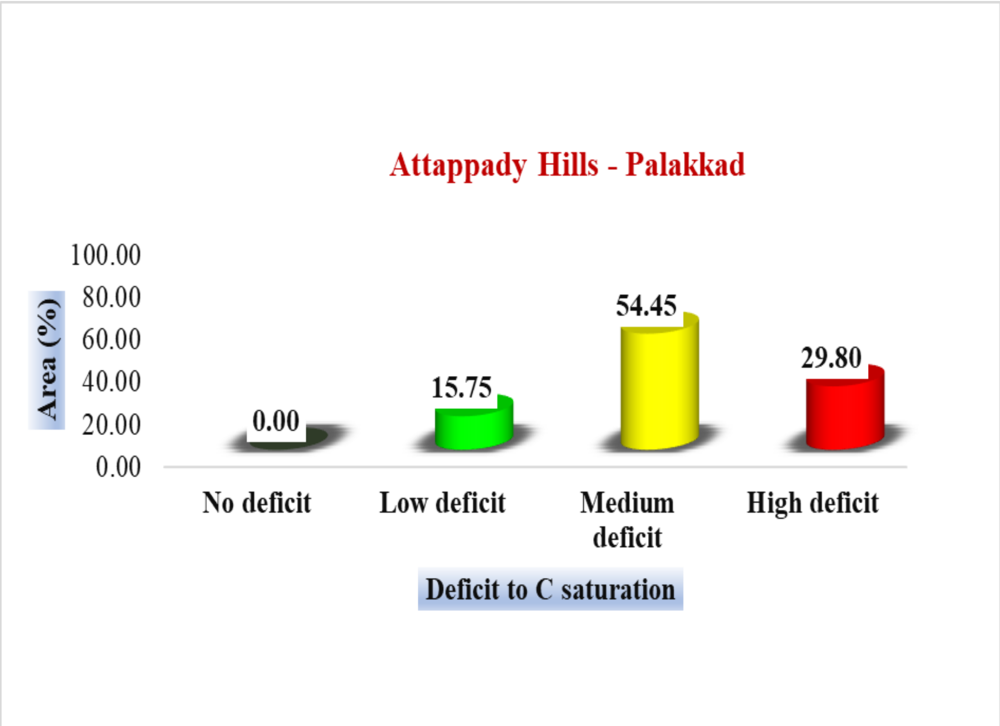

Fig: (22d)

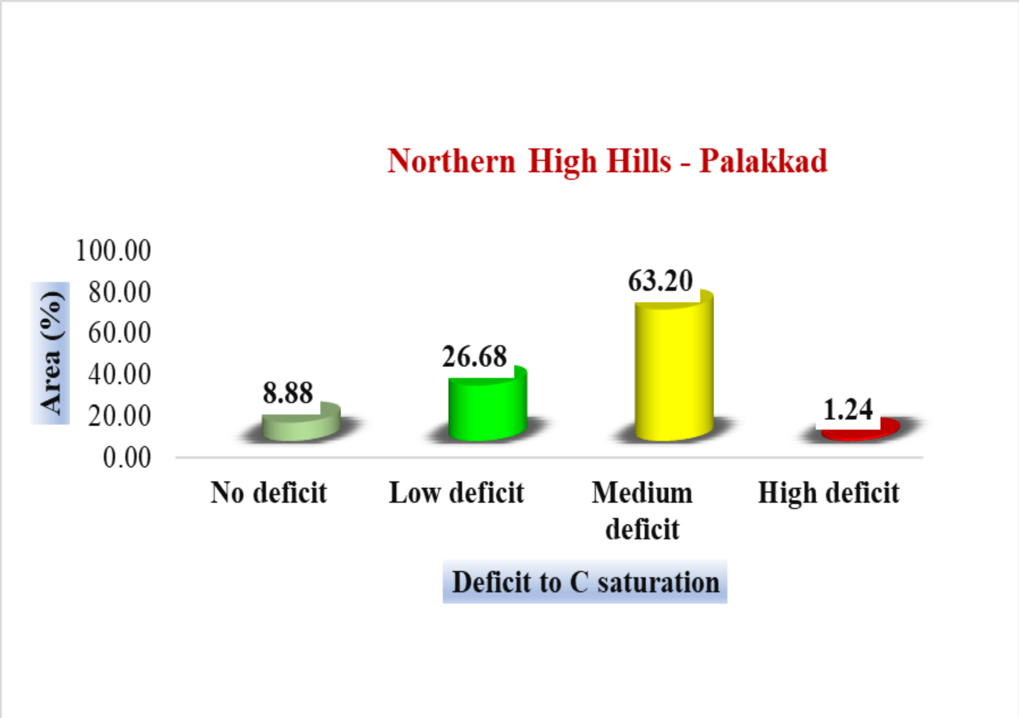

Fig: (22e)

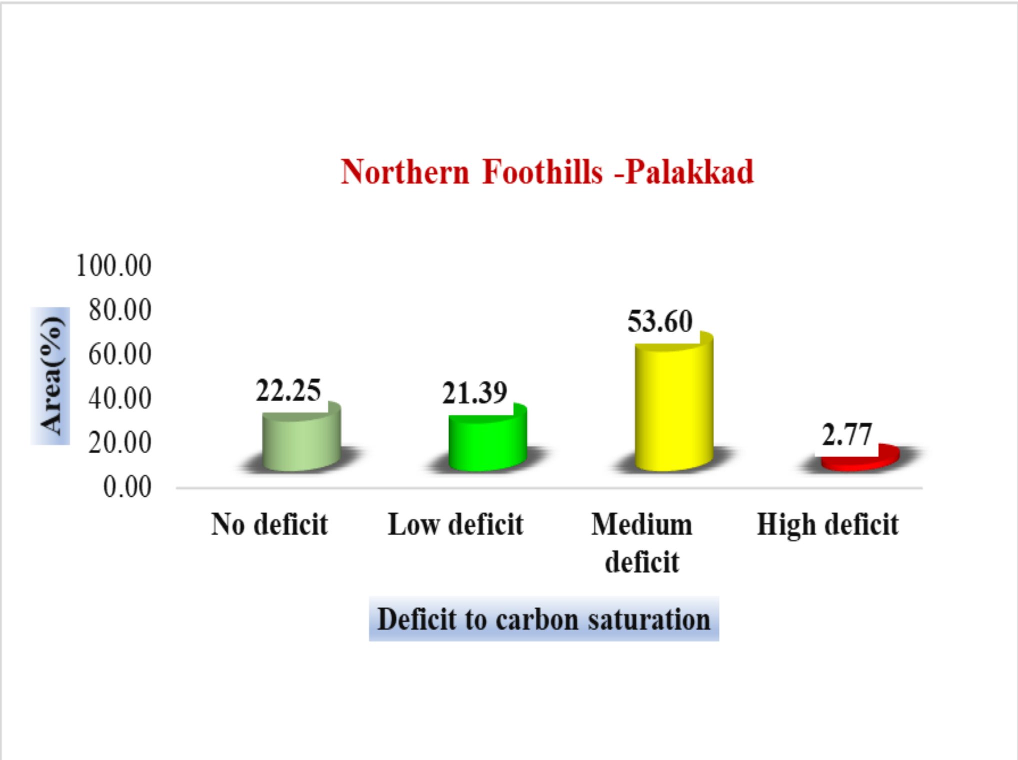

Fig: (22f)

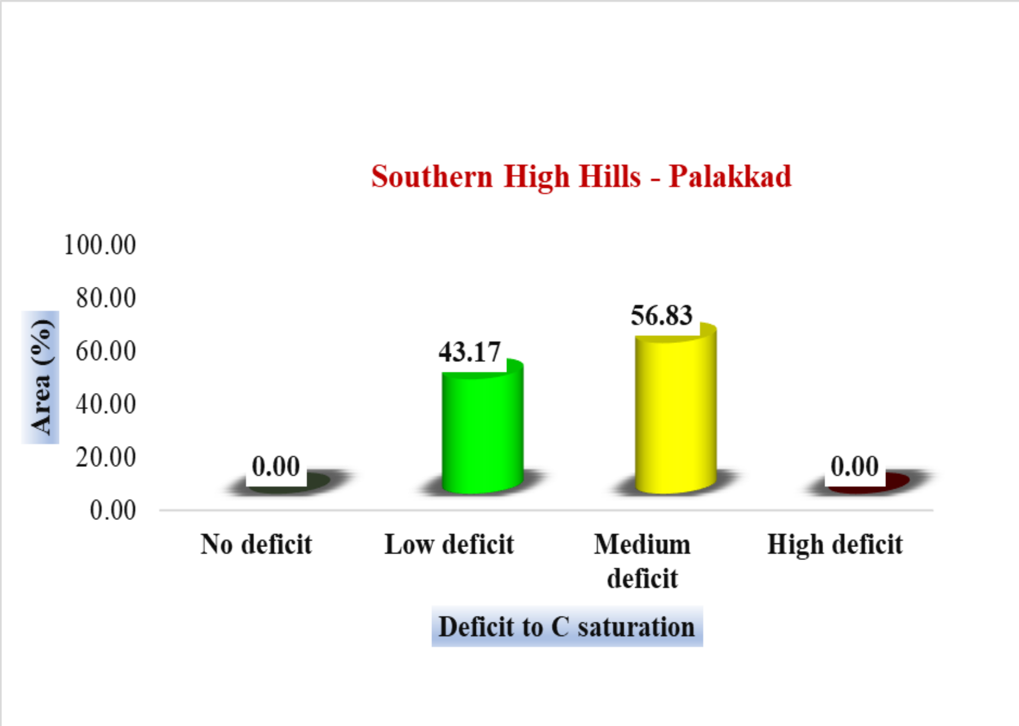

Fig: (22g)

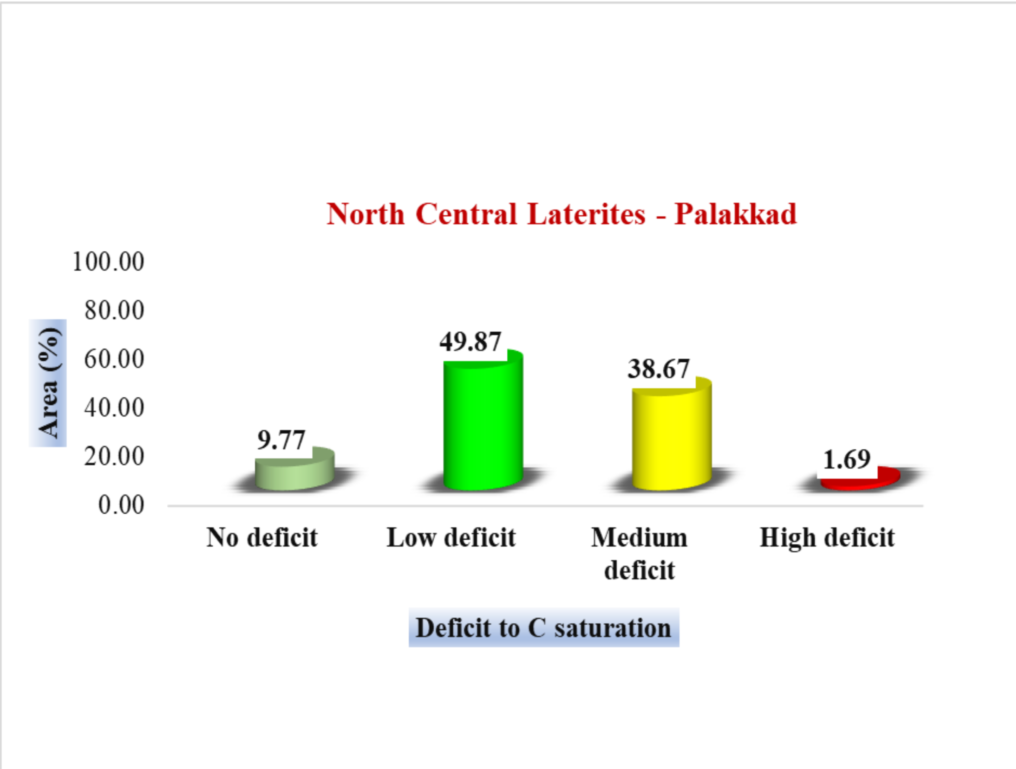

Fig: (22h)

Figures 22a, 22b, 22c, 22d, 22e, 22f, 22g, 22h: Graphs representing soil carbon range in different AEUs of Palakkad

Palakkad district has eight agroecological units, including Palakkad central plain, Palakkad eastern plain, Attappady dry hills, and Attappady hills, which are all unique to Palakkad. In the Palakkad central plain was found to have equal areas under no carbon deficit (37.03%), low carbon deficit (34.17%) and medium carbon deficit (28.79%). The area under high carbon deficit was found to be very low (0.01%) in this AEU. In Palakkad eastern plain, medium carbon deficit soil (69.47%) was highest followed by low carbon deficit (14.09%) and high carbon deficit (16.42%) soils. No carbon deficit (0.02%) soils were very rare in this AEU.

The Attappady dry hills are located in Palakkad's north-eastern corner and include parts of the Puthur, Agali, and Sholayar panchayats. The Attappady hills, which are spatially distributed as a narrow strip of land along the valley in the central part of the hills in North Palakkad along with Attappady dry hills, represent land areas with low rainfall. The no carbon deficit soils were absent in both units. Medium deficit (62.87-Attappady dry 54.45- Attappady hills) hills were found to be more common in both units followed by high and low carbon deficit soils.

Northern High Hills in Palakkad district was found to have more medium carbon deficit (63.2%) soil and very less area under high carbon deficit (1.24%) soils. Northern Foot Hills were found to have maximum area under medium carbon deficit (53.6%) soils and only few areas were found under high carbon deficit category (2.77%). Southern High Hills were found to have no soils under no carbon deficit and high carbon deficit. Maximum soils were under the low carbon deficit category (43.17%) and medium carbon deficit category (56.83%).

Northern Central Laterite had maximum area under the low carbon deficit (49.87%) category and had a minimal area under high carbon deficit soils (1.69%). Generally, AEUs in Palakkad district were mostly in the low and medium carbon deficit categories and extreme deficit situations were at a minimal.

4.2.10 Carbon Saturation in Agroecological Units of Malappuram District.

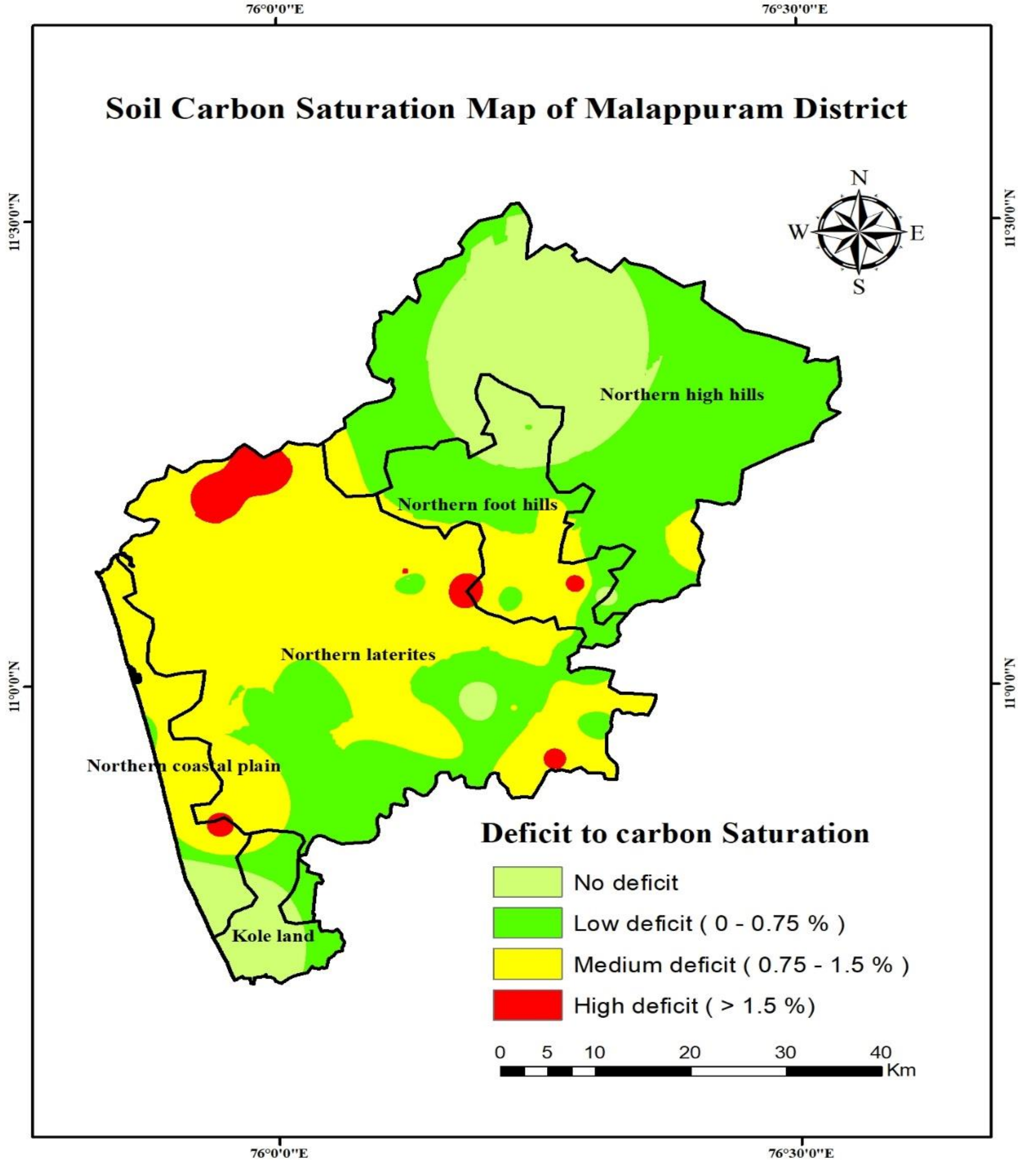

Figure 23: Soil carbon Saturation map in agroecological units of Malappuram District

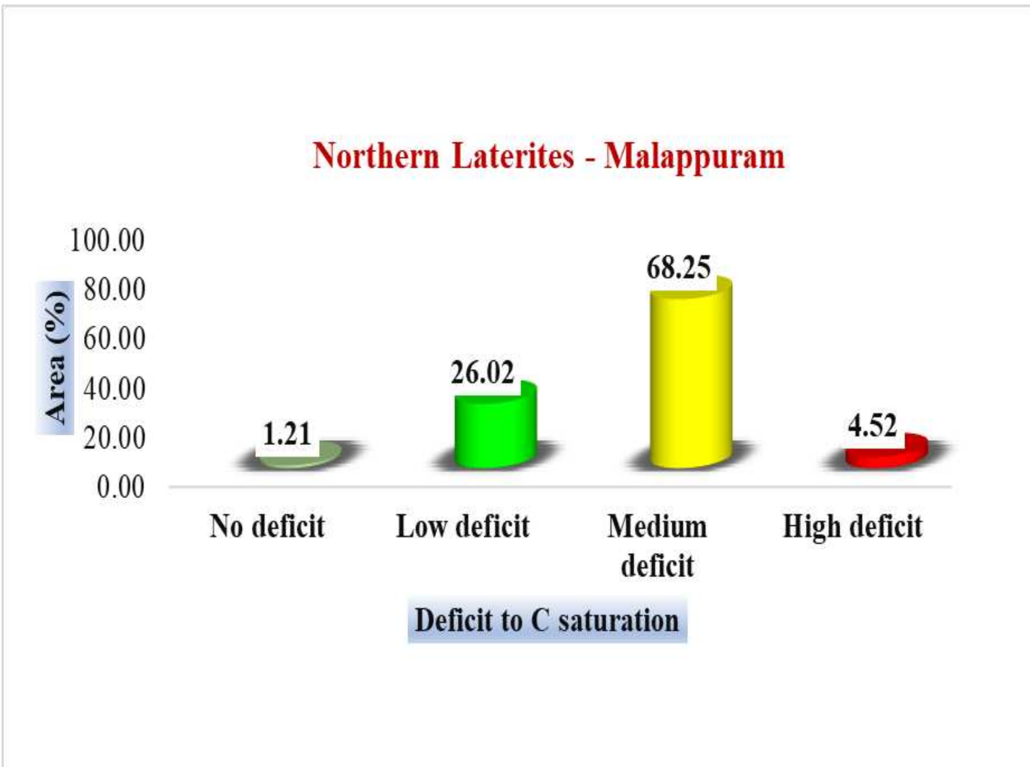

Fig:(24a)

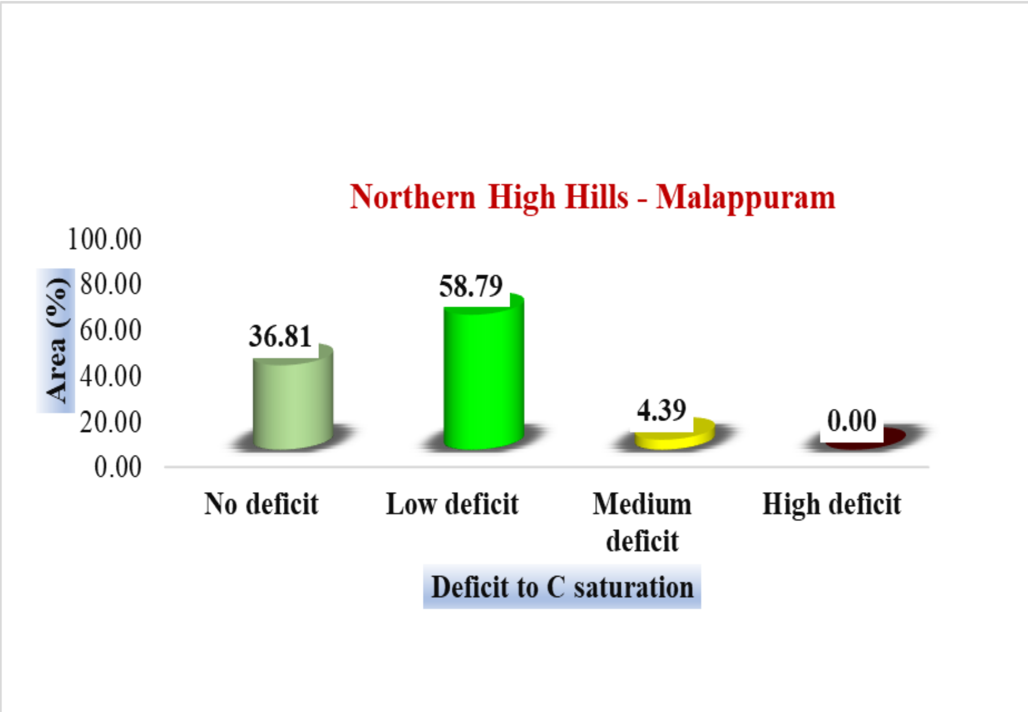

Fig:(24b)

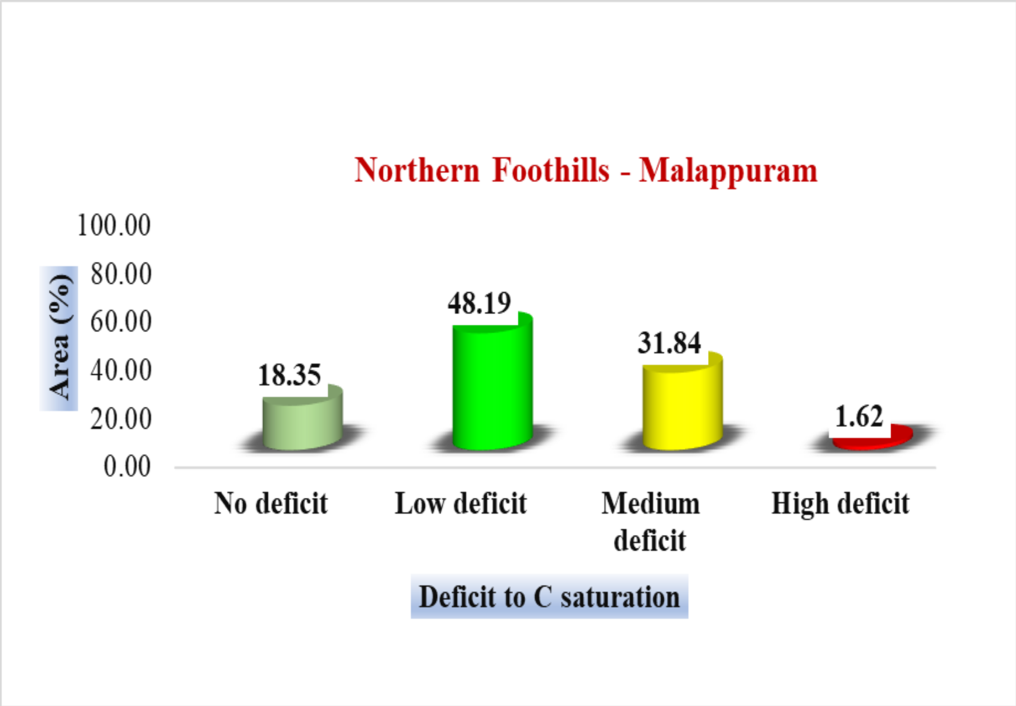

Fig:(24c)

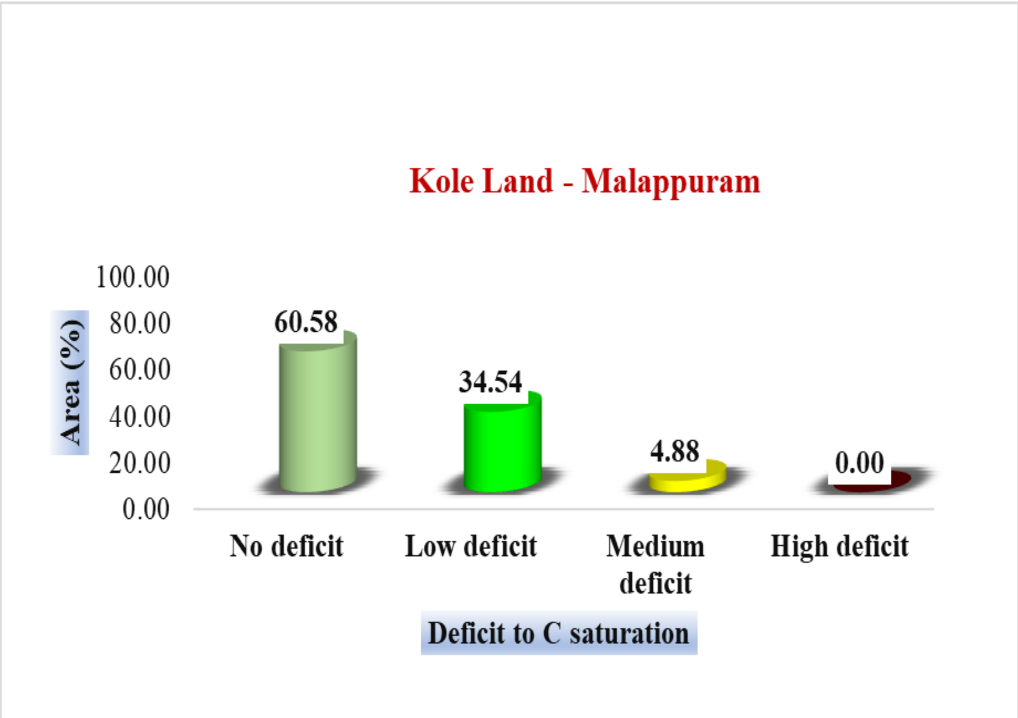

Fig:(24d)

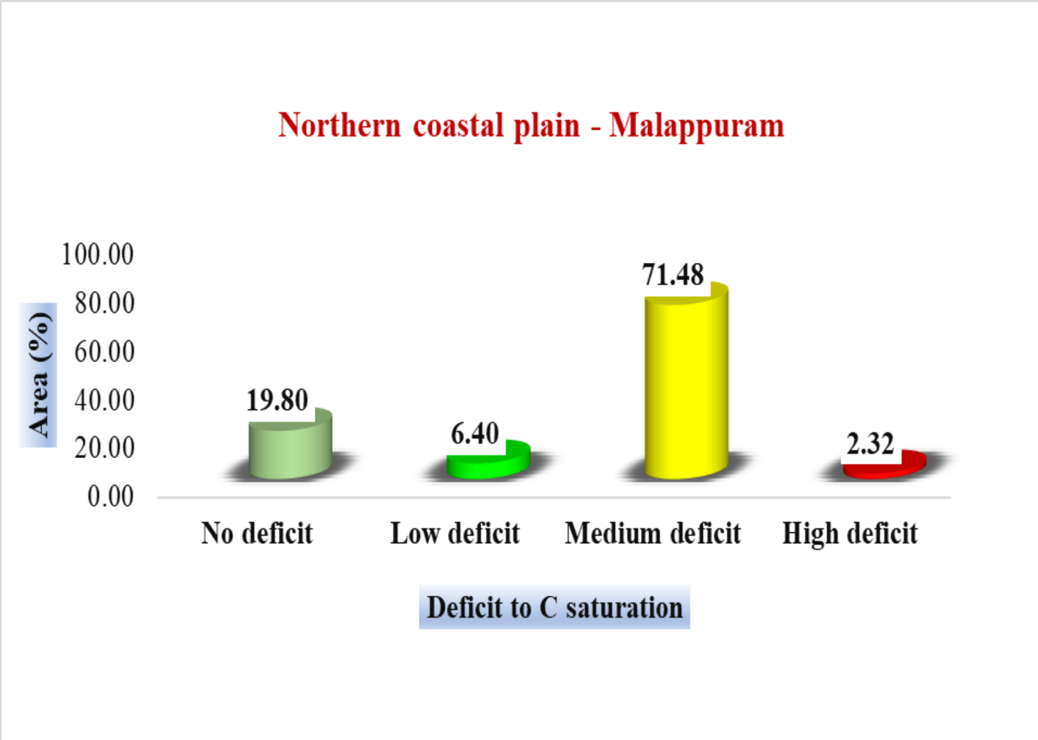

Fig:(24e)

Figures 24a, 24b, 24c, 24d, 24e: Graphs representing soil carbon range in different AEUs of Malappuram

Soils with high carbon deficit was very poor in Malappuram district and majority of soils in the different AEUs were in the medium and no carbon deficit soils. Northern laterites in Malappuram district were rich with medium carbon deficit (68.25%) soils, whereas Northern high hills were higher with low carbon deficit (58.79%) soils. In the case of Northern foothills, the order of carbon deficit varied as low carbon deficit (48.17%) category followed by medium carbon deficit (38.14%) and high carbon deficit (1.62%). High carbon deficit soil was absent in Malappuram kole lands and they majority of soils were with no carbon deficit (60.58%). In Malappuram, most of the soils were found to fall under low to medium carbon deficit categories.

4.2.11 Carbon Saturation in Agroecological Units of Wayanad District

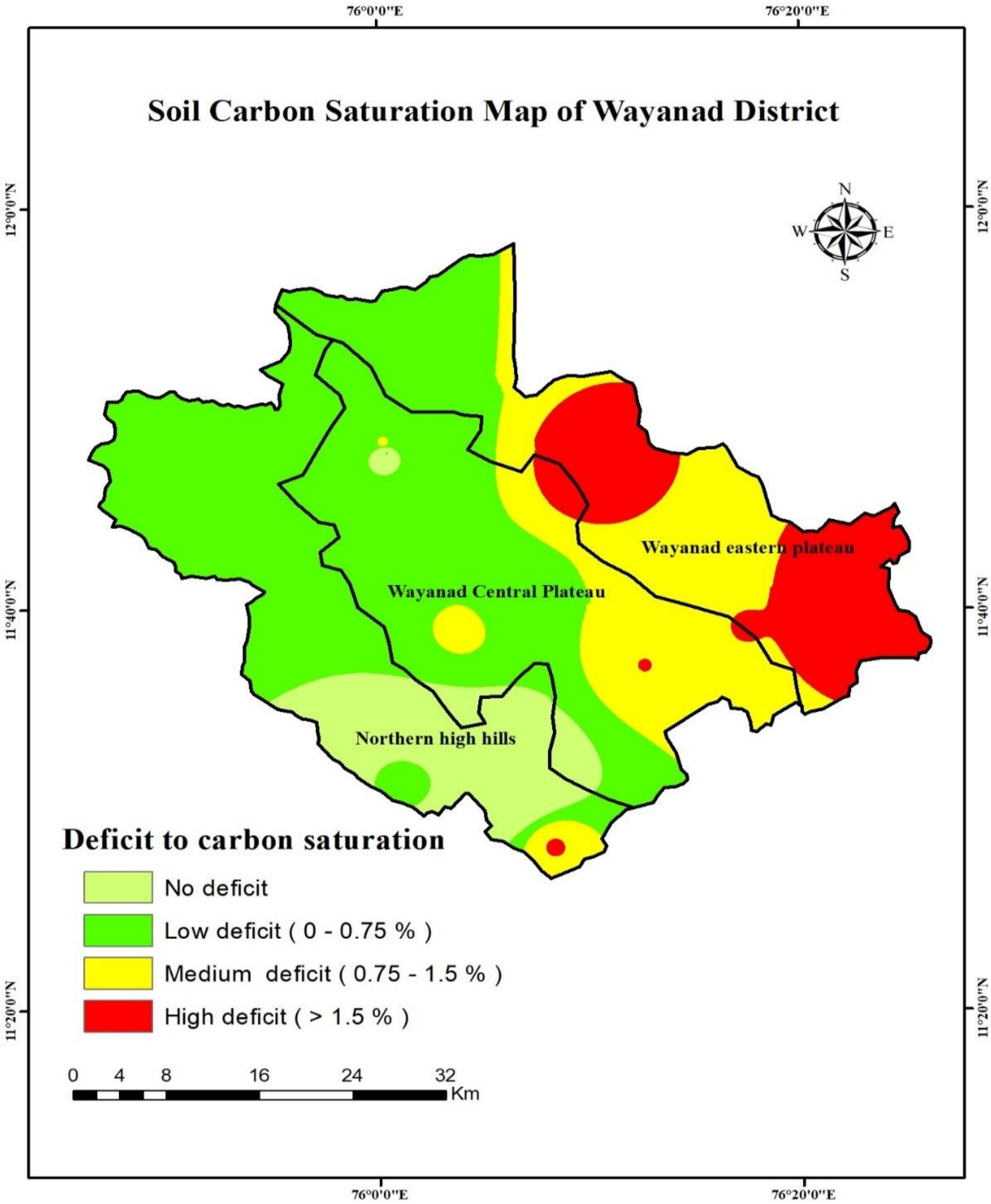

Figure 25: Soil carbon Saturation map in agroecological units of Wayanad District

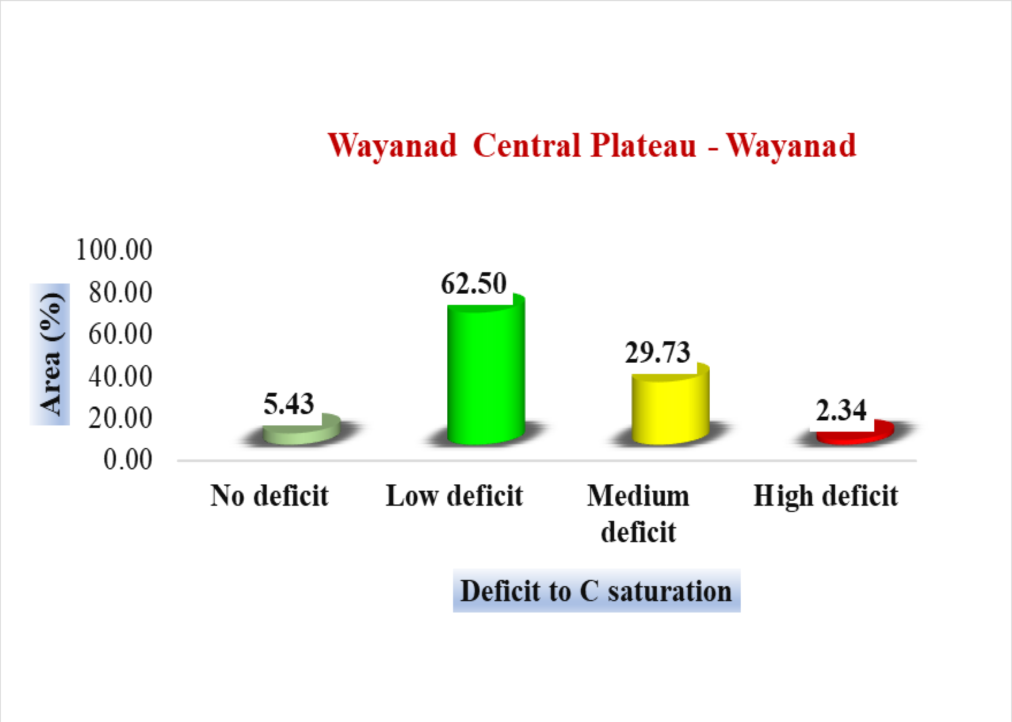

Fig:(26a)

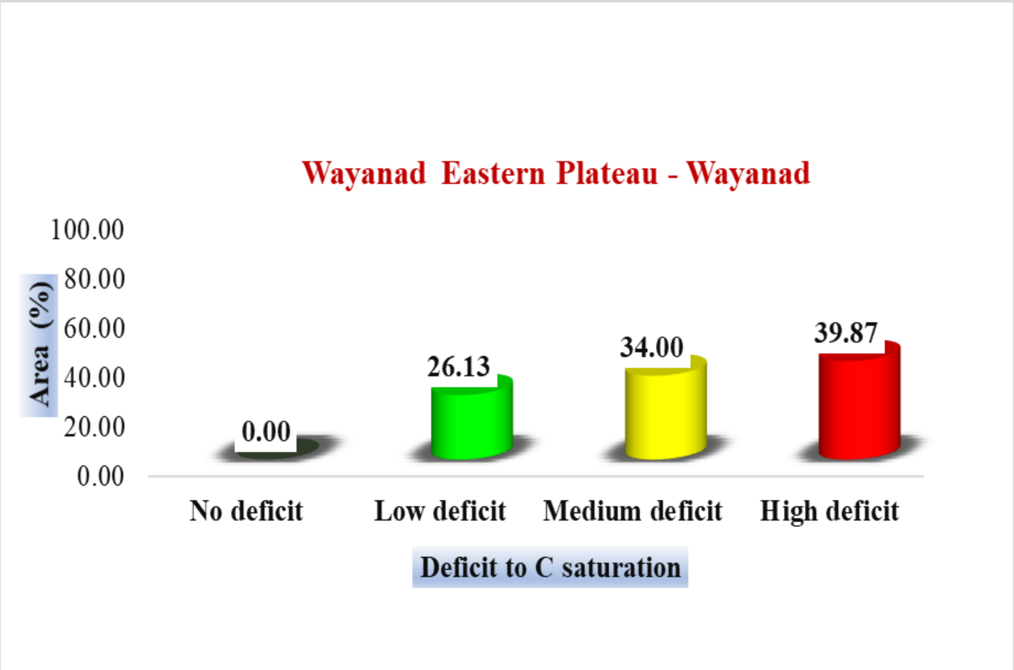

Fig:(26b)

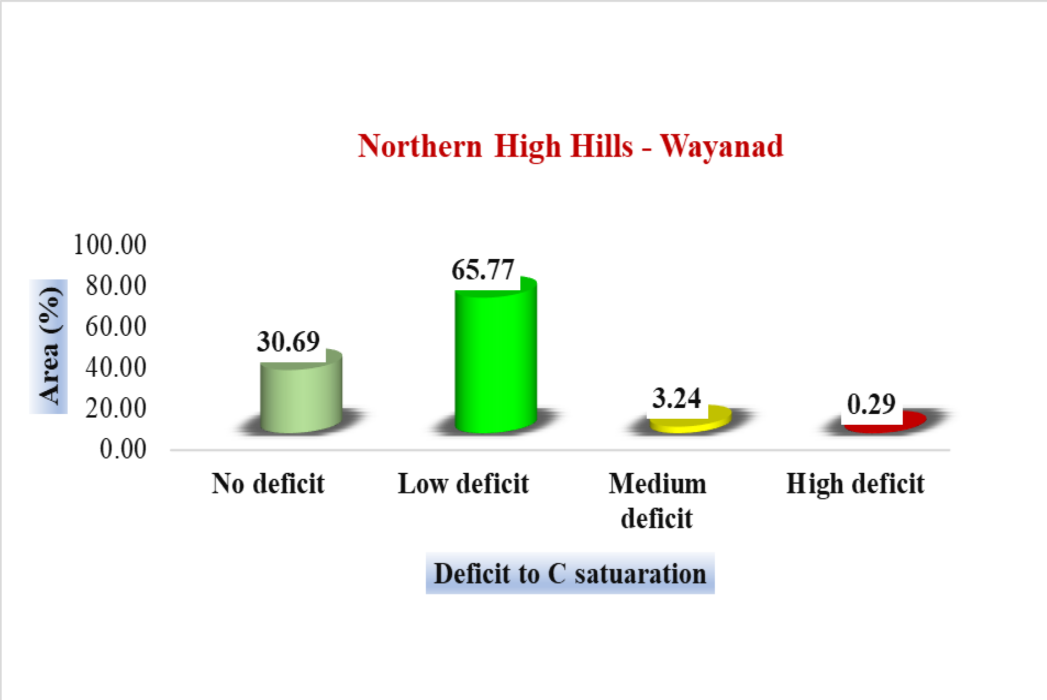

Fig:(26c)

Figures 26a, 26b, 26c: Graphs representing soil carbon range in different AEUs of Wayanad

Wayanad district has three agroecological units they are Wayanad eastern plateau, Wayanad central plateau and Northern high hills. Wayanad district has a higher level of low saturation deficiency.

Wayanad central plateau agroecological unit represents highland plateau with upland soil rich in organic matter with maximum area under low carbon deficiency with 62.50% area under this category. The Wayanad eastern plateau AEU represents parts of the high land plateau with lower rainfall and this unit differs from Central plateau in having lower rainfall and longer dry period. Here, it was found to have an approximately equal distribution of area under high (39.87%) and medium carbon deficit (34.00%) soils. Northern high hills were found to be abundant with low carbon deficit soils. In Wayanad district soils that are far from carbon saturation points were found to be more in Wayanad eastern plateau.

4.2.12 Carbon Saturation in Agroecological Units of Kozhikode District

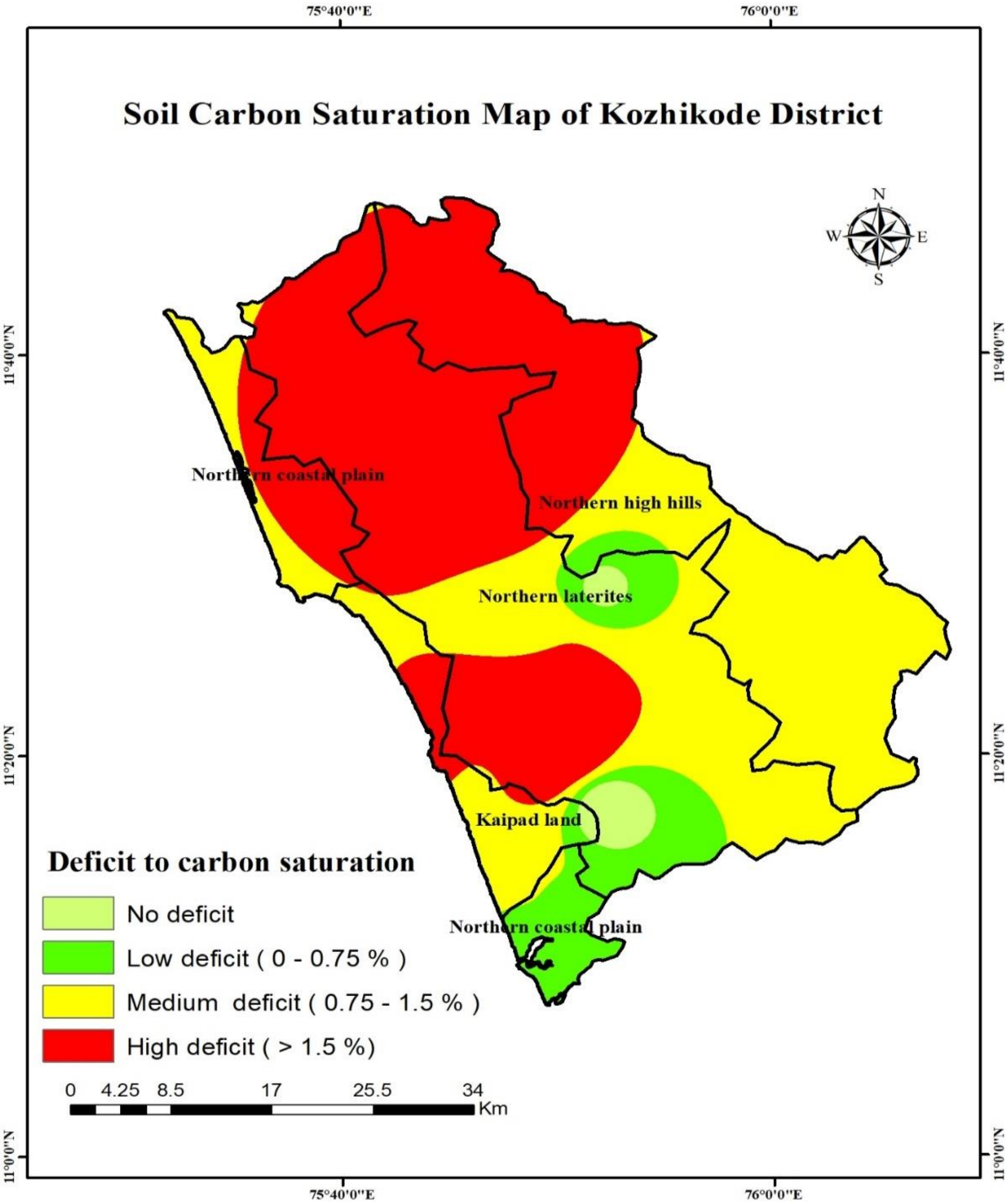

Figure 27: Soil carbon Saturation map in agroecological units of Kozhikode District

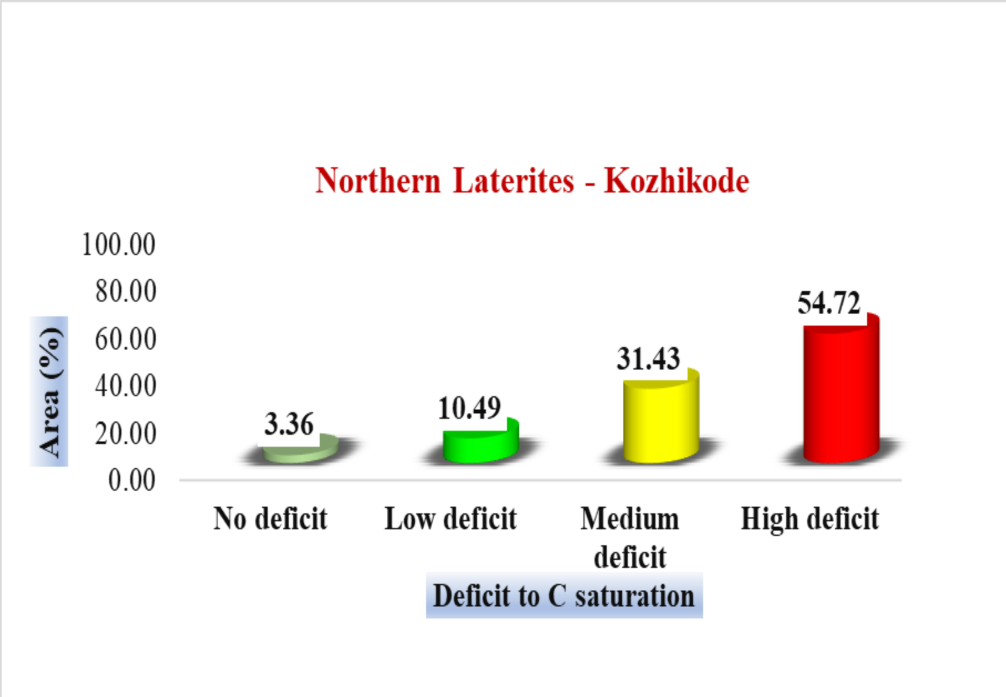

Fig:(28a)

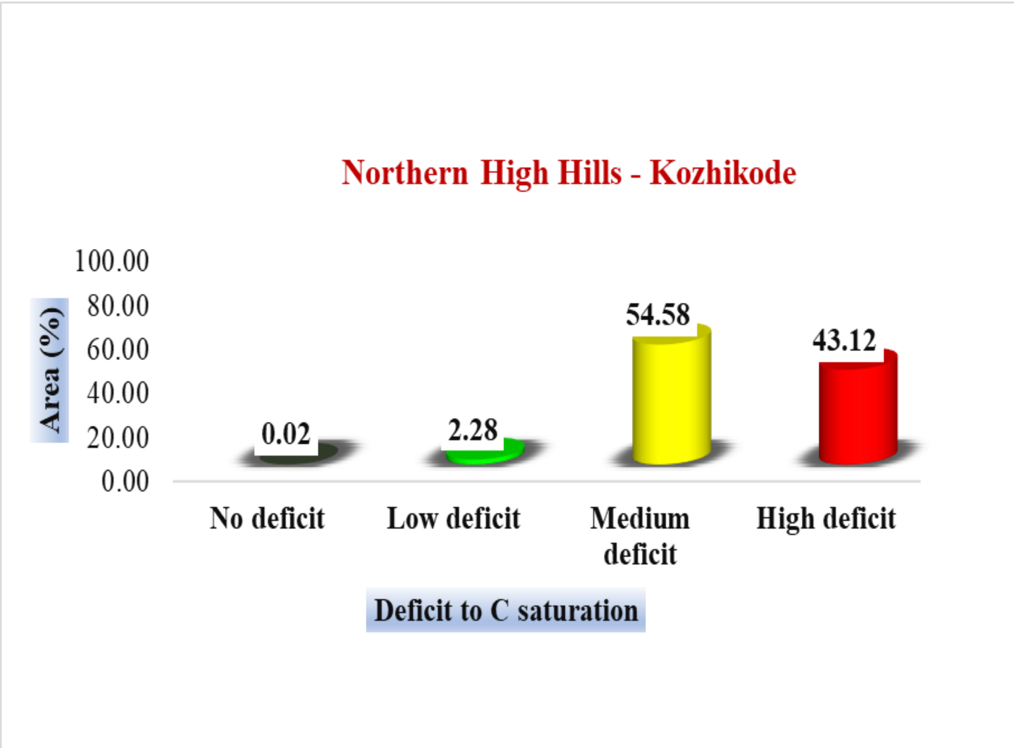

Fig:(28b)

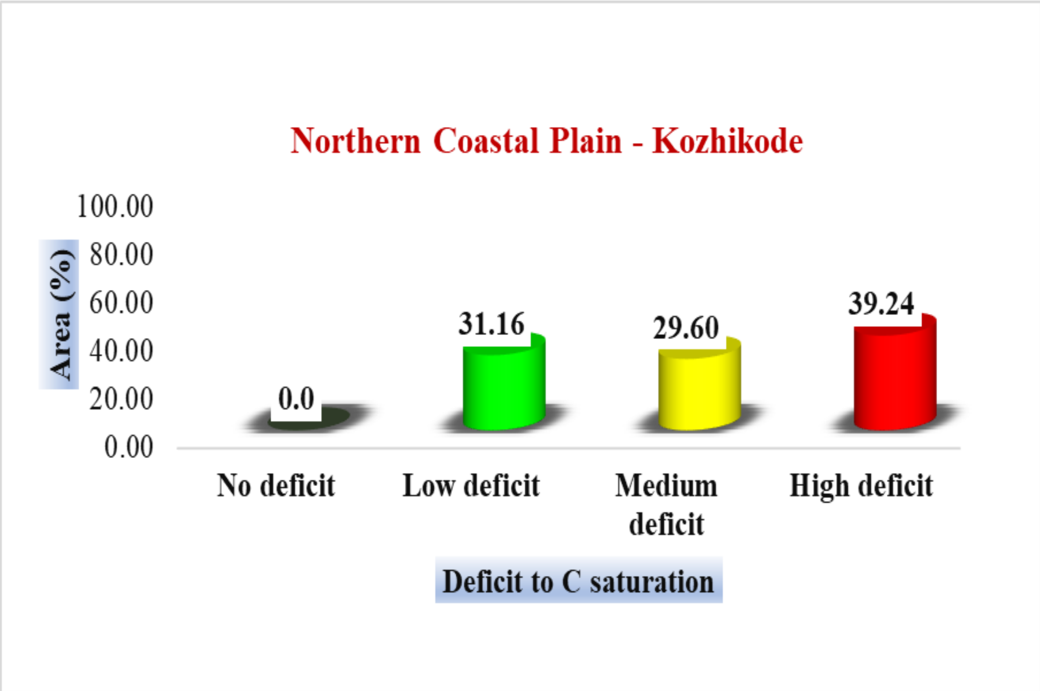

Fig:(28c)

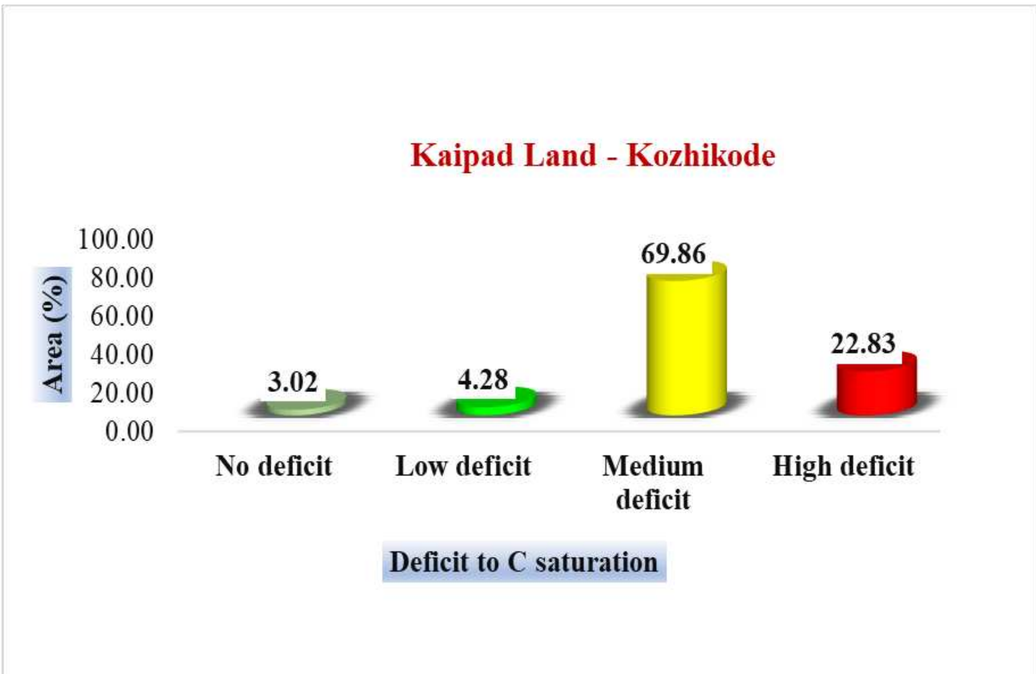

Fig:(28d)

Figures 28a, 28b, 28c, 28d: Graphs representing soil carbon range in different AEUs of Kozhikode

Kozhikode district has almost equal percentage of medium and high deficit soil and only minimal area was under no carbon deficit. The laterite soils in this region was found to have organic carbon values far away from their saturation points. Kaipad lands in this district was mainly with medium carbon deficit soils (69.86%) However, except Kaipad land high carbon deficit soil was more common in other AEUs.

4.2.13 Carbon Saturation in Agroecological Units of Kannur District

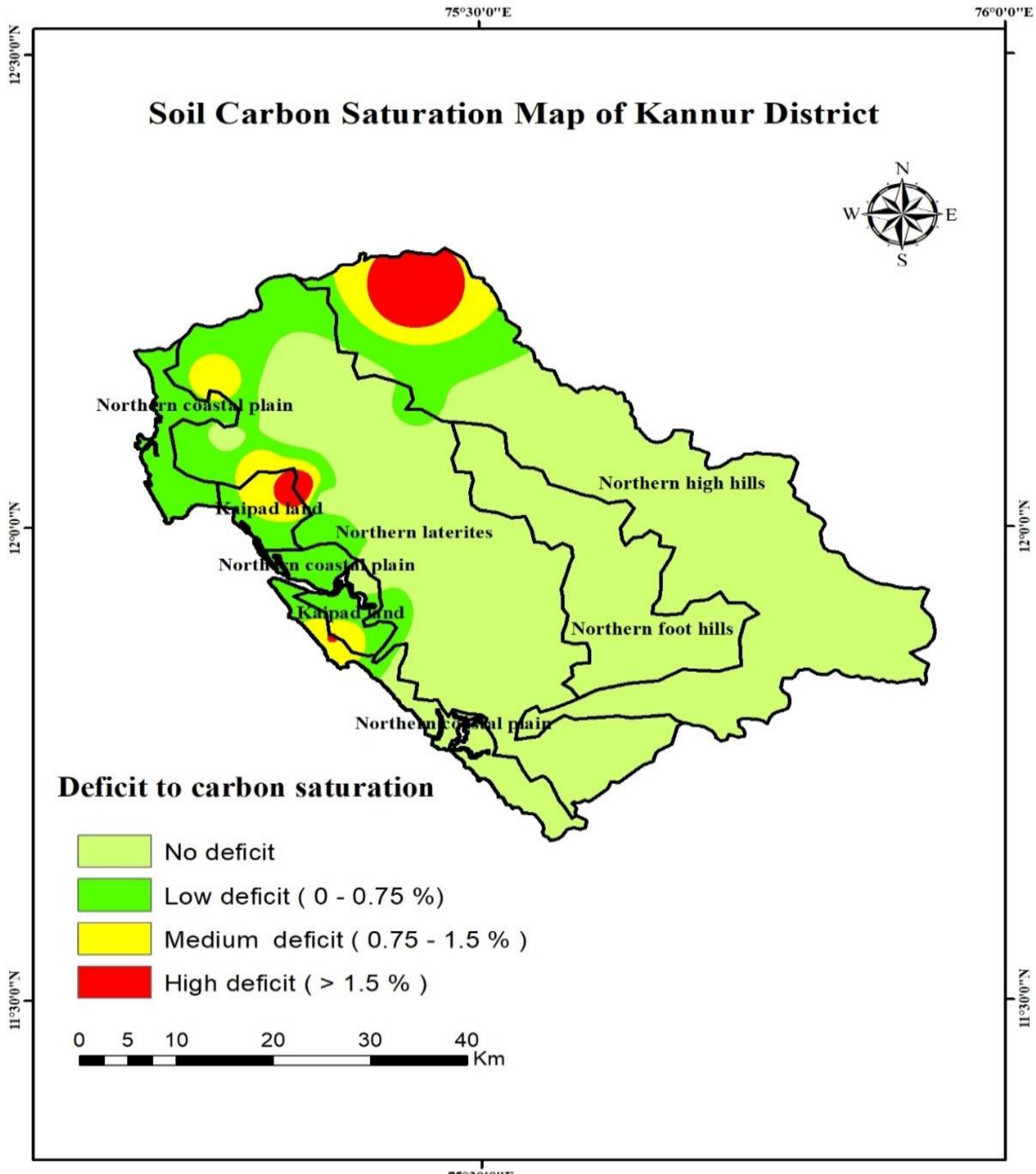

Figure 29: Soil carbon Saturation map in agroecological units of Kannur District

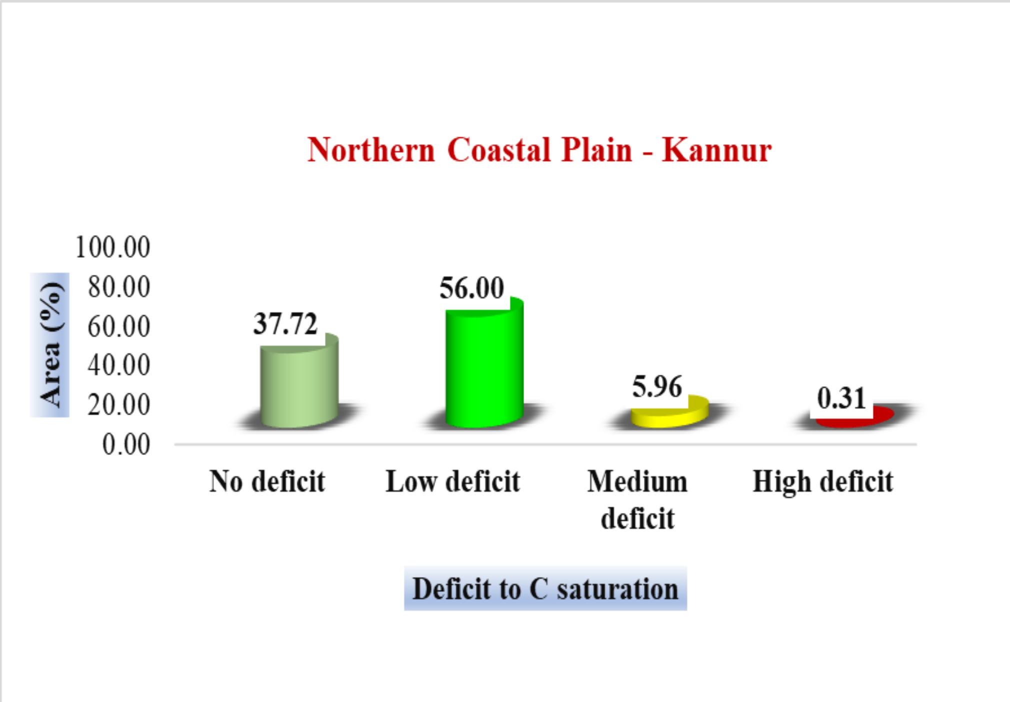

Fig: (30a)

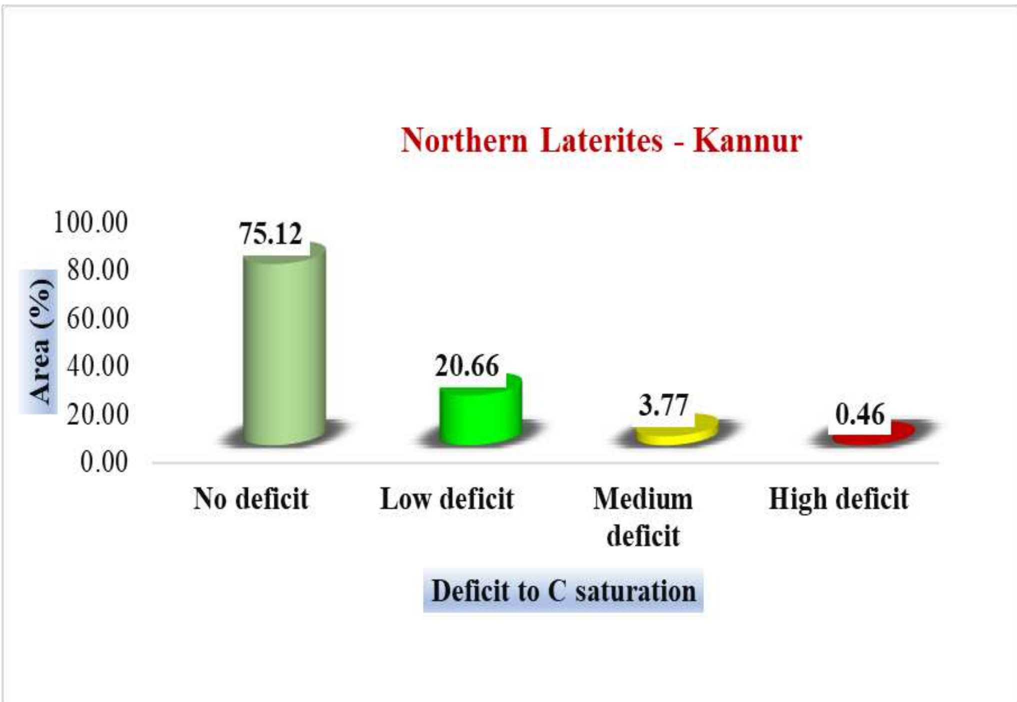

Fig: (30b)

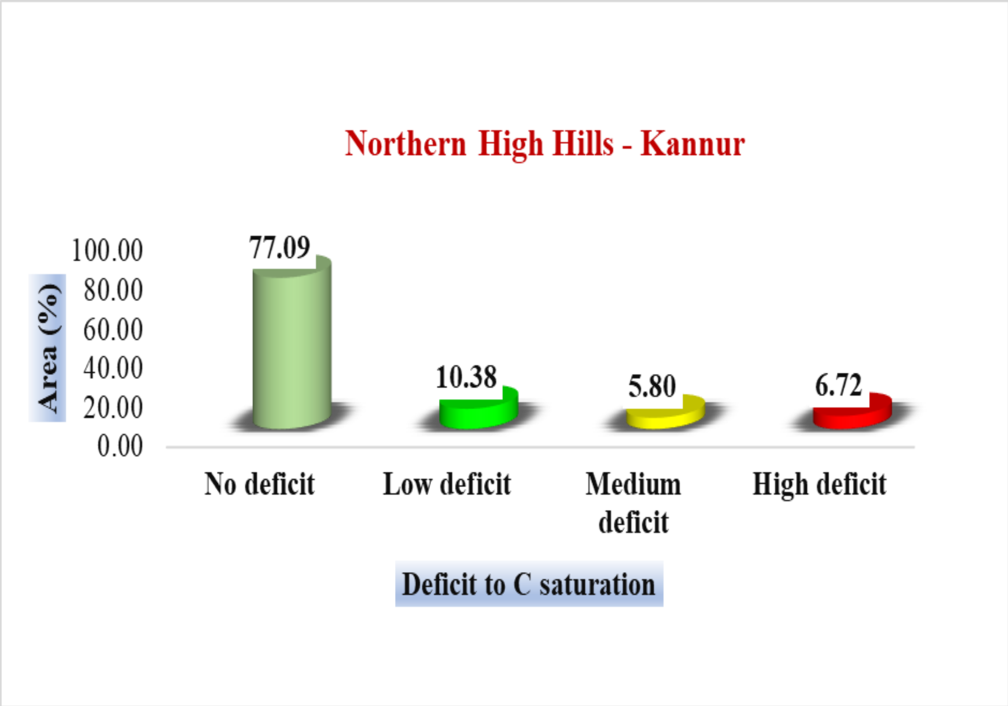

Fig: (30c)

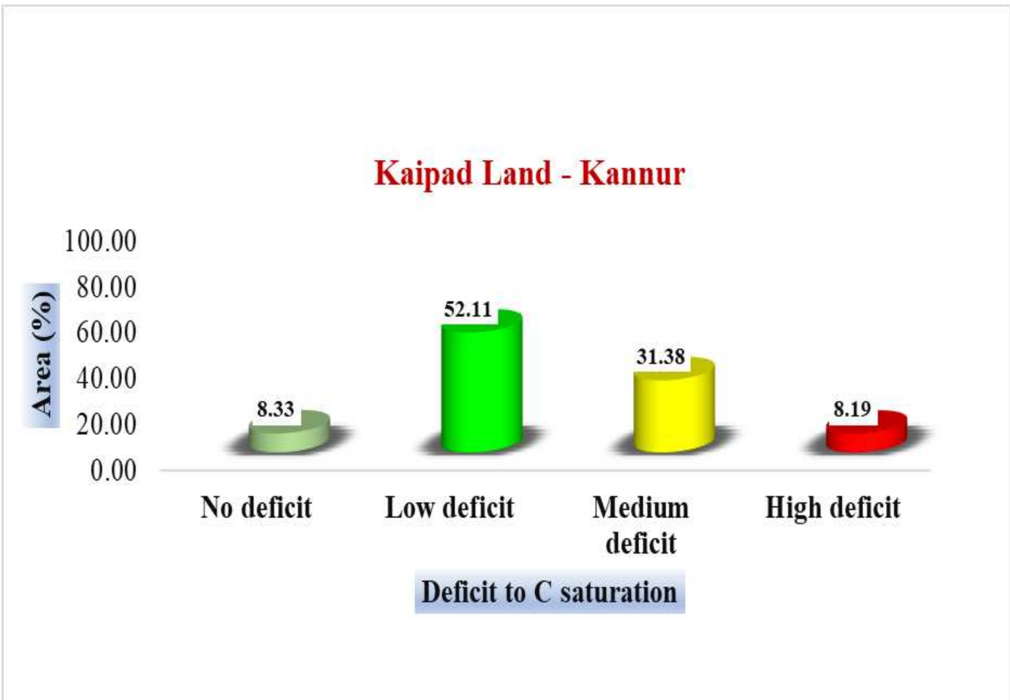

Fig: (30d)

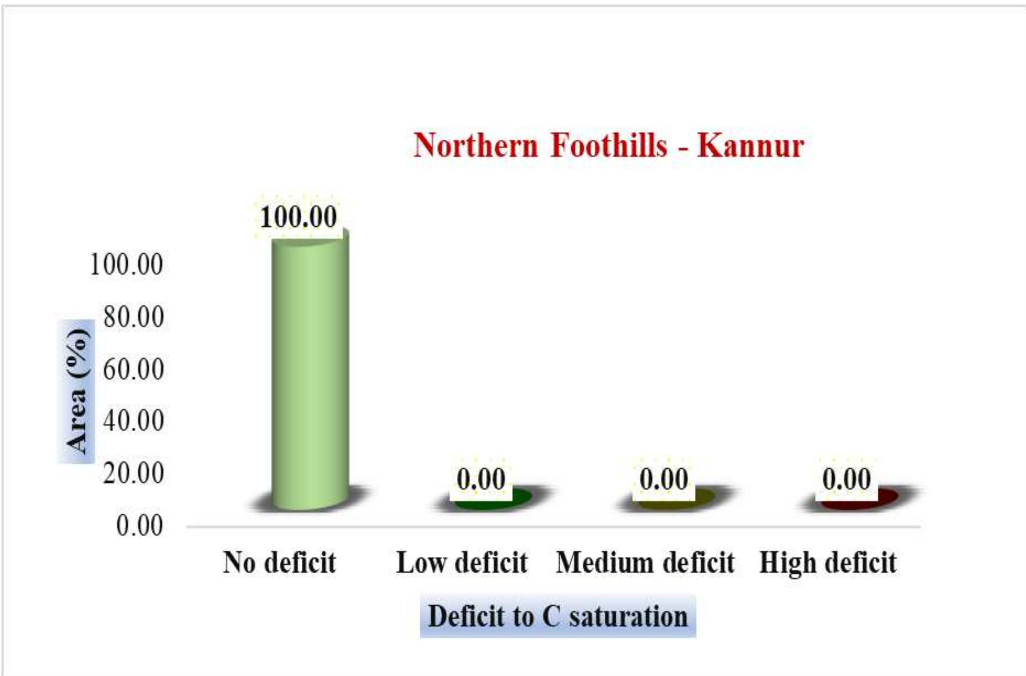

Fig: (30e)

Figures 30a, 30b, 30c, 30d, 30e: Graphs representing soil carbon range in different AEUs of Kannur

Among the five AEUs of Kannur district no carbon deficit soil was abundant in Northern Foot Hills. About fifty-six per cent of total area in Northern Coastal Plain was found in low carbon deficit category followed by 37.2% under no carbon deficit, medium carbon deficit (5.96%) and least under high carbon deficit (0.31%). Northern laterites are rich with no carbon deficit (75.12%) soils in this district. Northern High Hills also had maximum area under no carbon deficit (77.09%) category. Generally, Kannur district showed large tracts under low carbon deficit zones. Presence of intensively cultivated area, mangroves and paddy fields may be considered reasons for carbon rich soils in Kannur.

4.2.14 Carbon Saturation in Agroecological Units of Kasaragod District

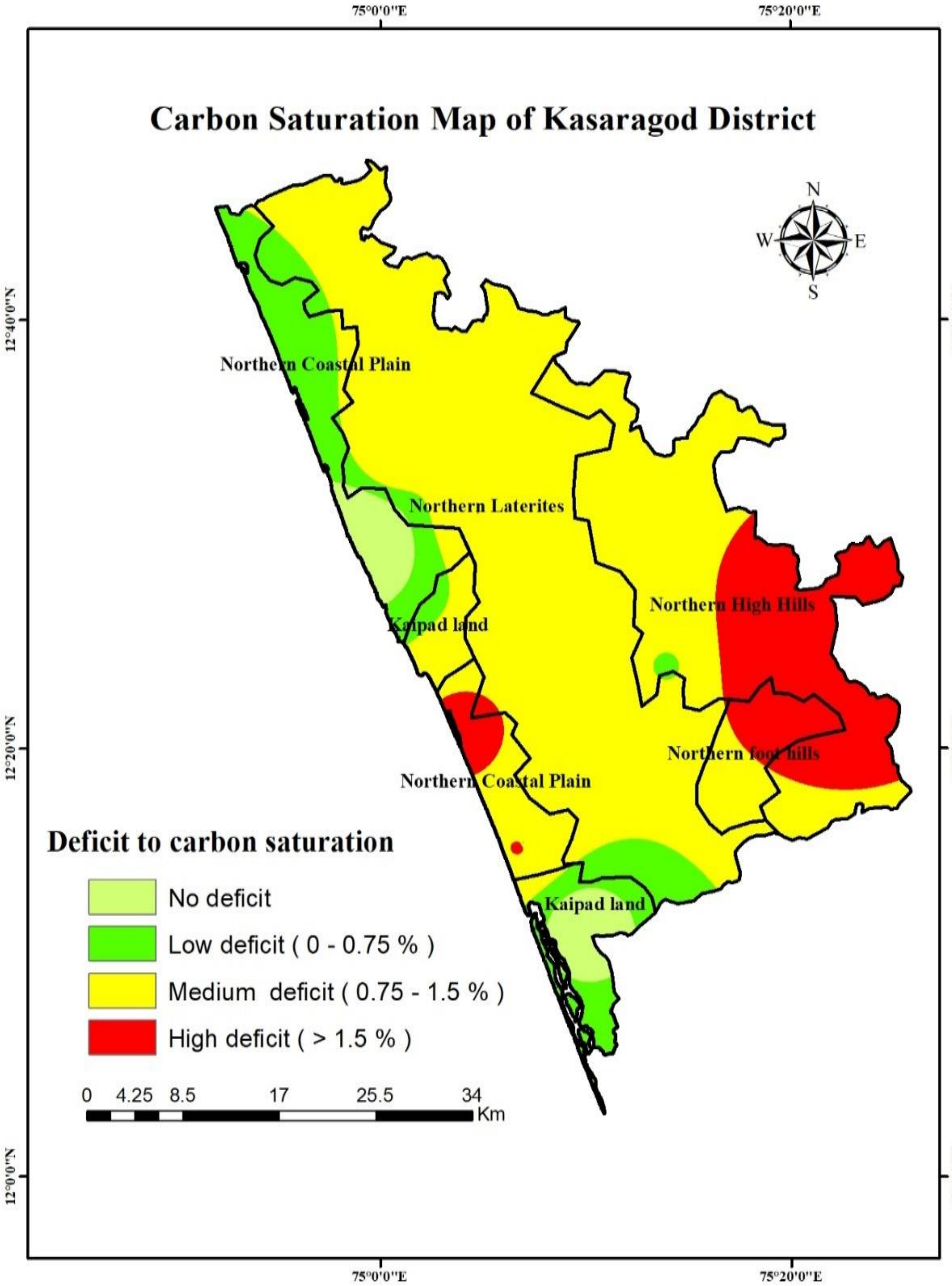

Figure 31: Soil carbon Saturation map in agroecological units of Kasaragod District

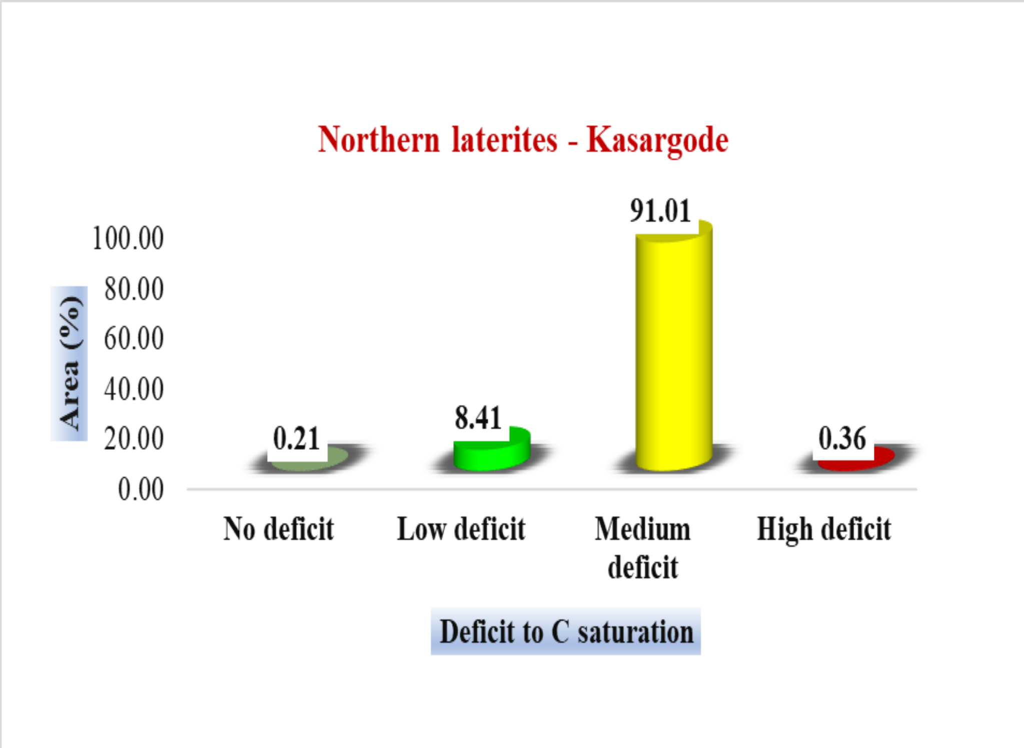

Fig: (32a)

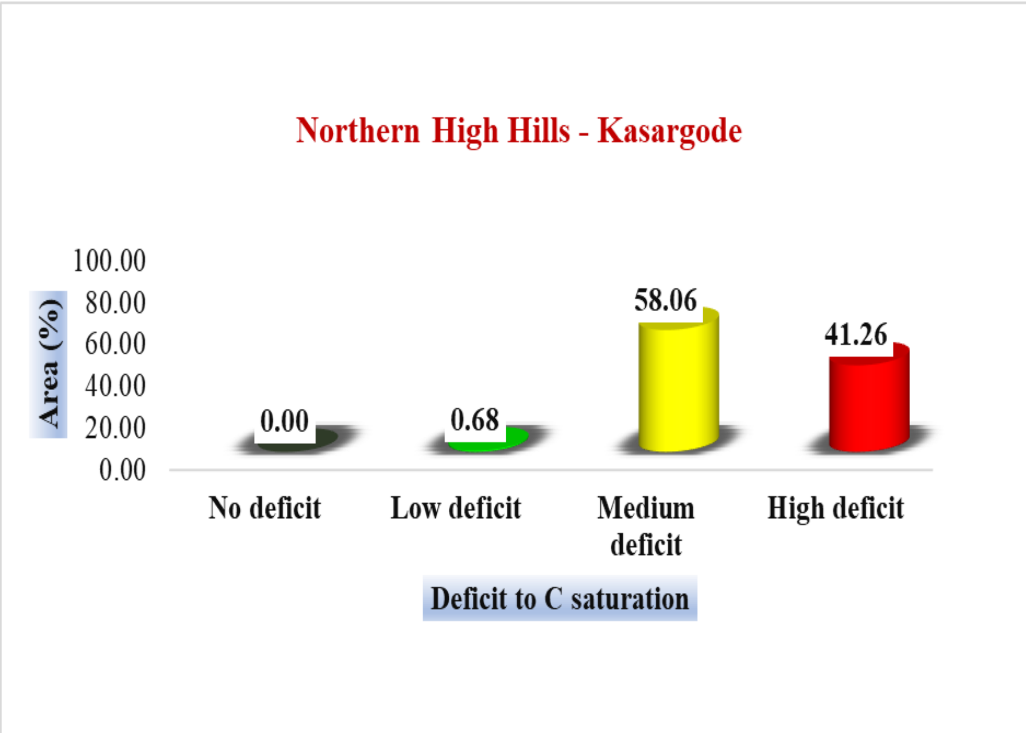

Fig: (32b)

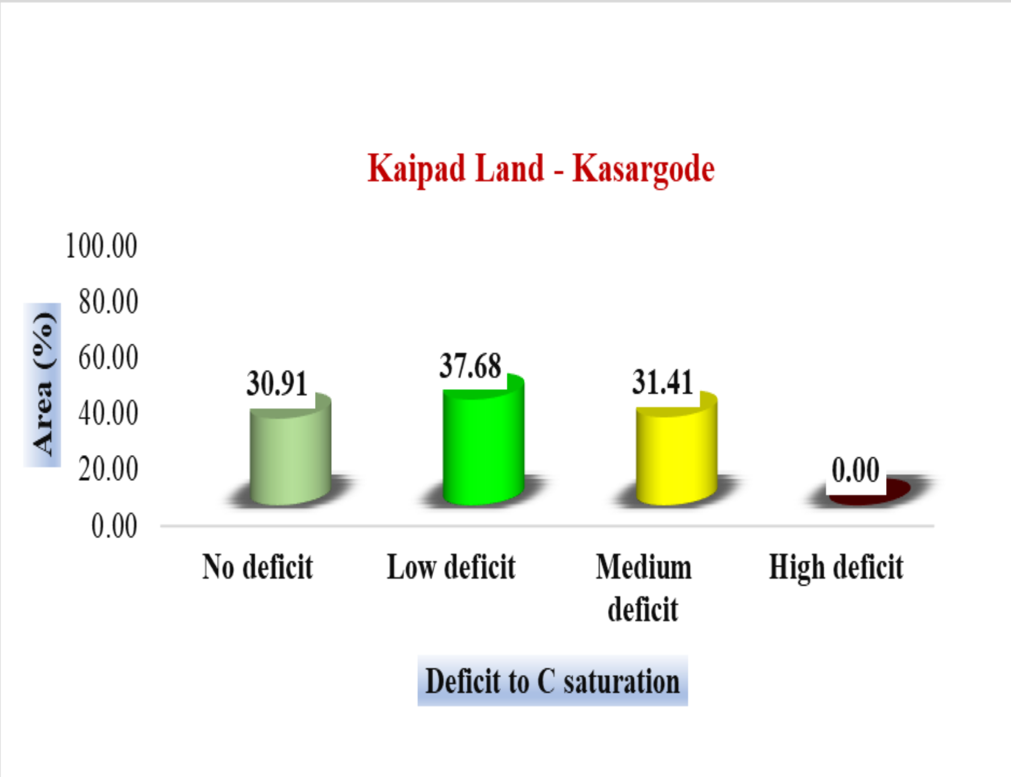

Fig: (32c)

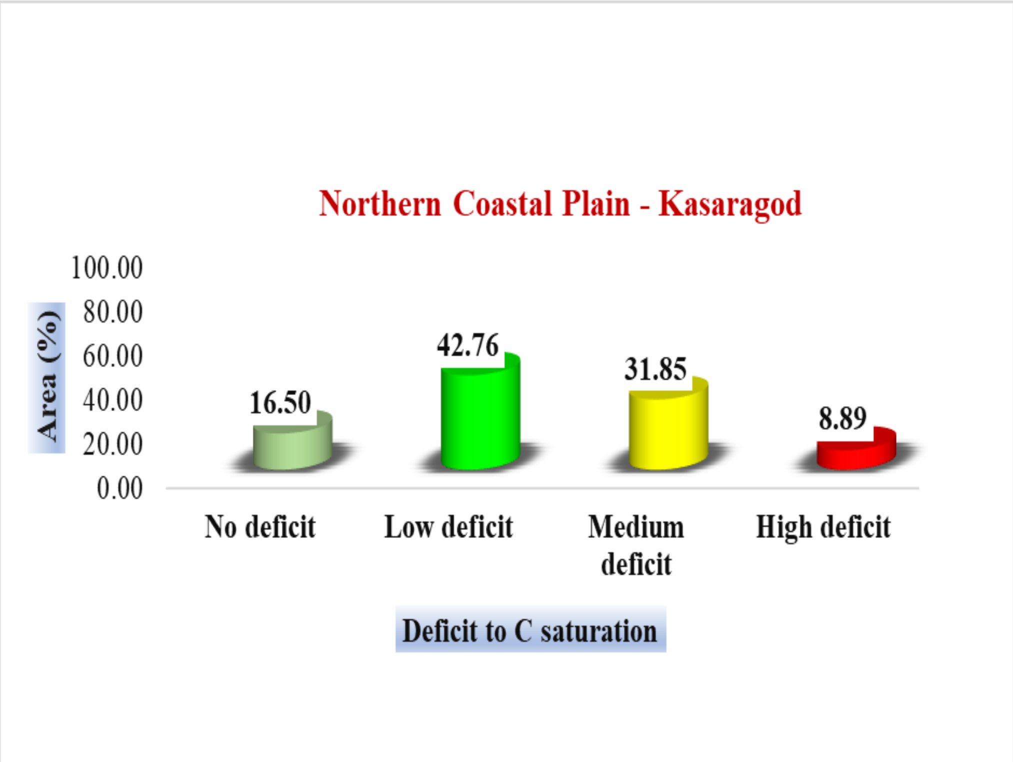

Fig: (32d)

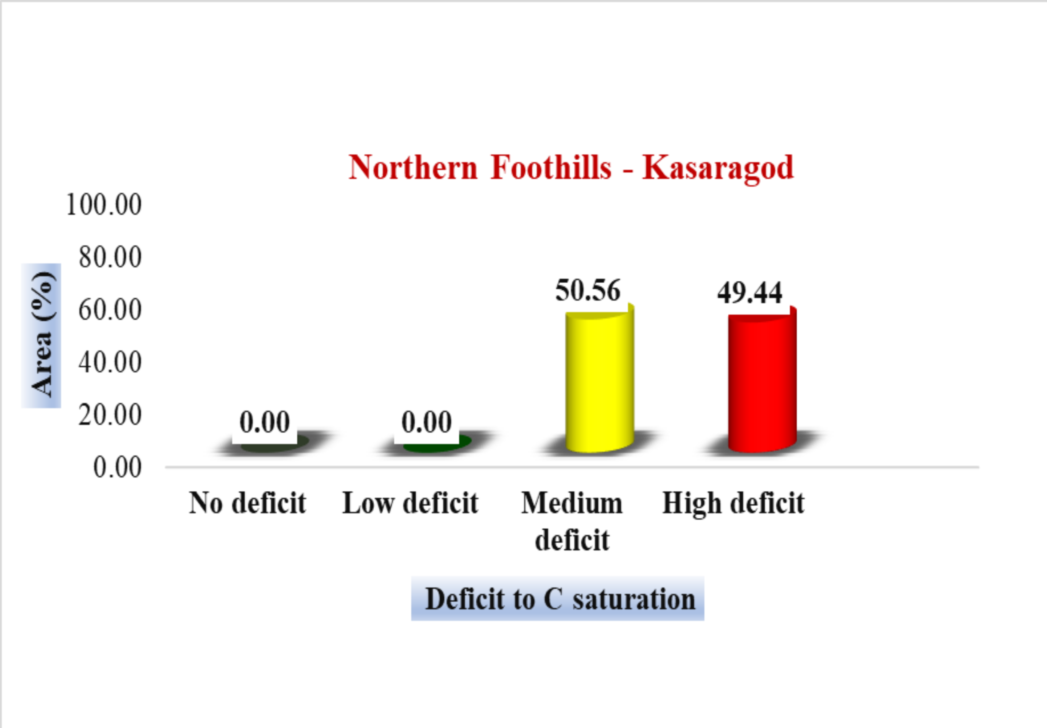

Fig: (32e)

Figures 32a, 32b, 32c, 32d, 32e: Graphs representing soil carbon range in different AEUs of Kasaragod

Kasaragod district had large tracts of area under medium carbon deficit soils. Northern laterites (58.06%), Kaipad (31.41%) and Northern Coastal Plain (31.85%) all had nearly one-third area under medium carbon deficit category.

CHAPTER 5

DISCUSSION

The carbon saturation deficit is useful for detecting areas with saturation as well as areas with more carbon storage capacity. Soil carbon saturation deficit is defined as the difference between soil carbon saturation and current carbon content. The saturation concept discusses that as the soil is far from saturation (high deficit) it has greater potential to store carbon, while if the soil is saturated or approaches saturation (low deficit) its ability to retain carbon gets reduced. If the soil is completely saturated (no deficit) then it lacks the potential to retain more carbon (Stewart *et al*., 2008a; 2008b). Increasing soil carbon storage has been found as an effective strategy for reducing carbon dioxide concentration in the atmosphere. The capacity of soil to sequester carbon could be determined by the carbon saturation deficit of that area. The present investigations show a low or medium carbon deficit in most of the AEZ and AEU.

The findings of this study reveal that high carbon saturation deficit soils are lower whereas, medium deficit, low deficit, and no deficit areas are higher. The results show that Kerala soils have a low or medium carbon deficit. The saturation deficit of soil is influenced by a number of factors (West *et al*., 2007; Di *et al*., 2018) such as climate variables (particularly temperature and precipitation), soil physical and chemical properties, quality of carbon input, Quantity of carbon input, land management activities, and physiography are the factors that influence an areas carbon saturation deficit. Disturbance in the soil also plays an important role in carbon stabilization (Jiaying *et al*., 2017; Feng *et al*., 2014a; Mayzelle *et al*., 2014; Kirschbaum *et al*., 2019). Changes in these factors can influence saturation capacity of an area.

The AEZs of Kerala shows that large areas have already been carbon saturated and this trend can be attributed to soil texture, land use management, and climate conditions (Whitehead *et al*., 2018). The two zones with the most carbon saturation are the High hills and the Foothills. High hills, which in the Western

Ghats, are one of the most carbon saturated AEZ in Kerala. The high carbon content in this AEZ is attributed to rich vegetation, presence of clay soil, inherent SOC content and low temperature, resulting in reduced carbon decomposition and loss (Claugherty *et al*., 2001; West *et al*., 2007). Foothills is another carbon rich zone in Kerala. Due to the presence of OM rich clay soil no deficit area is dominant in Foothills. Increase in SOM increases the carbon storage level. The Capacity to retain carbon in soil was more for clay textured soil. Clay soil is associated with organic material to form a certain complex which reduces the decomposition rate. Thus, more carbon can be retained in clay soil compared with coarse soil (Hassink *et al*., 1996;1997). Low temperature and high moisture also decline decomposition rate (Claugherty *et al*., 2001) which increases the carbon storage capacity this led to saturation condition (Meyer *et al*., 2017).

Generally, areas with high saturation potential are considered as carbon sink (Heitkamp *et al*., 2012). Comparatively more carbon saturation deficit area was seen in coastal plains of Kerala. This may be due to lower carbon input in this zone compared with foothills and high hills. Also, the soil texture being predominantly sandy doesn't favour high carbon retention in these soils. Carbon input and environmental factors play a crucial role in the saturation process (Goh, 2014). Sandy soils in coastal plain has smaller turn over time (Barre *et al*., 2017).

Kuttanad (AEU 4), Pokkali land (AEU 5), Kole land (AEU 6), Kaipad land (AEU 7) are rich with OM content, presence of acid saline soil and hydromorphic clay. These regions are abounded with high saturated areas due to high clay contents and retain good amounts of carbon. Also being fully saturated during most part of the year these soils have very low carbon loss. Most of the regions in these areas are submerged with water which slows down the decomposition rate (Bradford *et al*., 2016). Because of the lack of oxygen in the soil, the product acquired through decomposition alters (Claugherty *et al*., 2001).

Marayoor Hills (AEU17) (100%) and Kumily Hills (AEU16) (99.74%) are two of the AEUs with totally carbon saturated soils. The soil carbon saturation in these units may be attributed to high OM, clayey soil and low decomposition by way of climatic restrictions (Bradford *et al*., 2016). Soil with a clay texture has a stronger protective ability. Clay rich microaggregates retain OM and maintain soils near their saturation levels (Hassink *et al*., 1997; Beare *et al*., 2014). Hence, carbon inputs should be undertaken with supporting management strategies in these soils.

Southern and central foothills (AEU 12), Northern foothills (AEU 13), Southern high hills (AEU 14), and Northern high hills (AEU 15) had more saturated areas. Areas with no to low deficit regions are greater due to presences of high OM due to higher C input, climatic conditions, forest areas and little soil disturbances (Jiaying *et al*., 2017). Very small quantity of high deficit area was observed here with normal level of medium deficit area.

Southern coastal plain contributes (AEU 1) coastal land from Trivandrum, Kollam, and Alappuzha dominated by sandy soils. Coastal plain in Alappuzha district was dominated with no deficit area due to the presence of acid saline soil and water-logged areas which are rich in OM content (Neenu *et al*., 2020). Whereas other district shows vast amount of medium to high deficit area due to presences of sandy soil. Northern coastal plain (AEU 2) represents the coastal plain north of Ernakulam district and along the coast from Thrissur till the northern end of the state where saturation deficit condition was similar to southern Coastal plain. Sandy soil and low OM show higher deficit area in Onattukara sandy plain (AEU 3) regions.

Wayanad eastern plateau (AEU21) and Attappady dry hills (AEU19) have large areas under high and medium carbon deficits. Greater organic matter and carbon input can be added to areas with a high deficit. Soils in these locations have a greater potential to store carbon. Careful utilization of these areas would help increase more carbon storage. A high carbon saturation deficit in these units may be due to decreased carbon inputs, high temperatures facilitating carbon decomposition and loss, and soil texture. Variation in these factors would have led to both high carbon deficits in these soils (Feng *et al*., 2014b; Di *et al*., 2008; Carrington *et al*., 2012).

Attappady hills (AEU 18), Wayanad central plateau (AEU 20), Palakkad central plain (AEU 22) and Palakkad eastern plain (AEU 23) shows areas with medium to high deficit soil. It purely depends on the land use, amount of SOC already present in the soil, carbon input and soil properties of the unit (West *et al*., 2007). The other AEUs like Southern laterites (AEU 8), South central laterites (AEU 9), North central laterites (AEU 10), and Northern laterites (AEU 11) had more medium deficit areas due to the presence of laterite soil.

Among the 14 districts. soils in Kottayam, Idukki, and Kannur districts can be considered as highly carbon saturated. Kozhikode district has large tracks of the area under high carbon deficit and can accommodate large quantities of carbon additions. Southern Coastal Plain found in Thiruvananthapuram, Kollam, and Alappuzha districts also showed medium to high deficit areas. In Pathanamthitta district, majority of areas were found to be under medium to high deficit category. Wayanad Central plateau and Wayanad eastern plateau are the two important AEUs in the Wayanad district. Wayanad eastern plateau has more area under medium to high deficit category compared with central plateau. It is attributed to the presence of areas with less rain in the area as well as longer dry periods. The Kaipad AEU seen in Kozhikode, Kannur, and Kasaragod districts have inherently rich organic matter. Northern high hills and Northern foothills seen in the Kasaragod district shows large tracks of soils under medium to high deficit category. The presence of laterite soil in this area could be a contributing factor to the rise in high deficiency areas in the foothills and high hills.

The results of the present study confirms that these AEUs have minimal areas under carbon deficits (Chung *et al*.,2010). The results also justify the theory that clay textured soil reaches a carbon saturation point faster than coarse textured soil (White et al., 2014; Di *et al*., 2018). This study highly supports Hassink hypothesis on carbon saturation.

The majority of places where intensive farming is practiced were observed to have minimum carbon deficit areas. AEUs such as Kuttanad, Marayoor, high hills region and Kumily hills have reached their saturation potential and careful management practices like manure application, cover crop, crop rotation, sustainable farming methods, organic farming, irrigation, and no-tillage, etc. should be adopted to further raise their carbon accumulation potential (West *et al*., 2007; Stewart *et al*., 2007; Feng *et al*., 20014b; Wiesmeier *et al*., 2014). The practices like no- tillage reduce soil disturbance there by increase aggregate size, reduce temperature and increase moisture causes reduced decomposition rate and improves storage capacity (Briedis *et al*.,2017).

Several studies have found a significant link between carbon input and soil carbon intake (Kong *et al*., 2008). Studies show that just a small portion of retained soil carbon depends on carbon input perse, whereas the rest is determined by soil characteristics. This link is clearly seen in contrasting ecosystems such as forest and agricultural systems wherein conversion of forests to agricultural land leads to huge loses of carbon. However, when techniques like sustainable agriculture are implemented, carbon stocks in these places may rise (Goh *et al*., 2004).

Most of the studies agree that management of carbon saturated areas does not enhance carbon accumulation while some disagree (Goh *et al*.,2004). According to Kirschbaum *et al*., (2019), moving soil carbon from low saturation deficit areas to higher saturation deficit areas will improve carbon storage in soil. Likewise, some studies suggest the translocation of saturated soil within different soil horizons (Nicoloso *et al*., 2018) and that crop conversion (Fuentes *et al*., 2009), precision farming, no-tillage activities, improving the quality of organic carbon input, utilizing organic manures, converting agricultural land to grassland, and sustainable cropland management (Wiesmeier *et al*.,2014) would be strategies for improving the carbon saturation potential of soils.

CHAPTER 6

SUMMARY

One of the present scenario's challenges is climate change. To combat climate change, a variety of techniques are used. Enhancing carbon storage capacity is one approach in the process. Accumulation of soil carbon has an upper limit, where additional carbon cannot be sequestrated. This upper limit of soil is said to be carbon saturation. Soil is considered the largest terrestrial sink of carbon which offsets carbon emission. Certain models are used to estimate carbon saturation. Carbon saturation is identified to access soil with greater storage deficit and rate and potential at which soils reach maximum carbon level. According to saturation theory, increase in carbon, input enhances carbon storage level which forms a steady state. Management practices form a new steady state would change the saturation levels to a new limit and may enhance carbon accumulation potential of the soil. In most of the cases, soil carbon saturation is not considered in models as it shows a high degree of uncertainty.

In this study, we used the Hassink equation to analyse carbon saturation in AEZs and AEUs of Kerala. According to Hassink's linear regression equation, fine textured soils has a limited capacity to retain carbon than bulk soil. Based on Hassink theory we calculated the carbon saturation deficit wherein saturation deficit is taken as the difference between protective capacity and current carbon content. If soil is far from saturation, it has a greater ability to store additional carbon and as it approaches saturation, additional storage capacity would be poor. The finding of this study highly depicts the presence of carbon saturation soils in both AEZ and AEU.

Generally, low to medium carbon deficit soils were seen in Kerala. AEZ like High Hills and Foothills showed the presence of large tracts under high carbon saturation. whereas AEUs like Kuttanad, Marayoor and Kumily had maximum area under no carbon deficit where additional carbon storage is limited. High carbon deficit areas were found only in limited tracts in Kerala. Wayanad eastern plateau and Attappady dry hills are examples of AEUs with higher carbon deficit. Saturation deficit mainly depends on the quality and quantity of carbon input, soil physiology, land management practices, and climatic factors.

Hassink only accounts for the physical protective nature of carbon stabilization and does not adequately represent maximum carbon storage capacity of an area. Later more studies were done by considering other pools. Alternative approaches provided by Feng *et al*. for saturation estimates, such as carbon loading and boundary line analysis, are regarded may also be more effective and accurate in some cases. The present study gives an approximate idea of carbon saturation in different AEUs and AEZs of Kerala. Future studies should focus on evaluation of rate and turnover of carbon as well as translocation of carbon from high saturation regions to low saturation.

REFERNCE

Abdullahi, A.C., Siwar, C., Shaharudin, M.I., and Anizan, I.2018. Carbon Sequestration in Soils: The Opportunities and Challenges. Carbon Capture, Utilization and Sequestration. Available: 10.5772/intechopen.79347 [12 september 2018].

Angers, D.A., Arrouays, D., Saby, N.P.A. and Walter, C.2011. Estimating and mapping the carbon saturation deficit of French agricultural topsoils. *Soil Use Manag*.27(4): 448-452.

Barre, P., Angers, D.A., Basile-Doelsch, I., Bispo, A., Cécillon, L., Chenu, C., Chevallier, T., Derrien, D., Eglin, T.K. and Pellerin, S. 2017. Ideas and perspectives: Can we use the soil carbon saturation deficit to quantitatively assess the soil carbon storage potential, or should we explore other strategies?. *Biogeosciences Discussions*:1-12(in press).

Beare, M.H., McNeill, S.J., Curtin, D., Parfitt, R.L., Jones, H.S., Dodd, M.B. and Sharp, J. 2014. Estimating the organic carbon stabilisation capacity and saturation deficit of soils: a New Zealand case study. *Biogeochemistry*, 120(1):71-87.

Bradford, M.A., Wieder, W.R., Bonan, G.B., Fierer, N., Raymond, P.A. and Crowther, T.W. 2016. Managing uncertainty in soil carbon feedbacks to climate change. *Nat Clim Chang*. 6(8):751-758.

Briedis, C., Moraes, J.C., Lal, R., Tivet, F., Franchini, J.C., Oliveira, F. A., Hartman, C.D., Schimiguel, R., Bressan, P.T., Inagaki, T.M. and Romaniw, J., 2018. How does no-till deliver carbon stabilization and saturation in highly weathered soils?. *Catena*. 163: 13-23.

Carrington, E.M., Hernes, P.J., Dyda, R.Y., Plante, A.F. and Six, J. 2012. Biochemical changes across a carbon saturation gradient: lignin, cutin, and suberin decomposition and stabilization in fractionated carbon pools. *Soil Biol. Biochem*. 47:179-190.

Castellano, M, J., Kaye, J, P., Lin, H., and Schmidt, J, P.2012. Linking Carbon Saturation Concepts to Nitrogen Saturation and Retention. Ecosystems (N. Y., Print). 15(2): 175-187.

Chen, S., Arrouays, D., Angers, D.A., Martin, M.P., and Walter, C.2019. Soil carbon stocks under different land uses and the applicability of the soil carbon saturation concept. *Soil Till Res* .188(0): 53-58.

Childs, C., 2004. Interpolating surfaces in ArcGIS spatial analyst. *ArcUser, July-September*. 3235(569):32-35.

Chung, H., Ngo, K.J., Plante, A., and Six, J.2010. Evidence for Carbon Saturation in a Highly Structured and Organic-Matter-Rich Soil. *Soil Sci. Soc. Am. J.* 74(1):130-138.

Cotrufo, M.F., Ranalli, M.G., Haddix, M.L., Six, J. and Lugato, E. 2019. Soil carbon storage informed by particulate and mineral-associated organic matter. *Nat. Geosci.* 12(12):989-994.

Di, J., Fenga, W., Zhanga, W., Caia, A., and Xua, M.2017. Soil organic carbon saturation deficit under primary agricultural managements across major croplands in China. *Ecosyst. Health Sustain*. 3(7):1-12.

Di, J., Xu, M., Zhang, W., Tong, X., He, X., Gao, H., Liu, H., and Wang, B. 2018. Combinations of soil properties, carbon inputs and climate control the saturation defcit dynamics of stable soil carbon over 17-year fertilizaiton. Scientific report. 8(1). Available:https://www.nature.com/articles/s41598-018-31028-x

Feng, W., Plante, A.F., Aufdenkampe. A., and Six, J. 2013. Improving estimates of maximal organic carbon stabilization by fine soil particles. *Biogeochemistry* 112: 81-93.

Feng, W., Plante, A.F., Aufdenkampe. A., and Six, J. 2014a. Soil organic matter stability in organo-mineral complexes as a function of increasing C loading. *Soil Biol. Biochem.* 69(0): 398-405.

Feng, W., Xu, M., Fan, M., Malhi, S. S., Schoenau, J. J., Six, J. and Plante, A. F. 2014b. Testing for soil carbon saturation behaviour in agricultural soils receiving long-term manure amendments. *Can. J. Soil Sci*. 94(3): 281-294.

Fuentes, A.J., Martínez, C., Sanchez, L. M.V., Paustian, K., Denef, K., Stewart, C.E. and Ugarte, A.J.L. 2009. Soil aggregation and soil organic carbon stabilization: effects of management in semiarid Mediterranean agroecosystems. *Soil Sci. Soc. Am. J.* 73(5); 1519-1529.

Fujisaki, K., Chapuis, L., Albrecht, A., Razafimbelo, T., Chotte, J.L. and Chevallier, T. 2018. Data synthesis of carbon distribution in particle size fractions of tropical soils: Implications for soil carbon storage potential in croplands. *Geoderma*, 313: 41-51.

Goh, K.M. 2004. Carbon sequestration and stabilization in soils: Implications for soil productivity and climate change. *Soil Sci. Plant Nutr*. 50(4): 467-476.

Gulde, S., Chung, H., Amelung, W., Chang, C. and Six, J., 2008. Soil carbon saturation controls labile and stable carbon pool dynamics. *Soil Sci. Soc. Am. J.* 72(3):605-612.

Hassink, J. 1996. Preservation of plant residues in soils differing in unsaturated protective capacity. *Soil Sci. Soc. Am. J.* 60(2): 487-491.

Hassink, J., 1995. Decomposition rate constants of size and density fractions of soil organic matter. *Soil Sci. Soc. Am. J.* 59(6): 1631-1635.

Hassink, J.1997. The capacity of soils to preserve organic C and N by their association with clay and silt particles. *Plant Soil*. 191(0): 77-87.

Heitkamp, F., Wendland, M., Offenberger, K. and Gerold, G. 2012. Implications of input estimation, residue quality and carbon saturation on the predictive power of the Rothamsted Carbon Model. *Geoderma*. 170(0): 168-175.

Hu, J., Guo, H., Xue, Y., Gao, M., Zhang S., Tsang, Y.F., Li, J., Wang, Y. and Wang, L.2019. Using a Mixture of Microalgae, Biochar, and Organic Manure to Increase the Capacity of Soil to Act as Carbon Sink. *J. Soils Sediments*.19(11): 3718-3727.

Kettler, T.A., Doran, J.W. and Gilbert, T.L., 2001. Simplified Method for Soil Particle-Size Determination to Accompany Soil-Quality Analyses. *Soil Sci. Soc. Am. J. 65*(3): 849-852.

Khan., Rashid, H., Blume, H., Adachi, T., Pfisterer, U. and Thomsen, U. M.2005. Source and Sink Strength of Carbon Dioxide, Methane and Distribution of Sulfate in Salt-marsh Soils at the Wadden Sea Coast of Northern Germany. *J. Appl. Sci. Environ. Manage. June, 2007*. 11(2): 223-229.

Khandakar, T., Guppy, C., Tighe, M., Rabbi, S.M.F., and Daniel, H. 2017. Increased carbon stabilization in Australian ferrosol with high carbon saturation deficit. *Commun. Soil Sci*. Plant Anal. 48(15): 1772-1780.

Kirschbaum, M.U., Moinet, G.Y., Hedley, C.B., Beare, M.H. and McNally, S.R., 2020. A conceptual model of carbon stabilisation based on patterns observed in different soils. *Soil Biol Biochem*, 141(0):p.107683.

Kong, A.Y., Six, J., Bryant, D.C., Denison, R.F. and Van Kessel, C. 2005. The relationship between carbon input, aggregation, and soil organic carbon stabilization in sustainable cropping systems. *Soil Sci. Soc. Am. J*. 69(4): 1078-1085.

Lal, R., Negassa, w. and Lorenz, K.2015. Carbon Sequestration in Soil. *Curr Opin Environ Sustain* .15(0):79-86.

Manjula, K.R., Jyothi, S. and Varma, S.A.K. 2010. Digitizing the forest resource map using ArcGIS. *Int. J. Comput. Sci. Appl*. 7(6):300.

Mayzelle, M.M., Krusor, M.L., Lajtha, K., Bowden, R.D. and Six, J. 2014. Effects of detrital inputs and roots on carbon saturation deficit of a temperate forest soil. *Soil Sci. Soc. Am. J.* 78(S1):76-83.

McClaugherty, C., 2001. Soils and decomposition. eLs. Available: https://doi.org/10.1038/npg.els.0003187 [30 May.2001].

Meyer, N., Bornemann, L., Welp, G., Schiedung, H., Herbst, M. and Amelung, W.2017. Carbon saturation drives spatial patterns of soil organic matter losses under long-term bare fallow. *Geoderma*, 306(0):89-98.

Neenu, S. and Karthika, K.S., 2020. Kuttanad soils: the potential acid sulphate soils of Kerala. Harit Dhara E Magazine 3(2):19-23. http://krishi.icar.gov.in/jspui/handle/123456789/53110

Nicoloso, R.S., Rice, C.W., Amado, T.J., Costa, C.N. and Akley, E.K. 2018. Carbon saturation and translocation in a no-till soil under organic amendments. *Agric. Ecosyst. Environ*. 264: 73-84.

Pravia, M.V., Kemanian, A.R., Terra, J.A., Shi, Y., Macedo, I. and Goslee, S. 2019. Soil carbon saturation, productivity, and carbon and nitrogen cycling in crop-pasture rotations. *Agric. Syst*. 171(6):13-22.

Six, J., Conant, R.T., Paul, E.A and Paustian, K.2002. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant Soil.* 241(2): 155-176.

Smith, P .2014. Do grasslands act as a perpetual sink for carbon?. *Glob. Change Biol.* 20 (9): 2708-2711.

Stewart, C.E., Paustian, K., Conant, R.T., Plante, A.F., and Six, J. 2007. Soil carbon saturation: concept, evidence and evaluation. *Biogeochemistry*. 86(1):19-31.

Stewart, C.E., Plante, A.F., Paustian, K., Conant, R.T., and Six, J. 2008a. Soil carbon saturation: Evaluation and corroboration by long-term incubations. *Soil Biol. Biochem*. 40(7): 1741-1750.

Stewart, C.E., Plante, A.F., Paustian, K., Conant, R.T., and Six, J. 2008b. Soil Carbon Saturation: Linking Concept and Measurable Carbon Pools. *Soil Sci Soc Am J*.72(2): 379-392.

Vicente, J.L., Gomez, B., Centeno, M.B., Smith, P. and Garcia, R. 2017. Carbon saturation and assessment of soil organic carbon fractions in Mediterranean rainfed olive orchards under plant cover management. *Agric Ecosyst Environ.* 245: 135-146.

West, T, O., and Six, J. 2006. Considering the influence of sequestration duration and carbon saturation on estimates of soil carbon capacity. *Clim. Change*. 80(1): 25-41.

White, C.M., Kemanian, A.R. and Kaye, J.P. 2014. Implications of carbon saturation model structures for simulated nitrogen mineralization dynamics. *Biogeosciences*. *11*(23): 6725-6738.

Whitehead, D., Schipper, L.A., Pronger, J., Moinet, G.Y., Mudge, P.L., Pereira, R.C., Kirschbaum, M.U., McNally, S.R., Beare, M.H. and Arbestain, M. 2018. Management practices to reduce losses or increase soil carbon stocks in temperate grazed grasslands: New Zealand as a case study. *Agric Ecosyst Environ*. 265: 432-443.

Wiesmeier, M., Hubner, R., Sporlein, P., Geu, U., Hangen, E., Reischl, A., Schilling, B., von Lutzow, M. and Knabner, I. 2014. Carbon sequestration potential of soils in southeast Germany derived from stable soil organic carbon saturation. *Glob Chang Biol*. 20(2): 653-665.

ABSTRACT

Organic carbon stored in soils slows the removal of CO_2 into the atmosphere and it also improves soil quality and productivity. The total amount of organic carbon stored in the soil is the sum of added and emitted carbon. The threshold of SOC accumulation defined by inherent physicochemical properties is known as soil carbon saturation. Carbon saturation is necessary for identifying areas with low saturation levels. The purpose of this study was to determine the soil carbon saturation in Kerala's agro ecological zones and agroecological units. The Hassink linear regression equation was used in the research. Soil carbon saturation deficit is determined using the Hassink equation and classified into four categories: no deficit, low deficit, medium deficit, and large deficit. With the help of ArcGIS software saturation deficit areas were identified. The findings support the occurrence of carbon-saturated soils and the Hassink hypothesis. Kerala's agroecological zones large tracks of area fall under the low and medium deficit category. Kuttanad, Marayoor, and Kumily Hills show highly saturated areas due to soil properties, land use, carbon input, and climatic conditions. Onattukara sandy plain, Wayanad Eastern Plateau, Attappady hills, and Attappady dry hills have large areas under the high deficit category. The High deficit area has more potential to add additional carbon hence greater organic matter and carbon input can be added to these regions. Sensible management like manure application, cover crop, crop rotation, sustainable farming methods, organic farming, irrigation, and no-tillage, etc. should be adopted to further raise their carbon accumulation potential.

APPENDIX 1

An overview of data collected for the study

SL NO:	LOCATION	Latitude	Longitude	DISTRICT	LAND USE TYPE	SOC (%)	SOIL TYPE/TAXONOMY	SOIL TEXTURE	DEPTH	pH	SAND	COURSE SAND	FINE SAND	SILT	CLAY	N	P	K	Ca	Mg	REFERENCE
1	Amaravila series	8.377	77.1338	trivandrum		2.8	fine	clay loam - clay	0-20	4.7		6.2	15.5	24.2	37.3			0.23	1.4	0.7	Kumaraswamy et al.,2014
2	Kazhakuttam series	8.576	76.8638	trivandrum		0.3	coarse loamy	loamy sand - sa	0-20	6.8		29.6	6.9	3.2	18.7			0.18cmol(	0.42cmol(	0.12cmol(+	Sankaran et al.,2008
3	Nedumangadu serie	8.60086	77.009884	trivandrum		1.3	clayey-skeletal	gravelly sandy c	0-20	4.6		12	16.6	8.6	32.2			0.6	0.2	0.1	Lakshmi et al.,2016
4	Neyyattinkara	8.399936	77.090548	trivandrum	Rice	1.38	Laterritic alluvi	clay	0-20	4.8		20	16	9.3	51.4	0.13	0.148	0.01	0.32	0.25	Subhrajit et al.,2009
5	Ponmudi series	8.7555	77.125	trivandrum		1.9	fine loam	sandy loam-san	0-20	4.9		15.2	12.1	5	18.6			0.6	0.6	0.3	Krishnani et al.,2011
6	Trivandrum series	8.5861	76.8863	trivandrum		0.9	clayey-skeletal	sandy loam - gr	0-20	4.7		12.4	24.6	10.8	18.8			0.28	0.4	1.1	Kumar et al.,2016
8	Arackal	8.955568	76.869956	Kollam		0.8	Ultisol		0-20	4.6	73.6			10	16.4			0.1	1.6	1.08	Chandran et al.,2005
9	Arienkav	8.974	77.1505	kollam	Teak planta	0.7			0-20	5.3	57			7	14						Harishma et al.,2020
10	Kayamkulam	9.169119	76.500145	Alappuzha	dry land	0.5406	sandy soil	loamy sand	0-20	5.5											Sujatha et al.,1997
11	Kottukulangara	9.191719	76.487247	Alappuzha	Rice	0.51	coastal sandy a	loamy sand	0-20	4.8		74	13.1	2.1	10	0.036	0.018	0.05	0.42	0.08	Kumar et al.,1998
12	Chithramangalam	9.630428	76.523718	kottayam	Paddy	2	Kayal		0-20	7.2		6.9	19	27.7	36.3						Philip et al.,2019
13	Devikulam	10.054376	77.118885	kottayam	Shola forest	5.56		sandy loam	0-20	5.5		38.6	29.4	24	8	0.46	0.32	0.06	0.28	0.13	Gladis et al.,2019
14	Pampadumpara seri	9.79722	77.1681	Idukki		0.1	Ustic Kandihun	silty clay to clay	0-20	5.4		5.8	15.2	14.4	54.4			0.1	0.8	0.5	Chandran et al.,2020
15	Anamudi series	10.2041	77.0861	Idukki		7.5	Typic Kandihur	silt loam to clay	0-20	4.5		8.1	5.8	39.4	29			1.73	3.2	0.2	Sujatha et al.,2008
16	Adoor series	9.11666	76.6888	Pathanamthitta		0.1	Typic Plinthustu	gravelly sandy c	0-20	4.7		5.7	7.6	8.2	55			0.86	0.6	0.1	Abraham .,2015
17	Airavan series	9.11944	76.6894	Pathanamthitta		1.6	Fluventic Dystr	sandy loam - cla	0-20	5.7		1.5	10.4	21.1	56.6			0.35	3.5	0.3	Sankaran et al.,2014
18	Pattikkadu-Thrisssur	10.54966	76.33294	Thrissur		1.11	Laterite-Oxisol	sandy clay loam	0-20	5.4	0.5496			0.1199	0.3196		0.0003	0.003			Keerthi et al.,2019
19	Pattambi	10.80573	76.195665	palakkad	Rice	3.78	laterite soil		0-20	5.2		32.8	26.4	12.3	34						Beena et al.,2016
20	Angadipuram series	10.9775	76.2047	Malappuram		0.4	Typic Kanhaplu	gravelly loam tc	0-20	5.4		5.3	10	14.4	57.5			0.03	1	1.1	Varghese et al.,2012
21	Chaliyar series	11.258397	75.981023	Malappuram		0.69	Riverrine alluvi	sandy clay loam	0-20			11.8	36.6	23.2	24.1						Gahlod et al.,2017
22	Pulpally series	11.7833	76.1666	Wayanadu		0.2	Typic Dystruste	sandy loam to si	0-20	6.2		3.3	15.6	52	11.5			0.06	1.7	5.41	Gladis et al.,2020
23	Sulthan Bathery seri	11.65	76.2583	Wayanadu		2.4	Oxic Haplustep	sandy loam to s	0-20	5.5		6.4	24.6	12	18.9			0.28	2.1	0.8	Vijayan et al.,2015
24	Thiruvampadi series	11.5563	75.8	Kozhikode		0.3	Oxic Dystruste	gravelly sandy l	0-20	5.2		8	26.9	8.1	15.4			0.15	0.1	0.4	Vishnu et al.,2017
25	Narikkot series	12.0411	75.3275	kannur		0.9	Oxyaquic ustifl	loam to clay	0-20	4.4		0.2	2.6	35.6	60			0.36	4.75	3.15	Krishnan et al.,2020
26	Edanad series	12.5166	75.0794	Kasargode		0.2	Oxic Dystruste	gravelly loam -	0-20	5.7		14.4	11.8	6.6	46.3			0.12	1.3	0.1	Bygu et al.,1998
27	Payalam series	12.3972	75.2333	Kasargode		2.6	Ustic Kanhaplo	gravelly loam -	0-20	5.1		10.8	10.5	6.4	30.6			1.15	0.3	0.1	Thampatti et al.,2000