IMPACT OF SOIL AND WATER CONSERVATION MEASURES ON CARBON SEQUESTRATION IN THE WATERSHED

by

Shelar Rahul Sanjay

(Reg. No. 2019/04)

DOCTOR OF PHILOSOPHY (AGRICULTURAL ENGINEERING)

DEPARTMENT OF SOIL AND WATER CONSERVATION ENGINEERING
DR. ANNASAHEB SHINDE COLLEGE OF AGRICULTURAL ENGINEERING AND TECHNOLOGY
MAHATMA PHULE KRISHI VIDYAPEETH
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Dedication

Affectionately Dedicated to

Parents,

Teachers, Farmers and well wishers

…… Mr. Shelar Rahul Sanjay

CANDIDATE'S DECLARATION

I hereby declare that this thesis or part
there of has not been submitted
by me or other person to any
other University or Institute
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The assistance and help received during the course of this investigation have been duly acknowledged.

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LIST OF ABBREVIATIONS

Abbreviations		**Description**
AGB	:	Above Ground Biomass
AISLUSA	:	All India Soil and Land Use Survey
BGB	:	Below Ground Biomass
C	:	Crop Management Factor
CCM	:	Constant of Channel Maintenance
CCS		Carbon Capture and Storage
CER	:	Carbon Enrichment Ratio
CH_4	:	Methane
CO_2	:	Carbon Dioxide
DBH	:	Diameter at Breast Height
DCCT	:	Deep Continuous Contour Trench
D_d	:	Drainage density
DEM	:	Digital Elevation Model
D*i*	:	Drainage Intensity
Dr. ASCAE&T	:	Dr. Annaseheeb Shinde College of Agricultural Engineering and Technology
Engg.	:	Engineering
FAO	:	Food and Agriculture Organization
Fig.	:	Figure
F_s	:	Stream Frequency
GIS	:	Geographic Information System
GOI	:	Government of India
Govt.	:	Government
GPS	:	Global Positioning System
H	:	Relief
H_2O	:	Water Vapor
H_n	:	Relief Ratio
ICAR		Indian Council of Agricultural Research
ICFRE		Indian Council of Forestry Research and Education
IPCC	:	Intergovernmental Panel on Climate Change
IWM	:	Irrigation Water Management
K		Soil Eodibility Factor
LC	:	Land cover
L_g	:	Length of overland flow
LS		Topographic Factor
L_u	:	Stream length of order u

LU : Land use
LULC : Land use land cover
MPKV : Mahatma Phule Krishi Vidyapeeth
N_2O : Nitrous Oxide
NBSS&LUP : National Bureau of Soil Survey and Land Use Planning
No. : Number
N_u : Number of stream of order u
P : Conservation Practice Factor
pp : Page
Proc. : Proceeding
R : Rainfall Erosivity Factor
R_b : Bifurcation ratio
R_c : Circularity ratio
R_e : Elongation ratio
R_f : Form factor
Rn : Ruggeddness Number
R_R : Relative relief
R_r : Relief ratio
RS : Remote Sensing
R_t : Textural Ratio
SCS : Soil Carbon Sequestration
SOC : Soil Organic Carbon
SOI : Survey of India
SOM : Soil Organic Matter
SRTM : Shuttle Radar Topography Mission
SWC : Soil and Water Coservation
u : Stream order
USDA : United States Department of Agriculture
USGS : United States Geological Survey
USLE : Universal Soil Loss Equation
Viz. : Namely
WSG : Wood Specific Gravity

LIST OF SYMBOLS

Symbols	Description
%	Per cent
C	Carbon
°C	Degree Celsius
cc	Centimeter cube
et al.	And Others
gm	Gram
ha	Hectare
hr	Hour
i.e.	That is
kg	Kilogram
km^2	Square Kilometer
m	Metre
mm	Millimeter
Pg	Petagram
R^2	Coefficient of Determination
Tg	Teragram
t	tonnes
MJ	Million Joule
m/s	Meter per Sec
yr	year
μ	Mean
°	Degree
/	Per
>	Greater than
<	Less than
&	and

ABSTRACT

Impact of Soil and Water Conservation Measures on Carbon Sequestration in the Watershed

by

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Climate change is the defining issue of our time and we are at a defining moment. Without drastic action today, adapting to these impacts in the future will be immensely difficult and costly. Therefore, technically and economically feasible strategies are needed to mitigate the consequences of increased atmospheric CO_2. One such strategy that has gained considerable attention and importance is carbon sequestration. It implies transferring atmospheric CO_2 into long-lived pools and storing it securely so it is not immediately reemitted. There are several effective methods to achieve carbon sequestration, such as afforestation and reforestation, soil carbon sequestration, carbon capture and storage (CCS) and direct air capture. However, the potential role of soil and water conservation (SWC) measures in carbon sequestration is often overlooked and undervalued on a global scale. SWC measures are crucial components of watershed development programs that have the potential to significantly contribute to climate change mitigation. Therefore, the purpose of this study was to investigate and quantify the impact of soil and water conservation measures on mitigating climate change, particularly their potential to decrease carbon emissions and increase carbon sequestration.

The research was conducted at the “Central MPKV Campus Watershed” located in the Rahuri tahsil of Ahmednagar district, Maharashtra, India. The total geographical area of the watershed is 1260 ha. The watershed is situated in the rain shadow region of the Sahyadri hills, receiving an average of 592 mm of rainfall annually. The watershed had already been treated with various scientifically planned SWC measures, including both drainage line and land area treatments under the Adarsh Gaon Yojana. The study analyzed the long-term impact of these conservation measures on land use, soil loss and carbon sequestration. SWC measures significantly impacted land use in the watershed, increasing agricultural, natural forest, horticultural, settlement and waterbody land cover classes and decreasing barren and current fallow land. The implementation of water conservation measures in the watershed resulted in an increase of the watershed's water storage capacity by 123.4 thousand cubic meters. Overall, SWC measures improved the socio-economic status of people living in the watershed while conserving natural resources.

The study estimated the terrestrial carbon stock in the watershed by assessing biomass and soil carbon stocks across various land covers. The total carbon stock was found to be 39191.74 tonnes, with 45% in vegetation biomass and 55% in the soil. Natural forest land cover had the largest carbon content (56%), followed by barren land (17%), agricultural land (14%) and horticultural land (13%). It was observed that natural forest land is highly efficient in carbon sequestration and storage, as it stores the largest amount of terrestrial carbon per unit area. On the other hand, barren land in the watershed, which accounts for a significant proportion (38%) of the area, only stores 17% of the total carbon in the watershed. This indicates that there is potential for carbon sequestration through restoration activities in barren land. So, it is inferred that protecting and managing soil health is crucial, as it stores a significant proportion of the watershed's carbon stock. Understanding the carbon stock distribution across different land covers is essential for designing effective strategies to enhance a watershed's carbon storage potential.

SWC measures found to have a significant impact on soil carbon sequestration (SCS) rates in the watershed. Compartment bunding in agricultural land has resulted in a higher SCS rate of 343 kg C/ha/yr, compared to untreated agricultural lands with a rate of 190 kg C/ha/yr. Natural forest, horticulture and barren lands treated with DCCT had higher SCS rates of 470, 382 and 211 kg C/ha/yr, respectively, compared to untreated land covers with rates of 270, 213 and -112 kg C/ha/yr. Untreated barren lands were found to be a net source of carbon emissions, but with SWC measures, they act as natural carbon sinks. Appropriate SWC measures, plantation and agroforestry practices are required in untreated watershed areas to reduce carbon loss from the soil and increase SCS rates. It was observed that scientifically planned SWC measures play a crucial role in mitigating climate change by enhancing terrestrial carbon storage.

The study evaluated the impact of conservation measures on soil erosion and associated carbon loss in the watershed. After the adoption of conservation measures, the average annual soil loss decreased by 50% to 9.41 t/ha/yr, and the average annual carbon loss decreased by 45% to 190.52 kg C/ha/yr. Conservation measures in the watershed reduced soil carbon loss and CO_2 emissions up to 218.95 tonnes of C/year and 802.88 tonnes of CO_2/year, respectively, from their initial levels of 398.46 tonnes of C/year and 1461.15 tonnes of CO_2/year. The findings showed that scientifically planned SWC measures mitigate climate change by reducing soil loss rates and carbon emissions while increasing soil carbon sequestration, serving as both climate change mitigation and adaptation strategies.

The untreated parts of the watershed lack SWC measures, so additional conservation strategies are recommended to reduce soil erosion, carbon emissions and increase carbon sequestration. Proposed drainage line treatments include 109 structures and land area treatments include compartment bunding, contour bunding, DCCT and bench terraces. Implementation of these measures is expected to reduce the current soil loss rate by 35% and decrease the current carbon loss rate from 190.52 kg C/ha/yr to 125.64 kg C/ha/yr. Converting entire barren land into natural vegetation cover through afforestation can increase the watershed's carbon stock by 1075.88 tonnes of carbon per year, while agroforestry on entire barren land can add 736.38 tonnes of C/yr. Implementing crop residue management, mulches, cover crops, no tillage and crop rotation in entire agricultural lands can increase carbon stock by 103.5, 129.95, 95.22, 51.52 and 79.35 tonnes per year, respectively. The study proposed a sustainable plan for land utilization in the watershed, with priority given to farmers' income and productivity and conversion of barren land into agriculture, agroforestry or afforestation based on land suitability criteria. According to the proposed land suitability map, 25% of the barren land area is suitable for agriculture, 54% is suitable for agroforestry and 21% is suitable for afforestation. The proposed plan has the potential to increase the carbon stock in the watershed by 731.78 tonnes of C/year. The implementation of suitable SWC measures along with the proposed land covers can effectively contribute to reducing soil loss and enhancing carbon sequestration.

The implementation of SWC measures in the watershed has provided a twofold benefit of achieving sustainable natural resource management and mitigating climate change. These measures can contribute to the development of a carbon neutral climate smart watershed, where the amount of carbon emissions is less than the amount of carbon sequestration. These strategies can significantly assist developing nations in their fight against climate change and help them achieve their goal of carbon neutrality.

1. INTRODUCTION

Climate change refers to the long-term shifts in temperature and weather patterns that are primarily caused by the buildup of greenhouse gases in the atmosphere. It is widely regarded as one of the most serious threats facing our planet in the 21st century, and it poses significant risks to the livelihoods, food security and overall development of countries around the world (Myers *et al.*, 2017). It is mainly driven by the greenhouse effect. The greenhouse effect is a phenomenon that occurs when certain gases in Earth's atmosphere trap the heat from the sun and prevent it from escaping back into space (Manabe, 2019). This long-term heating of the Earth's surface results in global warming. The primary gases responsible for the greenhouse effect are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), water vapor (H_2O) (all of which occur naturally), and fluorinated gases (which are synthetic). Many of these gases are present in the atmosphere naturally in limited amounts. However, since the beginning of the industrial revolution, anthropogenic activities have rapidly increased the concentrations of greenhouse gases in the atmosphere, especially the amount of CO_2 (Ebi and Loladze, 2019). The present concentration of CO_2 in the Earth's atmosphere is 412 parts per million (ppm) and it is rapidly increasing. Later is proved by an 11% increase since 2000, when the concentration was close to 370 ppm, and a 47% increase since the start of the Industrial Era, when the concentration was close to 280 ppm (Lindsey, 2022). The main sources of CO_2 emissions into the atmosphere are the burning of fossil fuels (coal, natural gas, and oil) for energy, deforestation, land use changes and land degradation (Lamb *et al.*, 2021).

India is one of the most vulnerable nations to climate change (IPCC, 2022). The country is already facing catastrophic events caused by climate change, including water stress, heat waves, droughts, severe storms, flooding and the resulting detrimental effects on health and livelihoods. According to the UN Intergovernmental Panel on Climate Change study, India has already lost 16% of its per capita GDP since 1991 as a result of exposure to increasing sea levels and shifting monsoon patterns (IPCC, 2022). The impacts of climate change are widespread and need immediate action to secure a liveable future. Hence, immediate adoption of suitable mitigation and adaptation strategies is extremely important to combat the consequences of climate change. Mitigating climate change refers to reducing and preventing the release of greenhouse gas emissions into the atmosphere (Environment, 2017). Climate change mitigation can be accomplished by reducing the source of greenhouse gases or by improving the "sinks" that accumulate and store these gases (such as the oceans, forests, and soil). In this regard, carbon sequestration can be a prudent step in the long run, especially in low-income nations.

Carbon sequestration refers to the process of transferring atmospheric carbon dioxide (CO_2) into long-lived carbon pools and storing it securely so that it cannot be easily reemitted into the atmosphere (Lal, 2007). In other words, it refers to removing CO_2 from the atmosphere and storing it in a reservoir. A carbon pool is a carbon reservoir and component of the climate system that can store, collect or release carbon (Falkowski, 2000). It is a technically and economically feasible strategy to mitigate the negative consequences of climate change. The carbon sequestration process is generally subdivided into two types: geological sequestration and biological sequestration. Geologic carbon sequestration is the process of removing CO_2 from the atmosphere and permanently depositing it underground in geological formations. In this process, CO_2 is often compressed until it becomes a liquid before being injected into porous rock formations in geologic reservoirs. Whereas a biological sequestration process refers to the storage of atmospheric carbon in vegetation, soils, wood products and aquatic environments. Of these, vegetation and soil are the largest natural carbon sinks in terrestrial ecosystems and play an important part in the process of terrestrial carbon sequestration (Kuppan and Chavali, 2019).

Terrestrial carbon sequestration refers to the process by which carbon dioxide is removed from the atmosphere by trees and plants through the process of photosynthesis and then stored as carbon in the biomass (the trunks, branches, foliage, and roots of trees) and soil (Post *et al*., 2009). The terrestrial carbon pool is the third largest in the global carbon cycle, and it's an intermediate-sized pool between the ocean and the atmosphere (Sha *et al.*, 2022). It consists of two parts that are linked but distinct: the biotic C found in plants and the pedologic C found in the soil. The above-ground and below-ground parts of the biotic pool have 550±100 Pg of C (1 Pg = 10^9 tonnes), and the litter and detritus parts have an additional 300±100 Pg of C (Lal, 2010). Biotic and pedologic pools interact very closely with the atmospheric pool. Their interaction is the result of processes like photosynthesis, soil and plant respiration, deforestation and changes in land use. The pedologic pool has a greater capacity for C storage than both the biotic and atmospheric pools. The total carbon storage capacity of a pedologic pool is 1500±2000 Pg of C in the top 1 m of depth and as much as 2300 Pg of C up to 2 m of depth (Abdullahi *et al.*, 2018). It is estimated that the total terrestrial C pool on Earth stores 2,844 Pg of C, of which 558 Pg of C is plant-C and 2286 Pg of C is soil-C. The ratio of soil-C to plant-C is about 4:1. The single largest reserve of plant-C is in natural forests (415 Pg C), which accounts for 74% of the entire plant-C pool. Similarly, the largest reservoir of soil C is in peatlands, consisting of 675 Pg of C (29.5 %), followed by 600 Pg (26.2 %) in the forest and 490 Pg (21.4 %) in savanna and grasslands. Agricultural ecosystems contribute around 147 Pg (6.4%) of the total soil C pool (Lal, 2008).

The ultimate objective of carbon sequestration activities is to mitigate climate change by reducing carbon emissions. Therefore, these activities need to be monitored in the wider context of the global carbon cycle to develop sustainable management practices. Adopting sustainable agricultural and forestry management strategies could significantly boost terrestrial carbon storage (Ontl *et al.*, 2019). In recent years, terrestrial carbon sequestration activities have received global attention. Various researchers around the world have estimated the terrestrial carbon stock and studied the potential of the terrestrial carbon pool in climate change mitigation (Keenan and Williams, 2018, Tang *et al.*, 2018, Hari and Tyagi, 2022). But a comprehensive study at watershed scale highlighting the role of terrestrial carbon management for climate-smart watershed development is lacking. To develop long-term carbon management strategies, it is necessary to first understand carbon flux between terrestrial carbon sinks and the atmosphere. The majority of human-induced carbon emissions are driven by land degradation and land use change, which are the main drivers of carbon flux between terrestrial ecosystems and the atmosphere (Houghton *et al.*, 2012).

Land degradation exacerbates CO_2-induced climate change by releasing CO_2 into the atmosphere and by reducing the ability of degraded land to sequester carbon (Ai *et al.*, 2018). One of the most common and pervasive forms of land degradation is soil erosion, which is closely related to unsustainable land management practices. Erosion removes topsoil, which typically contains the greatest organic carbon stocks, facilitating the mineralization and release of CO_2 into the atmosphere (Li *et al.*, 2019). It has a significant impact on both the lateral SOC dispersion within a landscape and the vertical CO_2 fluxes into the atmosphere. Van Oost *et al.*, 2007 highlighted three important mechanisms affecting soil-atmosphere C flux: 1) SOC replacement at eroding sites, 2) deep burial of carbon-rich topsoil towards depositional sites and 3) increased SOC degradation through physicochemical soil breakdown during detachment and transport processes.

Globally, water erosion translocates 4 to 6 Pg C/yr, of which 2.8 to 4.2 Pg C/yr is redistributed from its initial location to the depressional site and 0.4 to 0.6 Pg C/yr is transferred into the ocean. Carbon that enters the ocean is either converted into minerals or buried in coastal sediments and ecosystems. The remaining 0.8 to 1.2 Pg C/yr is emitted into the atmosphere (Lal, 2003). The entire amount of human emissions in 2019 was around 11.5 Pg, with 10%–15% of that amount coming from soil carbon transported by water erosion (IPCC, 2022). In India, erosion transports around 4.87 Pg of soil and 115.36 Tg of C each year (1 Tg = 10^6 tonnes), emitting approximately 34.61 Tg of CO_2 into the atmosphere. In terms of erosion-related carbon loss among Indian states, Madhya Pradesh had the highest estimate (20.33 Tg C/yr), followed by Chhattisgarh (9.98 Tg C/yr), Maharashtra (9.81 Tg C/yr), Uttar Pradesh (9.11 Tg C/yr), and Andhra Pradesh (8.70 Tg C/yr) (Mandal *et al.*, 2020). The negative consequences of intense soil erosion on land degradation, food and nutrition security, water quality/sedimentation, etc. have been widely recognized for a long time. However, its effects on the global carbon (C) cycle and emissions of CO_2 and other greenhouse gases (GHGs) have not received the attention they deserve. In order to implement effective soil conservation and restoration strategies, it is necessary to have an accurate estimate of the amount of carbon lost due to soil erosion.

In the 21st century, soil conservation should receive top priority to ensure a balanced climate cycle and healthy agricultural production (Bhattacharyya *et al.*, 2016). Effective control of soil erosion and restoration of degraded soils can contribute as a net sink of atmospheric CO_2 (Ran *et al.*, 2018). Moreover, keeping soil in place requires far less energy than rebuilding SOC. Keeping the soil in place can be achieved by adopting recommended soil and water conservation (SWC) measures. Generally, SWC measures are intended to slow the runoff to a non-erosive velocity, store in-situ rainwater, trap sediment and nutrients, protect the soil from erosion, help in flood protection, lessen sedimentation in waterways, streams and rivers, increase land productivity and supply a wide range of ecosystem services (Chen *et al.*, 2020). The SWC measures provide a wide range of environmental benefits. The effectiveness of SWC techniques in preserving soil quality and fertility has been widely investigated and acknowledged worldwide (Jiru and Wegari, 2022). However, their significance in carbon sequestration has garnered limited global attention. Scientific research with on field data is needed to demonstrate the significance of SWC measures in the global carbon cycle and carbon sequestration.

Watersheds are the ideal planning units for integrated soil and water resource management. A watershed is any area that collects and drains surface runoff to a single outlet. A healthy watershed is essential to our social, environmental and economic well-being and it is achieved through sound watershed management activities (Wang *et al.*, 2016). Watershed management is a comprehensive, adaptive and integrated multi-resource management planning process (Kumbhar, 2013). Its main purpose is to protect soil and water resources for both short-term and long-term benefits. Soil and water conservation are inherent parts of any watershed management programs. Sound watershed management through the adoption of recommended SWC measures has proven effective in erosion/sedimentation control, water harvesting and flood control. However, its significance for storing carbon and mitigating climate change has not yet been acknowledged. Technical knowledge on the efficiency of SWC measures in carbon sequestration will provide a sustainable land management option for climate smart watershed development, especially in countries where it's hard to get financing for large scale climate change mitigation projects. Carbon sequestration will also help in planning carbon negative watersheds where carbon sequestration will be more than carbon emission. A carbon-neutral watershed sequesters or offsets as much carbon as it emits, meaning that the amount of carbon absorbed or stored in the watershed through various methods equals or exceeds the amount of carbon emitted through human activities, such as burning of fossil fuels, deforestation and agricultural practices like burning crop residues. It will greatly assist developing nations in their fight against climate change. Accordingly, the present study was undertaken to investigate the role of SWC measures in climate change mitigation. The research was conducted at the “Central MPKV Campus Watershed” located in the Rahuri tehsil of Ahmednagar district, Maharashtra, India. The watershed is situated in the rain shadow region of the Sahyadri hills and receives an average of 592 mm of rainfall annually. Almost half of the watershed is already treated with various scientifically planned SWC measures, including both drainage line and land area treatments under the Adarsh Gaon Yojana of Government of Maharashtra. Hon'ble Popatrao Pawar, Executive President of Adarsh Gaon Yojana, Govt. of Maharashtra, has generously provided financial assistance and support for the watershed development activities at the Central MPKV Campus Watershed. The temporal impact of these conservation measures on land use, soil loss and carbon sequestration were studied using advanced techniques of remote sensing (RS) and geographic information system (GIS). For this purpose, present study entitled “Impact of Soil and Water Conservation Measures on Carbon sequestration in the Watershed” is undertaken with following specific objectives.

1. Estimation of carbon stock in various carbon sinks under different land use patterns in watershed.
2. Assessment of temporal impact of soil and water conservation measures on carbon sequestration.
3. Assessment of the impact of soil erosion on carbon loss in the watershed.
4. Development of conservation strategies for carbon sequestration in the watershed.

2. REVIEW OF LITERATURE

This chapter deals with an overview of the key literature relevant to carbon stock estimation in different land use patterns, impact of soil and water conservation (SWC) measures on carbon sequestration with time, impact of soil erosion on carbon loss and different conservation strategies for climate change mitigation.

2.1 Estimation of carbon stock in various carbon sinks under different land use patterns in the watershed.

Kaul *et al.* (2010) studied the carbon storage and sequestration potential of selected tree species in India. A dynamic growth model (CO2FIX) was used to estimate the carbon sequestration potential of sal (Shorea Robusta Gaertn. f.), Eucalyptus (Eucalyptus Tereticornis Sm.), poplar (Populus Deltoides Marsh) and teak (Tectona Grandis Linn. f.) forests in India. The study results indicated that long-term total carbon storage ranged from 101 to 156 Mg C/ha, with the largest carbon stock in the living biomass of long rotation sal forests (82 Mg C/ha). The net annual carbon sequestration rates were achieved for fast growing short rotation poplar (8 Mg C/ha/yr) and Eucalyptus (6 Mg C/ha/yr) plantations followed by moderate growing teak forests (2 Mg C/ha/yr) and slow growing long rotation sal forests (1 Mg C/ha/yr).

Haghparast *et al.* (2013) estimated carbon sequestration potential in Pune university campus using geographical information system. The study found that Dalbergia melanoxylon and Gliricidia sepium are the most dominant species in terms of carbon sequestration, whereas species such as Ficus bengalensis and Samania saman, Cocos nucifera and Delonix regia were categorized next to these two species. The highest recorded sequestration volume for Dalbergia melanoxylon was 106.4 t/ha at the Shivaji Garden, front of the Botany Department and Range hills sampling sites. Dalbergia melanoxylon and Gliricidia sepium account for 49% and 30% of total carbon sequestration, respectively, in the Pune university campus. The study concluded that in order to mitigate climate change and achieve sustainable development, rapidly developing cities like Pune must conserve and improve their terrestrial carbon pool.

Ahmad and Nizami (2015) estimated carbon stocks in different land uses in the Kumrat valley, Hindu Kush Region of Pakistan. Biomass and soil carbon stock were estimated by field inventory under forest land (FL), agriculture land (AL) and range land (RL). Soil carbon was determined to depths of 0–15 and 16–30 cm. The study found that average carbon stocks (C stocks) in all land uses ranged from 28.62 ± 13.8 t/ha in AL to 486.6 ± 32.4 t/ha in pure Cedrus deodara forest. The results of the study confirmed that forest soil and vegetation stored the maximum amount of carbon, followed by RL. The study concluded that conversion of FL and RL to AL led to a total loss of about 56 % (from FL conversion) and 37 % (RL conversion) of soil carbon over the past decade.

Iqbal and Tiwari (2017) performed a comparative study of soil organic carbon storage in Achanakmar, Chhattisgarh, under different land use and land cover. The study was undertaken to estimate the soil carbon sequestration potential of four land uses (forestland, grassland, agricultural land and wasteland) and five land covers (sal, teak, bamboo, mixed, open and scrub). The results of the study showed that the highest soil carbon storage potential was found in forestland (118.14 t/ha) followed by grassland (95.54 t/ha), agricultural land (75.70 t/ha) and the least was found in wasteland (57.05 t/ha). Among the different land covers, maximum soil carbon storage potential was found in the soils under mixed land cover (118.18 t/ha) followed by teak (76.64 t/ha), bamboo (67.21 t/ha), sal (64.28 t/ha) and least under soils of open and scrub (48.72 t h/a) land cover. The study concluded that forest land use with mixed land cover has a greater role in carbon storage compared to the mono-cropping system.

Marak and Khare (2017) estimated the carbon sequestration potential of selected tree species in the Campus of Sam Higginbottom University of Agriculture Technology and Sciences (SHUATS), Allahabad, India. In the present study above ground biomass, below ground biomass and carbon sequestration potential of a few important multipurpose tree species viz., Alstonia scholaris, Anthocephalus cadamba, Delonix regia, Emblica officinalis, Mimusops elengi, Moringa oleifera and Peltophorum pterocarpum was estimated by non-destructive method. It was found that total above and below ground biomass was highest for Anthocephalus cadamba with 5.92 t/tree and of 0.88 t/tree, respectively. The highest amount of carbon sequestration was found in Anthocephalus cadamba, which sequestered 215.14 t C/tree, and the lowest in Delonix regia, which sequestered 16.84 t C/tree.

Salas Macías *et al.* (2017) estimated above-ground live biomass and carbon stocks in different plant formations and in the soil of dry forests of the Ecuadorian coast. Five 250 m^2 sample plots were established to estimate carbon stored in two pools for each of the plant formations identified (Dry Scrubland, DS; Dry Deciduous Forest, DDF; Dry Semideciduous Forest, DSF). Allometric equations were used to estimate the amount of carbon in above-ground biomass, taking the total height (H) and the diameter at breast height (DBH) of trees whose DBH is equal to or greater than 5 cm. The study found that carbon stored in live above-ground biomass was higher in DSF (59.77 Mg C/ha) followed by the formation of DDF (38.49 Mg C/ha) and DS (33.47 Mg C/ha). Similarly, soils of the DSF formation have more stored carbon (63.28 Mg C/ha) than the DDF (31.13 Mg C/ha) and DS (26.83 Mg C/ha). The total carbon stock was found higher in DSF (123.05 Mg C/ha) than the formations of DDF (69.62 Mg C/ha) and DS (60.30 Mg C/ha).

Ghimire *et al.* (2018) studied soil organic carbon stocks under different land uses in the Chure region of Makawanpur District, Nepal. The study was conducted to compare soil organic carbon (SOC) stocks of four main land use types such as forest, degraded forest and cultivated land (Khet and Bari). A stratified random sampling method was used for collecting soil samples.

Organic carbon content was determined by Walkley and Black method. The study found that the total SOC stock in different types of land followed the order: as forest (110.0 t/ha) > Bari (96.5 t/ha) > Khet (86.8 t /ha) > degraded land (72.0 t/ha). The SOC% at 0–20 cm depth was highest (1.26 %) recorded in the forest soils and lowest (0.37%) at 80- 100cm depth in degraded forest land. The study concluded that the SOC stock varied with land use systems and soil depths and suggested a need for an appropriate land use strategy and sustainable soil management practices to improve SOC stock.

Mulat *et al.* (2018) estimated soil organic carbon stock (SOCS) under different land use types in Kersa Sub Watershed, Eastern Ethiopia. The soil organic carbon stock was estimated in major land use types (grazing, cultivated, and fallow lands) and replicated soil samples from 0 to 20, 20 to 40, and 40 to 60 cm depth were collected. The results of the study revealed significant difference in soil organic carbon stock under the different land use types ($P \leq 0.05$). Soil under grazing land use type had significantly higher values of SOCS (42.9 t/ha and 32.9 t/ha) than cultivated land use type (32.6 t/ha and 26.3 t/ha) and fallow land use type (23 t/ha and 12.5 t/ha) in surface and sub surface layers, respectively. Similarly, SOCS decreased with soil depth in all the land use types and showed positive and significant correlation ($P \leq 0.05$) with clay content while negatively and significantly correlated with bulk density. The results of the study showed that vegetation cover has the potential to enhance soil organic carbon sequestration.

Singh *et al.* (2018) studied the effect of land use changes on carbon stock dynamics in major land use sectors of Mizoram, Northeast India. The study assessed the change in vegetation biomass carbon stock (VBCS) and soil organic carbon stock (SOCS) following conversion in major land use sectors (agriculture, agroforestry, forest and plantation). The study found that SOCS was the highest in agroforestry (50.85 Mg C/ha) and the lowest in agriculture (33.99 Mg C/ha). VBCS was found to be highest in plantation (131.66 Mg C/ha) and the lowest in agriculture (7.44 Mg C/ha). The highest positive TECS change rate was observed when agriculture was converted to plantation (6.61 Mg C/ha/yr), while negative rate of change in carbon stock was observed following the establishment of agriculture from other land use. A positive rate of change was observed in both VBCS and SOCS with TECS rate of 3.58 Mg C/ha/yr when agriculture got converted to agroforestry. The study concluded that the absolute carbon stock change rates were higher in VBCS than SOCS signifying the importance to maintain tree-based vegetation cover.

Solomon *et al.* (2018) studied the effects of land cover change on carbon stock dynamics in the Wujig Mahgo Waren forest, a dry Afromontane forest in northern Ethiopia. The total carbon stocks of the Wujig Mahgo Waren forest ecosystems were estimated using a multi-disciplinary approach that combined remote sensing with a ground survey. The mean carbon stocks in the dense forests, open forests, grasslands, cultivated lands and bare lands were estimated at 181.78±27.06, 104.83±12.35, 108.77±6.77, 76.54±7.84 and 83.11±8.53 Mg C/ha, respectively. The study concluded that the obtained estimates of mean carbon stocks in ecosystems representing the major land cover types are of importance in the development of a forest management plan aimed at enhancing the mitigation potential of dry Afromontane forests in northern Ethiopia.

Kenye *et al.* (2019) conducted the study to assess soil organic carbon (SOC) concentration and stock under eight major land uses: shifting cultivation, wet rice cultivation, homegardens, forest (natural), grassland, bamboo plantation, oil palm plantation and teak plantation of Mizoram, Northeast India. Soil samples at different depths (0–15, 15–30 and 30–45 cm) were collected from each of the land uses under study to estimate SOC content in the laboratory. It was found that the forest has the highest mean SOC concentration with 2.74% at 0–45cm depth and the lowest in the bamboo plantation (1.09%). The mean SOC stock for 0–45 cm soil depth ranged from 27.68 to 52.74 Mg C/ha in grassland and forest, respectively. Both SOC concentration and SOC stock decreased with increasing soil depth. Soil bulk density of fine soil (<2mm) was significantly negatively correlated with SOC concentration and positive with SOC stock. The study results indicated the importance of SOC stocks in different land uses, which may help devise appropriate management practices to increase the soil carbon sequestration potential in the wake of mitigating climate change.

Mauya *et al.* (2019) estimated carbon stock for different land cover classes in Mainland Tanzania based on an analysis of Tanzania’s national forest inventory data generated through the National Forest Resources Monitoring and Assessment (NAFORMA). In the present study, carbon stocks were estimated in three carbon pools, namely aboveground, belowground, and deadwood for each of the three land cover classes (i.e., forest, non-forest, and wetland). It was found that weighted average carbon stock was 33.35 t C/ha for forest land, 4.28 t C/ha for wetland and 5.81 t C/ha for non-forest land. The uncertainty values were 0.9% for forest land, 11.3% for wetland and 1.8% for non-forest land. The study concluded that to reduce emissions from deforestation all land covers should be managed properly.

Priyadarshini *et al.* (2019) estimated carbon stock in different land covers at the sub-watershed of Sumber Brantas, Batu city, East Java. The carbon stock was estimated under four major land cover types: mixed forest, farmland, plantation forest and scrubland. It was found that tree biomass contributed about 60% of the C-stock on average, while the understorey and necromass contributed C-stock about 2% and 5%, respectively. The mixed forest has the highest total C-stock 316.64 Mg/ha, followed by plantation forest (247.19 Mg/ha), farmland and scrubland i.e., 51.57 Mg/ha and 12 Mg/ha, respectively. This study showed that C-stock will be maintained by managing and planting woody plant which has high tree biomass.

Toru and Kibret (2019) conducted study in Hades sub-watershed, eastern Ethiopia, to explore the carbon stock under four major land uses: natural forest, coffee agroforestry, grazing land and cropland. For the present study, samples were collected from four carbon pools:

aboveground, belowground, litter, and soil. The results indicate that organic carbon concentration decreased with soil depth though substantial amount of carbon was found in the lower soil depths under land use with woody perennials. The mean total organic carbon stock ranged from 138.95 t/ha in the cropland to 496.26 t/ha in the natural forest. The soil organic carbon stock was found to be relatively higher than that of the vegetation carbon stock in the natural forest and coffee agroforestry land uses. The study highlighted the importance of assessing watershed level carbon stock for better and carbon-friendly land use decision-making. The study concluded that land uses with woody perennials have high carbon stock than those without. To enhance carbon sequestration in the sub-watershed study suggested, conservation-based production systems with inclusion of woody perennials.

Gessessea *et al.* (2020) studied the total terrestrial stock of organic carbon and its controlling factors in prevalent land-use systems in semi-arid Ethiopia (610 mm of annual rainfall), as part of the impact assessment of the National Integrated Watershed Management (IWM) program. Above- and below-ground biomass and soil organic carbon (SOC) stocks of major land-use systems (i.e., exclosure, cropland, rangeland, and bare land) were quantified after field sampling along a topographic gradient. The study found that aboveground carbon stocks peaked in the 15-year-old exclosures (9.08 ± 1.44 Mg/ha) owing to intact woody and grass vegetation as well as substantial litter cover (> 20% of the total biomass). Croplands cultivated with wheat and rangelands vegetated with perennial grasses showed average aboveground carbon stocks of 3.16 ± 0.24 and 1.45 ± 0.19 Mg/ha, respectively. The belowground biomass carbon stock was particularly low in croplands (0.76 ± 0.09 Mg/ha), exceeded by that in both exclosures and rangelands, where values averaged 3.67 ± 0.06 and 3.04 ± 0.42 Mg/ha, respectively. The topsoil (0–30 cm) SOC stocks also varied with land-use systems but showed a different order, peaking in rangelands (53.9 ± 10.1 Mg/ha) and exclosures (41.4 ± 8.1 Mg/ha), followed by bare lands (29.0 ± 11.5 Mg/ha) and croplands (26.4 ± 4.6 Mg/ha). The study concluded that the highest total SOC stock found in exclosures established primarily on degraded hillslopes indicates successful IWM restoration efforts. However, croplands exhibited the lowest SOC stock, which implies the need for urgent interventions to improve the soil fertility.

Olorunfemi *et al.* (2020) estimated the overall-ecosystem carbon stocks under different land cover types in some parts of Southwestern Nigeria, sub-Saharan Africa (SSA). Soil carbon concentrations were measured at 0–10, 10–20 and 20–30 cm soil depths for four land covers (forests (FOR), plantations (TP), woodlands (WD) and croplands (CP)). The aboveground biomass carbon (Mg C/ha) followed the order: FOR (118.19 Mg C/ha) > TP (64.57 Mg C/ha) > WD (31.09 Mg C/ha) > CP (17.31 Mg C/ha). Soil organic carbon (SOC) concentration in all land uses decreased significantly ($p < 0.05$) with depth increment. Total SOC stock in 0–30 cm soil layer follows the order: FOR land use (93.62 Mg C/ha) > TP (60.87 Mg C/ha) > WD (55.21 Mg C/ha)

> CP (50.23 Mg C/ha). The majority of carbon stocks in the study area were concentrated in the aboveground and soil carbon pool. The results of the study indicated that forests store a larger amount of TCS compared to croplands and woodlands. The study concluded that agroforestry, forest plantations and forestry should be given serious considerations as strategies to sequester carbon.

Anokye *et al.* (2021) quantified soil carbon stock (SCS) in three land-use systems viz. arable land, oil palm plantation and forestland in the semi-deciduous forest zone of Ghana. The study found that soil organic carbon concentration at the 0–15 cm layer in the forestland was 62 and 23% greater than that in the arable land and palm plantation, respectively. The SCS along the 1.0-m profile was found to be 108.2, 99.0 and 73.5 Mg/ha in the forestland, palm plantation and arable land, respectively. The study provides relevant information on carbon storage abilities of the three land-use types in tropical climate and calls for drastic climate change actions to reduce degradation of forest cover and soil disturbance in agro-ecosystems in sub-Saharan Africa.

Sharma *et al.* (2021) assessed the carbon sequestration potential of tree species in Amity University Campus, Noida, India. In the present study above- and below-ground biomasses were estimated using the non-destructive sampling method. Individual trees on the campus were measured for their height and diameter at breast height (DBH) and estimates of carbon storage were performed using allometric equations. There are a total of 45 different tree species on the campus with the total carbon sequestration potential (CSP) equivalent to approximately 139.86 tonnes. The results also revealed that Ficus Benjamina was the predominant species on the campus, with CSP equivalent to 30.53 tonnes, followed by Alstonia Scholaris with carbon storage of 16.38 tonnes. The present work highlights the role of urban forests or urban green spaces, not only as ornamental and aesthetic plantations but also in mitigating the impacts of climate change at a local level. The study concluded that higher education institutes have an important role in expanding their green cover to act as local carbon sinks.

Houssoukpevi *et al.* (2022) quantified the C stocks in plant biomass, woody necromass, litter and soil (0–30 and 30–100 cm) for the five main land uses – forest, tree plantation, young and adult palm groves, croplands – of Ferralsols on the Allada plateau in southeast Benin. The study found that forests have the highest total C stocks (389 ± 54 Mg C/ha) compared with other land uses (222 ± 33, 154 ± 6, 105 ± 2, 77 ± 3 Mg C/ha in tree plantations, adult palm groves, young palm groves and croplands, respectively). The C stocks are higher in the biomass than in the soil (0–100 cm), e.g., in the forest, stocks were 279 ± 54 Mg C/ha in the biomass versus 83 ± 2 Mg C/ha in the soil. Differences in soil C stocks between land uses are low (≈ 28 Mg C/ha) and concentrated in topsoils. The study concluded that the structure and species diversity of the forest partly explained the variability and the high C biomass compared to tree plantations. The type of forest and plantations is important to consider in conserving C stocks in landscapes.

Hussein (2022) estimated carbon stock potential across different land covers in tropical ecosystems. The research was conducted at Damota Kebele, in the Oromia regional state of Ethiopia, to examine the carbon sequestration potentials among three land covers (i.e., farmland (FL); bushland (BL), and woodland (WL)). Study results showed that WL had significantly higher above-ground carbon (AGC) with 67.9 ± 11.4 Mg/ha, whereas BL had significantly higher below-ground carbon (BGC) stocks with 16.32 ± 5.5 Mg/ha, compared to other gradients. However, FL had the lowest AGC (53.2 ± 4.5 Mg/ha) and BGC (8.04 ± 2.9 Mg/ha). FL exhibited a significantly higher SOC value than the other two land covers, followed by WL. The BL had the lowest SOC value. SOC across the three soil profiles follows a reduction trend from topsoil depth to lower soil depth with significant variation. WL had relatively higher total carbon TC than the other gradients and FL had the lowest TC stock. The study concluded that due to a high amount of human and animal interference in FL, weak security and law enforcement measures, it has a low TC. FL should embrace the better ecological, policy and socioeconomic considerations than the other land covers.

2.2 Assessment of temporal impact of soil and water conservation measures on carbon sequestration.

Stroosnijder and Hoogmoed (2004) studied the contribution of soil and water conservation (SWC) to carbon sequestration in Semi-arid Africa. The study found that soil and water conservation practices reduce erosion, improve soil qualities and increase ground water utilization efficiency (GWUE). SWC measures implemented in Burkina Faso cari saved 8 t/ha/yr in erosion, which is equivalent to 16-40 kg C/ha/yr. The study concluded that SWC can stop the current decrease in SOC provided that land use systems are regreened.

Adhikary *et al.* (2016) estimated soil erosion and carbon sequestration in shifting cultivated degraded highlands. The performance of two contour hedgerow (Gliricidia sepium and Leucaena leucocephala) systems with and without miniature trenches was evaluated as conservation measures in the shifting cultivated degraded Eastern Ghats Highlands of Odisha, India. It was found that the treatment Gliricidia + miniature trench (G+MT) reduced runoff by 23.3–32.5 %, soil loss by 49.5–52.7 % and loss of soil organic carbon (SOC) by 44.1–47.6% when compared to no conservation treatment (control). Whereas the treatment Leucaena + miniature trench (L + MT) reduced runoff by 18.6–18.9%, soil loss by 42.4–43.7% and loss of soil organic carbon by 30.9–40.2%, over control. Within 0–20 cm soil profile, G+MT sequestered 1.62 Mg/ha/yr SOC, of which 0.93 Mg/ha/yr was sequestered due to soil reclamation and 0.69 Mg/ha/yr was retained due to the barrier effect, whereas L+MT sequestered 1.21 Mg/ha/yr SOC. The decrease of SOC stock by 40–102 kg/ha/yr in the control plots from the initial level indicated the ongoing erosion process in unprotected lands. The study findings will help to promote hedgerow based agroforestry for resource conservation and improved SOC sequestration in sloping lands.

Mesfin *et al.* (2018) studied the effects of integrated soil and water conservation measures on soil organic matter and soil organic carbon stock of smallholder farmlands in semi-arid Northern Ethiopia. Soil and water conservation (SWC) measures such as stone bunds and trenches integrated with fodder species (ISWC) have been implemented to tackle soil erosion in Ethiopian highlands. Fifteen disturbed composite and 15 undisturbed soil samples were collected from cropland sites treated with ISWC measures, SWC structures alone and no SWC measures (NSWC). The study found that SOCS (t/ha) and SOM contents are: 12.7 and 1.7% for sites with ISWC, 8.0 and 1.2% for SWC alone and 6.3 and 0.7% for NSWC. SOCS and SOM content was significantly higher ($p<0.01$) for cropland sites treated with ISWC compared to those treated with SWC alone and NSWC. However, there are insignificant differences ($p>0.05$) in SQ and SOCS, between sites with SWC alone and NSWC. This study concluded that the application of ISWC measures has considerable potential to enhance SOCS and SOM content.

Hombegowda *et al.* (2019) assessed hedge row intercropping impact on run-off, soil erosion, carbon sequestration and millet yield in Eastern Ghats highland, India. The treatment Gliricidia + Trench planting (G + TP) reduced run-off by 29%, soil loss by 45–48% and loss of soil organic carbon (SOC) by 42–47% over control. Similarly, for Leucaena + Trench planting (L + TP), the values were 17–19, 27–40 and 28–37, respectively, over control. The SOC conservation efficiency of G + TP was 42–47% on 5 and 10% land slopes. Gliricidia hedge row intercropping showed promise for improving the conservation potential of the system by maintaining high productivity. The findings of this study will serve as a technical reference for the adoption of Gliricidia-based hedge row technology for increasing intercrop productivity and conserving soil resources on sloping agricultural lands in the Eastern Ghats.

Mahajan *et al.* (2020) assessed the impact of soil and water conservation measures on soil carbon sequestration under cashews in the Western Ghats, Goa. A long-term (13-year) experiment was conducted to evaluate the impact of soil and water conservation measures on soil carbon sequestration at three different depths under cashew nut cultivation on a 19% slope. Five soil and water conservation measures - continuous contour trenches, staggered contour trenches, half-moon terraces, semi-elliptical trenches, and graded trenches all with vegetative barriers of Stylosanthes scabra and Vetiveria zizanoides and control were evaluated for their influence on carbon sequestration under cashews. The study found that soil and water conservation measures significantly improved soil organic carbon, soil organic carbon stock and carbon sequestration rate compared to the control condition (without any measures). Among the measures tested, continuous contour trenches with vegetative barriers outperformed the others with respect to soil organic carbon stock and carbon sequestration rate. The study concluded that soil and water conservation measures for cashews are a potential strategy to improve the soil carbon sequestration rate.

Mekonnen and Getahun (2020) estimated the contribution of soil and water conservation practices (SWCPs) in trapping sediment and soil organic carbon in the Minizr watershed, northwest highlands of Ethiopia. Three different SWCPs, five different check dams (CDs) and 30 micro-trenches were evaluated for their sediment and SOC trapping efficiency. The volume of sediment trapped was quantified using field measurements of the deposited sediment and SOC was determined in a soil laboratory. The study found that the SWCPs, CDs and micro-trenches trapped ~584,745 kg SOC together with 32,105 tonnes of sediment. The percentage of SOC was higher in the CD sediments (1.98%) than SWCPs (1.38%) and micro-trenches (1.49%). A large amount of SOC was deposited in vegetative-supported CDs than in CDs constructed from structures alone. The study concluded that SWCPs, CDs and micro-trenches reduce soil erosion or land degradation by enhancing sediment deposition. They also trap large amounts of SOC together with the sediment, which reduces the greenhouse gases emission into the atmosphere.

Terefe *et al.* (2020) studied the impact of sustainable land management (SLM) interventions on carbon sequestration in plant biomass and soil in a mixed crop-livestock system in the Geda watershed, central highlands of Ethiopia. The major SLM interventions practiced in the study area include the prohibition of free grazing, soil bunds and soil bunds supported by biological interventions mainly with tree lucerne (Chamaecytisus palmensis) and Phalaris (Phalaris acquatica, Phalaris arundinacea), percolation pits and contour trenches. The study explored the impact of SLM interventions on biomass production, carbon stock, and carbon sequestration. The study found that plant biomass production, carbon stock, and carbon sequestration varied highly significantly ($P \leq 0.001$) among sub-watersheds, landscape positions, and land uses. Higher mean values were observed for the treated sub-watershed, lower landscape position, and tree lucerne plot. The higher mean values in the lower landscape position of the treated sub-watershed were due to tree lucerne plantation. Similarly, topsoil (0–15 cm) carbon stock was statistically higher ($P \leq 0.001$) in the treated sub-watershed and at tree lucerne plot ($P \leq 0.05$). In addition, carbon stock in sub-surface soil (15–30 cm) was significantly higher ($P \leq 0.001$) in the treated sub-watershed under crop and grazing lands but the higher value was in cropland and in the upper position. Six years of SLM interventions led to the sequestration of 12.25, 7.77, and 13.5 Mg C/ha under cropland, tree lucerne and grazing plots, respectively.

Hailu and Betemariyam (2021) conducted a study to examine and compare the status of soil organic carbon (SOC) stocks between farmlands treated with level soil bund (LSB) of three and six years and adjacent farmland without conservation measures (control) at Somodo Watershed, South-western of Ethiopia. Soil samples were collected from farmland treated with LSB-3 years, LSB-6 years and control using a randomized complete block design. A total of 108 composite soil samples (3 treatments × 6 replications × 3 bund zones × 2 depths (0–20 and 20–40 cm)) were collected for analysis and determination of the Organic Carbon fraction (OC). The result indicated that farmland treated with LSB-6 years has insignificantly higher SOC (98.43±11.55 Mg/ha) stock than control SOC (93.01±13.51 Mg/ha) stock. Likely, farmland treated with LSB-6 years has insignificantly higher SOC stock than farmland treated with LSB-3 years SOC (96.61±11.45 Mg/ha) stock. With respect to the age of LSB, farmland treated with LSB-6 years accumulated more SOC stock (5.83%) than control. This study concluded that the age of LSB conservation measures has a critical role in enhancing soil fertility through maintaining and sequestering SOC.

Mahajan *et al.* (2021) conducted the long-term study from 2001 to 2013 (13-years) to assess the effect of soil and water conservation (SWC) measures on carbon sequestration under high density (4 m × 4 m) cashew nut on 19% sloping land in the west coast region of India. Five SWC measures namely, continuous contour trenches + vegetative barrier (CCT+VB), staggered contour trenches + vegetative barrier (SCT+VB), crescent shape trench + vegetative barrier (CST+VB), vegetative barrier (VB) and control with no SWC measures were evaluated. The CCT+VB showed the best performance with significantly higher soil organic carbon (SOC) (1.41 to 2.02%) and SOC stock (SOCS) (44.9-57.8 Mg C/ha) compared to control up to a depth of 0-0.9 m. The same treatment had significantly higher SOC sequestration rate (SOCSR) of 1.5 Mg C/ha/yr. The study concluded that SWC measures in cashew could be adopted as a strategy to improve microbial activity and soil carbon sequestration alongside advantages of reduced soil loss, runoff, and nutrient loss.

Hu *et al.* (2022) studied the impacts of SWC measures on the SOC stock change in a typical small watershed in the Mollisol region of Northeast China. A total of 292 soil samples were collected in the same locations in 2005 and 2016. The results indicated that the average annual increase rate of SOC was 5.43%. The equivalent soil mass (ESM) method indicated that the change rate of the SOC stock significantly increased from 2005 to 2016, with an average annual increase rate of 3.33%. The study found that grassland had a greater change rate of the SOC stock than the other SWC measures ($P < 0.05$). The change rate of the SOC stock in forestland significantly increased with an increase in the initial SOC level, but the opposite trend was found in the grassland and terrace ($P < 0.05$). In addition, soil erosion occurred on the upper and middle slopes, and soil deposition occurred on the foot slope in the typical sloping farmland ($P < 0.05$); forestland had a better control effect on soil erosion than farmland. The study findings provided science-based recommendations for enhancing SOC storage in agricultural sites by implementing SWC measures.

Jiru and Wegari (2022) studied the effect of soil and water conservation (SWC) practices on soil organic matter and soil organic carbon in Ethiopia. The study found that SWC practices influenced the soil physicochemical properties and crop yield either positively or negatively. The mean values of available soil organic matter (4.4%, 3.8%) and soil organic carbon (2.2%, 1.8%)

were on treated and untreated farmland under physical SWC practices, respectively. Similarly, the mean values of these variables were higher on treated farmland than on untreated farmland under both biological and integrated SWC practices. The mean value of bulk density was higher on untreated farmland than on treated one and statistically significant under all SWC practices. Graded and stone-faced soil bund constantly increased crop yield, whereas soil bund and stone bund did not. The study concluded that proper implementation of SWC technologies through integrating physical and biological measures will boost the effectiveness of the practice in restoring soil physicochemical properties and improving crop yield.

2.3 Assessment of the impact of soil erosion on carbon loss in the watershed.

Kimble *et al.* (2001) studied the effect of erosion on the soil carbon pool in the soils of Iowa, United States of America. The study assessed the soil organic carbon (SOC) content in the top 25 cm layer of 250 soil profiles comprising 208 Mollisols, 27 Alfisols and 15 Entisols from Iowa. Soil profiles were stratified into three erosional classes involving slightly eroded, moderately eroded and severely eroded. The study found that soil erosion caused changes in soil structure, which was mostly granular in slightly eroded; sub-granular blocky in moderately eroded and cloddy in severely eroded phases. The range of SOC lost by erosion in the top 25 cm of moderately and severely eroded soils was between 19 and 51% for Mollisols and 15 to 65% for Alfisols. The study concluded that restoration of eroded soils has the potential to re-sequester carbon and reduce risks of the potential greenhouse effect.

Mchunu and Chaplot (2012) studied the land degradation impact on soil carbon losses through water erosion and CO_2 emissions in in KwaZulu-Natal, South Africa. The study performed under sandy-loam Acrisols investigated three proportions of soil surface coverage by plants (Cov), from 100% (Cov100) for the “non-degraded” treatment to 25–50% (Cov50) and 0–5% (Cov5). The study found that at the “non-degraded” treatment of Cov100, plant-C inputs to the soil profile were 1950± 180 $gC/m^2/yr$ and SOC stocks in the 0–0.02 m layer were 300.6± 16.2 gC/m^2. Soil-C inputs by plants significantly ($P < 0.05$ level) decreased by 38.5± 3.5% at Cov50 and by 75.4± 6.9% at Cov5. The SOC losses by water erosion were 0.75 gC/m^2 at Cov100 increased from 66% at Cov50 (i.e., 3.76± 1.8 gC/m^2) to a staggering 213% at Cov5 (i.e., 7.08± 2.9 gC/m^2). These losses were for the most part in particulate form (from 88.0% for Cov100 to 98.7% for Cov5). Plant cover reduction significantly decreased both the cumulative $C–CO_2$ emissions (by 68% at Cov50 and 69% at Cov5) and the mineralization rate of the soil organic matter (from 0.039 $gC– CO_2/gC$ at Cov100 to 0.031 $gC– CO_2/gC$ at Cov5). The study emphasized the importance of additional in-situ research studies to determine whether grassland degradation causes net C-emissions to the atmosphere.

Dlamini *et al.* (2014) studied the impact of land degradation on soil organic carbon and nitrogen stocks of sub-tropical humid grasslands in South Africa. A degraded grassland showing an aerial cover gradient from 100% (Cov100, corresponding to a non-degraded grassland) to 50–75% (Cov75), 25–50% (Cov50) and 0–5% (Cov5, corresponding to a heavily degraded grassland), was selected in South Africa. Soil samples were collected in the 0.05 m soil layer at 48 locations along the aerial cover gradient and were subsequently separated into the clay + silt (2–20 µm) and sand (20–2000 µm) fractions, prior to total C (n = 288). The decline in grass aerial cover from 100% to 0–5% had a significant ($P < 0.05$) impact on SOC stocks, with losses of upto 1.25 kg/m^2 in SOC, which corresponded to an 89% depletion rate. The study concluded that the staggering decline in SOC stocks raises concerns about the ability of acidic sandy loam soils to sustain their main ecosystem functions.

Wang *et al.* (2014) studied the soil organic carbon redistribution by water erosion and the role of CO_2 emissions in the carbon budget. The study was conducted in South Limburg, The Netherlands. The study measured fluxes of SOC, dissolved organic C (DOC) and CO_2 in a pseudo-replicated rainfall-simulation experiment. The study found that erosion, transport and subsequent deposition resulted in significantly higher CER of the sediments exported ranging between 1.3 and 4.0. In the exported sediments, C contents (mg per g soil) of particulate organic C (POC, C not bound to soil minerals) and mineral-associated organic C (MOC) were both significantly higher than those of non-eroded soils indicating that water erosion resulted in losses of C-enriched material both in forms of POC and MOC. The averaged SOC fluxes as particles (4.7 g C /m^2/yr) were 18 times larger than DOC fluxes. The cumulative emission of soil CO_2 slightly decreased at the erosion zone, while increased by 56% and 27% at the transport and depositional zone, respectively, in comparison to non-eroded soil. The study concluded that only 1.5% of the total redistributed C was mineralized to CO_2 indicating a large stabilization after deposition. The study underlines the importance of C losses by particles and as DOC for understanding the effects of water erosion on the C balance at the interface of terrestrial and aquatic ecosystems.

Mey *et al.* (2015) predicted soil loss and soil organic carbon loss due to erosion in the Girindulu watershed, central Java. The results showed that the Girindulu watershed area of 73,703.75 ha had a total soil loss due to erosion of 9,880,934.7 t/year, and a total soil organic carbon loss due to erosion of 153,120.2 t/year. The study concluded that soil conservation actions need to be taken through replanting of trees (reforestation) in marginal lands, incorporation of agricultural residues, mulching with organic matter from vegetation, and application of organic fertilizer on cultivated land to reduce the soil and carbon loss from the watershed.

Müller-Nedebock and Chaplot (2015) studied soil carbon losses by sheet erosion and its contribution to the global carbon cycle. In the study, empirical data from 240 runoff plots studied over entire rainy seasons from different regions of the world to estimate particulate organic carbon (POC) losses (POCL), and POC enrichment in the sediments compared to the bulk soil (ER), which can be used as a proxy of the fate of the eroded POC. It was found that the median POCL was 9.9

g C/m^2/yr with highest values observed for semi-arid soils (POCL = 10.8 g C/m^2/yr), followed by tropical soils (POCL = 6.4 g C/m^2/yr) and temperate soils (POCL = 1.7 g C/m^2/yr). Considering the mean POCL of 27.2 g C/m^2/yr, the total amount of SOC displaced annually by sheet erosion from its source would be 1.32 ± 0.20 Gt C, i.e., 14.6% of the net annual fossil fuel induced C emissions of 9 Gt C. The study concluded that because of low sediment enrichment in POC, erosion induced CO_2 emissions are likely to be limited in clayey environments, while POC burial within hillslopes is likely to constitute an important carbon sink. In contrast, most of the POC displaced from sandy soils is likely to be emitted to the atmosphere. These results underpin the major role sheet erosion plays in the displacement of SOC from its source and in the fate of the eroded SOC, with large variations across the different pedo-climatic regions of the world.

Cilek (2017) estimated the soil organic carbon losses by water erosion in Seyhan River Basin in Mediterranean Watershed, Turkey. The study found that the annual amount of soil eroded from the Seyhan River Basin was 7.8 million tonnes per hectare (t/ha/yr). The amount of fertile soil loss from agricultural areas was ~1.2 million tonnes per year. The maximum amount of soil erosion occurred in maintenance scrubland and degraded forest areas, contributing to 68% of erosion, followed by that in agricultural land, contributing to 27% of erosion, with the remaining in forests and urban areas. The study evaluated the depletion of soil organic carbon (SOC) due to soil erosion using a physically based, regionally scaled soil erosion model, concluding that SOC losses were highest in degraded forests (SOCL = 1,74,464 t/yr), followed by scrubland (SOCL = 1,40,774 t/yr) and arable land (SOCL = 34,612 t/yr). The study reported that SOC stored in forest ecosystems was washed out by water erosion. SOC stocks in soil decreased as forest ecosystems were converted to agricultural fields.

Naipal *et al.* (2018) estimated the global soil organic carbon removal by water erosion under climate change and land use change (LUC) during AD 1850–2005. The study found that over the period AD 1850–2005 acceleration of soil erosion leads to a total potential SOC removal flux of 74±18 Pg C, of which 79%– 85% occurred on agricultural land and grassland. Using best estimates for soil erosion, the study found that including soil erosion in the SOC-dynamics scheme results in an increase of 62% of the cumulative loss of SOC over 1850–2005 due to the combined effects of climate variability, increasing atmospheric CO_2 and LUC. This additional erosional loss decreased the cumulative global carbon sink on land by 2 Pg of carbon for this specific period, with the largest effects found for the tropics, where deforestation and agricultural expansion increased soil erosion rates significantly. The study concluded that the potential effect of soil erosion on the global SOC stock is comparable to the effects of climate or LUC. It is thus necessary to include soil erosion in assessments of LUC and evaluations of the terrestrial carbon cycle.

Li *et al.* (2019) studied the effect of soil erosion on soil organic carbon variations and soil respiration along a slope in Northeast China. The study found that the depositional profiles store

5.9 times more SOC than the eroding profiles and 3.3 times more SOC than the non-eroding profiles. A linear correlation between the SOC and ^{137}Cs (Caesium-137) was observed in this study, suggesting that the SOC decreased with increased soil erosion. The field results of soil surface respiration also suggest that the depositional topsoil SOC is prone to be mineralized and that SOC at this depositional context is stabilized at subsoil depth. In addition, the high-water contents at the depositional position can limit the decomposition rates and stabilize the SOC at the same time. The findings from this study support that a majority of the SOC at footslope is stored within most of the soil profile (i.e., below 10 cm) and submitted to long-term stabilization and meanwhile support that the depositional profile emits more CO_2 than the summit due to its high amount and quality of SOC.

Mandal *et al.* (2019) estimated the magnitude of erosion-induced carbon (C) flux and C-sequestration potential of eroded lands in India. The lateral transport of eroded C was estimated for individual Indian states using spatially referenced data for soil erosion rates that were assessed using the universal soil loss equation (USLE) applied to the information about 1649 soil association units and their SOC inventories across the country. The results indicated that soil erosion varies widely across the states. At the national level in India, erosion transported about 4.87 Pg of soil and 115.36 Tg of C every year, which consequently emits about 34.61 Tg of C to the atmosphere. Among the states in India, Madhya Pradesh had the highest value of erosion associated C loss (20.33 Tg C/yr), followed by Chhattisgarh, Maharashtra, Uttar Pradesh and Andhra Pradesh with losses of 9.98, 9.18, 9.11 and 8.70 Tg C/yr, respectively. The results revealed that between 19 and 27 Tg C/yr could be sequestered in soils by adopting achievable technological options in erosion-affected areas of India, offering the potential to reduce approximately 24.5% of the total greenhouse gas emissions from the agricultural soils of India (94 Tg C).

Tan *et al.* (2019) studied the role of soil erosion in the land carbon sink and its future changes. The study estimated that on average soil erosion displaces 5% of newly fixed land organic carbon downslope annually in the continental United States. In the lower Mississippi river basin and the Cascades, the fraction can be as large as 40%. About 12% of the eroded organic carbon is eventually exported to inland waters, which is equal to 14% of the simulated net carbon gain by terrestrial ecosystems. By comparing the eroded organic carbon export to rivers with the particulate organic carbon export to oceans, the study demonstrated that a large fraction of the carbon export to rivers could have been mineralized in inland waters.

Wang *et al.* (2019) studied the redistribution of soil organic carbon induced by soil erosion in the nine river basins of China. The study estimated the redistribution of sediment and SOC in the nine river basins of China during 1995–1996 and 2010–2012. It was found that over these two periods, 3.55–4.50 Pg of soil and 68.42–77.32 Tg C of SOC were eroded each year. For the SOC budget, on average 57% and 47% of the eroded SOC was deposited over land, 25% and 44% was deposited in the channel, and 18% and 8% was delivered into the sea during 1995–1996 and 2010–2012, respectively. Compared with the corresponding magnitudes during 1995–1996, the eroded SOC, the SOC deposited over land and the SOC discharged into the sea decreased during 2010–2012, and only the SOC deposited into the river channel increased (from 19.5 to 30.1 Tg C/yr). The study concluded that erosion-induced redistribution of SOC alters the carbon budget of the nation.

Lal (2020) studied the effect of soil erosion on gaseous emissions. The study reported that the global magnitude of soil organic carbon (SOC) erosion may be 1.3 Pg C/yr by water and 1.0 Pg C/yr by wind erosion. SOC erosion by water and wind has a strong impact on the global C budget (GCB). The study found that of the total SOC erosion by water, 40%–50% may be redistributed over the land, 20%–30% deposited in channels, and 5%–15% carried into the oceans. The cumulative gaseous emissions may decrease at the eroding site because of the depletion of its SOC stock but increase at the depositional site because of enrichment of SOC amount and the labile fraction. The study concluded that the SOC erosion by water and wind exacerbates climate change, decreases net primary productivity (NPP) and reduces soils C sink capacity to mitigate global warming. The study emphasized the need for multi-disciplinary and watershed-scale based research to measure and model the magnitude of SOC erosion by water and wind, multiple gaseous emissions at different landscape positions, and the attendant changes in NPP.

2.4 Development of conservation strategies for carbon sequestration in the watershed.

Katterer *et al.* (2012) studied the strategies for carbon sequestration in agricultural soils in northern Europe. The study found that minimizing the time with bare soil, improving recycling of organic materials and increasing yields through N fertilization were effective methods of increasing the C sequestration rate. The study results suggest that C stock increases by 1-2 kg C for each kg of mineral N fertilizer applied. Options for reducing C emissions from drained cultivated organic soils are limited when used as cropland. Extensive production leads to lower soil C stocks and requires more land. Increasing photosynthesis at the global scale by intensification of crop production was found to be the most effective mitigation option and is a prerequisite for preventing further areal expansion of agriculture.

Purakayastha *et al.* (2016) studied soil management strategies to enhance carbon sequestration potential of degraded lands. The study found that various management strategies like conservation agriculture, integrated nutrient management, afforestation, alternate land use, plantations and amendments and use of biochar hold promise for long term C sequestration. The study projected that in India the largest potential lies in erosion prevention (33.6–50.4 Tg/year), secondary carbonates and bicarbonates (21.8–25.6 Tg/ha), agricultural intensification (12.7–16.5 Tg/ year) and restoration of degraded soils (9.8–13.9 Tg/ha). The total potential of soil organic C (SOC) sequestration in India is 77.9 to 106.4 Tg/year. Conservation agriculture has tremendous potential for soil C sequestration to the tune of 1.8 t/ha/year during the first decade of adoption. Afforestation significantly increases C sequestration in tropical climates compared to temperate or boreal climates. Alternate land use by adoption of agroforestry system is a promising strategy for enhancing carbon sequestration by vegetation and soil.

Law *et al.* (2018) studied land use strategies to mitigate climate change in carbon dense temperate forest. The study examined the relative merits of afforestation, reforestation, management changes, and harvest residue bioenergy use in the Pacific Northwest. This region represents some of the highest carbon density forests in the world, which can store carbon in trees for 800 years or more. Oregon's net ecosystem carbon balance (NECB) was equivalent to 72% of total emissions in 2011–2015. By 2100, simulations show increased net carbon uptake with little change in wildfires. Reforestation, afforestation, lengthened harvest cycles on private lands, and restricting harvest on public lands will increase NECB by 56% by 2100, with the latter two actions contributing the most. The study found that utilizing harvest residues for bioenergy production instead of leaving them in forests to decompose increased emissions in the short term (50 y), reducing mitigation effectiveness. The study concluded that increasing forest carbon on public lands reduces emissions compared with storage in wood products because the residence time is more than twice that of wood products. Hence, temperate forests with high carbon densities and lower vulnerability to mortality have substantial potential for climate change mitigation.

Adarsh and Thomas (2019) studied the role of improved agricultural practices to reduce greenhouse gas emissions. The study found that cultivation using improved varieties, efficient cropping system, conservation tillage, proper crop residue management, cover crops and increased nutrient use efficiency tends to have a significant impact on climate change mitigation. Precision farming, use of slow-release fertilizers, proper water management in rice fields, substitution of fossil fuels with crop residues, use of dung and energy crops, need specific agroforestry and grazing management practices have a profound effect on reducing greenhouse gas emissions. Biochar produced from pyrolysis of plant and animal biomass sequesters carbon, improves soil fertility, reduces pollution and enhances crop residue recycling. The study concluded that improved conservation measures have long-term and positive effects on mitigating climate change. In addition, proper cultivation practices reduce greenhouse gas emissions and their after effects.

Chapman *et al.* (2020) studied the mitigation potential of adding trees to agricultural lands. The study estimated the current and potential carbon storage of trees in nonforested portions of agricultural lands. It was found that global croplands currently store 3.07 Pg of carbon (C) in aboveground woody biomass (i.e., trees) and pasture lands account for an additional 3.86 Pg C across a combined 3.76 billion ha. The study estimated the climate mitigation potential of multiple scenarios of integration and avoided loss of trees in crop and pasture lands based on region-specific biomass distributions. The study found that the majority of potential carbon storage from integration and avoided loss of trees in crop and pasture lands is in countries that do not identify agroforestry as a climate mitigation technique.

Domke *et al.* (2020) studied the potential of tree planting to increase carbon sequestration capacity of forests in the United States. The study used data from more than 1,30,000 national forest inventory plots to describe the contribution of nearly 1.4 trillion trees on forestland in the conterminous United States to mitigate CO_2 emissions and the potential to enhance carbon sequestration capacity on productive forestland. The study found that forests and harvested wood products uptake the equivalent of more than 14% of economy-wide CO_2 emissions in the United States annually, and there is potential to increase carbon sequestration capacity by ~20% (−187.7 million metric tons [MMT] CO_2 ±9.1 MMT CO_2) per year by fully stocking all understocked productive forestland. The study concluded that reforestation and afforestation activities will help to maintain and potentially enhance the forest C sink.

O'Dell *et al.* (2020) investigated the significance of conservation agriculture as a climate change mitigation strategy in Zimbabwe. The objective of this study was to investigate the C sequestration potential of conservation agriculture (CA) (defined by minimal soil disturbance, maintaining permanent soil cover, and crop rotations). The study used micrometeorological methods to measure carbon dioxide (CO_2) flux from several alternative CA practices in Harare, central Zimbabwe. Micrometeorological methods can detect differences in total CO_2 emissions of agricultural management practices; results found that CA practices produce less CO_2 emissions. Over three years of measurement, the mean and standard error (SE) of CO_2 emissions for the plot with the most consistent CA practices was 0.564 ± 0.0122 g CO_2 /m^2/ha, significantly less than 0.928 ± 0.00859 g CO_2/m^2/ha for the conventional tillage practice. The study concluded that overall CA practices of no-till with the use of cover crops produced fewer CO_2 emissions than conventional tillage and fallow.

Tanveer *et al.* (2020) studied soil carbon sequestration through agronomic management practices. The study revealed that improper tillage operations, crop rotations, residue management, fertilization and no or less use of organic fertilizers are the main agronomic practises responsible for soil carbon loss. These practices have led to the loss of soil organic matter in the form of CO_2. The study found that by adapting proper tillage operations, crop rotations that increase soil organic matter and the application of organic fertilizers, i.e., FYM, compost, and other organic amendments such as humic acid, vermicompost, etc., can be useful in soil carbon sequestration.

Mushore *et al.* (2021) conducted a study on the methods used by small-scale farmers in Zimbabwe's Nyanga District to adapt to and mitigate the effects of climate change. The study found that food aid, the use of traditional grains and other drought-resistant crops, early planting, multiple plantings, barter trade, and livelihood diversification were among the strategies used in the study area to adapt to climate change. Reforestation and afforestation, prevention of wildfires and preservation of wetlands were some of the mitigation strategies employed in study area.

Zaman *et al.* (2021) studied the different climate-smart agriculture practices (CSA) for mitigating greenhouse gas emissions. The study found that CSA practices have many roles to play in agricultural sustainability and in reducing GHG emissions, as well as in increasing soil C sequestration. Practices such as the use of nitrification and urease inhibitors, mulching, application of biochar to the soil, fertilization management and use of intercropping and crop rotations are all options available to landowners to effectively adapt to and mitigate regional to global climate change. The study concluded that region- or site-specific research is often needed prior to their application to determine if any of the CSAs might produce a positive result on climate change adaptation and mitigation.

2.5 Critique of Reviews

It is evident from the reviews that climate change mitigation through carbon sequestration has attracted global attention. Carbon sequestration through vegetation and soil has been identified as one of the most practically feasible and economically viable means of reducing greenhouse gas emissions and concentrations in the atmosphere. The research was conducted all over the world to determine the potential of various land covers for carbon sequestration. It has been revealed that the carbon sequestration capabilities of vegetation and soil differ at different locations. Global soils hold more carbon than vegetation and the atmosphere combined. Furthermore, different vegetation species have been discovered to have varying carbon sequestration potential, which is dependent on the type, canopy, girth, wood density and height of specific tree species. Higher rates of carbon sequestration are observed in forests with both dense tree populations and rapid tree growth. Researchers have highlighted the significance of regional studies in order to evaluate the potential of native trees for carbon sequestration.

It has been observed from few reviews that different land management practices have different effects on soil carbon sequestration. Agronomical measures such as crop rotation, cover crops, no-tillage, crop residue retention and grazing management are found to have variable positive effects on soil carbon sequestration. Land degradation due to soil erosion is one of the key obstacles that limit soil carbon storage. Land cover has been proven to have a major impact on soil carbon sequestration, with dense vegetation having a higher soil organic carbon content than bare soils. Soil organic carbon and bulk density are directly proportional to soil depth. It has been reported that as depth increased, soil organic carbon decreased but bulk density increased.

Soil erosion plays a very important role in the global carbon cycle. The researchers have found that accelerated soil erosion not only reduces soil fertility but is also a substantial source of carbon emissions. So, controlling soil erosion is critical for agricultural production and lowering carbon emissions. Sustainable land management strategies such as soil and water conservation measures have been acknowledged and adopted globally for effective soil erosion control. However, scientific knowledge about the significance of soil and water conservation measures for carbon loss reduction and carbon sequestration is limited.

Researchers have placed a strong emphasis on the creation of climate-smart watersheds for the sustainable development of regions. However, no comprehensive approach for watershed-based carbon management is proposed. The findings of various studies suggest that sustainably developed carbon negative watersheds could play a vital role in climate change mitigation.

Carbon sequestration rates are reported to rise with the use of sustainable land management strategies such as afforestation, reforestation and reduced deforestation. Implementing these techniques in watersheds, in conjunction with soil and water conservation measures, will boost the potential of terrestrial carbon sequestration. Low-income countries require long-term, cost-effective measures to combat climate change. In this regard carbon neutral climate smart watersheds can be a prudent step. Incorporating carbon sequestration into watershed planning and management will bring a new paradigm to climate change mitigation and boost the worldwide effort against climate change.

3. MATERIALS AND METHODS

This chapter deals with the description of study area, data collected, procedure adopted to estimate total terrestrial carbon stock (soil and biomass) in the watershed, different parameters and methodology used to estimate average annual soil loss and carbon loss from the watershed. The approach used to evaluate the carbon sequestration potential of various soil and water conservation measures, as well as the methodology used to identify appropriate conservation strategies for climate change mitigation in the watershed.

3.1 Description of the study area

3.1.1 Location and topography

The study was conducted at “Central MPKV Campus Watershed” located in Rahuri Taluka in Ahmednagar District of Maharashtra State, India. The study area is located between latitudes $19^0$21.77' N and $19^0$18.73' N and longitudes $74^0$37.79' E and $74^0$36.49’ E. The location map of the study area is shown in Fig. 3.1. It has north-south length of about 6 km and average east-west extension of about 3 km suggest that the watershed has an elongated shape with a longer axis oriented in the north-south direction. The study area covers 1260 ha, with elevation ranging from 441 to 542 m above mean sea level suggests that the watershed has some variability in elevation, with a difference of approximately 101 m between the highest and lowest points. The perimeter of the watershed is 19.42 km. The range of slopes for the watershed is from 0 to 30.23%. This means that the land surface within the watershed varies from flat to moderately steep.

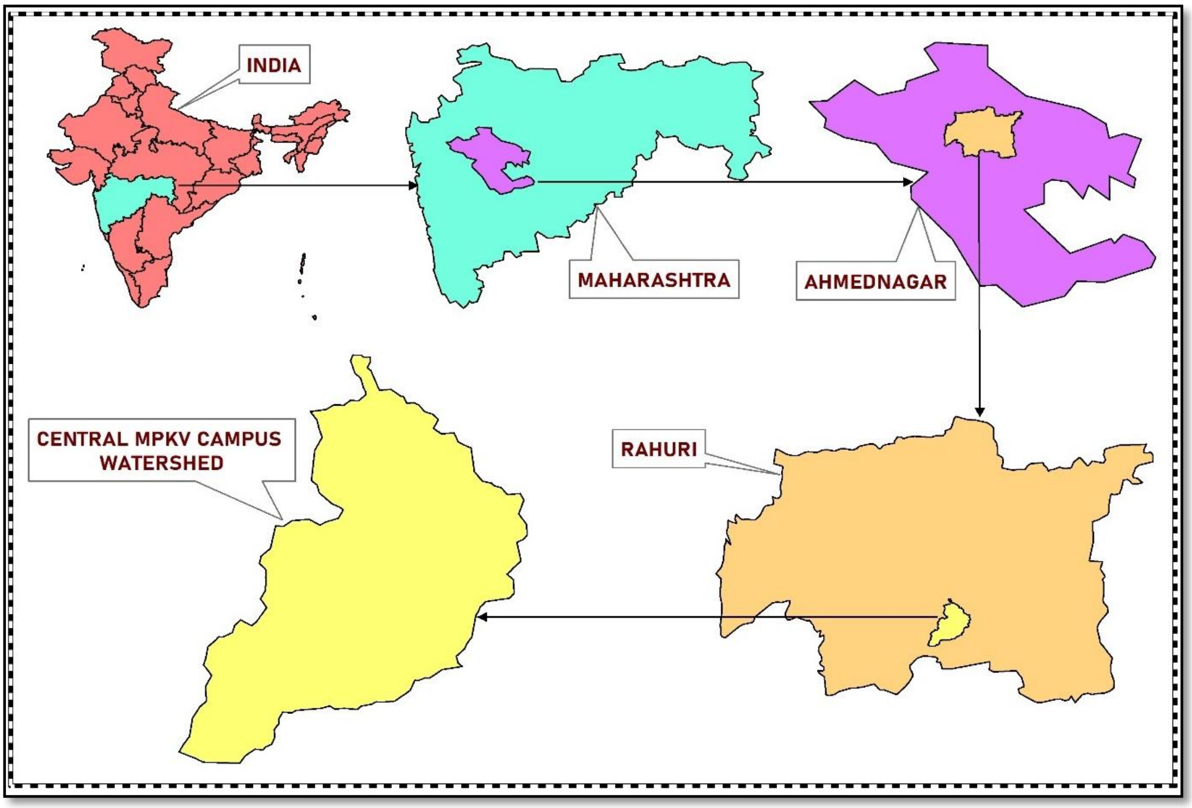

Figure 3.1 Location map of the study area (Central MPKV Campus Watershed)

3.1.2 Climate

The study area is characterized by a unimodal rainfall pattern, with the main rainy season extending from late June to early September. The annual rainfall of the study area varied from 313 to 948 mm with an average of 592 mm. This suggests that there is significant year-to-year variability in rainfall amounts and timing, which can affect water availability and vegetation growth in the watershed. The annual mean minimum and maximum temperatures are 19°C and 33°C, respectively. This suggests that the study area has a relatively warm climate with high temperatures during the day and relatively warm temperatures at night. The study area belongs to the hot and dry climate zone of tropical region.

3.1.3 Soil and Water Conservation Measures in the Study Area

The Central MPKV Campus Watershed is treated with various scientifically planned soil and water (SWC) conservation measures under watershed development program of Adarsh Gaon Yojana, Govt. of Maharashtra. Watershed development activities in the study area started in 2017 and in 2019 almost half of the watershed was treated with both land area and drainage line treatments. A total of 545 ha of the total watershed area has been treated with various soil and water conservation measures. The land area treatments in the watershed include deep continuous contour trenches (DCCT) and compartment bunding, while drainage line treatments include earthen nala bunds, loose boulder structures and percolation tank. Table 1 and Fig. 3.2 provide detailed information on the SWC measures that have been implemented in the watershed.

Table 3.1 Soil and water conservation measures in the watershed

SWC Treatments in the Watershed	
Total Study Area	1260 ha
Total Treated Area	545 ha
Perimeter of Treated Area	12.77 km
Area Under DCCT	495 ha
Length of DCCT	99,600 running m
Area Under Compartment Bunding	50 ha
Earthen Nala Bunds	38
Percolation Tanks	2
Loose Boulder Structures	97

3.2 Data Collection and Pre-processing

1. Daily rainfall data for the period of 1995 to 2021 for watershed was collected from Department of Irrigation Water Management (IWM), Mahatma Phule Krishi Vidyapeeth Rahuri, Maharashtra.
2. Soil samples were collected from 50 different locations in the watershed using a grid sampling method that covered a variety of land use patterns.

3. Soil samples were collected at 0–15 cm and 15–30 cm soil depths from each selected sampling site in the watershed to estimate soil physicochemical properties.
4. Soil samples were collected repeatedly for three consecutive years at the same location after a year gap to analyse changes in soil carbon stock over time.
5. The different physicochemical properties of the soil such as sand, silt, clay, bulk density and organic carbon were estimated in the soil analysis laboratory of the Department of Soil Science and Agricultural Chemistry, MPKV, Rahuri.
6. Land use/land cover data for the watershed was derived from Sentinel 2A satellite imagery with spatial resolution of 10 m. The Sentinel 2A imagery for study area was obtained from the USGS EarthExplorer portal (https://earthexplorer.usgs.gov/).
7. Shuttle Radar Topography Mission (SRTM) Digital elevation model (DEM) was obtained from USGS (United States Geological Survey) EarthExplorer portal to prepare topographic factor map of the watershed.
8. To estimate the carbon stock of individual tree species their height and diameter at breast height (1.3 m from ground surface) were measured. The height of individual tree species was measured using clinometer and diameter was measured using meter tape.

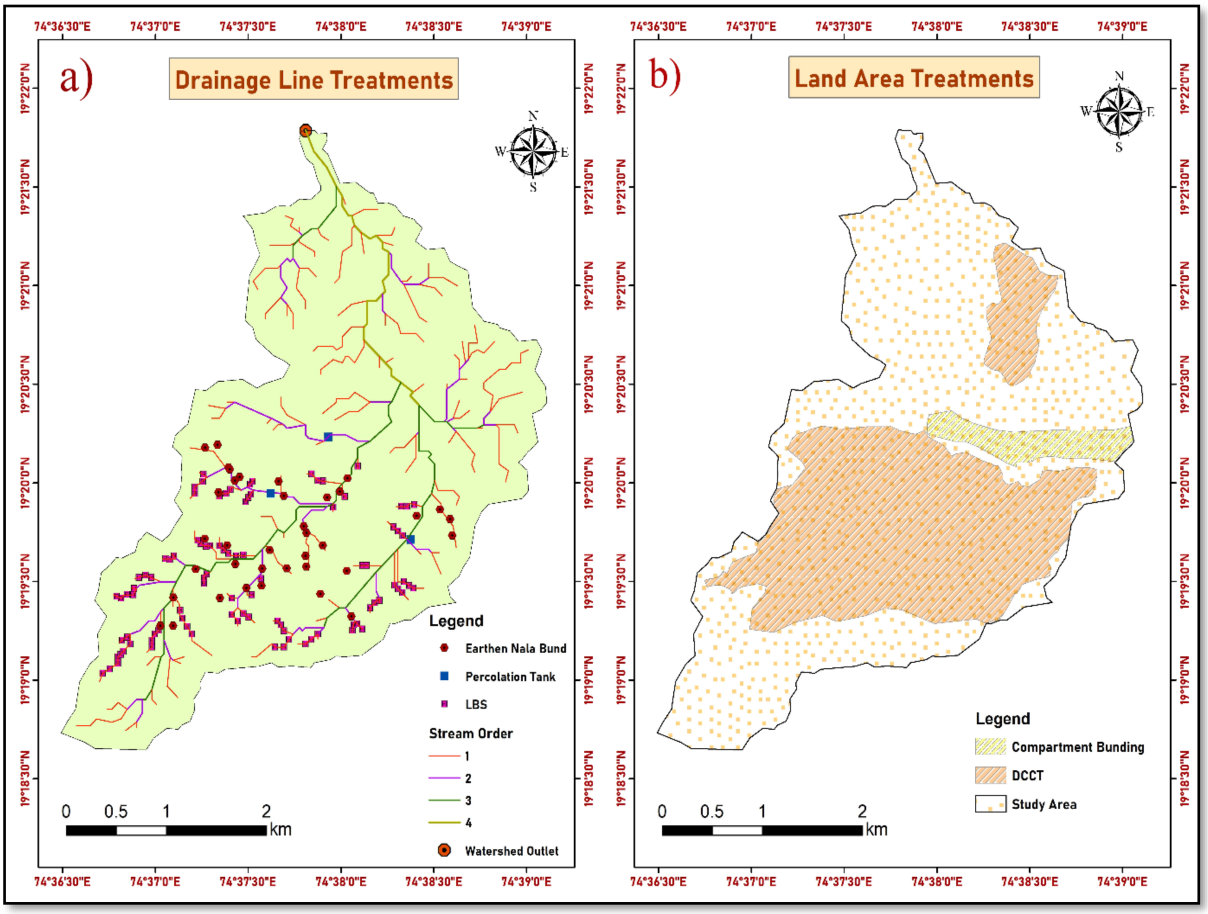

Figure 3.2 SWC measures in the watershed a) Drainage line b) Land area treatments

3.3 Watershed Delineation

A watershed is a hydrological unit from which precipitation-related runoff flows past a single point into a large stream, river, lake or pond. It is an ideal unit for managing natural resources such as land, water and vegetation. Watershed delineation plays an important role in watershed management. A field survey was conducted to identify the outlet point of the watershed. The coordinates of the outlet point were recorded using a handheld GPS device, which was then used to delineate the watershed. Arc-GIS 10.8 software was used for the purpose of delineating watershed area along with Survey of India (SOI) toposheet (scale 1:50,000). Toposheet provides information about the land cover, drainage network and contours. The Survey of India Toposheet (47I/11) at 1:50000 scale was used as a base map to delineate the watershed and to extract the drainage network of the watershed.

3.4 Morphometric Analysis of the Watershed

Morphometric characteristics are important in understanding the basic structure, geomorphological formations and hydrological features of any watershed (Karataş and Ekinci, 2014). It is the first and most important technique for conceptualizing the orientation of the drainage network, learning about erosion stages and different erosive agents, topographic strata, soil types, slopes and runoff characteristics of watersheds. Morphometric characteristics are divided into three primary aspects:

1) Linear aspects of drainage network
2) Areal aspects of drainage network
3) Relief aspects of drainage network

3.4.1 Linear Aspects of Drainage Network

Linear aspects of watershed are concerned with the streams and its network. In general, these are one dimensional properties. The linear aspects of morphometric analysis of drainage basin include stream order, stream number, stream length, mean stream length, stream length ratio and bifurcation ratio.

3.4.1.1 Stream Order (u)

The degree of stream branching within a watershed is represented by the stream order. The Strahler system (1952) for stream ordering is more popular because of its simplicity. In this system, the smallest, unbranched fingertip streams are referred to as first-order streams. Two first-order streams combine and form a larger second-order stream. Two second-order streams combine and form another larger third-order stream and so on. Small streams entering a higher order stream do not change their order number.

3.4.1.2 Stream Number (N_u)

The number of segments of a specific stream order is counted and expressed as the number of that specific order. It is a measure of the stream network complexity and used to describe the hydrologic connectivity and flow paths within a watershed. It can also be used to assess changes in the stream network over time, such as alterations due to land use changes or channelization.

3.4.1.3 Bifurcation Ratio (R_b)

The bifurcation ratio (R_b) is a measure of the branching pattern of a stream network within a watershed. It is defined as the ratio of the number of streams of a given order (N_u) to the number of streams of the next higher order (N_{u+i}), where i is the increment between stream orders. It is a useful metric for describing the hierarchical structure of a stream network and how it changes as it moves downstream. In general, higher values of R_b indicate a more complex and dendritic stream network, while lower values of R_b suggest a more linear stream network.

$$R_b = \frac{N_u}{N_{u+1}} \tag{3.1}$$

Where, R_b = Bifurcation ratio

N_u = Number of streams of order u

N_{u+1}= Number of streams of order u+1

3.4.1.4 Mean Stream Length (L_{sm})

The mean stream length (L_{sm}) is a measure of the average length of streams within a given order in a watershed. It is calculated by dividing the total length of streams of a given order (Lu) by the number of streams of that order (Nu). It is a useful metric for describing the characteristics of a stream network within a watershed. It can provide insight into the spatial distribution of streams within different orders and can be used to compare stream networks across different watersheds.

$$L_{sm} = \frac{L_u}{N_u} \tag{3.2}$$

Where, L_u= mean length of channel of order u

N_u = total number of stream segments of order u

3.4.1.5 Stream Length Ratio (R_L)

Stream length ratio (R_L) is defined as the ratio of the mean stream length of a certain stream order to the mean stream length of the next lower order. It is a useful metric for characterizing the relative lengths of streams within a stream network and provide insights into the branching pattern and topology of the stream network. Higher values of R_L indicate a more complex stream network, while lower values of R_L suggest a simpler, more linear stream network.

$$R_L = \frac{L_u}{L_{u-1}} \tag{3.3}$$

Where, L_u= mean stream length of order u

L_{u-1}= mean stream length of next lower order u-1

3.4.2 Areal Aspects of Drainage Network

The areal aspects of drainage morphometric analysis include form factor, circulatory ratio, elongation ratio, drainage density, constant of channel maintenance, length of overland flow, stream frequency, textural ratio and drainage intensity.

3.4.2.1 Form Factor (R_f)

Form factor (R_f) is defined as the ratio of the basin's area to the square of the basin's length and the value of 'R_f' varies from 0 (for basins with highly elongated shapes) to 1 (for a basin with perfect circular shape). It is a useful metric for assessing the shape and geometry of watersheds and provide insights into the hydrological and geomorphic processes that occur within them.

$$R_f = \frac{A}{{L_b}^2} \tag{3.4}$$

Where, A = Area of basin (km^2)

L_b = Length of basin (km)

3.4.2.2 Circulatory Ratio (R_c)

Circularity ratio (R_c) is a measure of the compactness of a watershed and is defined as the ratio of the area of the watershed to the area of a circle having the same circumference as the perimeter of the watershed (Miller, 1953; Strahler, 1957). The value of R_c ranges from 0 to 1, with higher values indicating a more circular or compact shape and lower values indicating a more elongated or irregular shape. Watersheds with high R_c values tend to have more uniform flow patterns and lower potential for erosion and sediment transport, while watersheds with low R_c values may have more complex flow patterns and higher potential for erosion and sediment transport due to their elongated shape and steeper slopes.

$$R_c = 12.57 \times \frac{A}{P^2} \tag{3.5}$$

Where, P= Perimeter of basin (km)

3.4.2.3 Elongation Ratio (R_e)

The elongation ratio (R_e) is a measure of the elongation or shape of a watershed and is defined as the ratio of diameter of a circle of the same area as the watershed to the maximum watershed length. The R_e ranges from 0 to 1, with higher values indicating a more elongated shape and lower values indicating a more circular shape. A value of 1 indicates a perfectly circular watershed, while values closer to 0 indicate highly elongated or irregular shapes (Strahler, 1957).

$$R_e = 2\frac{\sqrt{\frac{A}{P}}}{L_b} \tag{3.6}$$

3.4.2.4 Drainage Density (D_d)

Drainage density (D_d) is defined as the ratio of total length of all stream segments within the watershed to the total area of the watershed. It is an important parameter in watershed analysis as it provides information on the surface and subsurface runoff characteristics of the watershed. High drainage density values indicate that the watershed is more permeable and that water can move through the soil and subsurface layers more quickly. On the other hand, low drainage density values indicate that the watershed is less permeable and that water is more likely to be stored in the soil and subsurface layers.

$$R_f = \frac{\sum L_u}{A} \tag{3.7}$$

Where, Lu = Total length of all stream segment (km)

A = Watershed area (km^2)

3.4.2.5 Constant of Channel Maintenance (CCM)

The constant of channel maintenance (CCM) is defined as the reciprocal of the drainage density as a property for determining the overland runoff (Schumm, 1956). CCM is expressed in km^2/km. The CCM represents the area of the watershed that contributes to the flow of water in a given channel length. It is a measure of the channel-forming potential of a watershed and is used to estimate the volume and velocity of water that can be expected to flow over the land surface during a storm event.

$$CCM = \frac{1}{D_d} \tag{3.8}$$

3.4.2.6 Length of Overland Flow (L_g)

Length of overland flow (L_g) is roughly equal to half of the reciprocal of drainage density (Horton, 1945). It is used to describe the length of flow of water over the ground before it becomes concentrated in definite stream channels. This means that watersheds with a higher drainage density will have a shorter L_g, indicating that water is more quickly concentrated in stream channels. Conversely, watersheds with a lower drainage density will have a longer Lg, indicating that water travels further over the land surface before it is concentrated in streams.

$$L_g = \frac{1}{2 \times D_d} \tag{3.9}$$

3.4.2.7 Stream Frequency (F_s)

The stream frequency (F_s) is the ratio between the total number of stream segments of all orders in a watershed and the watershed area (Horton, 1945). It refers to the number of streams per unit area. A higher stream frequency indicates that there are more streams in a given area, which can have implications for flooding and water management.

$$F_s = \frac{\sum N_u}{A} \tag{3.10}$$

3.4.2.8 Textural Ratio (R_t)

Textural ratio (R_t) is a measure of the roughness or irregularity of the boundary of a watershed. It is defined as the ratio of the total number of stream segments to the perimeter of the watershed.

$$R_t = \frac{\Sigma N_u}{P} \tag{3.11}$$

3.4.2.9 Drainage Intensity (D_i)

Drainage intensity (Di) is the ratio of stream frequency to the drainage density (Faniran, 1968). It indicates the degree of integration of the drainage network in relation to the overall size of the watershed. Higher values of drainage intensity indicate a more dense and well-integrated drainage network, while lower values indicate a less integrated and more dispersed network.

$$D_i = \frac{F_s}{D_d} \tag{3.12}$$

3.4.3 Relief Aspects of Drainage Network

The relief aspects of the drainage basins are related to the study of the three-dimensional features of a watershed involving area, volume and vertical dimension of landforms. The relief aspects of drainage morphometric analysis include relief, relief ratio, relative relief and ruggedness number.

3.4.3.1 Relief (H)

Watershed relief is the elevation difference between the highest and lowest points in the drainage basin. It is a measure of the topographical variation in the watershed and can influence the flow of water in the drainage network. High relief areas are characterized by steep slopes and can lead to rapid flow of water, while low relief areas are characterized by gentle slopes and slower flow of water.

$$H = Z - z \tag{3.13}$$

Where, H = relief, (m)

Z= elevation of highest point in drainage basin, (m)

Z= elevation of lowest point in drainage basin, (m)

3.4.3.2 Relief Ratio (H_n)

Relief ratio (H_n) is a measure of the degree of relief of a drainage basin relative to its size. It is defined as the ratio of relief to the horizontal distance on which relief was measured. The relief ratio provides information on the steepness of the watershed and its potential for erosion and sediment transport. A high relief ratio indicates a steep and rugged landscape, while a low relief ratio indicates a relatively flat and gentle landscape.

$$H_n = \frac{H}{L_h} \tag{3.14}$$

Where, L_h = Horizontal distance, (m))

3.4.3.3 Relative Relief (R_r)

Relative relief (R_r), introduced by Melton (1957) is the ratio between the relief and perimeter of the watershed.

$$R_r = \frac{H}{P} \times 100 \tag{3.15}$$

3.4.3.4 Ruggedness Number (R_n)

The ruggedness number is an index that combines information about the steepness of the terrain (relief) and the amount of channelization (drainage density) within a watershed. It the product of relief and drainage density. It is an index that reflects the steepness and length of the slope. High values of ruggedness number indicate areas with high relief and/or high drainage density, which generally correspond to steep and rugged terrain. Low values indicate areas with gentle slopes and low channelization.

$$Ruggedness\ Ratio = H \times D_d \tag{3.16}$$

3.5 Impact of Soil and Water Conservation Measures on Land Cover

The impact of soil and water conservation (SWC) measures on the land cover was investigated through a change detection analysis of the watershed. Change detection analysis is a technique for identifying, describing and quantifying differences between images of the same scene taken at different times or under different conditions (Fichera *et al.,* 2012). Two Land Use/Land Cover (LU/LC) maps of the watershed were created in order to analyse the changes in land cover caused by SWC measures. One land cover map was created for 2016, when there were no SWC measures, and another for 2021, when half of the watershed was treated with various SWC measures. The changes in the LU/LC over a 5-year period were examined.

3.5.1 Land Use/Land Cover Mapping of the Watershed

The term land use of the watershed and land cover of the watershed are frequently used interchangeably, but each has its own distinct meaning. Land use refers to how people use the land, whereas land cover refers to the physical land type. Advanced geospatial techniques such as remote sensing (RS) and geographic information system (GIS) can facilitate better extraction and analysis of land use/land cover (LU/LC) information. Geographic Information System technology has the potential to generate a thematic layer of land use/land cover. Land use information contributes to a better understanding of the current state of land use aspects of cropping patterns, forests, agricultural land, urban areas, etc., which can be important for planning climate studies (Mallupattu and Sreenivasula Reddy, 2013). For the present study, the land use/land cover map was derived from satellite imagery. Sentinel-2 satellite imagery for the study area was downloaded directly from the USGS EarthExplorer portal at processing level 2A. Cloud-free satellite images were visually identified on the platform and selected for download. Thematic mapping of the different land use/land cover classes was achieved by a supervised image classification method. The maximum likelihood classifier technique was used to classify the image into seven land cover classes. Image processing was performed using Arc GIS 10.8 software as shown in the Fig 3.3.

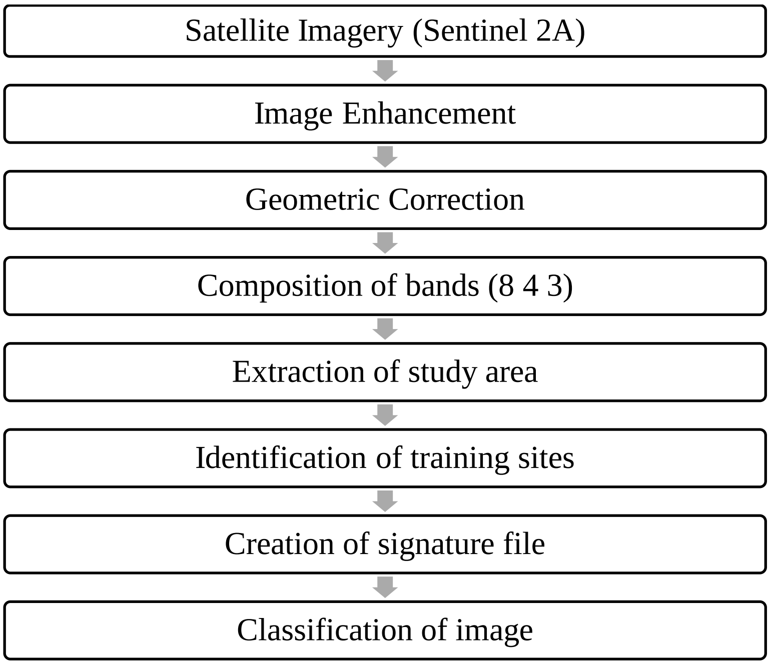

Figure 3.3 Flowchart showing methodology adopted for LU/LC mapping

3.6 Estimation of Carbon Stock Under Different Land Use Patterns in the Watershed

3.6.1 Carbon Stock

A carbon stock, or carbon pool, is a system that has the capacity to store or release carbon. A carbon flux refers to the amount of carbon exchanged between carbon pools over a specified time (Quetin *et al.*, 2020). In simple terms, it is the movement of carbon between land, oceans, atmosphere and living things. In the present study terrestrial carbon stock was estimated from the watershed. Terrestrial carbon stock is the carbon stored in the vegetation (biomass) and soil. The terrestrial carbon stock of the watershed was measured from different land covers. The biomass carbon stock was estimated using regression equations developed for local climatic conditions, while the soil carbon stock was determined through laboratory analysis of soil samples.

3.6.2 Carbon Sequestration

Carbon sequestration implies transferring atmospheric carbon dioxide (CO_2) into long-lived pools and storing it securely so that it should not be immediately reemitted into the atmosphere (Lal, 2007). Similarly, terrestrial carbon sequestration is the process through which CO_2 from the atmosphere is absorbed by trees and plants through photosynthesis and stored as carbon in soils and biomass (tree trunks, branches, foliage and roots). Carbon sequestration is associated with the capture of its compounds from the environment, which reduces the progress of the greenhouse effect (Lal *et al.*, 2015).

There are two basic methods of carbon sequestration *viz.* direct and indirect. The direct method is implemented by sequestering carbon compounds directly at the source before they are released into the atmosphere. Captured carbon is stored over long periods of time in specially designated landfills that are properly protected and environment friendly. The second sequestration method is the indirect method using plants that sequester CO_2 in the process of photosynthesis or in the soil as organic matter. In these methods, sequestration can take place through physical, chemical or biological processes.

3.6.3 Carbon Stock in Biomass

Biomass is an important element in the global carbon cycle, especially in the process of carbon sequestration. Biomass is defined as the total amount of living and inert or dead organic matter above and below ground, expressed in tonnes of dry matter per unit area (McKendry, 2002). The biomass of any tree or crop species is a function of stem density, the height of the species and the basal area of the species at a given location. Biomass plays two major roles in the carbon cycle: (i) photosynthesis removes carbon dioxide from the atmosphere and stores it in plants as biomass, some of which enters the soil during decomposition or is stored in protected soil carbon pools; (ii) biomass burned by fire releases CO_2 and other trace gases into the atmosphere.

According to the IPCC guidelines on land use, land change and forestry, the biomass carbon pools of terrestrial ecosystems are divided into above-ground biomass, below-ground biomass, dead matter and litter (Ansuategi, 2000). Above ground biomass includes all living biomass above the ground surface, including stem, stump, branches, bark, seeds and foliage (FAO, 2009). Below ground biomass includes all living biomass of living roots. It includes fine roots (< 2 mm in diameter), small roots (2-10 mm in diameter) and large roots (> 10 mm in diameter). Roots play an important role in the carbon cycle as they transfer significant amounts of carbon to the soil where it can be stored for relatively long periods of time. Fine roots are usually excluded, as they often cannot be distinguished empirically from soil organic matter or litter (FAO, 2009).

The biomass assessment methods described below are not limited to forests, agriculture or pastures. These methods can be applied to areas where trees are a dominant part of the landscape, including closed and open forests, plantations, gardens, live fences, etc., as well as to agricultural and grazing systems, including all types of crop rotations, crop mixtures, trees and willows (Raul, 2004). There are several methods for estimating biomass carbon stock. Some of the methods for estimating the carbon stock of biomass are explained below;

3.6.4 Methods for Estimating Above-Ground Biomass

3.6.4.1 Harvest Method

The principle of harvest method is to measure the weight of tree and non-tree biomass in selected sample plots at a given point in time. All trees in the sample plots are harvested and the weight of various components such as tree trunks, branches and leaves are measured. The harvesting method for non-tree biomass (shrubs, herbs, vines and grasses) also requires the harvesting of non-woody biomass and of woody biomass, if any, from sample plots. The method provides the most accurate estimate of the stock of woody and non-woody biomass at the time of harvest. The harvest method, while providing an accurate estimate of biomass at the time of harvest, has several limitations. First, it can be destructive to the ecosystem and disrupt natural processes. Second, it is time-consuming and expensive, as it requires the harvesting and weighing of all trees and non-tree biomass in sample plots. Lastly, it may not be feasible for large or inaccessible areas.

3.6.4.2 Carbon Flux Measurement (Eddy covariance) Method

The method involves installing a chamber to enclose a small area or a specific component of an ecosystem (e.g., soil, stems, leaves). Changes in the CO_2 concentration in the chamber or the difference between the concentrations in the supply and exhaust air are used to calculate the CO_2 flux. There are methods to measure the CO_2 flux for an entire ecosystem (less than 1 km^2) without an enclosure (Liu *et al.*, 2012). The most commonly used technique is the eddy correlation/covariance technique, where measurements are made continuously and semi-automatically (often at hourly intervals).

3.6.4.3 Satellite or Remote Sensing Method

Remote sensing includes several techniques such as aerial photography, optical parameters and radar that can be used effectively to track land use change in a study area. In addition, remote sensing techniques offer an alternative to traditional methods for estimating, monitoring and verifying changes in areas under different land use systems, as well as in biomass production and growth (Lourenço, 2021). Remote sensing techniques provide spatially unambiguous information and enable repeated monitoring even in remote locations. The basic approach to applying remote sensing is to understand the relationship between the parameters of a forest stand (e.g., diameter at breast height (DBH), tree height, canopy cover, footprint and even biomass stand) and their spectral representation depending on the characteristics of the study area and the sensor data used (Lu *et al.*, 2014). The interpretation of remote sensing images therefore requires ground truthing and field measurements.

3.6.4.4 Modelling of Carbon Stock Changes

Models are available for extrapolating biomass carbon stocks and above-ground biomass growth rates for various commercial plantations and forest types. These models can be used to complement field methods such as plot and plotless methods that measure and estimate carbon stock indicators. Models could be used to predict changes in biomass carbon stocks in forests and plantations. These growth models estimate biomass (kilograms/tree or tonnes/hectare) as a function of tree parameters such as DBH (in meters) and height (in meters).

3.6.4.5 Plotless Method

The plotless method involves measuring tree density and diameter (DBH) along a series of parallel sample lines (Macdicken, 1997) and includes the following steps:

1. Select the land-use category or project activity strata, and locate sample plots.
2. Establish a series of parallel sample lines in each stratum.
3. Locate sample points every 10 m along the sample line.
4. At each sample point, divide the area into four quarters.
5. Record the species name, DBH and height of the tree along with distance between the sample point and each tree or shrub.
6. Ensure at least 100 measurements per stratum.

Using the data on the distance between the sample point and trees along the sample line, the mean distance between trees in the plot can be estimated. The density of trees per hectare can then be calculated, either for each species or for all trees, using the estimated mean distance between trees. The above-ground biomass of trees can thus be calculated using DBH and tree height and biomass equations.

3.6.4.6 Plot Method

The principle of the plot method is to estimate the volume or weight of tree and non-tree biomass in a number of sample plots using the measured values of various indicator parameters such as DBH and tree height. There are several variants of the plot method, namely Quadrats (square or rectangular), Circular Plots and Transects (long rectangular plots). The broad approach involves the following procedure:

1. Select a land-use category; stratify and lay sample plots.
2. Lay separate sample plots for trees, shrubs and ground-layer vegetation (herbs).
3. Vary the size and number of sample plots depending on the type and size of the study area and diversity of vegetation.
4. Record the species name, height and DBH for each tree or shrub.
5. Estimate above-ground tree biomass per tree and per hectare using height and DBH data using different approaches, namely:
   a. Biomass estimation equation.
   b. Harvest method within the plots.
   c. Calculating the volume of each tree using DBH, height and tree form data and then converting the volume to weight using wood density.
6. Estimate the biomass for non-tree vegetation such as shrubs and grasses by adopting the harvest method.

The plot method is the most commonly used method for assessing above-ground biomass of tree and non-tree vegetation. The advantages of the plot method include:

1. Applicable to forests, plantations, grasslands, shelter belts and agroforestry systems.
2. Applicable equally to one-time measurement of biomass or long-term regular monitoring by the permanent plot method.
3. Can be adopted by any team with minimal resources and technical skills.
4. Inexpensive.
5. Suitable for sparse and dense vegetation.
6. Applicable to large or small piece of forest, plantation or grassland.
7. Suitable for both monoculture and diversified vegetation.
8. Suitable for both old-growth forest and young regenerating forest or plantation.

Table 3.2 Methodological options for estimating carbon pools

Carbon Pool	**Method**	**Suitability for carbon inventory of land use system**
Above ground biomass	Harvest Method	- Not suitable, not often permitted, leads to disturbance of forest and even carbon emissions, expensive
	Carbon flux method	- Not suitable, expensive, requires skilled staff
	Satellite/remote sensing	- May not be suitable for multiple land-use systems and project activities - Not suitable for small projects - Practical methods still evolving
	Modelling	- Suitable for projections - Requires basic input parameters to be obtained using other methods
	Plotless method	- Suitable, but less suitable for periodic monitoring and dense vegetation
	Plot method	- Most suitable, cost-effective, commonly adopted and familiar
Below ground biomass	Root extraction and weight measurement	- Expensive and not suitable - Requires uprooting of trees or grass and disturbs the soil
	Root to shoot ratio or conversion factor	- Most commonly adopted - Requires above-ground biomass estimate
	Biomass equations	- Requires input data on tree parameters, girth, height

3.6.5 Methods for Estimation of Below-Ground Biomass or Root Biomass

3.6.5.1 Root Extraction and Weight Measurement Method

The root extraction and weight measurement method measure the amount of root biomass present in a given volume of soil extracted from a known depth, which is usually 30 cm since most fine roots are confined to this shallow depth (Bruns and Croy, 1985).

3.6.5.2 Default Root to Shoot Ratio

The root biomass is usually within a small range of the fraction of the above ground biomass. A review by Cairns *et al.*, (1997), covering more than 160 studies from tropical, temperate, and boreal forests, estimated a mean root-to-shoot ratio of 0.26 with a range of 0.18−0.3. Therefore, it can be practical to use a mean default value of 0.26 for estimating root biomass in most forest projects.

3.6.5.3 Biomass Equations

Regression equations were developed linking root biomass to above ground biomass. Cairns *et al.*, (1997) have developed a set of equations for tropical, temperate and boreal forest types.

3.6.6 Estimation of Above Ground Biomass in the Watershed

The destructive or harvesting method is the most accurate method for biomass estimation. However, this leads to the loss of trees. On the other hand, the remote sensing method requires validation of data from the field. Therefore, an approach based on non-destructive allometric equations is one of the best options for biomass and carbon stock estimation, since inputs are only the measurable parameters such as diameter, height and wood specific gravity (WSG). In the present study, the above ground biomass of forest, plantations, shrubs and grasses was measured. The plot method was used together with a region-specific regression equation to calculate the above-ground biomass of forest and plantation trees.

In this study, regression equations were used to estimate the above ground biomass of tree species. Measurable tree parameters such as diameter at breast height (DBH), height and wood specific gravity were measured to estimate the tree’s above-ground biomass. The girth of each tree was measured 1.3 m above the ground surface using tape. The tree diameter was then calculated by dividing tree girth by π **(**3.14). The height of each tree species was calculated using clinometer device and the specific wood gravity was collected from the global wood density dataset (https://www.worldagroforestry.org/). Depending on the diameter at breast height, tree height, wood specific gravity and climatic conditions, regression equations developed by Chave *et al.*, (2005) was used to estimate the above ground biomass of individual trees in kg. In the current study, the regression equation (3.17) developed by Chave *et al.*, (2005) for dry forest areas was used to estimate the above ground biomass of individual tree species. Dry forests are characterized by a prolonged dry season during which the plants experience significant water stress. These forests receive rainfall below 1500 mm/year and have a dry season lasting over 5 months.

$$AGB = 0.112 \times (\rho D^2 H)^{0.916} \tag{3.17}$$

Where, AGB = Above ground biomass, (kg)

ρ = Wood specific gravity g/cm^3

D = Diameter at breast height, cm

H = Height of tree, m

3.6.6.1 Number of Trees for Measurement

The number of trees for measuring biomass is generally selected empirically. The number of trees for measuring biomass for the present study was selected based on the forest area covered as a percentage of the total watershed area. Regularly shaped sample plots with the dimensions 10 x 10 m for tree layer, 5 x 5 m for shrub layer and 1 x 1 m for grass, which are nested in each other, were defined as sampling units for the measurements of biomass (Raul, 2004). The nesting of sampling quadrants is shown in Fig 3.4.

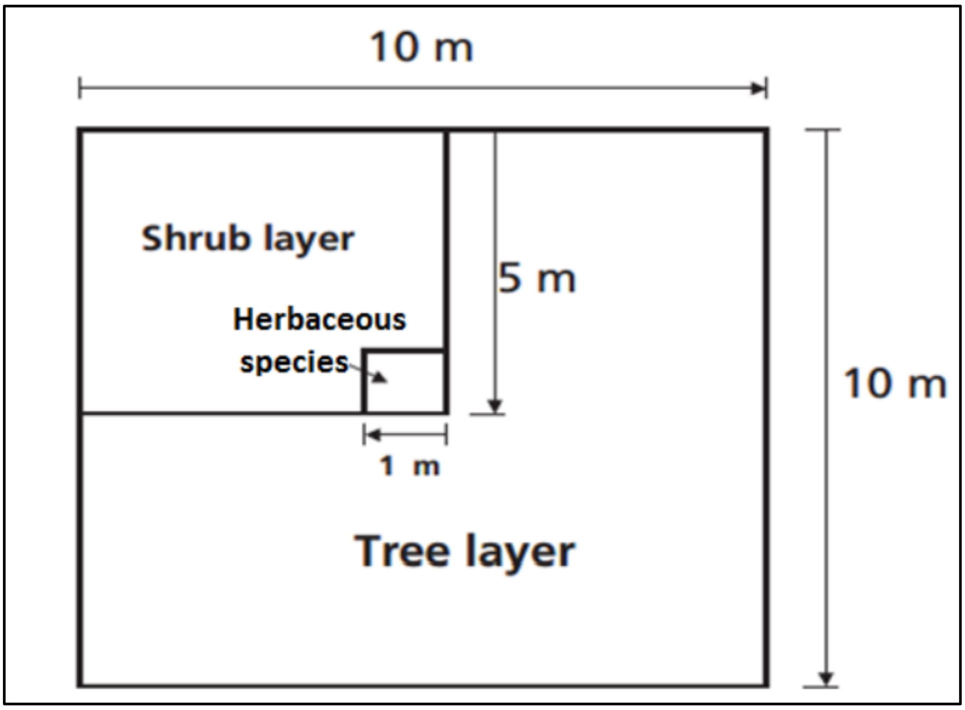

Fig. 3.4 Quadrants size for tree, shrub layer and herbaceous species

In this study, 10 x 10 m plots were randomly selected at 25 sites in the watershed forest area. The number of trees within the plot were counted and the tree parameters like girth at breast height (circumference) and tree height were measured. For the plantation area, 100 trees were randomly selected and their diameter and height measurements were taken to estimate tree biomass (FAO, 2009). Tree planting density and area under plantation were used to convert biomass per tree to tonnes per hectare of biomass.

The biomass of shrubs and grasses was measured using the harvest method. Shrub samples from 5 x 5 m plots and grass samples from 1 x 1 m plots were harvested completely and collected into bags. Harvested samples were dried in the sun for 2-3 days. Thereafter, these samples were placed in a hot-air oven at 60°C for 24 hours to completely remove moisture from the samples. The initial weight at the time of harvest and the final weight after drying were recorded.

3.6.7. Estimation of Below Ground Biomass in the Watershed

There is a relationship between shoot and root biomass for a tree of a given species and for a given forest or plantation type. It is possible to estimate biomass in roots based on above ground biomass data. Given the limitations of measuring below ground biomass in the field, it is desirable to use indirect methods to obtain the below ground biomass value. A comprehensive review by Cairns *et al*., (1997) includes more than 160 studies on native tropical, temperate and boreal forests that reported both below ground and above ground biomass. The ratio of underground (root) biomass to average above ground (shoot) biomass developed on the basis of these studies was 0.26 with a range of 0.18 to 0.30. The ratios did not vary significantly with latitude (tropical, temperate, or boreal), soil texture (fine, medium, or coarse), or tree type (angiosperms or gymnosperms). Therefore, in the present study, a root-to-shoot ratio of 0.26 was used to estimate the below ground biomass of trees.

$$BGB\ (kg) = 0.26 \text{ x AGB } (kg) \tag{3.18}$$

3.6.8 Estimation of Total Biomass in the Watershed

The total biomass of individual tree species was calculated by adding the above ground biomass to the below ground biomass. Then the biomass per tree was converted to biomass in tonnes per hectare. Tree spacing and area under each vegetation type were used to convert the biomass of individual tree species to biomass per hectare. The biomass stored in different vegetative species in the watershed was summed to obtain the total watershed biomass stock. In the present study, the biomass of forests, plantations, shrubs and grasses were added to get the total biomass stock in the watershed.

$$Total\ biomass\ (kg\ per\ tree) = \ AGB(kg) + BGB\ (Kg) \tag{3.19}$$

3.6.9 Estimation of Biomass Carbon Stock

The calculation of the carbon stock of biomass consists of multiplying the total biomass by a conversion factor that represents the average carbon content in biomass. The coefficient of 0.5 is widely used internationally and can therefore be applied on a project basis. Therefore, the coefficient of 0.5 (Dixon *et al.,* 1994; Ravindranath *et al.,* 1997) for the conversion of biomass to carbon was used in the present study.

$$Carbon\ stock\ =\ 0.5 \text{ x } biomass\ stock \tag{3.20}$$

3.7 Carbon Stock in Soil

Soil is the largest carbon store, accounting for 2011 GtC (1Gt = 10^9 tonnes) or 81% of all carbon in the terrestrial biosphere (Lal, 2016). The carbon flux between soil and atmosphere is a continuous process that is strongly influenced by land use and management (Ahirwal *et al.*, 2021). Soil organic carbon (SOC) is one of the most important components of soil organic matter (SOM) and represents the amount of carbon stored in the soil as a result of the decomposition of organic matter. Soil organic matter includes the entire non-mineral fraction of soil, ranging from decayed plant and animal matter to brown to black material that shows no trace of the original anatomical structure of the material and is usually defined as soil humus. Soil organic matter also includes living and dead microbial tissues, compounds synthesized by microorganisms, and derivatives of these materials formed as a result of microbial decay. Soil organic carbon as defined by IPCC (2006) includes organic carbon in mineral soils down to a certain chosen depth, including living and dead fine roots in the soil.

3.7.1 Methods for Inventory of Soil Organic Carbon

Several methods are available and in use to estimate soil organic carbon (SOC), ranging from simple laboratory estimates to diffuse reflectance spectroscopy (Ravindranath, 2008). The method most commonly used in practice is wet digestion or the titrimetric determination method, which is also a cost-effective method. The carbon, hydrogen and nitrogen (CHN) analyser, although very accurate, is rarely used in field studies because the instrument is expensive. Diffuse reflectance spectroscopy is also expensive and has yet to be widely used in the field (Glennie *et al.,* 2014). Modelling method of SOC estimation is limited by the availability of models and data to represent local conditions. The remote sensing method can only be used for large projects, but still needs to be modelled and validated by data obtained from other methods. So, in the present study, a wet digestion or titrimetric determination method was used to calculate the SOC content.

3.7.2 Procedure for Soil Carbon Stock Estimation

Soil carbon stock assessment involves estimating the amount of organic carbon present in the soil of a specific land use category or project activity at a specific depth. A soil carbon stock estimation involves

1. Estimation of bulk density of the soil at the specified depth
2. Estimation of the organic carbon content in the soil sample
3. Conversion of organic carbon content to tonnes of carbon per unit area (tC/ha) for a given depth of soil, using the bulk density.

3.7.2.1 Soil Sampling

Soil samples from the watershed were collected from different land cover patterns. Total of 50 soil samples were collected from the watershed and their location was recorded using GPS device. Soil samples were collected using soil auger at two different depths, one at 0-15 cm depth and another at 15-30 cm depth. Temporal soil samples were collected from the watershed to analyse the impact of soil and water conservation measures on the carbon stock in the watershed. Soil samples were collected at one year interval for three consecutive years. To evaluate the impact of SWC measures on carbon sequestration, a time gap of two rainy seasons, one after 2019 and another after 2020, was maintained. This gap allowed for the assessment of the effectiveness of conservation measures in the watershed two years after their implementation. The soil samples were collected at the end of the rainy seasons in 2020, 2021 and 2022. The collected soil samples were analysed in the soil analysis laboratory in order to estimate the physical and chemical properties of the soil. Soil properties such as texture, bulk density and organic carbon were determined.

3.7.2.2 Estimation of Bulk Density of Soil

The bulk density of the soil is defined as the oven-dry weight of the soil per unit of its bulk volume. Bulk volume includes the volume of soil solids and pore spaces. The bulk density is expressed in grams/cubic centimetres. Soil texture affects the bulk density. Fine-textured soils have lower bulk density than coarse-textured soils. Bulk density tends to increase with depth as the lower layers have little organic matter and microbial activity (Assouline, 2011). Although bulk density has a low spatial variability (the coefficient of variation is less than 10%), its values are required for converting soil organic matter content to tonnes of soil organic carbon per unit area (tC/ha). In the present study, clod method was used to estimate the bulk density of collected soil samples.

3.7.2.3 Clod method for Undisturbed Soil

The clod method measures bulk density by taking an undisturbed soil clod. Determine the volume of the clod and the dry weight of the soil. The bulk density can then be calculated as a weight to volume ratio. In the clod method, clod volume is measured by the volume of water displaced (clods are coated with paraffin or liquid plastic before being immersed in water). Bulk density can be measured by taking an intact clod of earth as follows (Hirmas and Furquim, 2006):

Step 1: Dig the soil and select a clod of soil using a pickaxe and note the depth from which the clod was collected

Step 2: Dry the clod in an oven and estimate the weight of the oven-dry clod

Step 4: Coat the clod with paraffin wax or liquid plastic

Step 5: Estimate the volume of the clod by using the water displacement method

Step 6: Estimate bulk density using the following equation

Bulk density (g/cc) = weight of the oven dried clod/ volume of the clod

3.7.3 Estimation of Soil Organic Carbon (SOC)

Soil organic carbon is routinely estimated in most land-based projects as an indicator of the impact of project activities on stock of soil carbon, soil fertility, moisture-holding capacity or soil erosion. In the present study, SOC was determined using wet digestion or titrimetric determination method (Nelson and Sommers, 1982). Wet digestion is a quick titration procedure used to determine the organic carbon content of soil (Angelova *et al.*, 2019). In wet digestion method, organic matter is oxidized with a mixture of $K_2Cr_2O_7$ and H_2SO_4. Unused $K_2Cr_2O_7$ is back-titrated with ferrous ammonium sulphate (FAS).

3.7.3.1 Determination of Soil Organic Carbon Stock

Soil carbon stock is a function of soil organic carbon (SOC) and bulk density. SOC stocks were assessed individually at two distinct depths (0-15 cm and 15-30 cm) for different types of land cover. The total SOC stock in the top 30 cm depth of soil was obtained by adding the SOC stocks from 0 to 15 cm and 15 to 30 cm depths. Further, SOC stock was transformed into soil carbon storage. The total quantity of soil carbon stored by a certain land cover is the soil carbon storage of that land cover. The total soil carbon storage was computed by multiplying the SOC stock of a given land cover by its whole area. Using the following equation, the SOC stock was estimated on a volume basis by multiplying C content (as a fraction) with soil bulk density and sampling depth (Lal, 1998).

$$SOC\ stock = \frac{SOC}{100} \times Corrected\ Bulk\ density \times Soil\ Sampling\ depth \times 10^4 \quad (3.21)$$

$$Corrected\ Bulk\ density = Bulk\ density\ \times \frac{(100 - Coarse\ Farction)}{100} \quad (3.22)$$

Where, Soil organic carbon in %, Corrected bulk density in g/cm^3, Soil sampling depth in m, Bulk density in g/cm^3, SOC stock in t/ha, Coarse fraction (Soil particles greater than 2 mm in diameter) in %.

3.7.4 Total Terrestrial Carbon Storage in the Watershed

The biomass carbon stored in different vegetation types (forest, horticulture, shrubs, and grasses) was combined together to calculate the total biomass carbon storage in the watershed. Similarly, soil carbon stored in various land cover types was combined together to calculate total soil carbon storage in the watershed. The carbon stored in the terrestrial ecosystem of watershed was determined by adding the biomass carbon stock and soil carbon stock.

3.7.5 CO_2 Sequestration in the Watershed

The multiplier of 3.667 (t CO_2/t C) was used to convert carbon to the corresponding value for CO_2 equivalent (Brander, 2012). Carbon has an atomic weight of 12 atomic mass units; however, carbon dioxide has an atomic weight of 44 since it contains two oxygen atoms that each weigh 16. To convert from one to the other, the following formula was used.

$$1\ tonne\ of\ carbon\ equals\ 44/12\ =\ 11/3\ =\ 3.667\ tonnes\ of\ carbon\ dioxide \quad (3.23)$$

3.7.6 Terrestrial Carbon Stock Mapping of the Watershed

Thematic mapping of the terrestrial carbon stock in the watershed was performed in Arc GIS 10.8 software. An interpolation technique was used to create thematic maps of the watershed. Interpolation is the technique of estimating unknown data values using known data values. The thematic maps produced for the watershed were used for exploratory analysis of spatial data, confirmation of hypotheses, synthesis of spatial data by revealing patterns and relationships and data presentation.

3.8 Assessment of Temporal Impact of Soil and Water Conservation Measures on Soil Carbon Sequestration

The impact of soil and water conservation (SWC) measures on soil carbon sequestration was investigated by comparing the carbon sequestration rate in different land covers in treated areas with carbon sequestration rate in untreated areas. Soil samples from the watershed were collected under 11 different land cover classes treated with different land area treatments. The details of land cover and land area treatment are given in the table 3.3. Soil samples for the untreated area were collected from adjacent areas of the watershed with no SWC treatments. The soil samples were collected periodically for three consecutive years from the two soil sampling depths, i.e., 0-15 cm and 15-30 cm. The collected soil samples were analysed in the laboratory to determine the soil carbon sequestration rate. The annual soil carbon sequestration rate was calculated using the following formula for different treatments in different land areas.

$$Soil\ carbon\ sequstraton\ rate\ \left(\frac{\frac{t}{ha}}{yr}\right) = SCS\ in\ year\ (Y) - SCS\ in\ year\ (Y-1) \qquad (3.24)$$

Table 3.3 Different land covers and SWC measures in the watershed

Land Cover	**Land Area Treatment**
Agriculture	Compartment Bunding
Barren	Deep Continuous Contour Trench
Coconut	Deep Continuous Contour Trench
Eucalyptus	Deep Continuous Contour Trench
Forest	Deep Continuous Contour Trench
Gliricidia	Deep Continuous Contour Trench
Hardwickia	Deep Continuous Contour Trench
Mango	Deep Continuous Contour Trench
Neem	Deep Continuous Contour Trench
Senegalia catechu	Deep Continuous Contour Trench
Tamarind	Deep Continuous Contour Trench

3.9 Estimation of Soil Loss from the Watershed

Soil erosion is the denudation of the upper layer of soil. It is a key contributor to land degradation. Soil loss is caused by significant soil erosion, which results in a loss of plant nutrients and organic matter, which can reduce land productivity (Gelagay and Minale, 2016). Estimating soil loss and identifying hotspot areas aid in preventing land degradation. Soil loss from the watershed was estimated to analyse the impact of SWC measures on land degradation. Soil loss from the watershed was estimated under two different scenarios: one before any conservation measures for year 2016 and another after conservation measures for year 2021. Numerous models of soil erosion have been utilised extensively throughout the world to estimate soil erosion. The most extensively used of these models is the Universal Soil Loss Equation (USLE) model (Balabathina *et al.,* 2020). USLE model coupled with RS and GIS technique was used to estimate the average annual soil loss from the watershed.

3.9.1 Soil Erosion Model-USLE

The Universal Soil Loss Equation (USLE) is a mathematical model developed by Wischmeier and Smith (1965) to predict soil erosion by rainfall and surface runoff on a field. The empirical result of the USLE is a long-term average annual rate of soil loss under different limatic conditions, soil types, topographic features, crop systems, and conservation practices. The USLE model is an empirical based equation, derived from a large mass of field data, especially erosion plots and rainfall simulator experiments, and computes sheet and rill erosion. The USLE equation is,

$$A= R\times K\times LS\times C\times P \qquad (3.25)$$

Where,

A = Average annual soil loss (t/ha/yr),

R = Rainfall erosivity factor (MJ-mm/ha-hr-yr),

K = Soil erodibility factor (t-ha-hr/ha-MJ-mm),

L = Slope length factor (m),

S = Slope steepness factor,

C = Crop cover-management factor, and

P = Conservation practice factor.

USLE is most widely accepted model owing to its simplicity and the accessibility of the data entries (Pham *et al.,* 2018, Alewell *et al.,* 2019). Several studies predicted soil loss by combining the USLE model with the RS and GIS technique (Parveen and Kumar, 2012). The RS and GIS can accurately quantify the heterogeneity of a watershed using a discretization technique (Dutta *et al.,* 2015). The USLE model was first developed for agricultural lands, but it has since been adapted to watersheds with varying land use patterns with satisfactory results at the national, regional, and watershed scales (Kruk *et al.,* 2020). Parameters used in USLE are rainfall erosivity, soil erodibility, topographic factor, crop management factor and conservation practices factor.

3.9.1.1 Rainfall Erosivity Factor (R)

Rainfall erosivity is the ability of rainfall to erode soil particles from an unprotected field. It depends on the physical properties of the raindrop, including droplet size, drop size distribution, kinetic energy, terminal velocity, etc. The concept of rainfall erosivity was introduced by Wischmeier (1959) to summarize the climatic influence on soil erosion in such a way that, when other variables are held constant, the rate of soil loss is directly proportional to the magnitude of rainfall erosivity. It is the energy of rainfall to detach the soil particles, as energy is needed to break down the soil aggregated into finer particles, so that they can be splashed out and subsequently carried away by runoff.

Rainfall erosivity factor was calculated using the regression equation already developed for Rahuri tehsil based on daily rainfall and EI_{30} data of Rahuri tehsil. (Barai *et al.*, 2014). The following equation implies the correlation between annual erosivity index and annual rainfall, with coefficient of determination of 0.90.

$$Y = 0.0022X^2 + 0.7526X + 152.35 \tag{3.26}$$

Where,

Y = Annual erosivity (MJ-mm/ha-hr-yr) and

X= Annual Rainfall (mm).

The average rainfall data of 30 years (1991 to 2021) was used to calculate the R factor of watershed. The R factor value for estimating soil loss before and after conservation measures was considered same so as to get the impact of conservation measures only.

3.9.1.2 Soil Erodibility Factor (K)

The soil erodibility factor (K-factor) is a quantitative description of the inherent vulnerability of a particular soil. It is a measure of the susceptibility of soil particles to detachment and transport by rainfall and runoff. For a particular soil, the soil erodibility factor is the rate of erosion per unit erosion index from a standard plot (Renard *et al.*, 1997). The physical properties of soil strongly influence the rate at which it erodes. Numerous soil parameters are involved in estimating soil erodibility, such as sand, silt and clay composition, organic matter content, soil structure and soil permeability.

Numerically the value of K varies from 0 to 1. Soil erodibility value close to zero indicates the soil is very difficult to erode, while a value close to one indicates the soil is prone to severe erosion. The K-factor values can be estimated from the nomograph when the distribution of grain size, organic matter content, structure and permeability of the soil data are known (Wischmeier *et al.*, 1971). Soils that have faster infiltration rates, higher levels of organic matter, and improved soil structure are more resistant to erosion. Sand, sandy loam, and loam textured soils have a lower erodibility than silt, very fine sand, and some clay textured soils. The K factor for the study area was calculated using the following equation (Tamene and Vlek 2007; Addis and Klik,, 2015; Wolka *et al.*, 2015).

$$\mathrm{K(factor)} = 2.77 \times 10^{-7}(12 - \mathrm{OM})\ \mathrm{M}^{1.14} + 4.28 \times 10^{-3}(\mathrm{s} - 2) + 3.29 \times 10^{-3}(\mathrm{p} - 3) \tag{3.27}$$

Where,

$$M = [(100 - C)(L + A_{rmf})] \tag{3.28}$$

C is % of clay (< 0.002 mm), L is % of silt (0.002–0.05 mm) and A_{rmf} is % of very fine sand (0.05–0.1 mm), OM is the organic matter content (%), p is a code denoting the class of permeability and s is a code for the structure size.

The different soil parameters such as sand, silt, clay, organic carbon was determined through soil sample analysis. The hydrometer method (Gee and Bauder, 1986) was used to analyse particle size distribution, whereas soil organic carbon was analysed using the wet combustion method proposed by Walkley and Black. (Nelson and Sommers, 1982). Soil erodibility factors was calculated for 50 locations in the watershed.

Smith and Browning (1947) have given the relationship between permeability classes and hydraulic conductivity which is given in table 3.4. Permeability classes of soils in study area were determined from the hydraulic conductivity. The permeability code for different permeability classes was obtained using table 3.5. The hydraulic conductivity was calculated using "Soil-Plant-Air-Water" (SPAW) model.

Table 3.4 Permeability classes based on hydraulic conductivity of soil

Permeability classes	Hydraulic conductivity(cm/h)
Extremely slow	< 0.0025
Very slow	0.0025-0.025
Slow	0.025-0.25
Moderate	0.25-2.5
Rapid	2.5-25.0
Very rapid	> 25

(Source: Smith and Browning, 1946)

Table 3.5 Permeability code for different types of soil

Code	Description	Rate (mm/h)
1	Rapid	>130
2	Moderate to rapid	60-130
3	Moderate	20-60
4	Slow to moderate	5-20
5	Slow	1-5
6	Very slow	<1

3.9.1.2.1 Soil Structure

Soil structure is defined by the way individual particles of sand, silt, and clay are assembled. Soil structure is an important physical property that influences water and nutrient flow, aeration to plants and microbes and resistance to soil erosion and compaction, through which it affects plant growth.

Soil structure data for the watershed was obtained by laboratory analysis of soil samples. The hydrometer method was used to identify particle size distribution and soil texture classes were determined using the SPAW model. The texture descriptions and structure codes used in the study were obtained from different particle sizes proposed by the United States Department of Agriculture (USDA) and National Bureau of Soil Survey & Land Use Planning (NBSS&LUP, 1988). These codes and descriptions are presented in table 3.6 and table 3.7, respectively. The particle size distribution of sand, silt and clay was used to identify the textural classes. Accordingly, structure codes were identified for each soil type using table 3.8.

Table 3.6 Textural class proposed by USDA

Soil Separate	Diameter range (mm)
Coarse sand	2.00 – 0.20
Fine sand	0.20 – 0.02
Silt	0.02 – 0.002
Clay	Below 0.002

Table 3.7 Structural classes of different types of soil

Soil class	Range
Very fine	Less than 1 mm thickness
Fine	1 – 2 mm thickness
Medium	2 – 5 mm thickness
Coarse	5 – 10 mm thickness
Very Coarse	More than 10 mm thickness

(Source: NBSS and LUP, 1988)

Table 3.8: Structure code for different types of soil

Code	Structure	Size (mm)
1	Very fine granular	<1
2	Fine granular	1 – 2
3	Moderate or Coarse granular	2 – 10
4	Blocky, platy or massive	>10

(Source: NBSS and LUP, 1988)

3.9.1.2.4 Soil Organic Matter

Soil organic matter (SOM) is a component of soil that consists of plant or animal tissue in various stages of decomposition. SOM serves as a nutrient reservoir for plants, increases nutrient exchange capacity, provides soil aggregates, retains soil moisture, reduces surface crusting and increases water infiltration into the soil. According to Yassoglou (1987), soils with less organic matter are more likely to erode. Soil organic carbon data of watershed was used for calculating SOM. About 58% of the mass of organic matter exists as carbon (Bianchi *et al.*, 2008).

Therefore, the conversion factor of 1.72 (derived from 100/58) was used to calculate SOM from SOC.

$$\text{Soil Organic matter} = \text{Soil organic carbon} * 1.724 \tag{3.29}$$

Soil erodibility factor (K) values were calculated for 50 locations using equation 3.3 and applied to each sampling location in ArcGIS software. The Soil Erodibility (K) map of the study area was created using the Inverse Distance Weighting (IDW) interpolation technique.

3.9.1.3 Topographic Factor (LS)

The slope length and steepness factor (LS-factor), combinedly known as the topographic factor and describes the combined effects of slope length and slope gradient (i.e., grade or relief) on soil erosion. It represents the ratio of soil loss per unit area on a site to the corresponding loss from a 22.1m long experimental plot with a 9% slope. Slope length is defined as the distance from the point of origin of overland flow to the point where the slope decreases sufficiently for deposition to occur or to the point where runoff enters a defined channel. The slope steepness is the segment or site slope, usually expressed as a percentage. Although the LS-factor has traditionally been expressed as two parameters in the USLE, it is universally computed as a combined term of topographic factor (Alkhasawneh *et al.,* 2013).

Topographic factor for study area was calculated using digital elevation model (DEM). The SRTM DEM with a spatial resolution of 30m was used to prepare a slope map of the study area. The DEM was pre-processed in an ArcGIS environment to remove discontinuation in the data set then different thematic layers such as flow direction, flow accumulation, slope steepness and slope gradients were generated. The following equation developed by Wischmeier and Smith (1978) was used to generate an LS factor map of the study area. A similar approach was also followed by other researchers (Shiferaw, 2011; Gerawork and Awdenegest, 2014; Gashaw, 2017).

$$\mathrm{LS} = (\mathrm{X}/22.1)^{m}\,(0.065 + 0.045\mathrm{S} + 0.0065S^{2}), \tag{3.30}$$

$$X = (FLow\ Accumulation \times Cell\ size\ value) \tag{3.31}$$

Where, LS = slope length–steepness factor/Topographic factor, S = slope gradient (%), X = length of slope (m) and m = exponent (slope-length exponent).

3.9.1.4 Crop Management Factor (C)

Crop management factor (C) is defined as the ratio of soil loss from a cropped land under specific condition to soil loss from a continuous fallow land with identical soil and slope under same rainfall conditions. It measures the impact of cropping and management strategies on soil erosion (Renard *et al.,* 1997). Similarly, distribution of rainfall within the year also affects the crop management factor ultimately which affects the soil loss. In USLE, the C factor has been considered most complex as well as critical factor (Mukharamova *et al.,* 2021). Besides this, one important reason for its importance is that it represents the conditions that can easily manage in order to reduce the soil loss (Almagro *et al.,* 2019).

Land use/land cover mapping of study area was performed to prepare crop management factor map of the study area. The Sentinel-2A satellite imagery was used to generate the land use/land-cover map of the watershed. Image classification was performed using supervised digital image classification technique in the ArcGIS 10.8 software. To create LU/LC maps before and after conservation measures, satellite images from December 15, 2016 and December 16, 2021 were used.

The image classifier was trained using a signature file made up of 125 training samples. The satellite image was classified using a maximum likelihood classification method. The validation of the land cover classification was performed using Google Earth. A total of 105 reference points were generated in Google Earth and these points compared to the obtained land cover classification. Finally, seven LU/LC classes were identified as agriculture, horticulture, barren, natural vegetation, current fallow, settlement and waterbody. The standard C-factor values of various LU/LC classes were assigned to the appropriate landcover class using the 'Reclassify tool' in the ArcGIS 10.8 environment to obtain the C-factor raster layer for watershed. The C factor values used for the different land covers are given in the table 3.9.

Table 3.9 Crop management (C) factor for different land cover classes

Sr. No.	Land use/land cover	C value
1	**Forest (Rasool *et al.,* 2014)**	0.04
2	**Barren land (Rasool *et al.,* 2014)**	0.84
3	**Settlement (Rasool *et al.,* 2014)**	0
4	**Horticultural crops (Pal and Samanta 2011)**	0.1
5	**Agriculture land (Pancholi *et al.,* 2015)**	0.45
6	**Waterbody (Pancholi *et al.,* 2015)**	0
7	**Current fallow (Pancholi *et al.,* 2015)**	0.6

3.9.1.5 Conservation Practice Factor (P)

The conservation practice factor (P) is defined as the ratio of soil loss expected for a given soil conservation practice to that expected for up and down plowing on hillside (Wischmeier and Smith, 1978). It is a reflection of the effects of soil and water conservation measures on soil erosion. The P-factor value ranges from 0 to 1, with 0 indicating complete protection from soil erosion and 1 indicating no protection against soil erosion.

The area under different conservation practices in the watershed was mapped by conducting a field survey. The GPS device was used to map the areas under different conservation measures. The P factor value of one was given for the entire watershed before conservation measures. However, after the implementation of recommended SWC measures on half of the watershed areas, corresponding P factor values were assigned to the conservation measures in the Arc GIS 10.8 environment. Finally, P factors raster layer of watershed was created by allocating adapted P factor values for conservation measures. The P factor values used for different conservation measures are given in table 3.10.

Table 3.10 Conservation practice (P) factor for different conservation measures

Sr. No.	Conservation Measure	Area (ha)	P factor
1	**Deep Continuous Contour trench (Singh *et al.*, 1990)**	495	0.15
2	**Compartment Bunding (Singh *et al.*, 1990)**	50	0.03

3.10 Estimation of Carbon Loss from the Watershed

Soil erosion and the subsequent transport of sediments by runoff represent a key pathway for soil carbon lateral transfer at the land surface, which has a profound effect on the carbon budget of the watershed (Zhang *et al.,* 2014). The C-loss due to soil loss depends on soil erosion rate, soil organic carbon concentration and carbon enrichment ratio values. The C-loss from the watershed before and after conservation measures was estimated using following equation developed by Mandal et al. (2020)

$$C - loss\left(\frac{\frac{t}{ha}}{yr}\right) = \frac{Soil\ loss\left(\frac{\frac{t}{ha}}{yr}\right)\times \text{SOC (\%)}\times \text{CER}}{100} \tag{3.32}$$

3.10.1 Soil Organic Carbon Content in the Watershed

The soil organic carbon (SOC) data prior to conservation measures was obtained from the previous studies of Department of Soil and Water Conservation Engineering, Mahatma Phule Krishi Vidyapeeth, Rahuri. The SOC data after conservation measures was obtained from soil sample analysis. The SOC layer for the watershed for before conservation measures and after conservation measures was generated in the Arc GIS environment by providing corresponding SOC values to the soil sample locations. The raster layer of SOC content for before and after conservation measures was prepared using interpolation techniques.

3.10.2 Carbon Enrichment Ratio (CER) for the Watershed

The carbon enrichment ratio (CER) is defined as the ratio of SOC content in the eroded sediment sample to that of the original soil (Kadlec et al., 2012). The preferential removal of SOC by water erosion is indicated by a high enrichment ratio of SOC in sediments compared to that of the surface soil from which the sediments originated. Therefore, the enrichment ratio for SOC in alluvial sediments is greater than 1 and may reach 12. Soil erosion leads to a preferential transport of SOC because it has a low bulk density and is mostly concentrated in the surface soil layer. In cases where sediments are derived from subsoil (i.e., gully erosion), the enrichment ratio can be less than 1 (Lal, 2020). Mandal *et al.,* (2020) estimated CER values for various erosion classes of Maharashtra state. The erosion classes and CER values for Maharashtra are given in table 3.11. In the Arc GIS environment, these values were assigned to the various erosion classes of the watershed and CER layers for the watershed before and after conservation measures were generated.

Table 3.11 Erosion classes and CER values for Maharashtra

Sr. No.	Erosion class	Erosion range (t/ha/yr)	CER value
1	**Very low**	< 5	3.62
2	**Low**	5 to 10	3.28
3	**Moderate**	10 to 20	2.3
4	**Severe**	20 to 40	2.3
5	**Extremely severe**	>40	2.04

3.10.3 Carbon Loss from the Watershed

The average annual carbon loss from the watershed was estimated using a raster calculator tool in the Arc GIS 10.8 environment. Soil loss rate, SOC concentration and CER layers generated in the Arc GIS 10.8 software were used for the estimation of C-loss from the watershed. The Eq. 6 was used in the ‘Raster Calculator’ to generate a C-loss layer of the watershed.

3.11 Development of Conservation Strategies for the Watershed.

Changes in the climate regime impact the hydrologic cycle and various processes of a watershed system. The potential impacts of climate change include changes in runoff, sediment loading, nutrient enrichment and evapotranspiration rates in watershed (Nasr *et al.*, 2019). Indeed, climate change is expected to intensify extreme weather events such as floods and droughts whose impacts especially depends on land use. This is expected to make watersheds more vulnerable to climate change impacts. As a result, climate-smart approaches to watershed management are essential for mitigating the growing impacts of climate change. Watershed is an ideal unit from the climate change management perspective as it allows to anticipate the impacts of climate change from upstream to downstream.

Watershed management is management of land, water and other natural resources on a sustainable basis. Watershed management carries out number of activities with an integrated approach addressing proper land use, protecting lands from all forms of degradation, building and maintaining soil fertility, conserving water for farm use, proper management of water for drainage, erosion control, crop production, flood protection, sediment reduction and increasing productivity from all land uses (Adhitama *et al.*, 2022). There are numerous watershed management strategies available that not only aid in the conservation of natural resources but also aid in the mitigation of the impacts of climate change in a sustainable manner. Sustainable strategies for managing watersheds are those that reduce greenhouse gas emissions and prevent climate change by increasing the amount of carbon stored in soils, conserving existing soil carbon and decreasing carbon dioxide, methane and nitrous oxide emissions into the atmosphere.

Various carbon sequestration strategies were suggested for the central MPKV campus watershed to increase the carbon sequestration potential of the watershed. The watershed management practices in which carbon is retained or absorbed by natural carbon pools are called carbon sequestration strategies. The land management strategies for the watershed were suggested based on the topographic and climatic conditions of the watershed.

3.11.1 Identification of Suitable Sites for Soil and Water Conservation Measures

Appropriate adoption of soil and water conservation measures in watershed is critical to ensuring food security and ecological balance. Erosion control and water conservation structures are essential components of watershed management and are an integral aspect of soil and water conservation programmes (Nabi *et al.,* 2020). The formulation and implementation of a proper water resource development strategy could permanently lower the severity of drought in the watershed. Specifically, in rainfed areas, modest increment in the water availability can substantially increase crop yield and lower the risk of crop failure.

Soil and landscape management are critical components of carbon cycle. Soil degradation processes can contribute to the oxidation and release of soil organic carbon, reducing its content in the soil carbon pool, and can also contribute to off-site transport due to erosion (Olson *et al.,* 2016). Conservation techniques and management decisions that limit runoff and prevent soil erosion can help to mitigate climate change by accelerating atmospheric carbon sequestration. SWC measures are ideal for reducing runoff and soil erosion in watersheds. Therefore, implementation of sound SWC measures can contribute significantly to climate change mitigation and adaptation through carbon sequestration.

Nearly 45% of the Central MPKV campus watershed area is treated with diverse soil and water conservation measures. The remaining 55% of the watershed requires site-specific conservation measures in order to further reduce runoff and soil erosion. Therefore, new conservation measures are proposed for the watershed in the remaining places where there are no conservation measures. The additional SWC measures for the watershed were suggested based on the climatic conditions, soil characteristics and topography of the area. The various thematic layers of the watershed were overlapped in Arc GIS software to identify the suitable sites for conservation measures. Rainfall, drainage network, slope, LU/LC, soil depth and soil texture were the major parameters considered for the identification of suitable sites for the conservation measures.

3.11.2 Soil and Water Conservation Measures for Arable Lands

As per All India Soil and Land Use Survey (AISLUSA, 1990) land capability classes I, II, III and IV are suitable for crop production. The primary goal of conservation techniques for arable land is to limit or avoid erosion while maintaining optimal moisture levels for long-term productivity. Conservation measures are mostly determined by topographic conditions and rainfall patterns. Conservation measures can be broadly grouped into two types: biological measures and mechanical measures.

3.11.2.1 Biological Measures

Biological measures are applicable in the landscape of ≤2% slope. These measures reduce the impact of raindrops through the covering of soil surface and increasing infiltration rate and water absorption capacity of the soil which results in reduced runoff and soil loss. The main principle of biological measures is to prevent high velocity of water and conserve water within the soil (Sinore *et al.*, 2018).

3.11.2.2 Mechanical Measures

Mechanical measures or engineering structures are designed to modify the land slope, to convey runoff water safely to the waterways, to reduce sedimentation and runoff velocity. These measures are either used alone or integrated with biological measures to improve the performance and sustainability of the control measures. In highly eroded and sloppy landscape biological measures should be supplemented by mechanical structures. A number of permanent and temporary mechanical measures are available such as terraces, contour bunding, gabions, diversion drains, geo-textiles, etc. The mechanical measures are preferred based on the severity of erosion, soil type, topography and climate (Blanco-Canqui and Lal, 2010).

3.11.2.2.1 Contour Bunding

Contour bunding is used to conserve soil moisture and reduce erosion in the areas having 2–6% slope and mean annual precipitation of <600 mm with permeable soils. Contour bunding is the construction of a series of small bunds across the slope of the land along a contour, such that the long slope is divided into a number of smaller slopes. The primary goal of contour bunding is to minimise the length of the slope to prevent soil erosion and to impound water and allow more runoff infiltration to increase soil moisture.

3.11.2.2.2 Graded Bunding

Graded bunds or graded terrace or channel terrace are laid along pre-determined longitudinal grade instead of along contour. It consists of constructing wide and relatively shallow channels across the slope very near the contour ridges and at critical intervals. These terraces act primarily as drainage channels for inducing and regulating the excess runoff water and draining the same with a mild and non-erosive velocity. They are used for safe disposal of excess runoff in high rainfall areas (> 800 mm) with land slope of 2 to 8% and regions where the soil is relatively impervious/ having low infiltration rates.

3.11.2.2.3 Bench Terracing

A terrace is an earthen embankment constructed across a slope to reduce soil erosion and manage runoff. A terrace works as a land slope intercept, dividing the sloping land surface into strips. Bench terracing comprising of step like fields constructed along contours usually by half cutting and half filling procedure is used in hilly areas having slope of 6% to 33%. Bench terrace converts the long un-interrupted slope into several small strips and make protected platform available for farming.

3.11.2.3 Soil and Water Conservation Measures for Non-Arable Lands

As per All India Soil and Land Use Survey (AISLUSA, 1990) land capability classes V, VI, VII and VIII are unsuitable for crop production. The use of these classes is mainly limited to pasture, forest, wildlife and recreation. These areas are generally confined to upper reaches of watershed and have an undulating topography which is susceptible to soil erosion. The severity of soil erosion in non-arable areas is generally significant due to the steep slopes and lack of vegetation. In addition, unregulated runoff from these areas causes extensive damage into the lower reaches of watershed.

Vegetative and mechanical measures can be used in combination to prevent the degradation of non-arable areas. Mechanical measures help to regulate uncontrolled runoff, whilst vegetative measures help to improve land productivity. If managed appropriately, non-arable lands have a high potential for generating fodder, fuel, minor forest produce, fruits and timber. Therefore, it is crucial to treat these lands using suitable site-specific soil and water conservation measures in order to maximise the productivity of non-arable land.

Soil and water conservation measures suitable for non-arable areas of the watershed include contour trenching, contour wattling, crib structures, retaining walls, ravine land reclamation, grass land improvement and management, and mined land rehabilitation.

3.11.2.3.1 Contour Trenching

Contour trenching implies excavating a trench along the contour. The excavated soil is heaped on downstream side of the trench in the form of a bund. It is adopted in semi-arid or arid regions with high rainfall intensities and relatively higher soil permeability. It is also practiced for development of orchards on sloping lands and denuded slopes where revegetation is planned. Contour trenches are also used both on hill slopes and barren waste lands for soil and moisture conservation as well as for revegetation purposes. Contour trenches promotes absorption and storage of water in the soil profile to sustain vegetative growth, moderates flash floods and improves groundwater recharge and controls erosion on slopes where plant cover has deteriorated and revegetation is required.

3.11.2.4 Drainage Line Treatments

Drainage channels/gullies convey runoff and sediment in a watershed from the upper reaches to the outlet. Steep bed gradient (slope) of a channel causes high runoff velocities with associated heavy sediment flow. Hence, channel gradient needs to be reduced in order to bring the runoff velocities within permissible limits. Drainage line protection structures include temporary or permanent barriers to the flow of water in a drainage channel. It reduces runoff velocity, prevents soil loss, and allows for in-situ water harvesting. Check dams, loose boulder structures, earthen gully plugs, Kolhapur type (K.T.) weir and drop structures are commonly used drainage line treatments in the watershed. The appropriate drainage line measures for the watershed were recommended based on the drainage line features.

4. RESULTS AND DISCUSSION

This chapter presents and discusses the research findings. It includes the findings from geomorphological characteristics, change detection analysis and terrestrial carbon storage potential of the central MPKV campus watershed. The chapter describes the impact of conservation measures on carbon sequestration with time in the watershed. It also elaborates about average annual soil loss and carbon loss from the watershed before and after implementation of conservation measures. The additional conservation strategies suggested for improved carbon sequestration in the watershed are also given in this chapter.

4.1 Morphometric Analysis

The central MPKV campus watershed was delineated using SRTM DEM and toposheet (47I/11) at 1:50000 scale. The various thematic layers such as elevation, drainage network, contour and slope of the watershed were generated using Arc GIS 10.8 software for morphometric analysis. Figs. 4.1, 4.2, 4.3 and 4.4 show the elevation, drainage network, contour and slope maps of the watershed, respectively. The total geographical area of the watershed is 1260 ha, with a perimeter of 19.42 km. The linear, aerial and relief aspects of the watershed drainage network are discussed in the following sections and given in tables 4.1, 4.2 and 4.3, respectively.

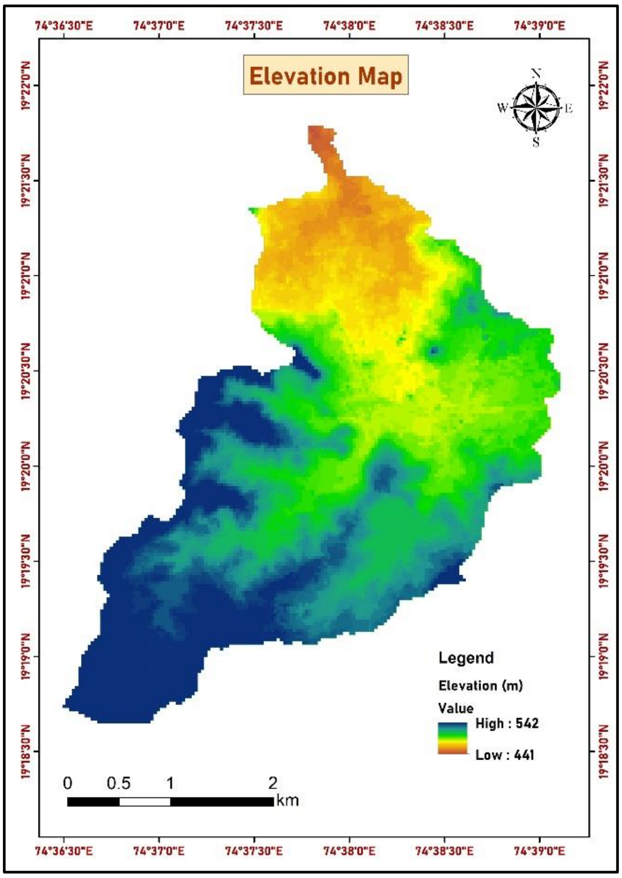

Figure 4.1 Elevation map of the watershed

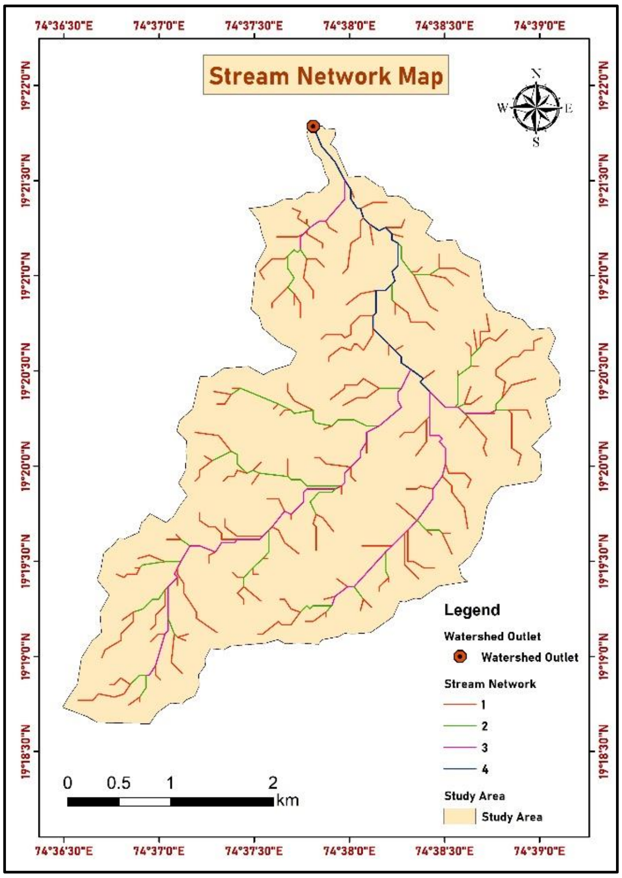

Figure 4.2 Stream network map of the watershed

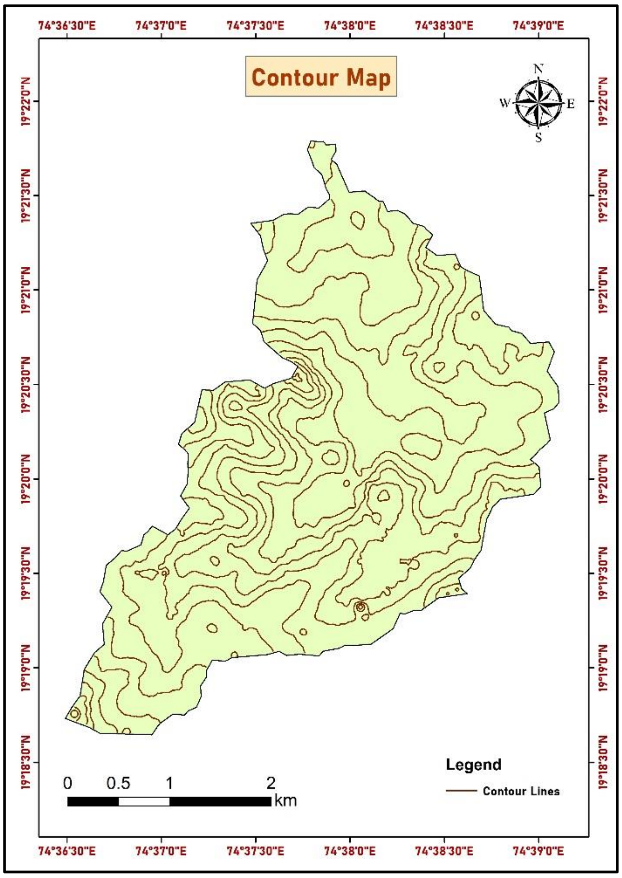

Figure 4.3 Contour map of the watershed

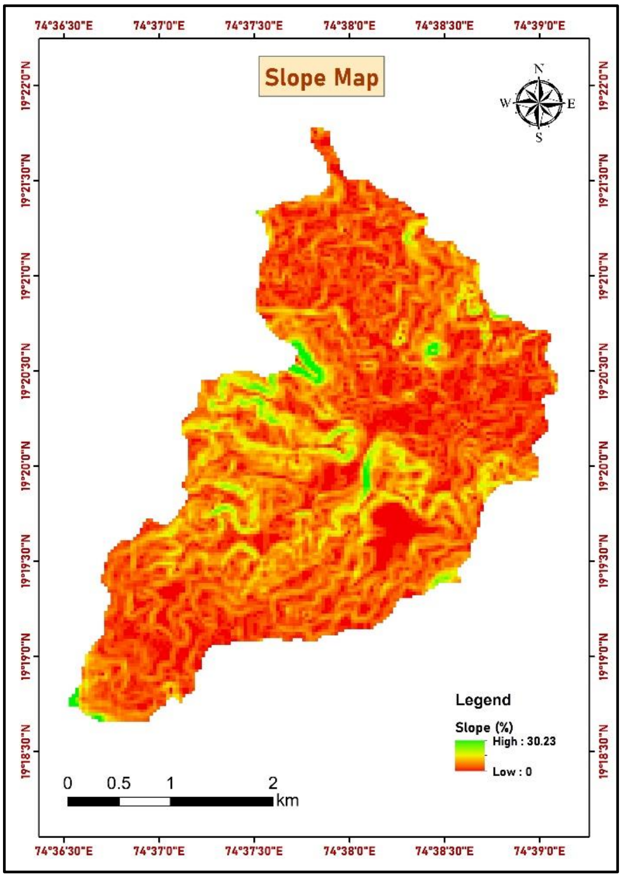

Figure 4.4 Slope map of the watershed

4.1.1 Linear Aspects of Drainage Network

4.1.1.1 Stream Order (u)

The streams are assigned an order based on the Strahler (1964) approach. The higher the stream order, the greater the discharge and velocity (Costa, 1987). The stream network in the watershed was outlined up to fourth order. The stream network of the watershed was characterized by the dendritic pattern. It forms in areas underlain by homogeneous material.

Table 4.1 Linear aspects of drainage network

Linear aspects					
Stream Order (u)	**1**	**2**	**3**	**4**	**Total**
Stream Number (Nu)	120	25	4	1	**150**
Stream Length (L_u) (km)	29.89	9.56	8.76	2.97	**51.22**
Mean Stream Length (L_{sm}) (km)	0.24	0.38	2.19	2.97	**-**
Bifurcation Ratio (R_b)	4.8	6.25	4		**5.01 (AVG)**
Stream Length Ratio (R_L)	3.12	1.08	2.95		**2.39 (AVG)**

4.1.1.2 Stream Number (N_u)

A total of 150 streams were found in the watershed. Among these, 120 were first orders, 25 were second orders, 4 were third orders, and 1 was a first order stream. The high number of first order streams in the watershed suggests a high degree of fragmentation and a high potential for infiltration and groundwater recharge (Chopra *et al.*, 2005). The number of streams decreased significantly as stream order increased. This is consistent with the Horton law of stream numbers, which states there is a geometric relationship between the number of streams and their order.

4.1.1.3 Bifurcation Ratio (R_b)

The bifurcation ratio is a helpful indicator in flood-prone areas as it gives insight into the runoff behaviour of the watershed. The bifurcation ratio of the watershed varied from 4 to 6.25 with a mean of 5.01. A high value of bifurcation ratio reflects a short time of concentration and a strong probability of flooding (Bogale, 2021).

4.1.1.4 Mean Stream Length (L_{sm})

The total stream length of all the streams of order first to fourth was 51.22 km. It was found that total stream length decreased with increasing stream order. The mean stream length was found highest in the fourth order stream (2.97 km) and the lowest in the first order stream (0.24 km). In contrast to stream length, the mean stream length increased with increasing stream order.

4.1.1.5 Stream Length Ratio (R_L)

The stream length ratio in the watershed varied from 1.08 to 3.12 with a mean of 2.39. The high degree of variation in the stream length ratio was due to slope and topographic variability in the watershed. It shows that the watershed is still in the geomorphic stages of development. This means that the region is prone to rapid and continual change in the future.

4.1.2 Areal Aspects of Drainage Network

4.1.2.1 Form Factor (R_f)

The form factor value of the watershed was 0.34. The lower form factor value implies that the watershed has an elongated shape. It suggests a longer duration of low peak flow from the watershed. It is easier to manage flood flow in an elongated watershed than in a circular watershed.

Table 4.2 Areal aspects of drainage network

Sr. No.	Areal aspects	
1	Form Factor (Ff)	0.34
2	Circularity Ratio (Rc)	0.42
3	Elongation Ratio (Re)	0.66
4	Drainage Density (Dd) km/km^2	4.05
5	Constant of channel maintenance (CCM) km^2/km	0.24
6	Length of overland flow (Lg) km	0.12
7	Stream Frequency (Fs) km^{-2}	11.87
8	Textural Ratio (Rt)	7.72
9	Drainage Intensity (Di) km^{-1}	2.92

4.1.2.2 Circulatory Ratio (R_c)

The circulatory ratio (R_c) of the watershed was 0.42. Rc values are ranging from 0.4 to 0.7 indicates that the watershed is elongated. This implies that the geologic composition of the watershed is largely uniform and porous in nature.

4.1.2.3 Elongation Ratio (R_e)

Elongation ratio (R_e) is also an important indicator of basin shape and provides information about the hydrological features of a drainage basin. A low value of the elongation ratio indicates a more elongated form, whereas a high number denotes a more circular one. The elongation ratio of the watershed was 0.66, indicating an elongated-shaped watershed. R_e values ranging from 0.6 to 0.8 are associated with steep topography and high elevation (Strahler 1964).

4.1.2.4 Drainage Density (D_d)

Drainage density (D_d) is a key parameter of the landform element and a quantitative measurement of surface runoff potential and basin dissection character. D_d is regarded as a crucial characteristic in influencing the time of concentration. D_d is influenced by the bedrock, topography, geomorphology, climate and vegetative cover of the basin. The D_d of the watershed is in moderate class (4-6 km/km^2) at 4.05 km/km^2. It suggests a rapid hydrological response to precipitation events in the watershed. Furthermore, moderate D_d indicates an impermeable subsurface layer, scarce vegetal cover and high relief.

4.1.2.5 Constant of Channel Maintenance (CCM)

Constant of channel maintenance (CCM) denotes the minimum area required for channel maintenance and development. The CCM value of the watershed was found to be 0.24 km^2/km. A low value of CCM suggests extensive surface runoff, steep slopes, low permeability and significant levels of structural disturbance in the watershed.

4.1.2.6 Length of Overland Flow (L_g)

Length of overland flow (L_g) is the distance over which runoff flows on the ground before being channelized into certain stream channels. The average travel time of runoff in the watershed before being concentrated in stream channels was 0.12 km. The low value of Lg in the watershed indicates that less precipitation is sufficient to contribute significant runoff to stream discharge. It makes the watershed highly susceptible to flash flooding.

4.1.2.7 Stream Frequency

The stream frequency of the watershed was 11.87 km^{-2} indicates that the watershed has a dense stream network. It describes the texture of the stream network and it is governed by basin lithology. A high frequency of streams in the watershed indicates an impermeable bedrock structure and substantial surface runoff.

4.1.2.8 Textural Ratio (R_t)

Textural ratio (R_t) is an important geomorphological concept that describes the basic lithology, infiltration characteristics and topographic relief of the basin. The watershed has fine drainage texture, with a value of 7.72. The higher the drainage texture value, the greater the chances of dissection and soil erosion.

4.1.2.9 Drainage Intensity (D_i)

The drainage intensity (D_i) in the watershed was 2.92 km^{-1}. A low drainage intensity value in the watershed implies that it is vulnerable to flash flooding, soil erosion and landslides.

4.1.3 Relief Aspects of Drainage Network

4.1.3.1 Relief (H)

The relief indicates the variance in altitude within the watershed. The watershed has a relief of 101 m, with a maximum and minimum elevation of 542 m and 441 m, respectively. Relief has a direct impact on runoff velocity, soil erosion rate, sediment transportation capacity and discharge rate of a watershed. The moderate relief of the watershed is indicative of moderate values of runoff velocity, soil erosion rate, sediment transit capacity and discharge rate.

4.1.3.2 Relief Ratio (H_n)

It quantifies the degree of erosion severity and assesses the relative steepness of a drainage watershed. The relief ratio of the watershed was 0.02. It indicated an elongated shape with low to moderate relief and a high degree of denudation processes.

Table 4.3 Relief aspects of drainage network

Sr. No.	Relief aspects	
1	Basin Relief (H) (m)	101
2	Relief Ratio (H_n)	0.02
3	Ruggedness Number (R_n)	0.41

4.1.3.3 Relative Relief (R_r)

Relative relief is directly proportional to slope and influences the hydrological processes within the watershed. It is an indicator of watershed erodibility that quantifies the watershed's steepness. The relative relief of the watershed was 0.52. This can influence the hydrological processes within the watershed, including surface runoff, infiltration and groundwater recharge. High relative relief values can lead to increased soil erosion and sedimentation in streams.

4.1.3.4 Ruggedness Number (R_n)

The undulation of surface topography has been measured by the roughness number. The watershed's ruggedness number was 0.42, indicating moderately undulating topography. It also implies that the slope is likely to be relatively steep and of moderate length, with a moderate peak discharge.

4.2 Land Use/Land Cover (LU/LC) Mapping and Change Detection Analysis

The watershed was classified into seven major land use/land cover (LU/LC) classes namely agriculture, barren, current fallow, forest, horticulture, settlement and waterbody. The result of land cover classification achieved through satellite imagery are presented in the Fig. 4.5 and table 4.4. The overall accuracy of image classification and Kappa coefficient for watershed were 88% and 0.78, respectively, for before conservation measures image and 89% and 0.80, respectively for after conservation measures image.

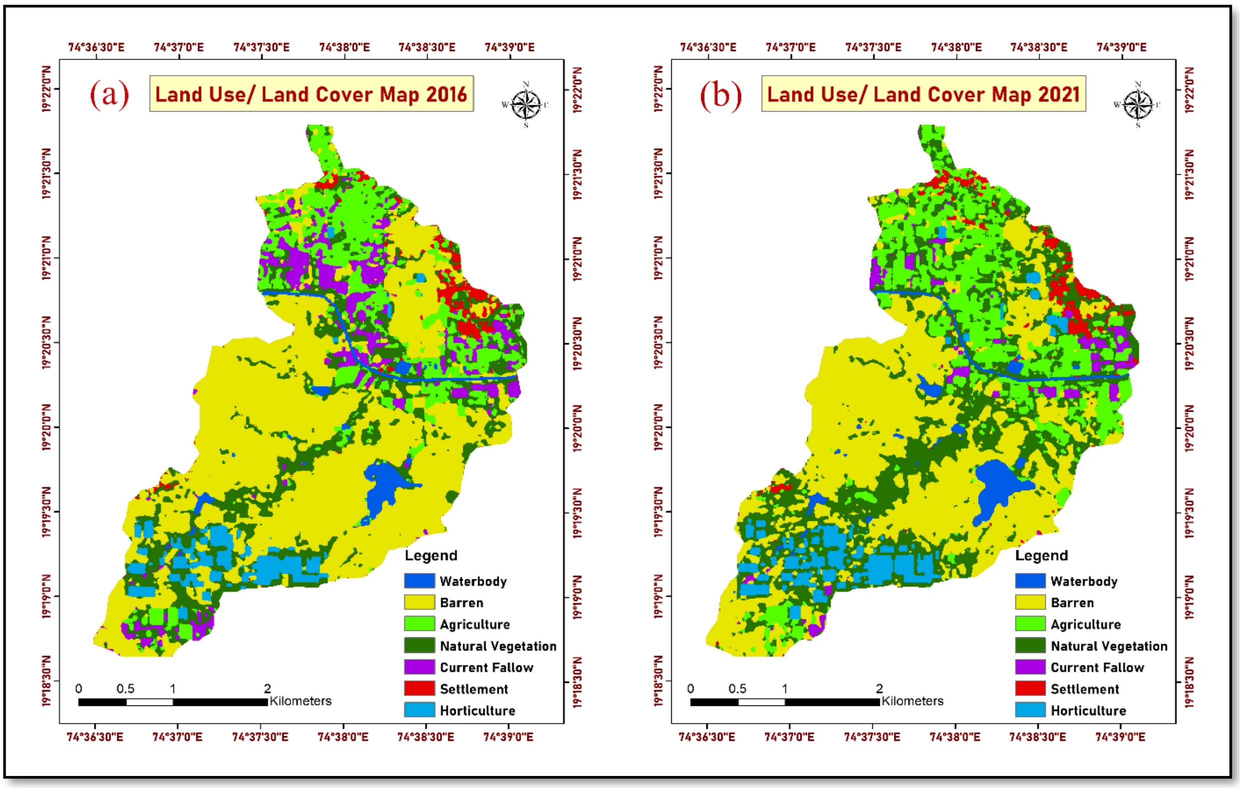

Fig 4.5 Land use/land cover map of the watershed (a) Before the adoption of conservation measures (b) After the adoption of conservation measures

Table 4.4 Area coverage by different land use/land cover classes before and after the adoption of conservation measures.

Land Cover Class	(Before Conservation Measures) Area (ha) 2016	(After Conservation Measures) Area (ha) 2021	Change in Area (ha)	Change in Area (%)
Waterbody	32.91	41.48	8.57	26.04
Barren Land	605.65	478.17	-127.48	-21.05
Agriculture	162.17	230.1	67.93	41.89
Natural forest	231.95	304.97	73.02	31.48
Current Fallow	93.74	40.49	-53.25	-56.81
Settlement	58.39	72.82	14.43	24.71
Horticulture	75.19	91.97	16.78	22.32

It was found that barren land was the most widespread land cover in the watershed, while the area covered by water bodies was the smallest. The waterbodies in the watershed were dispersed throughout the area. The forest in the watershed was an open type, with tree canopy densities between 10% and 40%. The majority of the agricultural land found inside the watershed was concentrated around the watershed's outlet, where the terrain is relatively flat compared to the remainder of the watershed. The majority of the horticultural area identified inside the watershed was in the upper reaches, where the terrain is sloping. Mango was the most widely found horticultural crop within the watershed, accounting for roughly 90% of the horticultural area.

It was observed that soil and water conservation (SWC) measures implemented in the watershed significantly affected the land utilization within the watershed. Agriculture, natural forest, horticulture, settlements and waterbody land cover classes expanded in area. In contrast, the extent of barren and current fallow land decreased. The highest positive increase in area was observed in agricultural land cover, which increased by 41.89%, while the lowest positive increase was observed in horticultural land cover, which increased by 22.32%. The increased demand for food and the need for employment generation led to an increase in agricultural area within the watershed. The highest negative increment in the watershed was observed in the current fallow land cover, which decreased by 56.81%. The fallow land in the watershed before conservation measures was 93.74 ha, which is due to the scarcity of water for irrigation purposes. But after the implementation of SWC measures in the watershed, water availability increased rapidly, leading to the conversion of barren land and current fallow land for agricultural food production. Barren land in the watershed decreased rapidly by 21.05%, which was converted for use as agriculture, forest, settlement and waterbody. The increased population and living standards increased the demand for residential buildings and transportation networks which significantly increased settlement area in the watershed by 24.71%. The SWC measures implemented in the watershed harvested and conserved rainwater which helped to replenish groundwater and increased surface water storage area. The surface water storage area in the watershed increased by 26.04%. The implementation of water conservation measures in the watershed has led to an increase in its water storage capacity by 123.4 thousand cubic meters (TCM). During the monsoon season, the storage structures are filled 5-6 times, resulting in an annual water harvesting of approximately 750 TCM. This additional water harvested in the watershed is utilized for agriculture, domestic use and livestock purposes. The increased water availability in the watershed has increased the overall vegetation area from 35% in 2016 to 50% in 2022. It was found that SWC measures not only helped in the conservation of natural resources but also increased the socioeconomical status of the people living in the watershed.

4.3 Estimation of Carbon Stock under Different Land Use Patterns of the Watershed

The total carbon stock in the watershed was estimated under different LU/LC classes. The LU/LC map of the watershed was used to identify the different land use covers in the watershed. The terrestrial carbon stock from the watershed was estimated under two major carbon sinks i.e., vegetation and soil and in eleven different land covers. The biomass carbon stock was estimated from two major categories of vegetation i.e., plantations and natural forest vegetation. Similarly soil carbon under these different tree species was also measured.

4.3.1 Total Biomass Stock of Plantations

The eight major plantations in the watershed were identified and their biomass stock was estimated. The list of major plantation species found within the watershed is given in the table 4.5. The basic tree parameters useful for biomass estimation such as diameter, height and wood density of individual trees were measured. The average dimeter at breast height, tree height and wood density of eight different tree species is given in the table 4.6.

Table 4.5 List of plantations within the watershed.

Sr. No.	English Name	Local Name	Botanical Name	Family
1	Coconut	Coconut	Cocos nucifera	Arecaceae
2	Eucalyptus	Nilgiri	Eucalyptus globulus	Myrtaceae
3	Gliricidia	Gliricidia	Gliricidia sepium	Fabaceae
4	Hardwickia	Anjan	Hardwickia binate	Caesalpiniaceae
5	Mango	Mango	Mangifera indica	Anacardiaceae
6	Neem	Neem	Azadirachta indica	Meliaceae
7	Senegalia catechu	Khair	Acacia catechu	Fabaceae
8	Tamarind	Chinch	Tamarindus indica	Fabaceae

Table 4.6 Diameter at breast height, wood density and tree height of different plantations.

Sr. No.	Tree Species	Avg. Diameter (cm)	Avg. Height (m)	Wood Density (g/cm^3)
1	Coconut	34.16	18.67	0.61
2	Eucalyptus	23.26	10.12	0.7
3	Gliricidia	22.38	4.72	0.68
4	Hardwickia	26.14	12.62	0.73
5	Mango	35.26	6.18	0.59
6	Neem	21.30	5.08	0.72
7	Senegalia catechu	27.21	4.91	0.88
8	Tamarind	23.64	4.60	0.99

4.3.1.1 Tree Diameter of Plantations

It was found that among eight tree plantations average diameter at breast height (DBH) was varied from 21.30 cm to 35.26 cm. Average DBH was found lowest in neem trees and highest in mango trees. Fig. 4.6 presents a comparison of the diameter at breast height of various tree species. A quadratic model of second order was fit between relation of tree diameter and age of tree. It was observed that foliage density increases with tree size. The diameter of a tree is an important indicator of its crown size, stocking level and overall health.

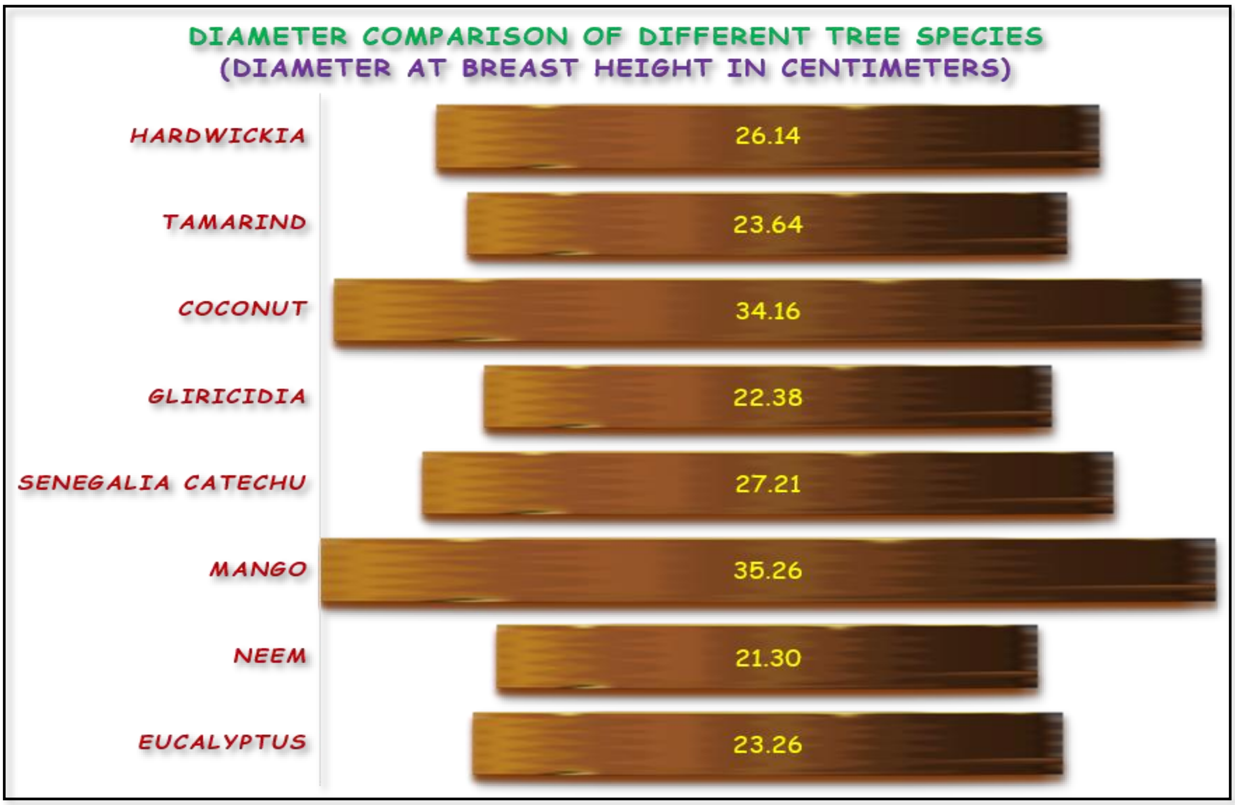

Figure 4.6 Diameter comparison of different tree species

4.3.1.2 Tree Height of Plantations

The average tree height among eight tree plantations was varied from 4.72 m to 18.67 m. The average height of trees was highest for coconut trees and lowest for gliricidia trees. Fig. 4.7 presents a comparison of tree heights of various tree species. The trunk of a tree becomes wider as it grows taller. Tree height is highly connected with other tree stand parameters such as volume, size, basal area and it serves as an indicator of the environmental conditions in the surrounding area. A linear relationship was found between tree diameter at breast height (DBH) and tree height for all eight tree species. The relation between tree height and diameter at breast height for different plantations are given in table 4.7. The scatter plot of the individual height and DBH values for individual trees species are presented in Annexure-C. A commonly used trendline functions were applied to fit the regression model. The linear function has given better coefficient of determination (R^2) than other functions. For eight tree species R^2 was found in the range of 0.79 to 0.98. The DBH-height relation was found excellent for neem (R^2 =0.98), gliricidia (R^2 =0.95), eucalyptus (R^2 =0.94), hardwickia (R^2 =0.94) and Senegal catechu tree (R^2 =0.91). These models are useful for predicting tree height when instruments for measuring tree height are unavailable.

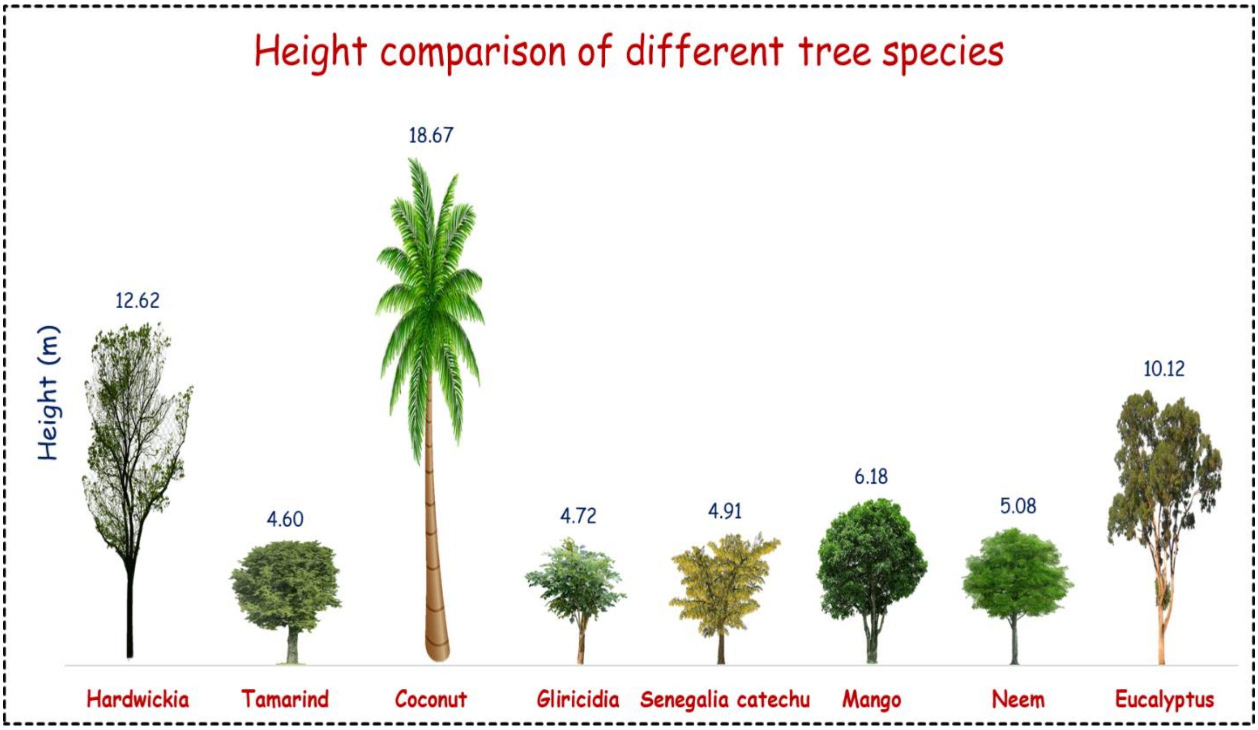

Figure 4.7 Hight comparison of different tree species

Table 4.7 Relation between tree height and diameter at breast height

Sr. No.	Tree Species	Relation Between Tree height and Diameter	Coefficient of Determination (R^2)
1	Coconut Tree	$y = 0.1186x + 14.618$ ($28 \leq x \geq 42$)	$R^2 = 0.8563$
2	Eucalyptus Tree	$y = 0.1256x + 7.2049$ ($11 \leq x \geq 33$)	$R^2 = 0.9452$
3	Gliricidia Tree	$y = 0.061x + 3.3604$ ($12 \leq x \geq 31$)	$R^2 = 0.9521$
4	Hardwickia Tree	$y = 0.2462x + 6.1859$ ($17 \leq x \geq 36$)	$R^2 = 0.9499$
5	Mango Tree	$y = 0.0708x + 3.6868$ ($19 \leq x \geq 46$)	$R^2 = 0.8446$
6	Neem Tree	$y = 11.843x - 119.01$ ($10 \leq x \geq 29$)	$R^2 = 0.9868$
7	Senegalia catechu Tree	$y = 0.0598x + 3.287$ ($18 \leq x \geq 36$)	$R^2 = 0.9145$
8	Tamarind Tree	$y = 0.0463x + 3.5089$ ($12 \leq x \geq 34$)	$R^2 = 0.7992$
	Where, y= Tree height (m), x= Tree diameter at breast height (cm)		

4.3.1.3 Wood Density of Plantations

Wood density, which refers to the amount of mass per unit volume of wood, is thought to be a key characteristic influencing tree species' growth strategies. It also tends to correlate with tree carbon stocks. The wood density among eight tree species varied from 0.61 g/cm^3 to 0.99 g/cm^3. It was found lowest in coconut tree species and highest in tamarind tree species. Low wood density species are associated with rapid growth, and high wood density species are associated with slow growth (Nam *et al.*, 2018).

4.3.1.4 Above Ground and Below Ground Biomass in Plantations

The average above ground biomass (AGB) per tree among eight tree species varied from 97.64 to 381.18 kg/tree. It was found lowest in gliricidia tree and highest in coconut tree. Average AGB per unit area among eight tree species varied from 17.58 to 62.89 tonnes/ha. It was found lowest in gliricidia trees and highest in coconut trees. The eight major plantations and corresponding biomass stocks are given in table 4.8. The spacing between trees and the density of the plantation are major factors in biomass storage. More biomass was found per unit area in densely populated trees than in sparsely populated ones. Environmental factors such as edaphic, topographic and hydrological attributes can cause changes in stand density and AGB at the regional and landscape scales (Ketterings *et al.*, 2001). It was revealed that wood density plays a crucial role in converting tree volume data to biomass, which is species-specific and may also be greatly influenced by location, climatic conditions and management techniques.

Table 4.8 Average above ground biomass and below ground biomass in plantations

Sr. No.	Tree Species	AGB (kg/tree)	BGB (kg/tree)	AGB (tonnes/ha)	BGB (tonnes/ha)
1	Coconut	381.18	133.93	62.89	22.1
2	Eucalyptus	216.93	76.22	39.05	13.72
3	Gliricidia	97.64	34.30	17.58	6.18
4	Hardwickia	330.14	116	56.12	19.72
5	Mango	244.93	86.06	48.99	17.21
6	Neem	98.66	34.66	17.76	6.24
7	Senegalia catechu	174.69	61.38	34.94	12.27
8	Tamarind	152.17	53.47	25.87	9.09

Similarly, average below ground biomass (BGB) per tree among eight tree species varied from 34.30 to 133.93 kg/tree. It was found lowest in gliricidia tree and highest in coconut tree. Average BGB per unit area among eight tree species varied from 6.18 to 22.10 tonnes/ha. It was found to be lowest in the gliricidia tree and highest in the coconut tree. The BGB gives valuable information on ecosystem carbon and nutrient storage and cycling, but it is more difficult to assess than the AGB. Although BGB has been evaluated as a fixed fraction of AGB, this relationship may change significantly along environmental gradients and in response to climate change and other global-change drivers (Hendricks *et al.*, 2006).

4.3.1.5 Total Biomass in Plantations

The total biomass of a tree is the sum of its AGB and BGB. The total biomass of eight tree species of the watershed was evaluated. The biomass of individual trees in the sample varied between 84.25 kg/tree and 648.35 kg/tree. Among the eight tree species, gliricidia had the least average biomass per tree (131.94 kg/tree), while coconut trees had the highest average biomass per tree (515.11 kg/tree). Biomass in tree stands was found to increase with age, height and volume, but decrease with density across a given chronosequence. The amount of biomass stored per unit area in plantation ranged from 23.75 to 84.99 t/ha. It was found highest in the coconut plantation and lowest in the gliricidia plantation. Biomass per unit area is influenced by the species type, plant growth characteristics and plantation density. The dominant tree species in the watershed was the mango plantation, which accounted for nearly 85% of the total area under plantation. Therefore, the total biomass among plantation in the watershed was found highest in mango trees (5673.34 tonnes) followed by hardwickia, tamarind, coconut, eucalyptus, senegalia catechu, neem, gliricidia trees. The total biomass of plantation in the watershed was 6422.86 tonnes, with mango plantation biomass accounting for 88% of the total plantation biomass. Similar biomass ranges were found in India for plantations of mango (70 to 104 t/ha) (Chavan and Rasal, 2011), hardwickia (63.61 to 139.55 t/ha) (Tanwar *et al.*, 2019), eucalyptus (40.21 to 81.23 t/ha) (Kholiya *et al.*, 2020), and neem (32.42 to 48.12 t/ha) (Noor Mohamed *et al.*, 2018).

A positive relation was found between diameter at breast height (DBH) and tree biomass for all plantations. A linear regression models were developed for estimation of tree biomass from DBH for individual tree species. The relation between tree biomass and tree diameter at breast height for different plantations are given in table 4.9. The coefficient of determination (R^2) values for all regression equations were above 0.90. Former was found highest for coconut tree regression equation (0.98) and lowest for neem tree regression equation (0.92). It revealed that DBH is a reliable tree parameter that can be utilized significantly for biomass estimation. These regression models can be applicable in watersheds with similar climatic and topographical conditions. It can also be utilized in areas where tree height measurement and wood density values are not readily available.

Table 4.9 Relation between tree biomass and diameter at breast height

Sr. No.	**Tree Species**	**Relation Between Tree Biomass and Diameter**	**R^2**
1	Coconut Tree	$y = 37.744x - 711.82$ ($28 \leq x \geq 42$)	$R^2 = 0.9829$
2	Eucalyptus Tree	$y = 23.751x - 259.52$ ($11 \leq x \geq 33$)	$R^2 = 0.976$
3	Gliricidia Tree	$y = 11.626x - 128.35$ ($12 \leq x \geq 31$)	$R^2 = 0.9775$
4	Hardwickia Tree	$y = 37.861x - 543.58$ ($17 \leq x \geq 36$)	$R^2 = 0.9823$
5	Mango Tree	$y = 18.156x - 309.28$ ($19 \leq x \geq 46$)	$R^2 = 0.9763$
6	Neem Tree	$y = 0.0781x + 3.4533$ ($10 \leq x \geq 29$)	$R^2 = 0.9234$
7	Senegalia catechu Tree	$y = 17.698x - 245.65$ ($18 \leq x \geq 36$)	$R^2 = 0.9802$
8	Tamarind Tree	$y = 16.071x - 174.31$ ($12 \leq x \geq 34$)	$R^2 = 0.9737$
	Where, y= Tree biomass (kg), x= Tree diameter at breast height(cm)		

4.3.1.6 Total Biomass Carbon Stock in Plantations

The biomass and carbon stock of different plantations are presented in table 4.10. The eight plantations in the watershed stored 3211.35 tonnes of carbon. The majority was stored by mango trees (88%), followed by hardwickia (2.97%), tamarind (2.47%), coconut (1.87%), eucalyptus (1.82%), senegalia catechu (1.62%), neem (0.76%), and gliricidia trees (0.12%). The carbon stock per unit area was highest in coconut (42.5 t/ha) and lowest in gliricidia trees (11.87t/ha). The biomass and carbon stock of plantations were primarily influenced by factors such as tree species, breast height diameter and tree height. Plantations were found to play an important role in terrestrial carbon storage. It is imperative that plantations in the watersheds be managed effectively to create a new carbon sinks and aid in the fight against climate change. Similar results of carbon stock were also found in other studies around the world for mango (33.85 t C/ha) (Dao *et al.,* 2021), hardwickia (31.6 ± 12.6 t C/ha) (Gupta *et al.,* 2019), Tamarind (20.21 ± 5.1 t C/ha) (Ragula and Chandra, 2020), coconut (51.14 t C/ha) (Bhagya *et al.,* 2017), eucalyptus (29.75 t C/ha) (Zhang *et al.,* 2020), neem (14.04 t C/ha) (Moussa *et al.,* 2018), gliricidia (13.79 t C/ha) (Prima *et al.,* 2018).

Table 4.10 The biomass and carbon stock of different plantation species

Tree Species	Total Biomass (kg/ tree)	Carbon stock (kg/tree)	Total Biomass (tonnes/ha)	Carbon Stock (tonnes/ha)	Area (ha)	Total carbon stock (tonnes)
Coconut	515.11	257.56	84.99	42.5	1.42	60.35
Eucalyptus	293.15	146.57	52.77	26.38	2.22	58.57
Gliricidia	131.94	65.97	23.75	11.87	0.35	4.16
Hardwickia	446.14	223.07	75.84	37.92	2.52	95.56
Mango	330.99	165.49	66.2	33.1	85.7	2836.58
Neem	133.32	66.66	24	12	2.05	24.6
Senegalia catechu	236.07	118.04	47.21	23.61	2.21	52.17
Tamarind	205.64	102.82	34.96	17.48	4.54	79.36

4.3.1.7 Carbon Sequestration by Plantations

Carbon sequestration by plantations refers to the quantity of carbon dioxide removed from the atmosphere and stored in the tree biomass via photosynthesis. The total amount of carbon sequestered by plantation in the watershed was 11776.02 tonnes of CO_2. Annually plantations in the watershed sequesters about 437.35 tonnes of CO_2. Carbon sequestration rates of different tree species are given in table 4.11. The mango plantation alone sequesters about 385.24 tonnes of CO_2/yr. Among the different plantations in the watershed, hardwickia exhibited the highest carbon sequestration rate of 34.08 kg/tree/yr, followed by eucalyptus (29.86

kg/tree/yr), mango (22.48 kg/tree/yr), gliricidia (20.16 kg/tree/yr), coconut (18.89 kg/tree/yr), neem (15.28 kg/tree/yr), senegalia catechu (14.43 kg/tree/yr) and tamarind (10.77 kg/tree/yr). Carbon sequestration rates per unit area in the watershed were found highest in hardwickia (1.58 t C/ha/yr) and lowest in Tamarind trees (0.50 t C/ha/yr). Hardwickia trees, known for their early maturity, were found to have the highest carbon sequestration rate. On the other hand, Tamarind takes its time to mature but lives for a very long time.

Table 4.11 Carbon sequestration rates of different tree species

Tree Species	Age of plantation	C storage (kg/tree/yr)	CO_2 seq. (kg/tree/yr)	C storage (t/ha/yr)	Total storage (t/yr)	Total CO_2 seq. (t/yr)
Coconut	50	5.15	18.89	0.85	1.21	4.43
Eucalyptus	18	8.14	29.86	1.47	3.25	11.93
Gliricidia	12	5.50	20.16	0.72	0.25	0.92
Hardwickia	24	9.29	34.08	1.58	3.98	14.60
Mango	27	6.13	22.48	1.23	105.06	385.24
Neem	16	4.17	15.28	0.75	1.54	5.64
Senegalia C.	30	3.93	14.43	0.79	1.74	6.38
Tamarind	35	2.94	10.77	0.50	2.27	8.31
Total					**119.29**	**437.45**

Carbon sequestration rates of plantation were discovered to vary locally based on tree dimensions, tree health and growth characteristics associated with species and local environmental conditions. Trees that grow more slowly store more carbon over the course of their entire lives, while trees that grow quickly store the most carbon during their first few years of growth but for a comparatively shorter period of time (Stephenson *et al.*, 2014). Planting native tree species has been discovered to be an important carbon reservoir in the watershed. Preventing and restoring degradation of local plantations is critical for improved carbon sequestration. This finding highlights the significance of choosing appropriate tree species for afforestation and reforestation programs to achieve maximum carbon sequestration and mitigate the adverse effects of climate change.

4.3.2 Total Biomass in Natural Forests

Similar to plantation biomass, the biomass of natural forest vegetation, comprising trees of varying ages, sizes and species was also estimated. The total area covered by natural forest vegetation in the watershed is 291.08 ha, which is approximately 23% of the total watershed area. The natural forest of the watershed is a type of open forest with a tree canopy density between 10 and 40%. The natural forest in watershed is home to numerous tree species, including Eucalyptus, Azadirachta indica, Vachellia nilotica, Hardwickia binate, Senegalia catechu, etc. The average diameter at breast height (DBH) of tree species found in natural forest area varies from 10.12 cm to 38.47 cm, with a mean of 21.86 cm. Similarly, average tree height varies from 2.7 m to 13.21 m, with a mean of 7.60 m. The species-specific wood density varied from 0.57 g/cm^3 to 0.99 g/cm^3.

The above ground biomass (AGB) in natural forest in sample plot varied from 47.21 to 105.35 t/ha, with a mean of 71.86 t/ha. Similarly, mean below ground biomass (BGB) in the natural forest was 25.24 t/ha. The total biomass in sample plots of the natural forest varied from 59.48 to 132.74 t/ha. The average biomass content in the natural forest was 97.11 t/ha and 194.22 kg/tree. It was observed that average biomass content in the natural forest was higher than the plantation biomass. The biomass content per sample plot varied depending upon type of tree species and tree density. The tree density per sampling plot of size 10×10 m varied from 5 to 12 trees. Similar results of biomass content were observed in other studies in open forests 151.4 t/ha (Chhabra, 2002), 64.13 t/ha (Padmakumar *et al.,* 2018), 104.86 t/ha (Din Dar *et al.,* 2019).

4.3.2.1 Total Biomass Carbon Stock in Trees of Natural Forest

The total tree biomass carbon stock in natural forest of the watershed was 14133.39 tonnes, with an average biomass carbon stock per unit area of 48.56 t/ha. It was varied from 31.24 to 62.21 t/ha in the sampling plots. The average carbon stock per tree in the natural forest was found to be 97.11 kg/tree. The biomass carbon stock in the natural forest was 3.5 times (10922.04 tonnes) higher than the carbon stock in plantations. This signifies that natural forest is one of the most important natural carbon sinks in the terrestrial ecosystem and plays a critical role in carbon sequestration. Therefore, the conservation of natural forest and the restoration of degraded forests should receive the highest priority in watershed planning and management. The results of the biomass carbon stock in the watershed's natural forest are consistent with the estimated carbon pool size of trees and forests in India, which ranges from 41 to 48 t/ha (Tanwar *et al.,* 2019).

4.3.3 Total Biomass Carbon Stock in Vegetation of the Watershed

The total biomass carbon stock in the vegetation of the watershed is the sum of the carbon stocks in plantations, natural forest, shrubs, and grasses. It was found that the total biomass in the vegetation of the watershed was 35572.63 tonnes and the carbon stock was 17786.21 tonnes. The biomass carbon stock in the watershed was distributed as follows: natural forest (80%), plantations (18%), and herbaceous plants and bushes (2%). These findings suggest that the natural forest cover in the watershed plays a significant role in carbon sequestration and storage. The results also highlight the potential of plantation as a carbon sink and the importance of considering herbaceous plants and bushes in carbon stock assessments. The different vegetation covers and corresponding carbon stocks are given in table 4.12.

Table 4.12 Total biomass carbon stock in different vegetative species

Vegetation Cover	Area (ha)	Carbon Stock (tonnes/ha)	Total Carbon Stock (tonnes)
Coconut	1.42	42.5	60.35
Eucalyptus	2.22	26.38	58.57
Forest	291.08	48.56	14133.38
Gliricidia	0.35	11.87	4.16
Hardwickia	2.52	37.92	95.56
Mango	85.7	33.1	2836.57
Neem	2.05	12	24.6
Senegalia catechu	2.21	23.61	52.17
Tamarind	4.54	17.48	79.36
Grass	523.3	0.49	256.417
Shrub	276.2	0.67	185.08
Total			**17786.21**

4.3.4 Soil Carbon Stock in Different Land Use Patterns

Similar to biomass carbon stock, the soil carbon stock of the watershed was measured in eleven distinct land cover classes. The soil carbon stock in the watershed was estimated at two different depths, 0-15 cm and 15-30 cm. The total soil carbon stock in the 0–15 cm and 15–30 cm soil depths in the watershed was 11816.04 and 9589.49 tonnes, respectively. It was discovered that as the depth of the soil sampling increased, the amount of carbon stock in the soil decreased. This emphasizes the importance of soil conservation practices that promote the buildup and retention of organic matter in the topsoil, as it is crucial for maintaining soil fertility, water-holding capacity, and carbon sequestration potential. The total amount of soil carbon stock in the top 0-30 cm of depth was 21405.53 tonnes. The land cover types and their corresponding soil carbon stocks are given in table 4.13. Soil carbon stock was highest in natural forest land cover (23.78 t/ha) and lowest in baren land cover (14.09 t/ha) for the top 0-30 cm depth. The higher soil carbon stock in the natural forest land cover compared to other land cover types suggests that these areas have been able to maintain their carbon sequestration potential better than other land cover types. The lower soil carbon stock in barren land cover (14.09 t/ha) may be due to the lack of vegetation cover and/or poor soil quality, which hinders carbon sequestration. The natural forest land cover in the watershed stores at around 6921.88 tonnes of carbon, accounting for 32% of total SOC storage. The higher percentage of soil organic carbon in natural forest may be attributable to the tree canopy and higher litter input, resulting in maximum carbon stock storage (Tanwar *et al.,* 2019).

Table 4.13 Total carbon stock in soil under different land covers

Land Cover	SOC stock (t/ha)	SOC stock (t/ha)	Total SOC stock (t/ha)	Soil Carbon Storage (tonnes)	Soil Carbon Storage (tonnes)	Total Soil Carbon Storage (tonnes)
	0-15 cm	**15-30 cm**	**0-30 cm**	**0-15 cm**	**15-30 cm**	**0-30 cm**
Agriculture	11.43	9.25	20.68	3092.84	2502.96	5595.80
Barren	7.77	6.32	14.09	3715.38	3022.03	6737.42
Coconut	10.97	8.81	19.78	15.58	12.51	28.09
Eucalyptus	10.27	8.41	18.68	22.80	18.67	41.47
Forest	13.21	10.57	23.78	3845.17	3076.72	6921.88
Gliricidia	10.08	8.09	18.17	3.53	2.83	6.36
Hardwickia	10.52	8.46	18.98	26.51	21.32	47.83
Mango	11.73	10.06	21.79	1005.26	862.14	1867.40
Neem	9.61	7.28	16.89	19.70	14.92	34.62
Senegalia C.	10.00	8.05	18.05	22.10	17.79	39.89
Tamarind	10.39	8.28	18.67	47.17	37.59	84.76
Total				**11816.04**	**9589.49**	**21405.53**

The dominant land cover in the watershed was barren land, covering 38% of the watershed area. Despite its significant coverage, it only stores soil carbon of 6737.42 tonnes, which is equivalent to only 31% of the total soil carbon stock of the watershed. This implies that barren land in the watershed is not an efficient carbon sink and efforts should be made to convert it into more productive land covers that can contribute to carbon sequestration. The total amount of soil carbon stored in the plantations of the watershed was 2150.43 tonnes, of which 86% was stored in the mango land cover. Among the different plantations in the watershed, the highest amount of soil carbon stock was found in mango land cover (19.78 t/ha) and lowest in neem land cover (16.89 t/ha). Agricultural lands, which comprise 18% of the watershed's land cover, store approximately 26% of the total SOC. Agricultural lands, despite occupying a smaller land cover, contribute significantly to the total soil carbon stock in the watershed. The distribution of soil carbon stock among different land covers in the watershed highlights the importance of considering land cover in soil carbon management and conservation strategies. The distribution of SOC in the soil profile of various vegetation types is primarily influenced by root distribution, litter production, and soil disturbance (Wan *et al.*, 2019, Liu *et al.*, 2022).

4.3.5 Total Terrestrial Carbon Stock in the Watershed

The total terrestrial carbon stock in the watershed is the sum of the carbon stored in biomass and soil across the watershed's various land cover types. The total amount of carbon in the watershed was found to be 39191.74 tonnes. Out of which, vegetation biomass stored 17786.21 tonnes (45%), while the soil stored 21405.52 tonnes (55%) of carbon. This suggests that while vegetation biomass is an important component of carbon storage in the watershed, soil is the primary reservoir of carbon. The total terrestrial carbon stock in the watershed was divided into four major land cover types, namely agricultural, barren, natural forest and horticulture. The distribution of carbon in different land cover types within the watershed provides valuable insights into carbon sequestration potential in various ecosystems (Fig. 4.8). The highest amount of carbon was found in natural forest (56%), followed by barren land (17%), agricultural land (14%) and horticultural land (13%). This indicates that natural forest areas are highly efficient in sequestering and storing carbon. Barren land, which covers the largest percentage of the watershed area (38%), stores 17% of the total carbon in the watershed, indicating the potential for carbon sequestration in this land cover type through restoration activities. The carbon storage in agricultural land (14%) and horticultural land (13%) highlights the potential for incorporating agroforestry and horticulture practices to enhance carbon sequestration in such areas. Natural forest has the largest carbon content due to the presence of plant biomass and the continuous generation and decomposition of litter biomass, which increases the SOC content (Assefa *et al.*, 2017, Hussein, 2021). Species-driven carbon sequestration in soil was primarily controlled by two processes: litter breakdown at ground level and root activity at deeper levels (Lemma *et al.*, 2007). The study's findings emphasize the role of natural forest cover in mitigating climate change. In addition, it signifies the importance of maintaining a healthy vegetative cover for enhanced carbon sequestration. Conservation of topsoil from land degradation and enhancement of the quality and quantity of vegetation can increase the watershed's capacity of carbon sequestration. Similar results have been observed by other researchers, revealing that natural forest land cover has a higher rate of carbon sequestration than other land coverings. It was found that forest vegetation carbon density is the primary factor influencing variation in vegetation carbon storage in Heilongjiang Province, China (Li *et al.*, 2021). It was also observed that agricultural land has the lowest total carbon stock due to the high amount of human and animal interventions. So, adopting sustainable land management methods is prudent step in order to prevent terrestrial carbon sinks from degradation and deterioration. These findings suggest that there is a need for a landscape-level approach to carbon sequestration, which involves a combination of conservation and restoration of natural forest ecosystems, adoption of agroforestry practices in agricultural and horticultural lands and utilization of degraded or unused land for carbon sequestration. Such an approach can significantly enhance the carbon sequestration potential of the watershed and contribute to global efforts to mitigate climate change.

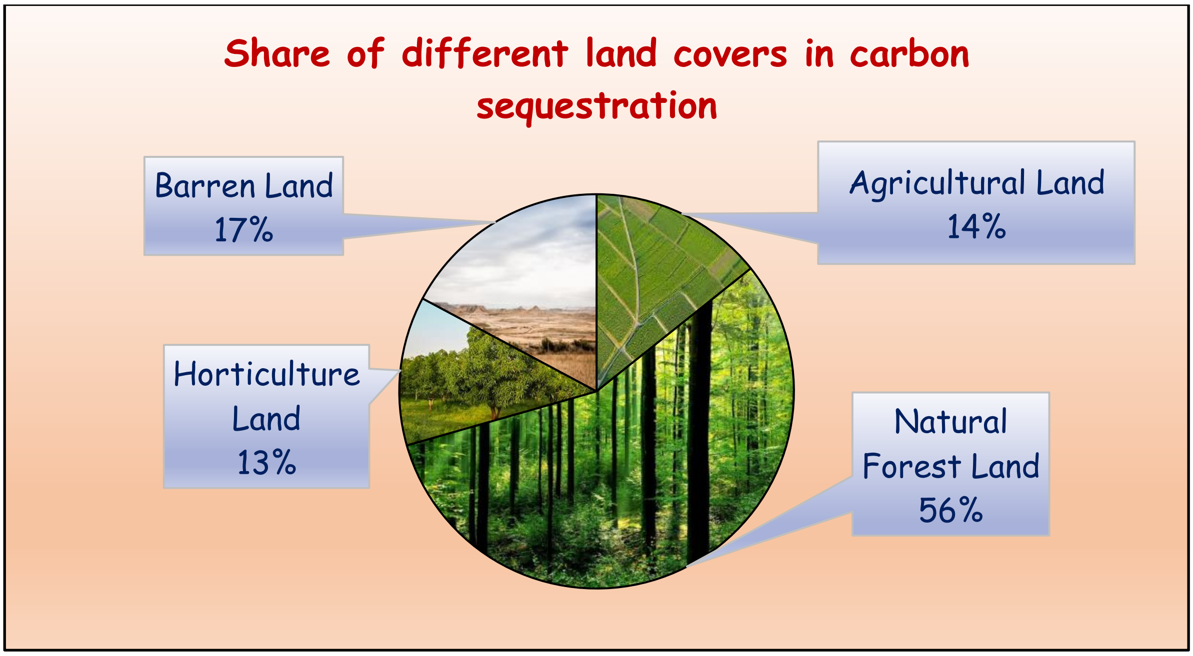

Figure 4.8 Share of different land covers in carbon sequestration in the watershed

4.4 Assessment of Temporal Impact of Soil and Water Conservation Measures on Carbon Sequestration

The temporal impact of soil and water conservation (SWC) measures on carbon sequestration was assessed by comparing rates of soil organic carbon (SOC) sequestration in treated and untreated areas. The annual soil carbon sequestration rates for various land cover types in treated and untreated areas were calculated by estimating SOC stocks for three consecutive years. Soil bulk density, SOC and coarse fraction of soil particles were used to calculate the temporal variability of soil carbon stock in various land cover types.

4.4.1 Bulk Densities in Various Land Cover Types in the Treated Areas of the Watershed

The bulk densities varied across the different types of land covers in the treated areas of the watershed. Land cover type and bulk density for three consecutive sampling years in the treated areas of the watershed is given in table 4.14. The average bulk density in the treated areas of the watershed ranged from 1.24 to 1.51 g/cm^3 for 0-15 cm depth and 1.32 to 1.60 g/cm^3 for 15-30 cm depth. It was found to be highest in barren land cover and lowest in agricultural land cover. The degree of soil compaction resulting from tillage operations on agricultural lands has a significant effect on soil bulk density. Osunbitan *et al.*, (2005) found that bulk density was much higher with no-till cultivation than with traditional tilling. The bulk density of land cover types with vegetation cover was discovered to be less than that of land cover types without vegetation cover. Similar to these findings, Gu *et al.*, (2018) found that bulk density declined substantially while aggregate stability increased marginally during vegetation restoration in the Tianlaochi catchment in Northwest China.

The average bulk density in the plantations ranged from 1.36 to 1.48 g/cm^3 for 0-15 cm depth and 1.38 to 1.56 g/cm^3 for 15-30 cm depth. Assefa *et al.*, (2020), also reported that forest, grazing and agricultural land with soil conservation had a lower bulk density than land uses without soil conservation. A similar finding was made by Belayneh *et al.*, (2019) in the Gumara watershed, Upper Blue Nile Basin, Ethiopia. They found that SWC had a small effect on mean soil bulk density, with slightly lower values observed in conserved plots. The relationship between bulk density and SOC was found to be inverse, with an increase in bulk density resulting in a decrease in SOC and vice versa. Since organic matter is lighter than an equal volume of solid soil and is more porous, hence a soil with higher organic matter leads to lower bulk density. Soil texture also affected bulk density in the treated areas of the watershed. The bulk density of sandy loam soil was greater than that of clayey loam soil. This is primarily due to increased granulation/aggregation of soil particles in clay soils. As aggregation and clay content increase, bulk density decreases. Xu *et al.,* 2017 reported that fine-textured soils like silt loam and clay loam had lower bulk densities than sandy soils in the province of Quebec, Canada. In similar studies, land cover, soil organic matter, soil texture and SWC measures were found to have a significant impact on bulk density in the treated areas of the watershed (Osunbitan *et al.,* 2005, Belayneh *et al.,* 2019).

Table 4.14 Temporal changes in bulk densities in different land cover types

Land Cover Type	**Bulk density (g/cm^3)**					
	2020		**2021**		**2022**	
	0-15 cm	**15-30 cm**	**0-15 cm**	**15-30 cm**	**0-15 cm**	**15-30 cm**
Agriculture#	1.37	1.43	1.37	1.44	1.38	1.45
Barren *	1.45	1.51	1.44	1.5	1.45	1.51
Coconut*	1.43	1.47	1.42	1.47	1.43	1.47
Eucalyptus*	1.42	1.48	1.43	1.48	1.43	1.48
Forest *	1.45	1.49	1.44	1.48	1.45	1.48
Gliricidia*	1.42	1.47	1.42	1.48	1.41	1.49
Hardwickia *	1.39	1.44	1.38	1.45	1.4	1.47
Mango*	1.42	1.47	1.43	1.48	1.41	1.47
Neem*	1.44	1.47	1.42	1.48	1.43	1.47
Senegalia catechu*	1.43	1.49	1.42	1.48	1.44	1.48
Tamarind*	1.42	1.48	1.41	1.48	1.42	1.47
Average	**1.422**	**1.473**	**1.416**	**1.475**	**1.423**	**1.476**
(Treatments: * DCCT and # Compartment Bunding)						

The average bulk density for three consecutive sampling years (2020–2022) in the treated parts of the watershed was found to be nearly constant at 1.42 g/cm^3 and 1.47 g/cm^3 for 0–15 and 15–30 cm depths, respectively. It was observed that after the implementation of SWC measures in the watershed, bulk density did not change significantly over a three-year period for both sampling depths. However, it was observed that soil bulk density increased as soil sampling depth increased. This is due to the fact that subsurface layers have less organic matter, aggregation and root penetration than surface layers and consequently contain less pore space. Additionally, subsurface layers are subject to the compaction of the soil above them. There was a direct correlation between bulk density and soil sampling depth. Similar kind of correlations were observed by Twum and Nii-Annang, 2015; Reintam *et al.*, 2009 and Bhavya *et al.*, 2018.

4.4.2 Soil Organic Carbon Contents in Various Land Cover Types in the Treated Areas of the Watershed

The soil organic carbon (SOC) content in the watershed was divided into five categories, ranging from very low (0.2%) to high (>0.8%) (Methods Manual Soil Testing in India, 2011). Area under different soil organic carbon classes at both sampling depths is given in table 4.15 and graphically presented in Figs 4.9 & 4.10. Nearly 35% of the watershed area was found in the moderately high carbon content class for 0-15 cm depth. After the adoption of conservation measures in the watershed, the area under the very low, low and moderately high carbon content classes decreased, whereas the area under the moderate and high carbon content classes in surface layer (0-15 cm depth) increased. Similarly, for the subsurface layer (15-30 cm depth), the largest area was found in the low carbon content class (34%). After the adoption of conservation measures in the watershed, the area under the subsurface layer with very low and low carbon content classes decreased, while the area with moderate, moderately high and high carbon content classes increased. The spatial distribution of SOC in the watershed over three consecutive years and at both sampling depths is shown in Figs. 4.11–4.16. The spatial distribution of SOC content in the watershed revealed that conservation measures had a significant impact on the watershed’s soil organic carbon content at both sampling depths. About 47% and 63% of the watershed’s surface and subsurface are still below the moderate carbon levels. Therefore, these areas of the watershed require sustainable land management practises to further increase the watershed’s soil carbon content.

Table 4.15 Area under different soil organic carbon classes at both sampling depths

Soil Organic Carbon Class	**Soil Organic Carbon (%)**	**Area (ha)**			**Area (ha)**		
		0-15 cm depth			**15-30 cm depth**		
		2020	**2021**	**2022**	**2020**	**2021**	**2022**
Very Low	<0.2	58	41	34	76	45	39
Low	0.2-0.4	212	183	172	433	410	375
Moderate	0.4-0.6	401	414	404	362	404	396
Moderately High	0.6-0.8	460	451	445	308	307	342
High	>0.8	129	171	205	84	97	111

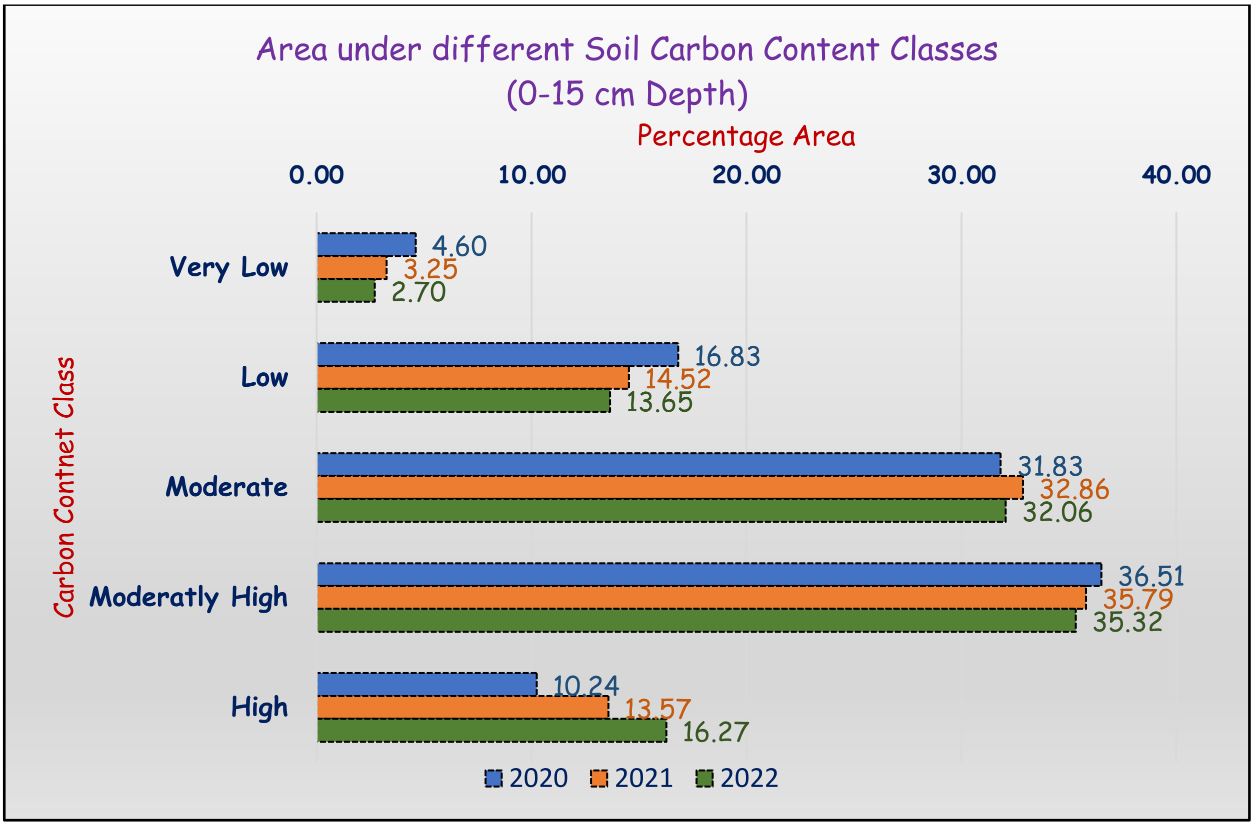

Figure 4.9 Area under different soil carbon content classes (0-15 cm Depth)

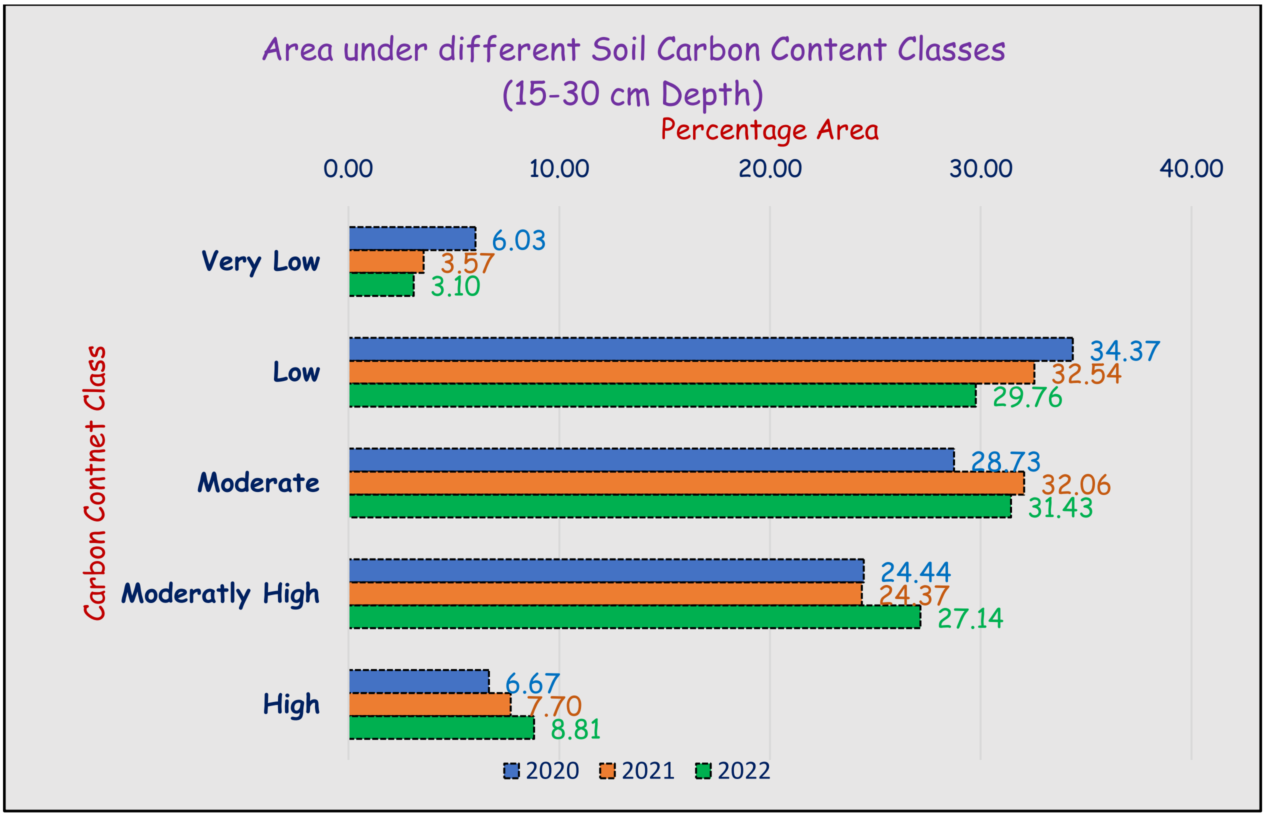

Figure 4.10 Area under different soil carbon content classes (15-30 cm Depth)

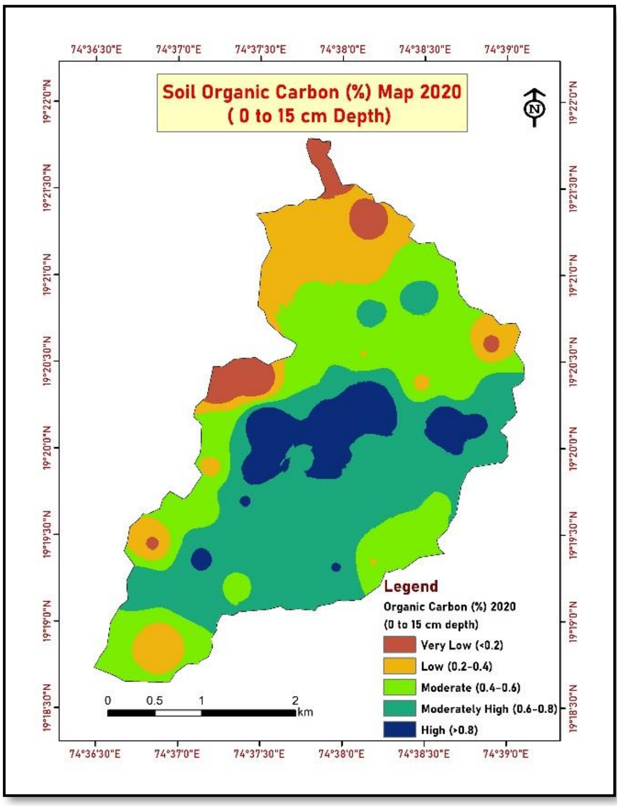

Figure 4.11 Soil organic carbon
(0-15 cm depth)
map of the watershed (2020)

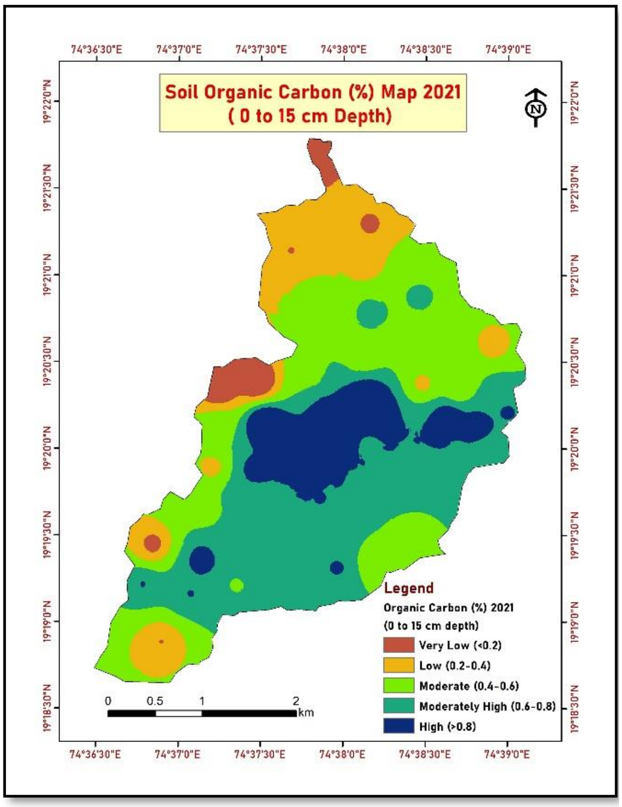

Figure 4.12 Soil organic carbon
(0-15 cm depth)
map of the watershed (2021)

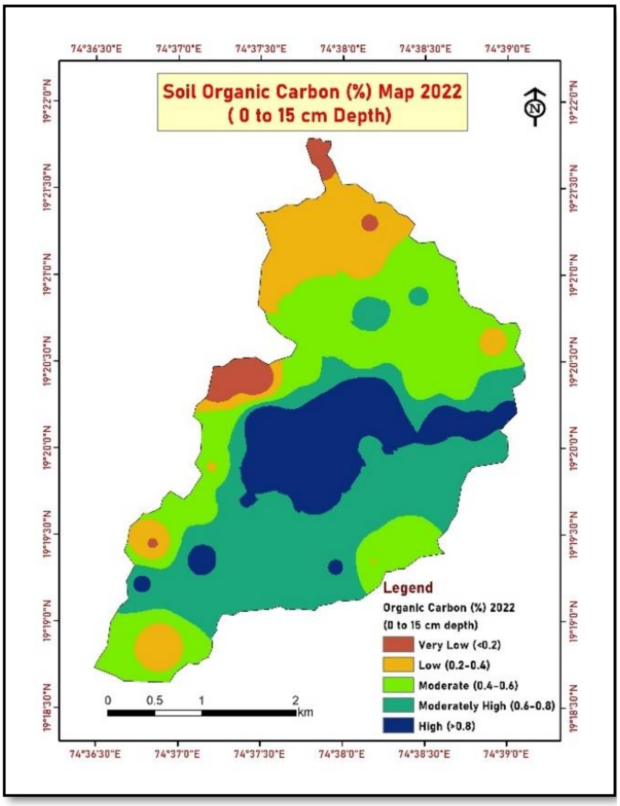

Figure 4.13 Soil organic carbon
(0-15 cm depth)
map of the watershed (2022)

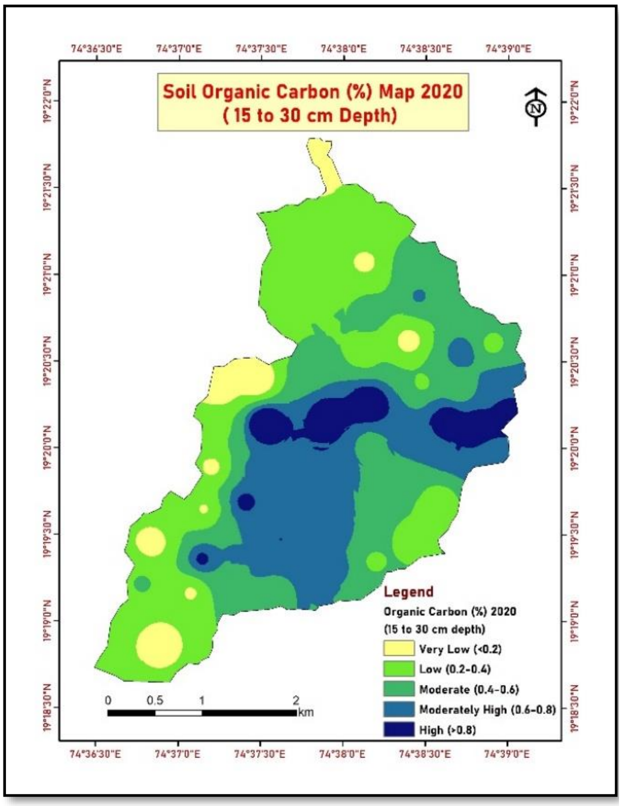

Figure 4.14 Soil organic carbon
(15-30 cm depth)
map of the watershed (2020)

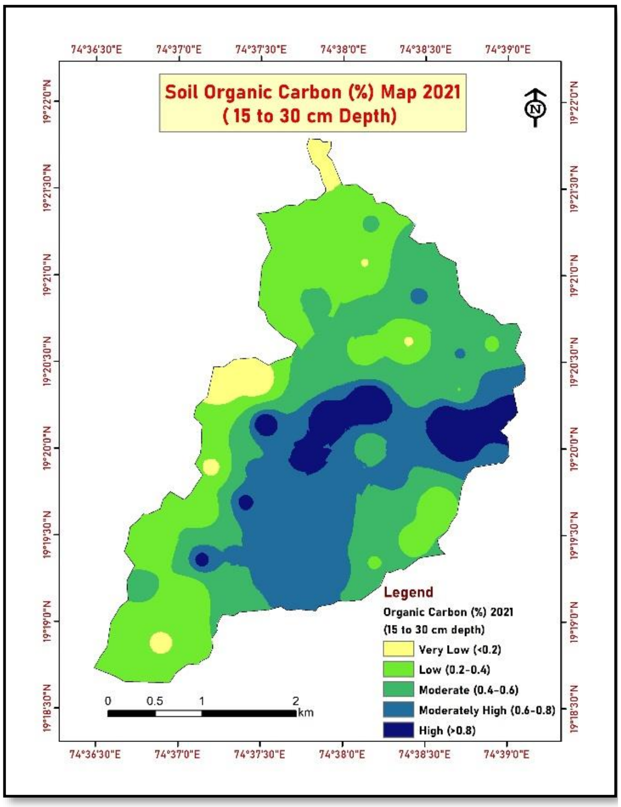

Fig. 4.15 Soil organic carbon (15-30 cm depth) map of the watershed (2021)

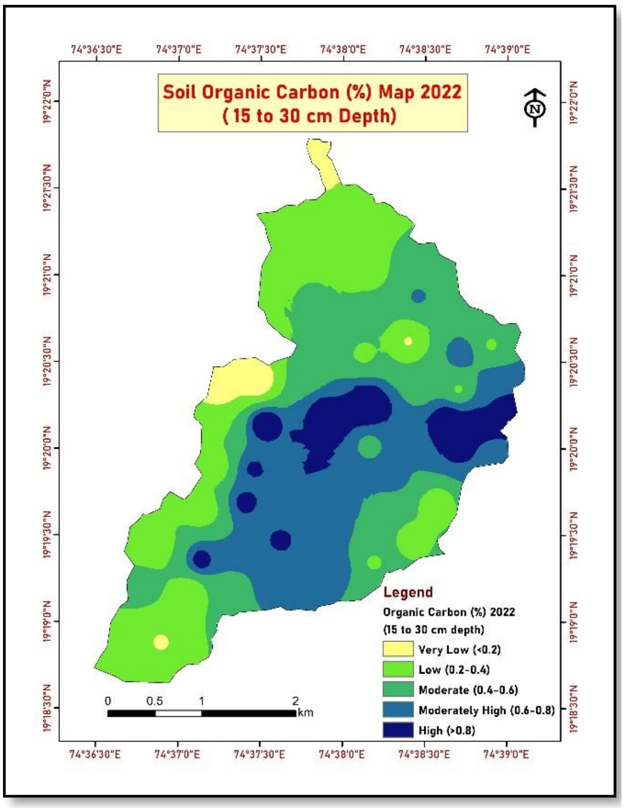

Fig. 4.16 Soil organic carbon (15-30 cm depth) map of the watershed (2022)

The land cover types and soil organic carbon (SOC) contents for three consecutive sampling years in treated areas of the watershed are given in table 4.16. It was observed that the average SOC increase rate in the 0–15 and 15–30 cm depths were 3.78 and 2.18%, respectively. The SOC increase rate in the subsurface layer (15-30 cm) was found to be lower than in the surface layer due to lower organic inputs. Forest land cover was found to have the highest SOC content across both soil sampling depths, while barren land cover had the lowest. It highlights the role of forest land cover in soil carbon storage in the watershed. There was a significant difference in SOC content between vegetation-covered land and bare soil. Several other studies have also reported a greater SOC content in forest land covers than in other land covers (Gebeyehu *et al.*, 2019, Sahoo *et al.*, 2021). SOC concentrations are proportional to the total mass of organic matter in the soil, which varies across land cover types (Wynn *et al.*, 2005). The presence of vegetation cover on the land surface continuously adds litter to the upper layer and increases root turnover in the subsurface layers, both of which contribute to the improvement of soil organic matter. (Korkanç, 2014). Therefore, it becomes essential to maintain healthy vegetation growth on the land surface in order to increase the carbon inputs to the soil. The primary determinants of SOC dynamics in soil are management practises, soil type and climatic conditions (Padalia *et al.*, 2018). The SOC content in both sampling depths increased for all land cover types in the treated parts of the watershed. But the rate of increase was found to be varying in both depths.

Table 4.16 Temporal changes in SOC contents in different land cover types

Land Cover Type	**Soil Organic Carbon (%)**					
	2020		**2021**		**2022**	
	0-15 cm	**15-30 cm**	**0-15 cm**	**15-30 cm**	**0-15 cm**	**15-30 cm**
Agriculture#	0.73	0.68	0.76	0.7	0.78	0.72
Barren *	0.53	0.47	0.56	0.49	0.58	0.5
Coconut*	0.7	0.65	0.73	0.67	0.75	0.68
Eucalyptus*	0.66	0.62	0.67	0.63	0.69	0.64
Forest *	0.77	0.73	0.81	0.74	0.84	0.77
Gliricidia*	0.65	0.6	0.67	0.61	0.69	0.62
Hardwickia *	0.69	0.64	0.72	0.66	0.75	0.67
Mango*	0.75	0.72	0.78	0.74	0.82	0.75
Neem*	0.61	0.54	0.63	0.54	0.66	0.56
Senegalia catechu*	0.64	0.59	0.66	0.6	0.68	0.6
Tamarind*	0.67	0.61	0.7	0.62	0.72	0.64
Average	**0.673**	**0.623**	**0.699**	**0.636**	**0.724**	**0.650**
(Treatments: * DCCT and # Compartment Bunding)						

The average annual SOC increase rate in forest land was 4.54 and 2.59% for the 0–15 and 15–30 cm depths, respectively. Similarly, the SOC increase rate in agricultural land cover was 3.42 and 2.73% for the 0-15 and 15-30 cm depths, respectively. The average annual SOC increase rate for 0–15 cm depth among the plantations was found highest in mango land cover (4.66%) and lowest in eucalyptus land cover (2.27%). Similarly, the average annual SOC increase rate for 15–30 cm depth was found highest in hardwickia land cover (2.17%) and lowest in tamarind land cover (0.78%). One of the major factors responsible for increased SOC content in the treated parts of the watershed is increased vegetation cover in the watershed as a result of increased water availability caused by SWC measures. Furthermore, soil loss from treated areas of the watershed has been reduced due to the barrier effect created by SWC measures, which has reduced soil degradation and minimized associated carbon loss and redistribution. (Cardinael *et al.,* 2017). The temporal changes in SOC stock indicate that SWC measures had a net positive effect on SOC accumulation in treated areas of the watershed. Hu *et al.,* 2022 found a 5.43% annual increase in SOC content with the implementation of SWC measures in the Tongshuang small watershed, Heilongjiang province, China. Lembaid *et al.*, 2021 found that land management practises on the semi-arid Merchouch Plateau in Morocco increased the SOC content by 1% to 5%. Similarly, Mulugeta and Karl, 2010; Hailu *et al.*, 2012; Abay *et al.*, 2016 and Hishe *et al.,* 2017 all observed significant variations in SOC levels with and without conservation measures.

The average soil organic carbon contents for three consecutive sampling years (2020–2022) in the treated areas of the watershed were 0.67, 0.69 and 0.72% in 0–15 cm depth. Similarly, for 15–30 cm depth, it was found at 0.62, 0.63 and 0.65%. These findings suggest that the treated areas of the watershed have experienced an increase in soil organic carbon content over the three-year period. SOC content was found to be higher in the topsoil and decreased with depth. It was consistent with other studies that found organic carbon content decreases with increasing soil sampling depth due to decreased organic matter in the subsurface layer (Gaudinski et al., 2000, Wynn *et al.*, 2005). Since the SOC content in the subsurface layer is less likely to be disrupted by environmental processes, it tends to be more stable over longer time periods (Hobley *et al.*, 2014). The increased concentration of SOC content in the treated parts of the watershed in all land covers and at both sampling depths was greatly influenced by SWC measures implemented in the watershed.

4.4.3 SOC Densities in Various Land Cover Types in the Treated Areas of the Watershed

The average soil organic carbon (SOC) densities for three consecutive sampling years (2020–2022) in the treated areas of the watershed were 10.08, 10.32 and 10.54 t/ha, for 0–15 cm depth. Similarly, it was found at 8.33, 8.42, and 8.51 t/ha, in the subsurface layer (15–30 cm depth). Similar to SOC content, it was found that SOC density decreased as soil sampling depth increased. The average SOC density in the surface layer (0-15 cm) was 21% to 24% greater than the SOC density in the subsurface layer (15-30 cm). The higher gravel proportion and low organic matter at subsurface layers resulted in a lower SOC density in the subsurface layer. Similar results were found by Zhang *et al.*, 2017 in a small karst watershed in China, where SOC density at 10 cm intervals from depths of 20 to 100 cm in the sampling area of each soil type progressively decreased with increasing depth and generally became stable near the bottom of the soil profile. The SOC density in the treated parts of the watershed was greatly influenced by land cover, SOC content, bulk density, gravel content and land management practices. Temporal changes in the SOC density in different land covers are given in table 4.17.

The land cover types and SOC stocks at 0-30 cm depth for three consecutive years are given in table 4.18. The total SOC stocks in the watershed for three consecutive sampling years (2020–2022) were 2076.18, 2111.88, and 2150.43 tonnes, in the top 0–30 cm depth. SOC stock was found to increase by an average of 367.84 t/yr in the top 30 cm soil depth. The average SOC stock increase among four major land covers was observed highest in forest land (136.89 t/yr), followed by barren (101.07 t/yr), agricultural (92.75 t/yr) and plantation (37.12 t/yr) land covers. Among the different plantations in the watershed, mango plantation land cover alone adds 32.75 tonnes of C per year. Forest land cover accounts for 37.21% of the total SOC stock increase in the watershed, followed by barren (27.47%), agricultural (25.21%), and plantation (10.09%) land cover. A greater input of soil organic matter from vegetation and less soil disturbance led to an increase in SOC stock in forest land cover compared to other land covers. Barren lands, despite covering the largest area (38%) of the watershed, only account for 27.475 of the total SOC stock increase, highlights the potential of these lands to sequester carbon if they are restored or converted to other land use types such as forests or plantations. Soils with more organic material (bits of wood, decaying leaves, or dead creatures) can store more carbon because organic material easily binds loose carbon molecules and the organic material itself contains carbon (Zakaria *et al.,* 2021). Topsoil in the treated areas of the watershed was found to accumulate a significant amount of carbon.

Table 4.17 Temporal changes in the SOC densities (t/ha) in different land cover types

Land Cover Type	**SOC density (t/ha)**					
	2020		**2021**		**2022**	
	0-15 cm	**15-30 cm**	**0-15 cm**	**15-30 cm**	**0-15 cm**	**15-30 cm**
Agriculture#	10.95	9.04	11.21	9.16	11.43	9.25
Barren *	7.49	6.17	7.62	6.26	7.77	6.32
Coconut*	10.51	8.60	10.78	8.71	10.97	8.81
Eucalyptus*	9.84	8.26	10.03	8.33	10.27	8.41
Forest *	12.56	10.28	12.87	10.38	13.21	10.57
Gliricidia*	9.69	7.94	9.85	8.00	10.08	8.09
Hardwickia *	10.07	8.29	10.32	8.41	10.52	8.46
Mango*	11.18	9.84	11.42	9.97	11.73	10.06
Neem*	9.22	7.14	9.38	7.16	9.61	7.28
Senegalia catechu*	9.61	7.91	9.78	8.02	10.00	8.05
Tamarind*	9.99	8.13	10.21	8.21	10.39	8.28
Average	**10.08**	**8.33**	**10.32**	**8.42**	**10.54**	**8.51**
(Treatments: * DCCT and # Compartment Bunding)						

Table 4.18 Land cover types and their corresponding SOC stocks in the watershed

Land Cover Type	**SOC stock in 0-30 cm depth (tonnes)**		
	2020	**2021**	**2022**
Agriculture#	5410.29	5511.92	5595.80
Barren *	6535.28	6637.00	6737.42
Coconut*	27.14	27.68	28.09
Eucalyptus*	40.18	40.76	41.47
Forest *	6648.09	6767.61	6921.88
Gliricidia*	6.17	6.25	6.36
Hardwickia *	46.28	47.20	47.83
Mango*	1801.90	1833.12	1867.40
Neem*	33.55	33.91	34.62
Senegalia catechu*	38.72	39.34	39.89
Tamarind*	82.24	83.63	84.76
Average	**20669.83**	**21028.40**	**21405.53**

The average SOC densities for three consecutive years (2020–2022) were 18.41, 18.73 and 19.05 t/ha, for 0-30 cm depth. It was found that the SOC density changed along with the land cover. The average SOC density was found to be higher in the forest land cover and lower in the barren land cover. The higher value of SOC density associated with forest land cover was due to higher SOC content, higher bulk density with low gravel content and low soil erosion rates. Whereas the lower value of SOC density associated with barren land cover was due to lower SOC content, high bulk density with high gravel content and higher soil erosion rates than the other land covers. Agricultural lands (20.68 t/ha) had higher SOC density than plantations (18.88 t/ha) but lower than forest land cover (23.78 t/ha) in the treated areas of the watershed. Among the various plantations in the watershed, the mango plantation had the highest SOC density (21.79 t/ha), while the neem plantation had the lowest density (16.01 t/ha). The treated parts of the watershed showed variations in SOC density among major land covers, with the highest density found in forest, followed by agriculture, plantation and barren land cover. The SOC increase rate among different land covers was mainly influenced by vegetation cover, soil organic matter, soil texture and soil compaction. The land covers with higher vegetation growth rates, higher soil organic matter, finer in texture and less compacted were found to have a higher SOC density than other land cover classes. The reduction in topsoil loss caused by the barriers created by the implementation of conservation measures in the watershed also contributed significantly to the retention of SOC content in the topsoil layer. Similar results were observed by Amanuel *et al.*, 2018 in the Birr watershed, upper Blue Nile River Basin, Ethiopia, where they found that the overall mean SOC stock was higher under natural and mixed forest land use compared with other land use types and at all depths. Bhandari and Bam (2013) reported that land cover and soil depth both affected SOC stock significantly and forest land cover stored more SOC stock followed by agriculture and barren land cover in Chovar village, Nepal.

4.4.4 Soil Carbon Sequestration (SCS) Rates in the Treated Areas of the Watershed

The soil carbon sequestration rates of different land covers in treated parts of the watershed are given in the table 4.19. Among different land covers in the watershed, the highest average SCS rate was observed in forest land treated with DCCT (325 and 146 kg C/ha/yr) for both the soil sampling depths. Whereas the lowest average SCS rate was observed in barren land treated with DCCT (139 kg C/ha/yr) for 0-15 cm depth and neem land cover (69 kg C/ha/yr) treated with DCCT for 15–30 cm depth. The agricultural lands in the watershed treated with compartment bunding were found to have an SCS rate of 343 kg C/ha/yr for 0-30 cm soil depth. Similarly, the average SCS rates in plantations treated with DCCT was found to be 299 kg C/ha/yr for 0-30 cm soil depth. Among the different plantations in the watershed, the SCS rate was found to be highest in mango plantations (382 kg C/ha/yr) and lowest in neem plantations (261 kg C/ha/yr) land cover. It was observed that the rate of SCS in mango and coconut plantations was greater than that of agricultural land. This may be because mango and coconut plantations produce more litter than other plantations due to their larger tree canopies. Apart from this, tree species with a wider tree canopy prevent the direct impact of raindrops on the surface layers, thereby lowering soil loss in densely vegetated areas. The SCS rate in the barren land was found to be 211 kg C/ha/yr in the treated parts of the watershed due to the emergence of thick grass cover on the barren land as result of conservation measures. Seasonal grass covers on bare land increased biomass input to the topsoil and slowed runoff, thereby reducing soil loss. It resulted in increased soil organic matter in the barren land and decreased carbon loss associated with soil loss. The average soil carbon sequestration rate in the treated areas of the watershed was 231 and 89 kg C/ha/yr in the 0-15 and 15-30 cm depths, respectively. The average SOC increase rate in the surface layer (0-15 cm) was 1.5 times higher than in the subsurface layer (15-30 cm). The average SCS rate in topsoil (0-30 cm) was found to be 320 kg C/ha/yr. It was observed that the rate of soil carbon sequestration in the watershed was primarily influenced by land cover type and SWC measures. It was found that preventing soil surface deterioration through appropriate management is vital for carbon sequestration in the watershed. The combination of area treatments and vegetation cover has been identified as a viable method for mitigating the effects of climate change. Therefore, site-specific conservation strategies are needed for the barren lands to improve carbon sequestration.

Table 4.19 Soil carbon sequestration rates in different land covers

Land Cover Type	**SCS Rate (kg C/ha/yr)**						
	2020-21	**2021-22**	**Avg.**	**2020-21**	**2021-22**	**Avg.**	**Avg.**
	0-15 cm			**15-30 cm**			**0-30 cm**
Agriculture#	259	220	239	117	90	103	343
Barren *	127	150	139	86	60	73	211
Coconut*	270	190	230	111	100	105	335
Eucalyptus*	189	240	215	72	80	76	291
Forest *	309	340	325	101	190	146	470
Gliricidia*	159	230	194	62	90	76	270
Hardwickia *	249	200	225	116	50	83	308
Mango*	238	310	274	127	90	108	382
Neem*	157	230	193	16	120	68	261
Senegalia catechu*	170	220	195	108	30	69	264
Tamarind*	220	180	200	85	70	77	278
Average	**233**	**228**	**231**	**91**	**88**	**89**	**320**

It was found that conservation measures implemented in the watershed increased vegetation cover in the watershed, which primarily includes a thick grass cover on major land covers of the watershed. The vegetation cover on the land cover adds organic matter to the soil via plant root biomass in the subsurface layer and litter deposited from plant shoots on the surface layer. Plants play an essential role in soil erosion control because their roots compress the soil, lessening the impacts of rainfall and weathering on the soil surface. Therefore, land cover with dense vegetation will provide more resistant to soil erosion than land cover with little vegetation and bare ground. Other similar research has indicated that the presence of seasonal grass cover on the surface layer increases the surface SOC stock as a result of a greater input of biomass into the topsoil and a faster rate of biomass decomposition (Wei *et al.,* 2012, Bai and Cotrufo, 2022). The presence of high levels of soil carbon sequestration in the uppermost layers may be due to a vegetation cover, which may have improved the carbon sequestration by adding decomposable organic matter in topsoil. According to Walter *et al.,* 2003, the barrier effect created by SWC measures contributes to the improvement of SOC by retaining sediments and nutrients in treated areas. The findings of the study are consistent with earlier studies that indicate reduced erosion and increased soil carbon storage in SWC treated areas. Sustainable soil management practices resulted in a SCS rate of 0.62 t C/ha/yr in China (Wang *et al.,* 2010), 0.45±0.14 t C/ha/yr in Belgium (Buysse *et al.,* 2013), 0.4±0.61 t C/ha/yr in the United States (Johnson *et al.,* 2005), 0.57 t C/ha/yr in Nigeria (Raji and J.O. Ogunwole, 2005) and 0.38 t C/ha/yr in England (Poulton *et al.,* 2003).

4.4.5 SOC Content, Bulk Density and SOC Density in Untreated Areas

Similar to treated areas, variations were also observed in soil organic carbon (SOC) content, bulk density, and SOC stock in untreated areas. The four major land cover types treated with soil and water conservation (SWC) measures were compared to similar untreated land cover types to determine SCS variations. This land cover includes agriculture, forest, barren and mango. The average SOC contents in four major untreated land covers are given in table 4.20. The average SOC contents in untreated areas for three consecutive sampling years (2020–2022) were 0.57, 0.58 and 0.58%, for 0–15 cm depth and 0.52, 0.53 and 0.53%, for 15–30 cm depth. Untreated areas showed the same trend as treated areas, with the SOC content decreasing as the depth of the soil sample was increased. The temporal SOC content in untreated areas exhibited no significant carbon content variations. The low organic carbon concentration in untreated areas was mostly attributable to the lower intake of organic matter and much higher erosion rates. The SOC concentration in the untreated areas was considerably lower than in the treated areas for both sampling depths and all land cover types. The SOC content in untreated areas mirrored that of treated areas, with the highest value being found in forest land cover and the lowest value being found in barren land cover for both sampling depths. It was discovered that the SOC content of barren land declined, whereas the SOC content of agricultural, forest, and mango land increased slightly in untreated areas for the surface layer (0-15 cm). This is inferred that a lack of vegetation cover and obstacles to prevent topsoil from erosion on barren land has caused temporal decrease in SOC content. The SOC content of the subsurface layer (15-30 cm) was relatively constant across all land cover types. Observations revealed that the SOC content in untreated areas was 13%, 22%, 12%, and 13% lower in agriculture, barren forest, and mango land cover, respectively, than in treated areas.

Table 4.20 Soil organic carbon contents in untreated land covers

Land Cover Type	**Soil organic carbon (%)**					
	2020		**2021**		**2022**	
	0-15 cm	**15-30 cm**	**0-15 cm**	**15-30 cm**	**0-15 cm**	**15-30 cm**
Agriculture	0.6	0.55	0.62	0.56	0.63	0.55
Barren	0.42	0.37	0.41	0.37	0.39	0.38
Forest	0.65	0.6	0.66	0.6	0.68	0.61
Mango	0.63	0.59	0.64	0.59	0.65	0.6
Average	**0.575**	**0.528**	**0.583**	**0.530**	**0.588**	**0.535**

The average bulk densities in four major untreated land covers are given in table 4.21. The average bulk density in untreated areas for three consecutive sampling years (2020–2022) was found to be constant at 1.44 g/cm^3 for 0–15 cm depth and increased slightly from 1.48 to 1.50 for 15–30 cm depth. This increase in bulk density could potentially lead to decreased soil porosity and infiltration, which could have negative impacts on plant growth and soil health. Bulk density was found to be greater in untreated areas than in treated areas for both sample depths and all land cover types. Similar to treated areas, bulk density rose with increasing soil sampling depth in untreated areas. The bulk density variation in the untreated region was mostly influenced by land cover and soil organic matter concentration. Other studies have indicated that bulk density is substantially affected by soil organic matter, soil texture, the density of soil mineral and the packing arrangement of these minerals (Périé and Ouimet, 2008; Assefa *et al.,* 2020; Crnobrna *et al.,* 2022). Erosion also significantly impacts soil bulk density when eroded soil particles fill pore space, porosity is reduced and bulk density increases (Alemu and Melesse, 2019). Retta *et al.,* 2022 found higher bulk densities in nonconserved land than in lands conserved with SWC measures in the Dawnt watershed of Ethiopia, due to the presence of higher organic matters in conserved lands.

Table 4.21 Bulk densities in untreated land covers

Land Cover Type	**Bulk density (g/cm^3)**					
	2020		**2021**		**2022**	
	0-15 cm	**15-30 cm**	**0-15 cm**	**15-30 cm**	**0-15 cm**	**15-30 cm**
Agriculture	1.4	1.45	1.41	1.45	1.42	1.46
Barren	1.48	1.51	1.47	1.52	1.47	1.54
Forest	1.45	1.51	1.47	1.53	1.45	1.52
Mango	1.43	1.48	1.44	1.49	1.44	1.49
Average	**1.440**	**1.488**	**1.448**	**1.498**	**1.445**	**1.503**

The soil organic carbon (SOC) densities in untreated land covers are given in table 4.22. The SOC densities in untreated areas for three consecutive sampling years (2020–2022) were 8.16, 8.24 and 8.32 t/ha, for 0–15 cm depth and 7.20, 7.27 and 7.33 t/ha, for 15–30 cm depth. The highest SOC density in untreated areas was observed in forest land cover and lowest in barren land cover for both sampling depths. A slight decrease in SOC stock was observed in barren land cover in the surface layer, whereas for all other land covers, SOC stock slightly increased for both sampling depths. It may be the result of the mineralization or redistribution of soil carbon from the surface layer in untreated barren areas due to soil erosion. Similar to treated areas, SOC density dropped as soil sampling depth increased in untreated areas. The overall SOC densities in the top 0-30 cm of soil depth for three consecutive sampling years (2020-2022) were 15.36, 15.51 and 15.64 t/ha. The SOC densities in untreated areas at 0-30 cm depth were 27%, 29%, 19%, and 16% less in agriculture, barren, forest, and horticulture land covers, respectively, in comparison to treated areas. The decreased SOC densities in the untreated areas were related with less organic matter input, low SOC content, increased soil aggregation and greater soil erosion rates compared to the treated areas. A significant difference in SOC stock between treated and untreated areas was observed in barren land due to unprotected topsoil layers that increased the severity of carbon loss in untreated areas. Similarly, intensive tillage operations and the absence of any conservation strategies were the key factors linked to low SOC stock values in untreated agricultural areas. This study supports the findings of Li *et al.*, (2004), who found that croplands with soil conservation measures had much higher carbon concentrations and stocks than croplands without any protection. Similarly, Tadesse *et al.*, 2016 found a mean soil organic carbon sequestration of 12.48 t/ha for a cropland site treated with integrated soil bund, 10.47 t/ha for a cropland site treated with soil bund alone and 4.7 t/ha for cropland without SWC measures.

Table 4.22 Soil organic carbon densities (t/ha) in untreated land covers

Land Cover Type	**Soil organic carbon density (t/ha)**					
	2020		**2021**		**2022**	
	0-15 cm	**15-30 cm**	**0-15 cm**	**15-30 cm**	**0-15 cm**	**15-30 cm**
Agriculture	8.19	6.58	8.38	6.68	8.49	6.66
Barren	5.59	4.61	5.46	4.65	5.28	4.70
Forest	9.67	8.97	9.80	9.05	10.01	9.17
Mango	9.19	8.64	9.31	8.70	9.48	8.78
Average	**8.16**	**7.20**	**8.24**	**7.27**	**8.32**	**7.33**

4.4.6 Soil Carbon Sequestration Rate in Untreated Areas

Soil carbon sequestration rates in untreated land covers are given in table 4.23. The average soil carbon sequestration (SCS) rates in the untreated areas were 77 and 63 kg C/ha/yr for 0-15 and 15-30 cm soil depths, respectively. The average SCS rate for both the sampling depths was found higher in forest land cover. The surface layer of barren land cover had a negative SCS rate (-157 kg C/ha/yr). The negative SCS rate in the surface layers of barren land indicated that barren lands without any conservation measures act as carbon source for emission. The lowest SCS rate in the subsurface layer was found in agricultural land cover (40 kg C/ha/yr). This was due to the lower SOC concentration and high gravel content in the subsurface layer of untreated agricultural lands. The overall SCS rate in the top 0-30 cm soil depth was 140 kg C/ha/yr. The SCS rate in the untreated areas was found highest in forest followed by mango, agriculture and barren land cover. It was discovered that, similar to treated areas, vegetation cover on the land surface had a considerable impact on SCS rate in untreated areas. Soil degradation in untreated barren lands caused by substantial erosion has diminished the organic matter in the topsoil surface. As a result, barren soils in untreated areas have become a net carbon source for emission, emitting or redistributing 112 kg C/ha/yr. Untreated land covers with some form of vegetation have added a little quantity of organic matter to the top soil surface through activities such as photosynthesis, respiration and decomposition. Vegetation cover also acted as a natural barrier against soil erosion in untreated areas, reducing SOC transport. The vegetation density under different land cover types has a substantial impact on soil erosion rates (Ruiz-Colmenero *et al.,* 2013). This may be the reason behind the significant variation in SCS rate in different land covers of the untreated areas.

Table 4.23 Soil carbon sequestration rate in untreated land covers

Land Cover Type	**SCS rate (kg C/ha/yr)**						
	2020-21	**2021-22**	**Avg.**	**2020-21**	**2021-22**	**Avg.**	**Avg.**
	0-15			**15-30**			**0-30**
Agriculture	190	110	150	101	-20	40	190
Barren	-134	-180	-157	41	50	45	-112
Forest	130	210	170	81	120	100	270
Mango	121	170	145	58	77	68	213
Average	**77**	**77**	**77**	**70**	**57**	**63**	**140**

4.4.7 Comparison of SCS Rates in Treated and Untreated Areas

The soil and water conservation (SWC) measures had a considerable impact on soil carbon sequestration (SCS) rates in treated areas, with greater SCS rates found in treated areas than in untreated areas. Comparison of SCS rate between treated and untreated areas in surface and subsurface layer is shown in Figs. 4.17 & 4.18. The SCS rate in agricultural areas treated with compartment bunding was found to be 60% and 156% higher in 0-15 and 15-30 cm depths, respectively, when compared to untreated agricultural lands. The intense and faulty tillage practices without any soil conservation practices reduced soil carbon sequestration capacity in untreated agricultural lands. This leads to deterioration of the topsoil surface, which ultimately affects the soil fertility and quality (Tanto and Laekemariam, 2019).

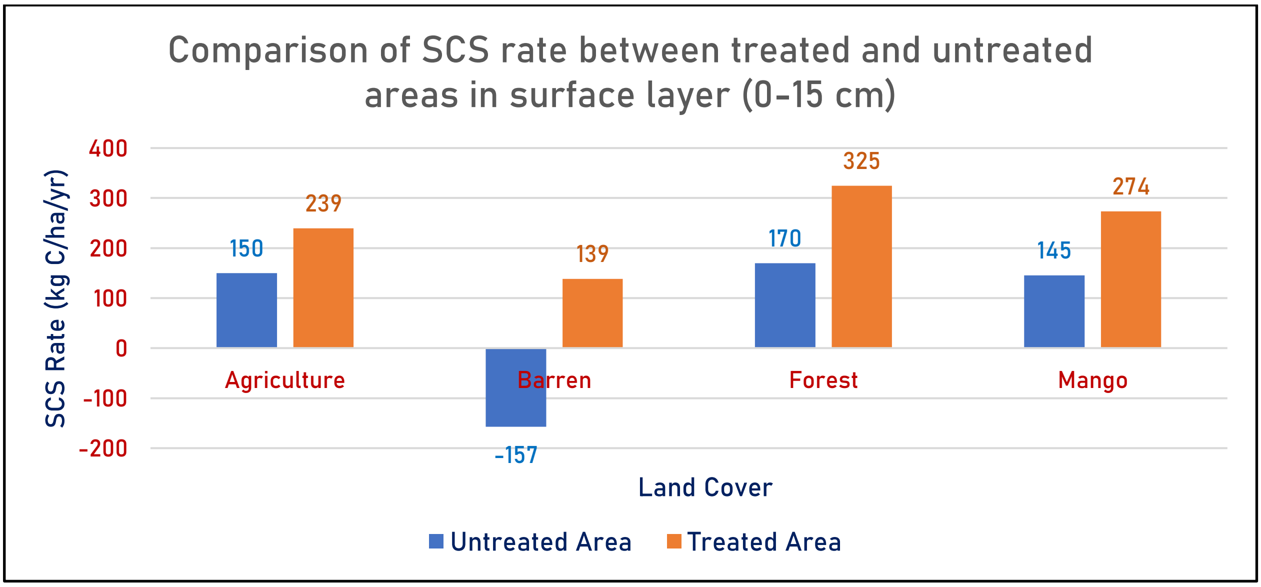

Figure 4.17 Comparison of SCS rate between treated and untreated areas in surface layer (0-15 cm)

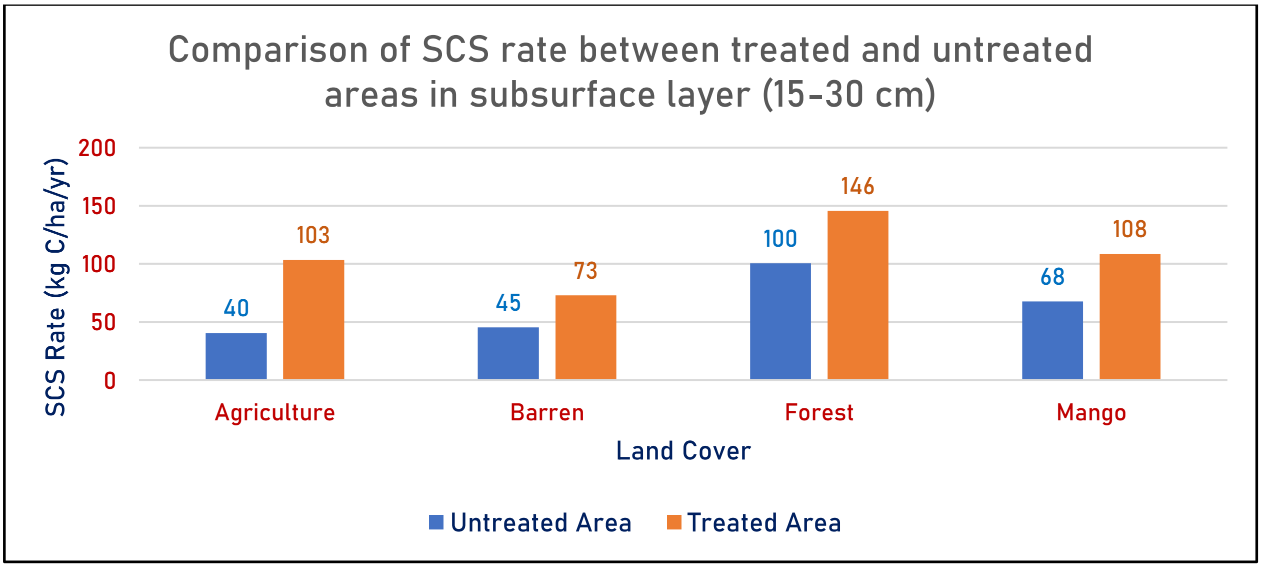

Figure 4.18 Comparison of SCS rate between treated and untreated areas in subsurface layer (15-30 cm)

The overall SCS rate in treated agricultural lands was found to be 80% higher in the 0-30 cm depth than in untreated agricultural lands. The reduced soil loss rate achieved through the implementation of compartment bunds in agricultural fields led to higher SCS rates in treated agricultural lands as compared to untreated ones. Similarly, the SCS rates in forest and mango plantation areas treated with DCCT were found to be 91% and 88% higher in 0–15 cm depth and 45% and 60% higher in 15–30 cm depth, respectively, compared to similar untreated land covers. The overall SCS rates for 0-30 cm depth in forest and mango land cover were found to be 74% and 79% higher, respectively, compared to similar untreated land covers. Higher biomass input in the surface layer as plant litter and root biomass in the subsurface layer as a result of increased vegetation cover increased SCS rates in treated land covers. The overall SCS increase percentage was higher in mango land cover due to larger tree canopy size of mango trees compared to forest tree species. Trees with a larger crown cover produce more leaf litter than trees with a smaller crown cover (Li *et al.*, 2017). In addition, the soil conservation achieved by DCCT in treated land covers contributed to the maintenance of soil fertility and limited carbon loss from the soil's surface. The SCS rate in barren lands treated with DCCT was found to be 138 kg C/ha/yr in the 0-15 cm depth, whereas untreated barren lands had exhibited carbon emissions in the surface layer. Thick grass cover developed on the barren land resulted from increased water availability in the top soil surface due to SWC measures reduced soil loss and increased biomass input in the surface layer of the treated barren lands. Controlled soil erosion on barren land in treated areas reduced further deterioration of the soil and aided in the conservation and protection of the surface layer from soil erosion. The continuous deterioration of top soil in barren land due to severe erosion rates acts as a carbon source, whereas properly managed top soils in barren land with appropriate SWC measures act as natural carbon sinks. In the subsurface layer (15–30 cm depth), the SCS rate in barren lands treated with DCCT was found to be 60% higher as compared to untreated barren lands. The SCS rate in the surface layer was found higher than the SCS rate in the subsurface layer for all land covers treated with SWC measures compared to untreated areas except the agricultural land cover. The SCS rate was found to be variable in both treated and untreated areas for all land covers and at both sampling depths. It was primarily influenced by soil erosion rates, the type of vegetation cover, tree characteristics, and SWC measures. In addition to this grazing management, reduced deforestation and reforestation were also important factors in increasing SCS rates in treated areas. The scientifically planned SWC measures were found to increase the SCS potential and can play a major role in mitigating climate change by increasing terrestrial carbon stock. Untreated areas in the watershed require site-specific SWC measures, as well as plantation and agroforestry practices, to reduce carbon loss from the soil and increase SCS rates.

4.5 Assessment of the Impact of Soil Erosion on Carbon Loss in the Watershed

The impact of soil erosion on carbon loss in the watershed was assessed by estimating the carbon loss associated with soil loss from the watershed. The soil loss and associated carbon loss from the watershed were estimated before and after the adoption of soil and water conservation (SWC) measures in the watershed.

4.5.1 Soil Loss from the Watershed Before the Adoption of Conservation Measures

4.5.1.1 Rainfall Erosivity (R) Factor

Rainfall erosivity (R) factor is a measure of the potential ability of rainfall to cause soil erosion. The average annual rainfall in the watershed for 30-year period (1991 to 2021) is 592 mm. The average rainfall erosivity (R) is 478.19 MJ-mm/ha-hr-yr. The mean annual erosivity of watershed reveals that the site is in the moderate erosion risk zone. The estimated moderately low rainfall erosivity index for the study area signifies further risk of soil erosion hazards, especially under conditions of increasing rainfall. The rainfall erosivity is highly dependent on the frequency and intensity of precipitation. Additionally, variations in climatic conditions and weather patterns can also affect the rainfall erosivity by modifying precipitation patterns and intensities. Consequently, fluctuations in rainfall erosivity can greatly impact soil erosion rates in the watershed.

4.5.1.2 Soil Erodibility (K) Factor

Soil erodibility is an important factor that determines the susceptibility of soil to erosion. It reflects the soil's inherent properties that affect the ability of the soil to resist or be displaced by erosive forces. Soil erodibility is dependent on several factors such as soil texture, organic matter content, structure and permeability. The permeabilities of soils in watershed were ranging from 16 to 42 mm/hr. So, the majority of soil comes under moderate permeability class. Therefore, permeability code 3 was used for estimation of K factor (Blake *et al.,* 2008). Soil permeability indirectly affect soil erodibility, as soils with high permeability may allow water to infiltrate more easily, reducing the amount of runoff and erosion. Soils that have high permeability rates tend to be less erodible than soils with low permeability rates. The soil structure in the watershed is medium or course granular (1-2 mm). Therefore, structure code of 2 was used for erodibility estimation.

The soil erodibility (K) in the study area varied from 0.0310 to 0.0599 t-ha-hr/ha-MJ-mm. A higher value of K indicates higher erodibility, and a lower value indicates lower erodibility. The soil erodibility map of the watershed is shown in the Fig. 4.19. The central MPKV campus watershed has three major types of soil: sandy clay loam, sandy loam and clay loam. The soil type and soil erodibility are given in table 4.24. Among the different soil types found within the watershed, sandy loam soil has the highest erodibility value and clay loam soil has the lowest erodibility value. The areas with clay loam soil type were found in the lower reaches of the watershed, where agriculture land is the dominant land cover. Therefore, the majority of agricultural land cover in the watershed was found to have lower soil erodibility values. Similarly, areas with sandy clay loam and sandy loam soil types were found in the upper reaches of the watershed, where barren land is the predominant land cover. Consequently, values of soil erodibility were found to be greater in the majority of barren land covers than in other types land covers. It indicates that barren lands with high soil erodibility values in the watershed are more vulnerable to soil erosion hazards and require immediate soil conservation measures.

Table 4.24 Soil type and soil erodibility (K) factor values (t-ha-hr/ha-MJ-mm)

Soil Type	Minimum	Maximum	Mean	Coefficient of Variation
Sandy Clay Loam	0.031	0.052	0.044	15.64
Sandy loam	0.052	0.059	0.056	4.48
Clay Loam	0.029	0.033	0.031	6.08

4.5.1.3 Topographic Factor (LS)

The topographic factor (LS) is a measure of the influence of slope length and steepness on soil erosion. The topographic factor for watershed varied from 1.02 in the plain areas to 5.92 in the hilly areas. The topographic factor map of the watershed is shown in Fig. 4.20. Lower value of LS factor, is indicator of low slope length and low slope and vice versa. The higher the value of LS factor severe the chances of soil hazard. The slope of the watershed ranges from 0 to 30.23%, with a mean slope of 4.17%. Around 90% of the watershed had a slope in the range of 0-9%, with the remaining 10% having a slope greater than 9%. This 10% area of the watershed with hilly terrain is located in the watershed's middle reaches and requires soil conservation measures that intercept long slopes into several short ones in order to keep runoff water at less than a critical velocity.

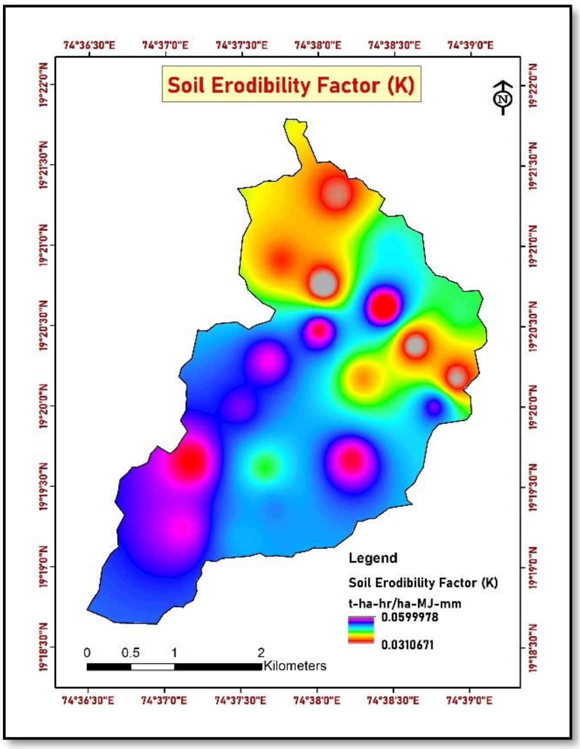

Figure 4.19 Soil erodibility map of the watershed

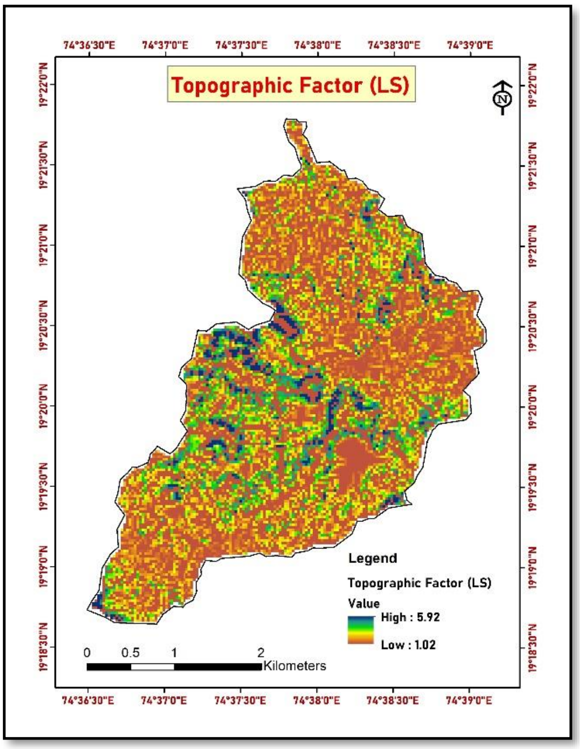

Figure 4.20 Topographic factor map of the watershed

4.5.1.4 Crop Management (C) Factor

The Crop management (C) factor indicates the impact of different crop management practices on soil erosion rates. The C factor values range from 0 to 1, with higher values indicating higher erosion potential due to poor management practices. The land cover classification of the central MPKV campus watershed indicated that barren land was the dominant land cover before the adoption of conservation measures, compared to other land covers. The crop management factor map of the watershed before the adoption of conservation measures is shown in Fig. 4.21a. The barren land has a maximum C-factor value, indicating that the area is at high risk of soil erosion. Similarly, a lower value of C-factor (0.04) was assigned to the dense vegetation cover that was found in forest areas. The C factor was set to zero for waterbodies and settlement areas because the soil is completely covered with other medium in these areas. The C factor values are high for those land cover where obstruction to soil erosion is less and low C factor values are for those land cover where there is greater obstruction to the eroding soil. So, in order to change land utilization and reduce soil loss from the watershed, sustainable land management practises must be implemented in the watershed's barren land cover.

4.5.1.5 Conservation Practice (P) Factor

The conservation practice factor (P) refers to the effect of soil conservation practices on reducing soil erosion rates. The factor takes into account the effectiveness of different conservation practices in reducing soil erosion. The conservation practice factor value generally ranges from 0 to 1. A zero value indicates there is complete protection of SWC measures against soil erosion, whereas one value indicates no protection of SWC measures against soil erosion. Before the adoption of conservation measures in the watershed, a P factor value of 1 was assigned to the entire area.

4.5.1.6 Soil Loss Rate Before the Adoption of Conservation Measures

The average annual soil loss from the watershed before the adoption of conservation measures varied from 0 to 78.23 t/ha/yr, with a mean soil loss rate of 18.68 t/ha/yr. Soil erosion alone resulted in the loss of 23119.36 tonnes of soil from the watershed each year. The tolerable soil loss limit for watershed in tropical region is 11 t/ha/yr (Hudson, 1995). The soil loss rate from the watershed before the adoption of conservation measures was well above the tolerable limit resulting in severe loss of fertile soil from the watershed. The soil loss rates were classified into five categories for easy interpretation of soil loss dynamics from the watershed: slight (0-5 t/ha/yr), moderate (5-10 t/ha/yr), moderately severe (10-20 t/ha/yr), severe (20-40 t/ha/yr) and extremely severe (> 40 t/ha/yr) soil erosion risk. It was found that 28.99% of the watershed area was under slight erosion class. This area was mainly in the plains of the watershed where agricultural land cover was dominant. Similarly, moderate erosion risk was found in 12.82% of the watershed area, moderately severe erosion risk in 17.18%, severe erosion risk in 31.52%, and extremely severe erosion risk in 9.49% of the watershed area. The severity of soil erosion was directly affected by the LU/LC, soil type, topography and rainfall intensity. Areas with dense vegetation cover, flat lands and cohesive soils were found to have less soil erosion. Whereas areas with no or sparse vegetation, steep and long slopes were found to have severe soil erosion. The results of soil loss before the adoption of conservation measures emphasise the importance of soil conservation within the watershed in order to maintain soil quality and fertility. Implementing site-specific conservation measures in the watershed can help to keep soil loss within a tolerable limit while also improving soil quality.

4.5.1.7 Soil Loss from the Watershed After the Adoption of Conservation Measures

The rate of soil loss before conservation measures has made it clear that soils within the watershed are more vulnerable to soil erosion hazards. Therefore, they should be conserved in order to maintain the fertility of the soil. As a result, site specific conservation measures were implemented in the watershed and their impact on soil erosion was analysed.

The soil loss from the watershed after conservation measures was measured similarly to the soil loss before conservation measures. Three of the five USLE model parameters were used in the same way as before conservation measures because these parameters are not impacted by conservation measures. These three parameters are rainfall erosivity (R), soil erodibility (K) and slope length (LS) factor. It was found that rainfall pattern, soil type and land slope fluctuate over long decades and only minor changes in these parameters occur on yearly basis. This minor change can be negligible therefore for measuring soil loss after conservation measures R, K and LS parameters were kept unchanged.

The change detection analysis showed that there were significant changes in the land use/ land cover (LU/LC) after the implementation of the SWC measures in the watershed. Therefore, the crop management factor (C) map, which depends entirely on LU/LC, has changed after the implementation of conservation measures. The C factor map of the watershed after the adoption of conservation measures is shown in Fig. 4.21b. The C-factor values used for different pre-conservation land covers were thought to be similar after conservation measures. Only the area under C-factor values changed with changing land cover area. After the adoption of conservation measures, the area under C-factor values for agriculture, forestry, horticulture, settlements and waterbodies increased, while the areas under barren land and current fallow land decreased.

Implementation of SWC measures directly affected the conservation practice (P) factor of the watershed. The various site-specific conservation measures implemented in the watershed changed the P factor values of the watershed. The P factor value of 1 was considered for entire watershed before the adoption of conservation measures, but after the adoption of conservation measures, the specific value of each conservation measures obtained from the previous literature was provided. The major land area treatments taken in the watershed were deep continuous contour trench (DCCT) on 495 ha area and compartment bunding on 50 ha area. The P factor values of 0.15 and 0.03 were used for the DCCT and compartment bunding, respectively (Singh *et al.*, 1990). The P-factor value of 1 was used for the remaining areas without any conservation measures. The P factor map of the watershed after the adoption of conservation measures is shown in Fig. 4.22.

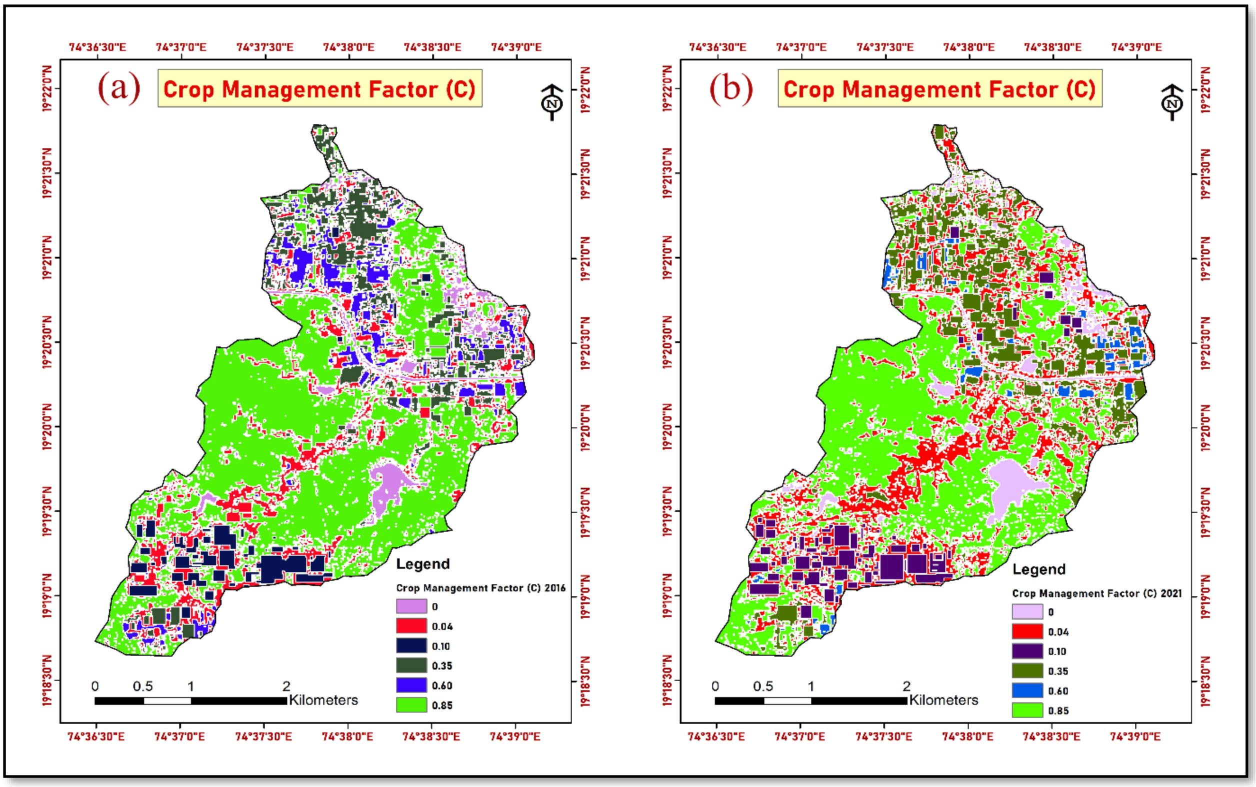

Figure 4.21 Crop management factor map of the watershed a) before the adoption of conservation measures b) after the adoption of conservation measures

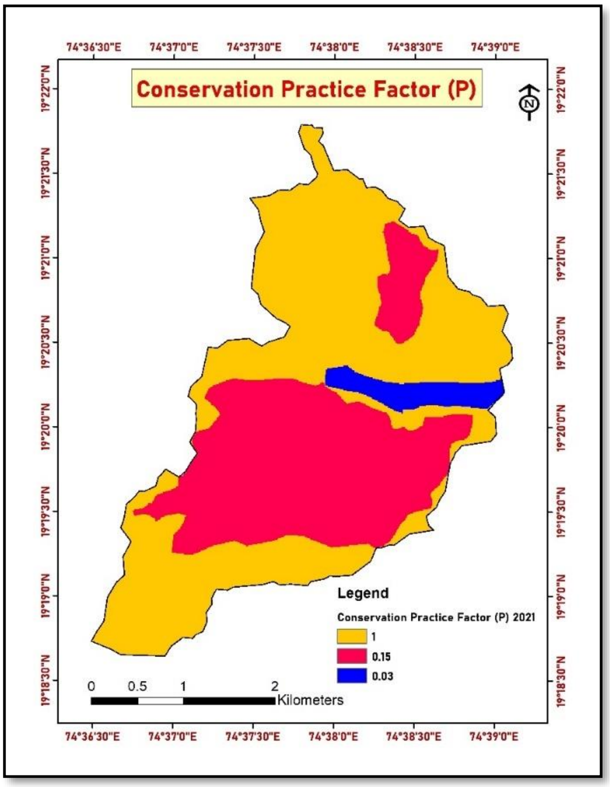

Figure 4.22 After the adoption of conservation measures P factor map of the watershed

4.5.1.8 Soil Loss Rate After the Adoption of Conservation Measures

The after the adoption of conservation measures soil loss from the watershed ranged from 0 to 53.24 t/ha/yr, with a mean soil loss rate of 9.41 t/ha/yr. The spatial distribution of soil loss from the watershed before and after the adoption of conservation measures is shown in Fig. 4.23. After adoption of conservation measures, soil loss from the watershed was reduced upto 11560.6 tonnes per year. This soil loss rate from the watershed is well below the tolerable soil loss limit. Indicating that there is balance of rate of soil formation and the rate of soil loss. The impact of scientifically planned and constructed conservation measures was visible not only in the treated part of the watershed but also in the surrounding areas of the watershed. The obstructions created in the upper reaches of the watershed to the flowing water by implementing SWC measures reduce runoff and subsequent sediment transportation in the upper, middle and lower reaches of the watershed.

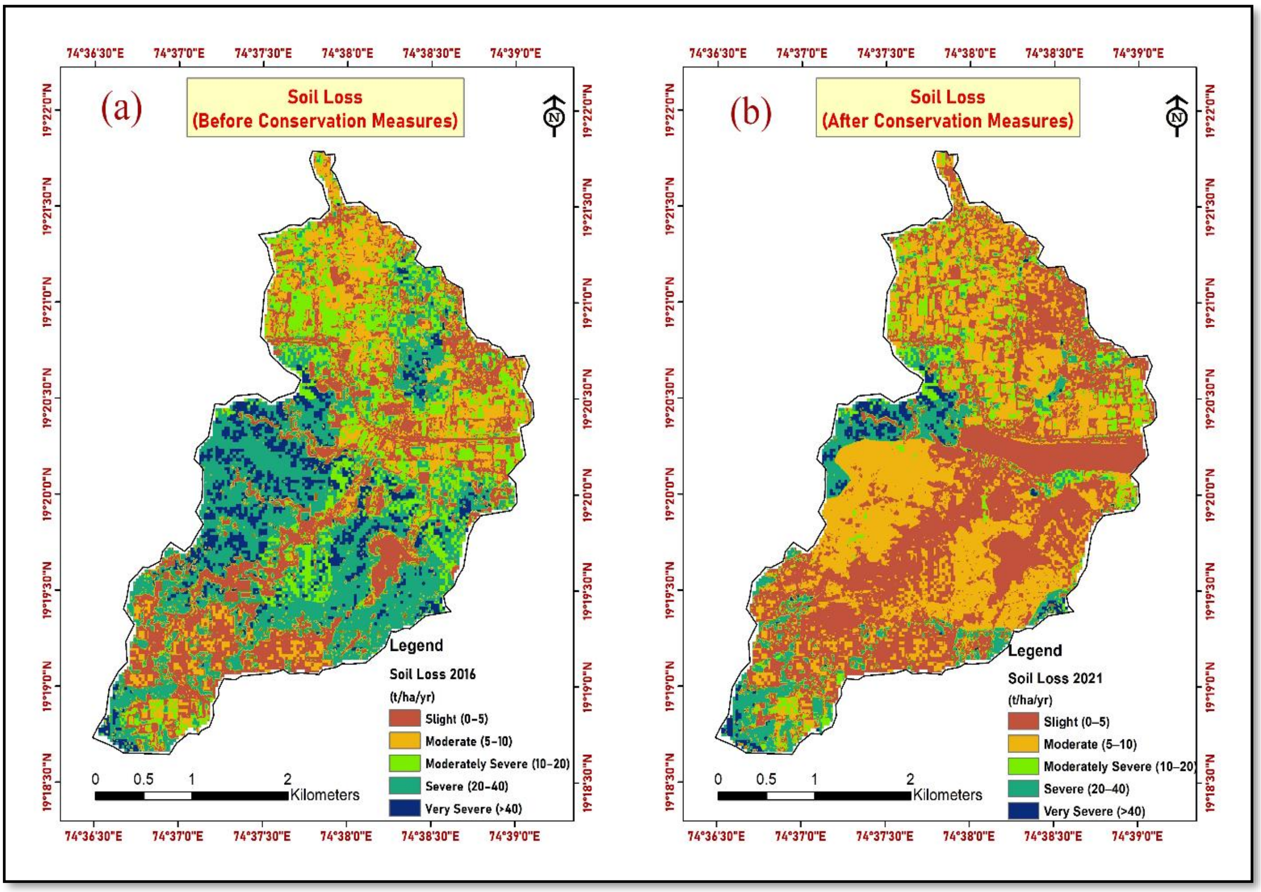

Figure 4.23 Soil loss map of the watershed a) before the adoption of conservation measures b) after the adoption of conservation measures

The adoption of conservation measures in the watershed resulted in a 50% reduction in soil loss rate compared to the rate before the adoption of conservation measures. The results were validated by examining soil accumulation in SWC measures. The soil accumulation in deep continuous contour trenches (DCCT) for three sampling years is given in the table 4.25. It was found that between 2020 and 2022, the DCCT built in the watershed accumulated a total of 4410 tonnes of soil. This demonstrates that SWC measures implemented in the watershed are highly effective in soil conservation. The higher efficiency of SWC measures in soil loss control is consistent with other local studies by Bhattacharyya *et al.,* 2015, Kumawant *et al.*, 2020 and Nasir Ahmad *et al.,* 2020.

Table 4.25 Yearly soil accumulation in deep continuous contour trenches

Year	2020	2021	2022	Total
Yearly depth of soil accumulated in DCCT (cm)	2.7	1.6	1.9	6.2

Similar to before the adoption of conservation measures soil loss rate classification, after the adoption of conservation measures soil loss rate was also classified into five classes. The classification of soil loss rate and area under each soil erosion class before and after the adoption of conservation measures is shown in table 4.26 and Fig. 4.24. It was observed that the area under slight and moderate erosion classes increased by 20% each and the areas under moderately severe, severe and extremely severe erosion classes decreased by 10%, 20% and 6%, respectively. This finding indicates that conservation measures can significantly reduce the risk of soil erosion in the watershed. Almost 75% of the watershed area is now classified as having a low to moderate risk of erosion and only 13% of the watershed area remains in the severe to extremely severe erosion risk class. The spatial distribution of soil loss reveals that areas with high erosion risk are situated in regions of long and steep slopes, sparse vegetation cover and fine textured soils with no conservation measures. This implies that the implementation of conservation measures should be approached with a strategic plan that prioritizes areas most vulnerable to soil erosion. In other words, the adoption of conservation measures should be targeted towards regions that are at the highest risk of soil loss to ensure maximum effectiveness. The study findings revealed that it is possible to achieve a significant reduction in the rate of soil loss provided that conservation measures are planned and constructed in a scientific manner.

Table 4.26 Area under different soil erosion classes before and after the adoption of conservation measures

Soil Erosion Class	Soil loss (t/ha/yr)	Before Conservation Measures	After Conservation Measures
		Area (ha)	Area (ha)
Slight	< 5	365.27	574.75
Moderate	5 to 10	161.54	414.36
Moderately Severe	10 to 20	216.51	102.53
Severe	20 to 40	397.13	130.12
Very Severe	>40	119.54	38.22

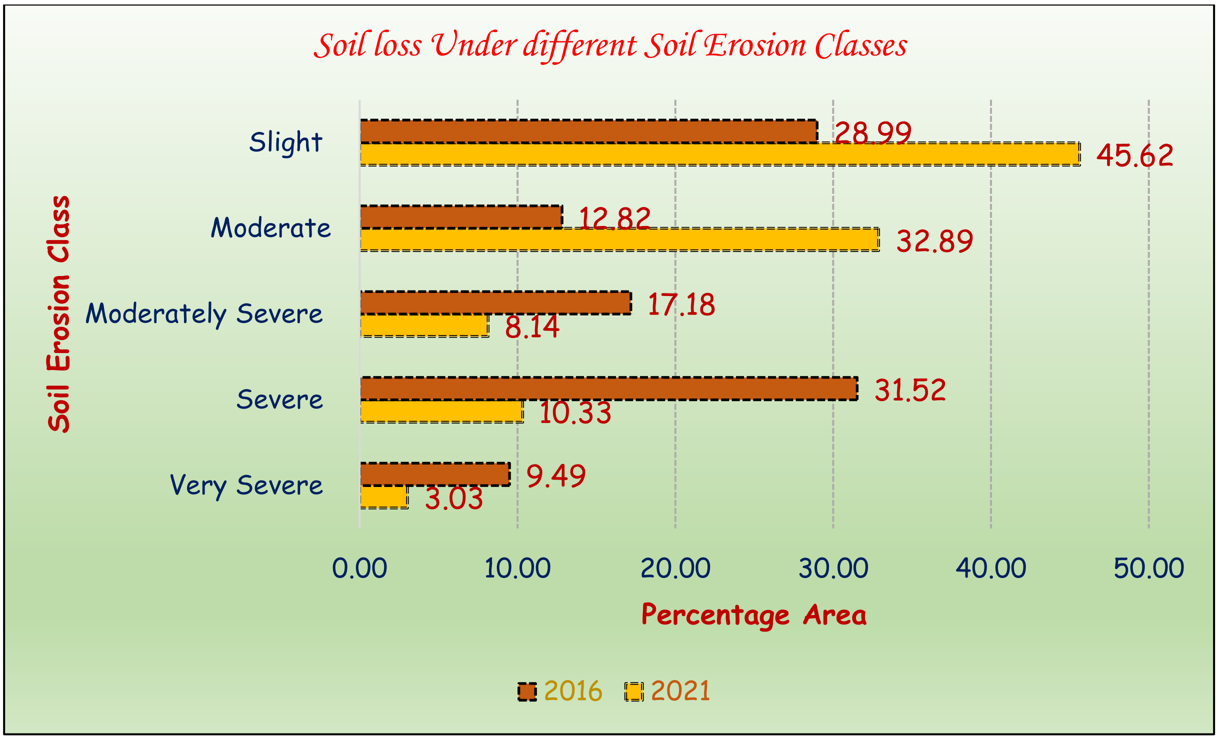

Figure 4.24 Soil loss under different soil erosion classes before and after the adoption of conservation measures

4.5.2 Carbon Loss from the Watershed

The carbon loss associated with soil loss from the watershed was estimated before and after the adoption of conservation measures. The carbon loss associated with soil loss is function of soil organic carbon content, soil erosion and carbon enrichment ratio. The carbon loss associated with soil loss can have significant implications for ecosystem health and function, as it can negatively impact soil fertility, reduce plant growth and productivity and increase greenhouse gas emissions.

4.5.2.1 Soil Organic Carbon Content Before and After the Adoption of Conservation Measures

The soil organic carbon (SOC) content before and after the adoption of conservation measures under different land covers in the watershed is given in table 4.27. The average SOC content before and after the adoption of conservation measures in the watershed was 0.62% and 0.72%, respectively. It was observed that SOC content was increased in each major land cover class but the rate of increase was varied depending on the land cover class. Natural forest land cover has the highest SOC increase rate while barren land has the lowest. Thematic layers of SOC generated with Arc GIS software were used to estimate carbon loss from the watershed. The spatial distribution of SOC content in the watershed before and after the adoption of conservation measures is shown in Fig. 4.25.

Table 4.27 Soil organic carbon content before and after the adoption of conservation measures under different land covers in the watershed

Land cover	SOC content before the adoption of conservation measures (%)	SOC content after the adoption of conservation measures (%)	Total number of samples
Agriculture land	0.64 ± 0.07	0.76 ± 0.10	10
Barren land	0.51± 0.10	0.56 ± 0.11	15
Natural forest land	0.70 ± 0.08	0.81 ± 0.07	15
Horticulture land	0.65 ± 0.04	0.78 ± 0.10	10
Average	**0.62**	**0.72**	

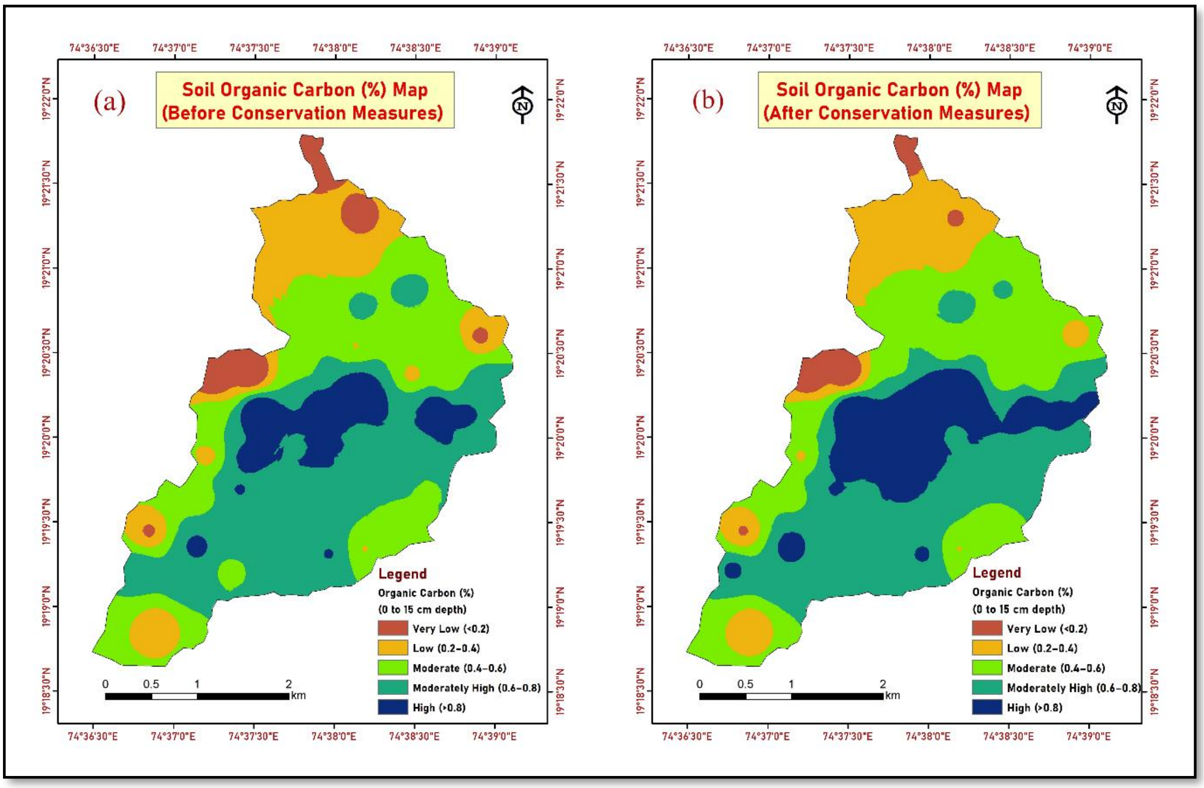

Fig. 4.25 Soil organic content map of the watershed a) before the adoption of conservation measures b) after the adoption of conservation measures

4.5.2.2 Carbon Enrichment Ratio Map of the Watershed

The carbon enrichment ratio (CER) layers generated using Arc GIS software were used in the estimation of carbon loss from the watershed. The spatial distribution of CER values in the watershed before and after the adoption of conservation measures is shown in Fig. 4.26. The CER value depends on the classes of soil erosion rate. Higher soil erosion rates have lower CER values, while lower soil erosion rates have higher CER values. Sheet erosion is the dominant mechanism at low soil erosion rates, resulting in the loss of fertile topsoil containing the majority of SOC and being the cause of high CER values at low soil erosion rates. Similarly, at high soil erosion rates, rill and channel erosions are the dominant mechanisms affecting the subsoil layer, which contains relatively less SOC and thus has a low CER value (Mandal *et al.*, 2020). The CER values in the watershed were ranged from 2.04 for extremely severe erosion class to 3.62

for slight erosion class. The 48% of watershed area was having the CER value of 2.3 before conservation measures and after conservation measures 45% area was having the CER value of 3.62. The change in the area under CER ratio was observed due to significant difference in the rate of soil erosion before and after conservation measures.

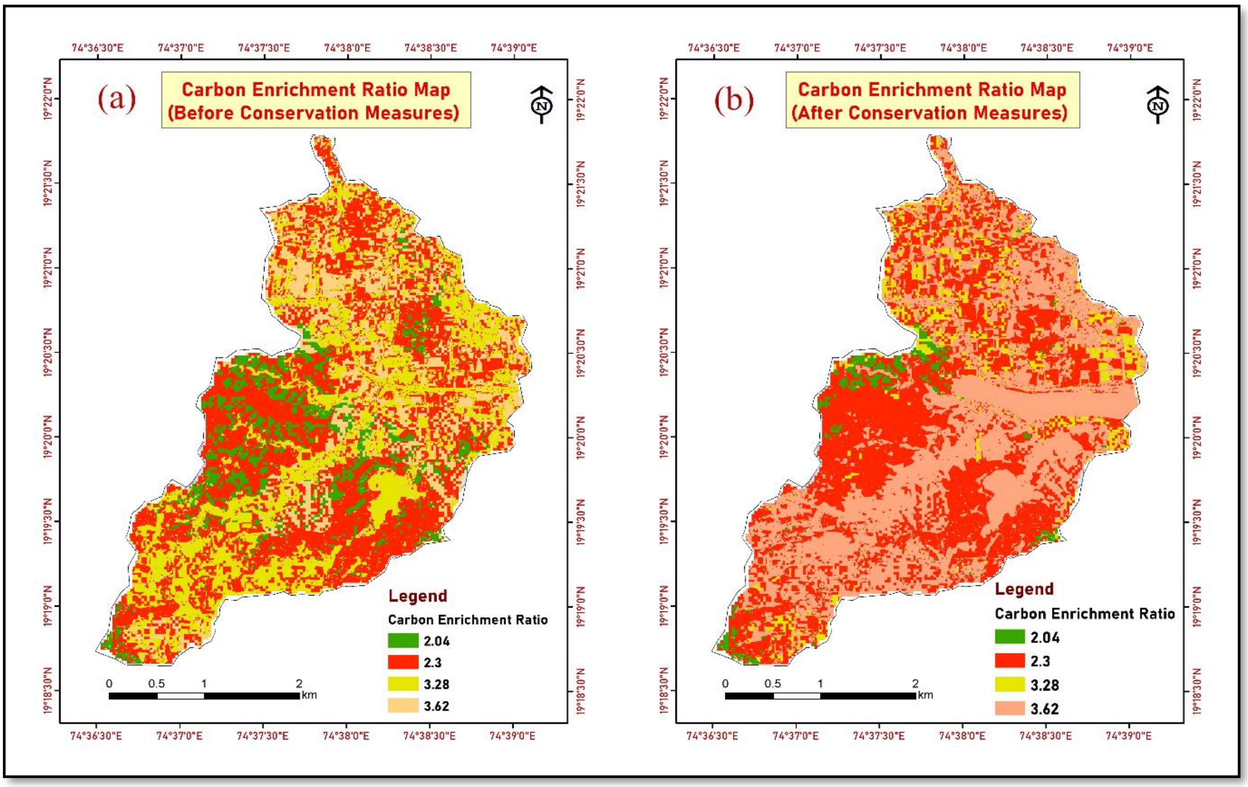

Figure 4.26 Carbon enrichment ratio map of the watershed a) before the adoption of conservation measures b) after the adoption of conservation measures

4.5.2.3 Before the Adoption of Conservation Measures Carbon Loss from the Watershed

The average annual carbon loss before the adoption of conservation measures from the watershed varied from 0 to 618.42 kg C/ha/year, with a mean carbon loss rate of 348.71 kg C/ha/year. Annual carbon loss through soil erosion from the watershed was 439.37 tonnes of carbon before the adoption of conservation measures. The severity of carbon loss was found in areas where soil erosion risk was moderate, moderately severe and extremely severe. The CO_2 emitted into the atmosphere due to soil erosion was 1611.16 tonnes of CO_2 per year. It was found that soil degradation due to erosion was one of the main causes of carbon emissions from the watershed. To understand the soil carbon emission dynamics of the watershed, carbon loss rate was categorized into five classes i.e., very low (0-100 kg C/ha/year), low (100–200 kg C/ha/year), moderate (200–300 kg C/ha/year), severe (300–400 kg C/ha/year), extremely severe (>400 kg C/ha/year) carbon erosion risk area. Out of the total watershed area, 25.63% area was found under a very low risk carbon loss area. This region was characterized primarily by flatlands with dense vegetation cover and low soil erosion rates. Similarly, the area under moderate, moderately severe, severe and extremely severe carbon erosion classes was 19.84%, 34.52%, 14.68% and 5.32%, respectively. Nearly 53% of the watershed area had a carbon loss rate above 200 kg C/ha/yr before the adoption of conservation measures. It was observed that as the severity of soil erosion increased, so did the rate of carbon erosion. The rate of carbon loss in the watershed varied according to land cover, with the highest rate observed in barren land and the lowest rate observed in natural forests. Soil carbon loss was also significantly affected by the organic carbon content and carbon enrichment ratio in the top soil layer. A greater rate of carbon loss was observed in land covers characterized by moderate to severe soil erosion rates, high SOC content and high CER values. Therefore, this area of the watershed requires soil conservation and restoration in order to reduce carbon losses.

4.5.2.4 After the Adoption of Conservation Measures Carbon Loss from the Watershed

After the adoption of conservation measures in the watershed, carbon loss from the watershed ranged from 0 to 438.30 kg C/ha/year, with a mean of 190.52 kg C/ha/yr. The spatial distribution of carbon loss from the watershed before and after the adoption of conservation measures is shown in Fig 4.27. The carbon loss after the adoption of conservation measures was reduced by 45% as compared to the carbon loss before conservation measures. The adoption of conservation measures in the watershed resulted in a decrease in annual soil carbon loss from 398.46 tonnes of C/year to 218.95 tonnes of C/year and a decrease in annual CO_2 emissions from 1461.15 tonnes of CO_2/year to 802.88 tonnes of CO_2/year. Carbon loss from a watershed can occur through mineralization, where organic carbon is converted to carbon dioxide and released into the atmosphere, or through the redistribution of carbon out of the watershed boundary, such as through erosion and transport of soil particles containing organic carbon.

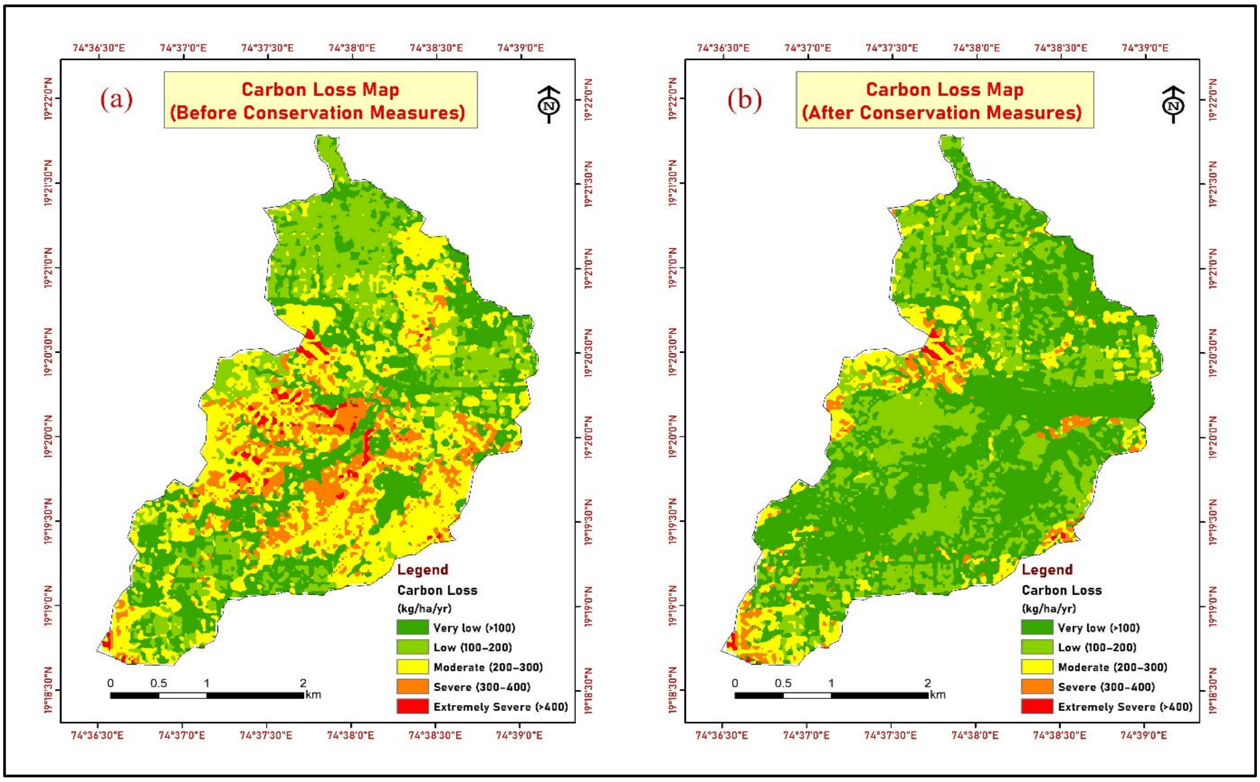

Figure 4.27 Carbon loss map of the watershed a) before the adoption of conservation measures b) after the adoption of conservation measures

Similar to the before the adoption of conservation measures carbon loss classification, after the adoption of conservation measures carbon loss was also classified into five classes. The carbon loss classification of the watershed before and after the adoption of conservation measures is shown given in table 4.28 and Fig. 4.28. It was found that the area under the very low carbon loss class was 44.44%. Similarly, the area under low, moderate, severe and extremely severe carbon erosion classes was found as 32.94%, 13.65%, 6.43% and 2.54%, respectively. The area under very low and low carbon erosion classes increased by 20% and 13%, respectively. Whereas areas under moderate, severe and extremely severe erosion risk classes decreased by 20%, 8% and 3%, respectively. Nearly 75% of the watershed area is under the very low to low carbon erosion class. It was found that adoption of site specific SWC measures not only helps with soil loss reduction but reduces soil carbon emissions from the watershed. Reduced carbon loss from the watershed was primarily achieved through reduced soil erosion rates in the watershed as a result of the implementation of site-specific conservation measures in the watershed. The findings of the study demonstrate that scientifically planned SWC measures in the watershed reduce soil loss rates, reduce soil carbon emissions, and increase soil carbon sequestration. The SWC measures in the watershed serve as climate change mitigation and adaptation measures, aiding in the fight against climate change. In order to develop climate-smart watersheds, the adoption of location specific SWC measures should be considered as component of climate change mitigation during the planning and management of watersheds. Remaining, 25% of the watershed area is classified as having severe to extremely severe carbon loss. This area of the watershed requires long-term conservation strategies to further reduce carbon losses and increase carbon sequestration.

Table 4.28 Area under different carbon loss classes before and after the adoption of conservation measures

Carbon Loss Classes	Carbon Loss Range (kg C /ha/yr)	Before Conservation Measures	After Conservation Measures
		Area (ha)	Area (ha)
Very low	<100	323	560
Low	100-200	250	415
Moderate	200-300	435	172
Severe	300-400	185	81
Extremely Severe	>400	67	32

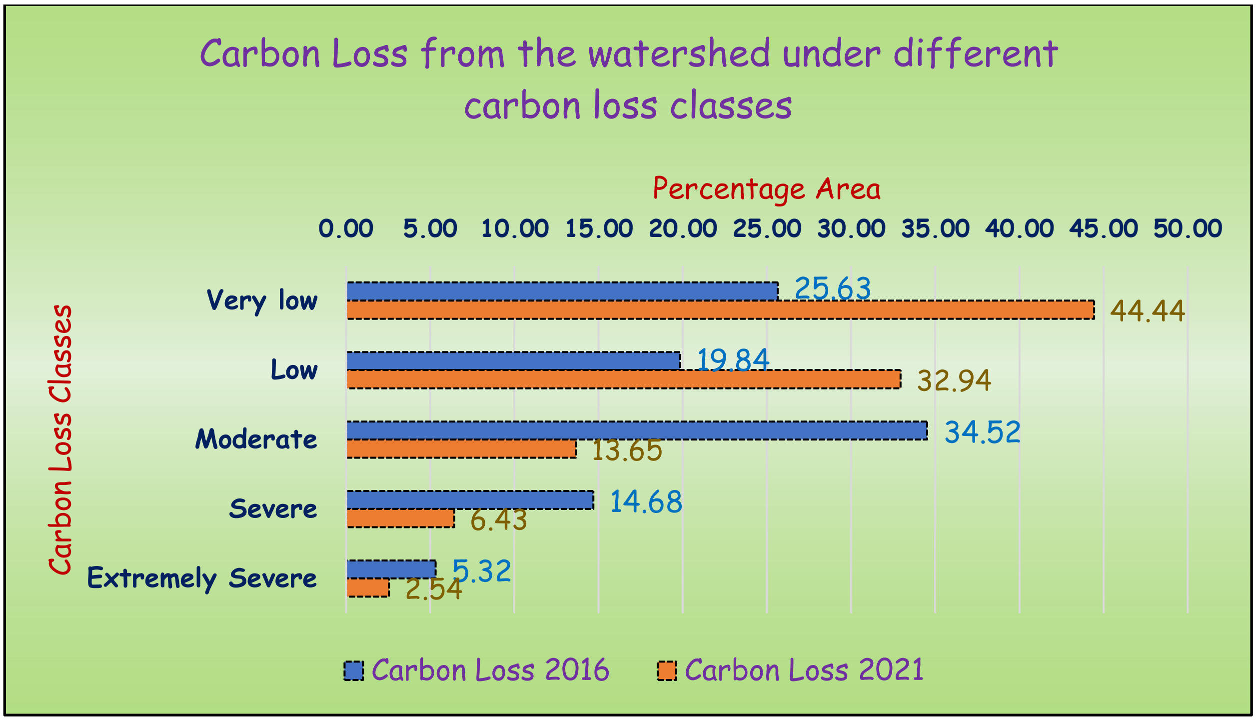

Figure 4.28 Carbon loss from the watershed under different carbon loss classes

4.6 Development of Conservation Strategies for Carbon Sequestration in the Watershed.

The central MPKV campus watershed has recently undergone scientifically planned soil and water conservation (SWC) treatments. Approximately 45% of the watershed has undergone diverse SWC measures, which include both drainage line and land area treatments. It has been observed that the SWC measures implemented in nearly half of the watershed have significantly affected land utilization, soil erosion rates, carbon loss rates and carbon sequestration. These measures have increased water availability, accelerated vegetation growth, reduced soil loss, minimized carbon emissions and redistribution and increased carbon sequestration in the watershed. However, half of the watershed area still lacks SWC measures, indicating the potential to further reduce soil loss and associated carbon loss. This would help minimize soil carbon emissions from the watershed and increase its carbon sequestration capacity. Considering this, additional SWC strategies are recommended for the untreated areas of the watershed.

4.6.1 Recommended Soil and Water conservation Measures in the Watershed

Soil and water conservation (SWC) measures are crucial in watersheds for several reasons. They prevent soil erosion and protect water quality by reducing sedimentation in water bodies. Additionally, these measures can improve water availability by increasing the amount of water stored in the soil, which is essential for maintaining stream flow during dry periods. Soil and water conservation measures also support biodiversity by providing food and habitat for a variety of plant and animal species. By safeguarding the health and productivity of the ecosystem, these measures ensure the long-term sustainability of the watershed (Belay and Eyasu, 2019).

Soil and water conservation (SWC) measures can play a critical role in mitigating climate change and promoting carbon sequestration. By reducing soil erosion, these measures also prevent carbon loss from the soil, which can be a significant source of greenhouse gas emissions. Additionally, SWC measures help to improve soil health and fertility, which increases plant growth and productivity, leading to more carbon uptake from the atmosphere. Therefore, the implementation of these measures can help to reduce greenhouse gas emissions and increase carbon sequestration thus contributing to global efforts to mitigate the impacts of climate change.

Soil and water conservation (SWC) measures for the watershed were recommended based on a thorough analysis of climatic, soil and topographic conditions. Various thematic layers, such as rainfall, drainage network, slope, land use/land cover, soil depth and soil texture, were generated in the ArcGIS environment. The 'Overlay Analysis' tool in ArcGIS was utilized to identify suitable sites for both drainage line and land area treatments. The methodology, including the criteria for site selection of SWC measures for arable and non-arable land, is detailed in section 3.11. The identified sites for drainage line and land area treatments are presented in Figs. 4.29 and 4.30 while tables 4.29 and 4.30 provides a list of both newly recommended and existing drainage line and land area treatments in the watershed.

Table 4.29 Recommended drainage line treatments in the watershed

Drainage Line Treatments	Existing Treatments	Newly Suggested	Total
Earthen Nala Bund	38	12	50
Cement Nala Bund	-	3	3
Percolation Tank	2	1	3
Check Dam	-	4	4
Loose Boulder Structure	97	87	184
Kolhapur Type Weir	-	2	2

Table. 4.30 Recommended land area treatments in the watershed

Land Area Treatments	Existing Area (ha)	Newly Suggested Area (ha)	Total Area (ha)
Compartment Bunding	50	304	354
Contour Bunding	-	192	192
Deep CCT	495	89	584
Bench Terraces	-	130	130

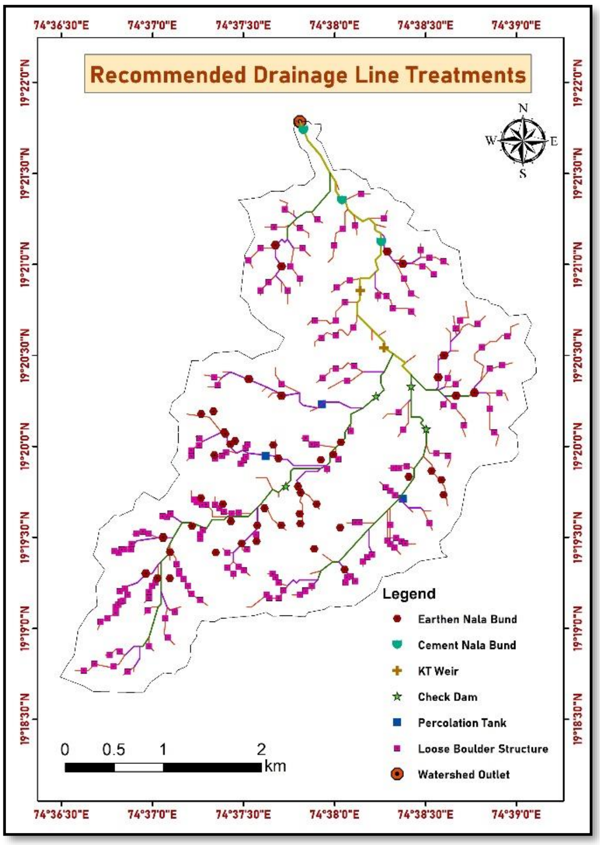

Figure 4.29 Recommended drainage line treatments in the watershed

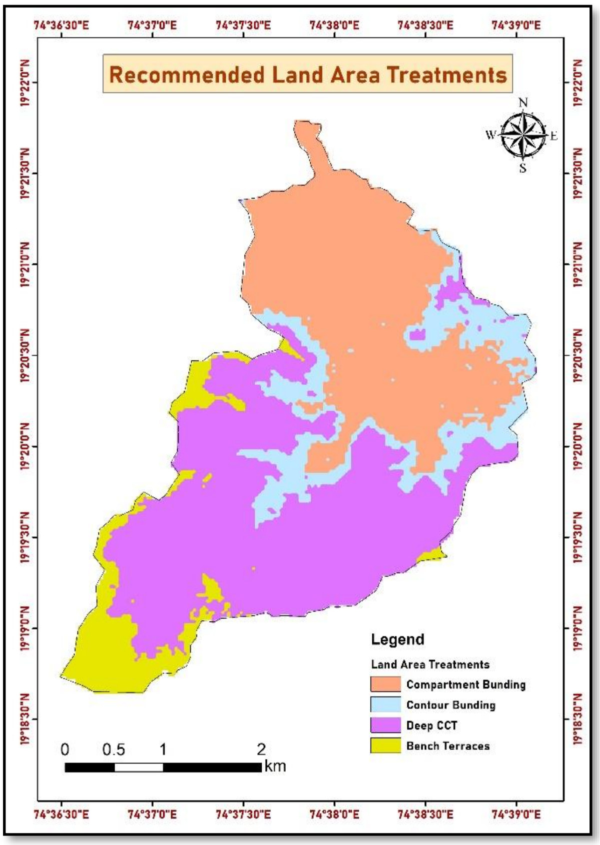

Figure 4.30 Recommended land area treatments in the watershed

4.6.1.1 Recommended Drainage Line Treatments in the Watershed

Currently, there are 137 existing drainage line treatments in the watershed, which include earthen nala bunds (38), percolation tanks (2), and loose boulder structures (97). The proposed drainage line treatments for the watershed comprise of 109 structures, consisting of earthen nala bunds (12), cement nala bunds (3), percolation tanks (1), check dams (4), loose boulder structures (87) and Kolhapur Type (KT) weirs (2). Once the recommended drainage line treatments are implemented, there will be a total of 246 drainage line structures in the watershed. By combining the existing and newly proposed drainage line treatments, the watershed will have a comprehensive network of structures to control soil erosion and improve water resource management. Implementation of suggested drainage line treatments in the watershed can provide several benefits, including the control of soil erosion and the management of water resources. Drainage line treatments can reduce the velocity of water and prevent soil erosion caused by high velocity runoff. This, in turn, helps to maintain soil productivity and reduce sedimentation in water bodies. Additionally, by retaining water in the soil, drainage line treatments can help to recharge groundwater resources and maintain the water level in streams and rivers, even during dry periods. These treatments can also help to reduce the impact of floods by preventing or reducing the accumulation of water in low-lying areas. Therefore, the implementation of drainage line treatments can help in storage of water resources for longer period, to promote sustainable land use practices and support the long-term health and productivity of the watershed.

4.6.1.2 Recommended Land Area Treatments in the Watershed

Currently, land area treatments in the watershed consist of compartment bunding on 50 ha and deep continuous contour trenches (DCCT) on 495 ha, covering a total of 545 ha or approximately 45% of the watershed. However, the remaining area of the watershed is still susceptible to severe soil erosion, necessitating additional land area treatments. The newly recommended treatments for the watershed include compartment bunding (304 ha), contour bunding (192 ha), DCCT (89 ha) and bench terraces (130 ha). While compartment bunding, contour bunding and bench terraces are proposed for arable land, DCCTs are recommended for non-arable land. The proposed treatments are intended to cover the remaining area of the watershed and are expected to improve soil conservation and reduce soil erosion risk. The land area treatments proposed for the watershed are expected to have a positive impact on soil quality and facilitate vegetation growth, which in turn can enhance carbon sequestration in the soil. Furthermore, these treatments can reduce soil erosion, which can prevent carbon loss from the soil. Therefore, it can be inferred that the suggested land area treatments in the watershed will not only promote sustainable land use practices but also boost the carbon sequestration capacity of the soil while reducing the risk of soil erosion.

4.6.1.3 Impact of Recommended Soil and Water Conservation Measures on Soil Loss

The impact of the recommended soil and water conservation (SWC) measures on soil loss was assessed by estimating the amount of soil loss from the watershed after the implementation of these measures. Soil loss was estimated using the same method that was used to estimate soil loss before the implementation of the SWC measures. To evaluate the impact of the SWC measures on soil loss, all parameters of the Universal Soil Loss Equation (USLE) model were kept constant, except for the conservation practice factor.

4.6.1.4 Improved Conservation Practice Factor (P)

Implementing the suggested SWC measures in the watershed will enhance the conservation practice factor of the area. Initially, the P factor of the entire watershed was considered as one before implementing any conservation measures. However, after the recommended conservation practices are put in place, the entire watershed will come under some form of soil conservation treatment. This results in an enhanced conservation practice factor for the watershed, achieved by assigning corresponding weighted P factor values to the relevant SWC treatments in an ArcGIS environment. Table 4.31 shows the P factor values allocated to the land area treatments, and the improved P factor map of the watershed is illustrated in Fig 4.31.

Table 4.31 Land area treatment and conservation practice factor

Land Area Treatments	Conservation practice factor (P)
Compartment Bunding	0.03
Contour Bunding	0.1
Deep CCT	0.15
Bench Terraces	0.2

(Singh *et al.*, 1990)

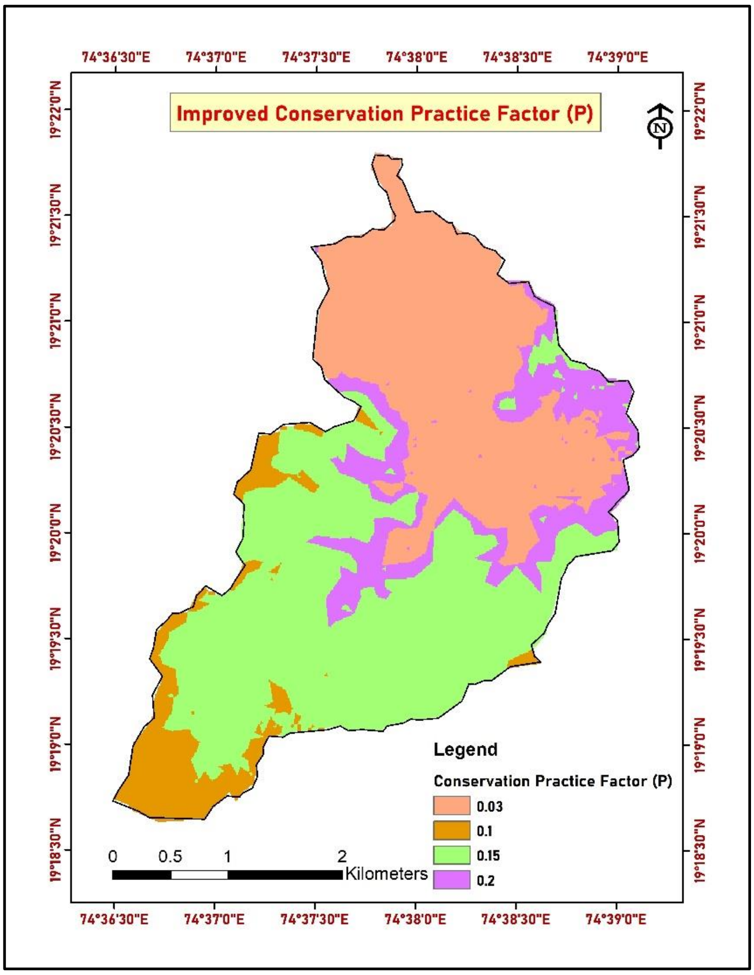

Figure 4.31 Improved conservation practice factor map of the watershed

4.6.1.5 Soil loss from the Watershed After the Implementation of Recommended SWC Measures

The implementation of recommended conservation measures in the watershed is expected to result in an average annual soil loss rate ranging from 0 to 19.53 t/ha/yr, with a mean soil loss rate of 6.17 t/ha/yr. This average annual soil loss rate is approximately half of the tolerable soil loss limit. In addition to soil conservation, the suggested additional conservation measures will also enhance soil quality. The implementation of these conservation measures is expected to result in a 65% reduction in soil loss rate compared to the soil loss rate without conservation measures, and a 35% reduction compared to the current soil loss rate of partial watershed treatment. After the implementation of recommended conservation measures, the average soil loss in the watershed is expected to decrease from the current level of 11560.6 tonnes per year to

6940.2 tonnes per year. The spatial distribution of soil loss after implementing recommended SWC measures is illustrated in the Fig. 4.32.

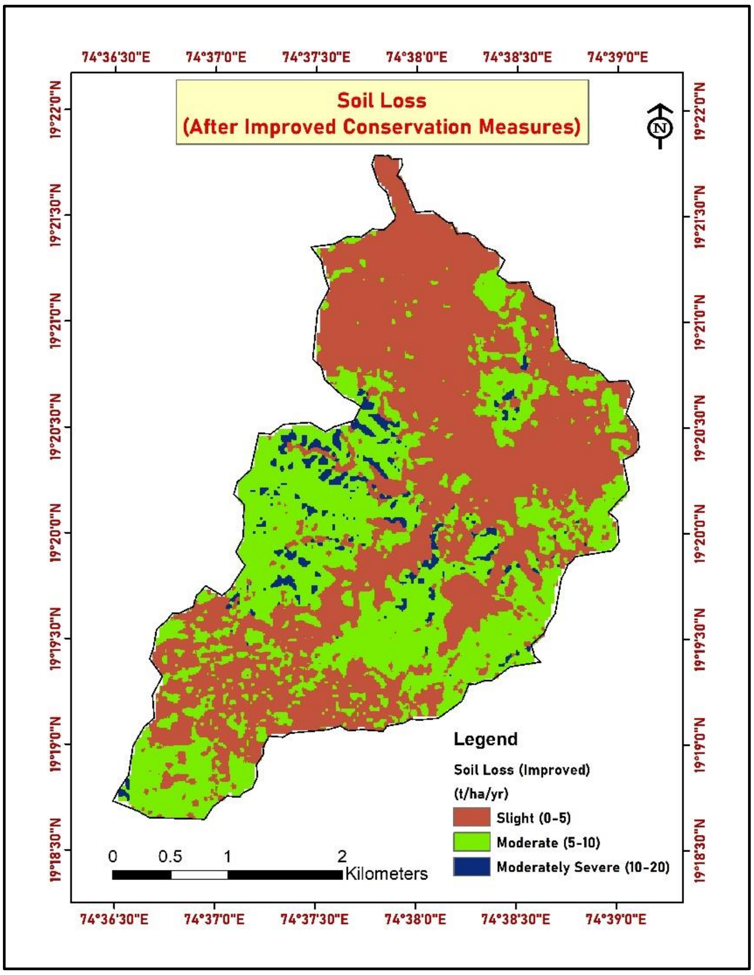

Figure 4.32 Soil loss from the watershed after the implementation of recommended SWC measures

After the implementation of recommended SWC measures in the watershed, the soil loss rate was classified into three categories. Table 4.32 provides information on the different soil erosion classes and the corresponding area of each erosion class. The results showed that 50% of the watershed area will experience a slight erosion rate, followed by a moderate erosion rate (43%) and a moderately severe erosion rate (7%). The combined area under slight and moderate erosion will increase to 93% from the current 78% of the watershed area. Although the area under moderately severe erosion will decrease slightly, there will be no area in the watershed with soil erosion rates in the severe and extremely severe erosion categories after implementing the recommended SWC measures. The implementation of additional recommended SWC measures in the watershed will offer a range of benefits, including reduced soil erosion, improved soil quality and fertility, healthy vegetation growth, flood and drought mitigation, enhanced water quality, and improved biodiversity. The improved SWC measures will reduce soil erosion rates, preventing the loss of fertile topsoil and safeguarding crops from damage caused by sedimentation. This can eventually result in increased crop yields, promoting food security for local communities. In general, soil conservation in a watershed is a vital aspect of promoting sustainable land use practices and protecting natural resources for future generations.

Table 4.32 Soil erosion classification and corresponding area under each class

Soil Erosion Class	Soil loss (t/ha/yr)	Area (ha)	Area (%)
Slight	< 5	631	50.08
Moderate	5 to 10	543	43.10
Moderately Severe	10 to 20	86	6.83

4.6.1.6 Carbon Loss from the Watershed After the Implementation of Recommended SWC Measures

After the implementation of recommended conservation measures in the watershed, it is expected that the average annual carbon loss rate will range from 0 to 286.45 kg C/ha/yr, with a mean carbon loss rate of 125.64 kg C/ha/yr. This represents a 35% reduction in average carbon loss rate compared to current levels. The resultant reduction in soil carbon emissions from the watershed will contribute to climate change mitigation. Specifically, the implementation of conservation measures is expected to reduce carbon loss from the current level of 218.95 tonnes of C per year to 143.85 tonnes of C per year. To further elaborate, the carbon loss after the implementation of conservation measures was classified into three categories. The corresponding carbon loss rate and area under each category are provided in the table 4.33. It was observed that 47% of the watershed area will experience very low carbon loss rates, i.e., below 100 kg C/ha/yr, and the area under low carbon loss rate will increase from 33% to 44%. The area under moderate carbon loss rate will decrease from 9% to 14%. Ultimately, 91% of the watershed area will experience carbon loss rates below 200 kg C/ha/yr, up from the current 77% of the watershed area. The spatial distribution of carbon loss expected after the implementation of conservation measures in the watershed is shown in Fig. 4.33.

Table 4.33 Carbon erosion classification and corresponding area under each class

Carbon Loss Class	Range (kg C/ha/yr)	Area (ha)	Area (%)
Very low	0-100	595	47.22
Low	100-200	552	43.81
Moderate	200-300	113	8.97

The implementation of recommended conservation measures in the watershed will significantly reduce the soil carbon loss rate, which will positively impact the environment in multiple ways. For instance, reduced carbon loss will help to enhance the soil's carbon sequestration capacity, which will improve soil health, nutrient availability for plants, and water holding capacity. As a result, crop yields will increase, leading to better food security for communities dependent on agriculture. Furthermore, the preservation of soil carbon in the watershed will prevent it from being released into the atmosphere and contribute to reducing the levels of carbon dioxide in the air. Overall, the reduced soil carbon loss rate resulting from the implementation of recommended SWC measures will promote sustainable land use practices, making it a highly recommended course of action.

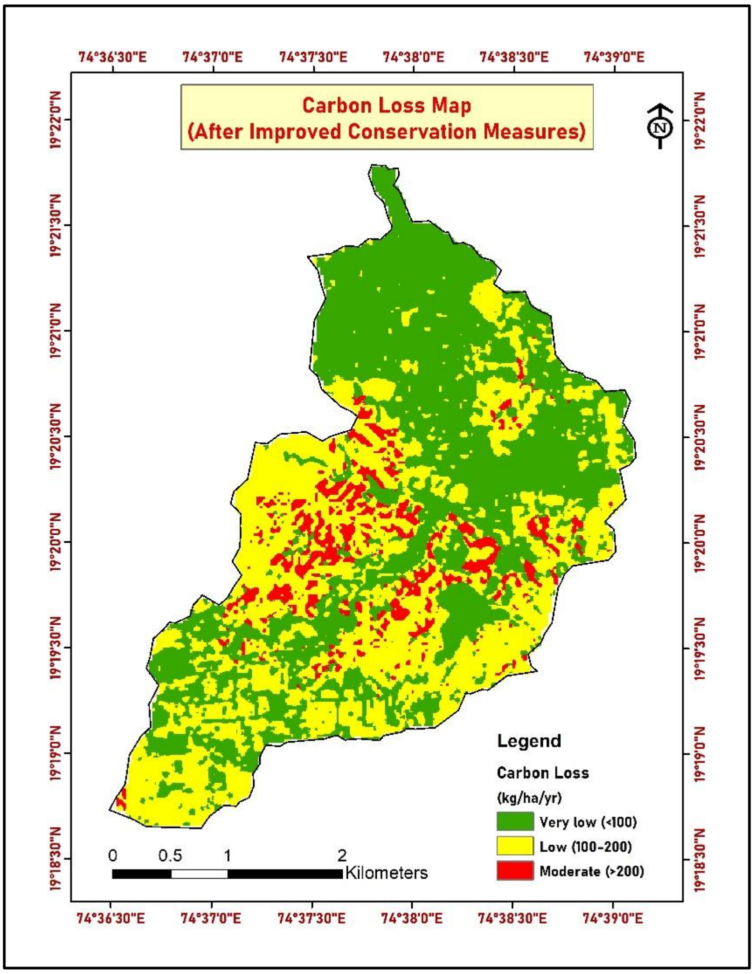

Figure 4.33 Carbon loss map of the watershed after the implementation of recommended SWC measures

4.6.1.7 Improved Carbon Sequestration After the Implementation of Recommended SWC Measures

Implementing recommended soil and water conservation measures in the watershed can significantly enhance its carbon sequestration capacity. As of now, the carbon sequestration rate in the treated part of the watershed stands at 320 kg C/ha/yr, whereas in the untreated areas, it's just 140 kg C/ha/yr. Currently, a vast area of nearly 600 ha, except waterbodies and settlement, lacks any SWC measures, which presents a significant opportunity for improvement. If suggested measures are implemented in this area, the stock of soil organic carbon in the watershed can increase by 192 tonnes of C per year, a remarkable improvement over the 84 tonnes of C per year increase that untreated land will experience.

Furthermore, the implementation of recommended SWC measures in untreated areas of the watershed can increase the annual soil carbon stock in the watershed by 128%, compared to the increase rate without conservation measures. The implementation of recommended conservation measures in the watershed will have a two-fold positive impact. Firstly, it will contribute to the natural resource management of the watershed by improving soil health, reducing erosion, and increasing water retention. Secondly, it will increase the carbon sequestration rate in the watershed. The increased carbon sequestration capacity of the watershed will aid in mitigating the negative effects of climate change. Thus, it's highly recommended to implement additional conservation measures in the watershed to improve carbon stock and increase carbon sequestration rates, which will bring benefits to the ecosystem and the wider environment.

4.6.2 Afforestation and Agroforestry Practices

Afforestation and agroforestry practices are two important conservation measures that can contribute significantly to carbon sequestration, helping to mitigate climate change. Afforestation involves planting trees on land that was previously without forest cover. Trees are excellent carbon sinks, as they absorb carbon dioxide from the atmosphere and store it in their biomass and in the soil. In afforestation, large areas of land can be converted into forests, resulting in a significant increase in carbon sequestration capacity.

The central MPKV campus watershed currently has 478.17 ha of barren land, which represents 38% of the watershed area. Converting this land into vegetation cover through afforestation could significantly increase the carbon stock in the watershed. The Indian Council of Forestry Research and Education (ICFRE) has reported that afforestation projects in India have an average annual carbon sequestration rate of 2.25 tonnes per hectare per year, ranging from 0.75 to 3.75 tonnes per hectare per year (ICFRE, 2020). By converting half of the barren land into natural forest cover, the watershed's carbon stock could increase by 537.94 tonnes of carbon per year. If all the barren land is converted, the increase would be even higher, at 1075.88 tonnes of carbon per year. The potential for increased carbon stock through afforestation at different percentages of barren land area is summarized in a table 4.34.

The barren land in the watershed was assessed for its potential suitability for afforestation using remote sensing and GIS techniques, and the results showed that a significant portion of the land is highly suitable for afforestation. Specifically, out of the total barren land, approximately 55% (261.84 ha) was classified as highly suitable for afforestation according to the provided land suitability criteria. Additionally, moderately and marginally suitable land for afforestation was found on 26% (126.19 ha) and 19% (90.14 ha) of the barren land, respectively. These findings indicate that there is considerable potential for afforestation in the watershed. Nearly half of the barren land can be effectively utilized for afforestation, while the moderately and marginally suitable lands, with proper conservation measures, can also be utilized for afforestation. Overall, this information can be valuable for decision-makers and land managers in the development of afforestation plans and programs in the watershed. The criteria used for land suitability assessment is given in table 4.35 and land suitability map for afforestation is given in Fig. 4.34

Table 4.34 Afforestation on different percentage of barren land and potential carbon stock increase

Sr. No.	Afforestation on barren land (%)	Potential increase in carbon stock (tonnes)
1	10	107.59
2	20	215.18
3	30	322.76
4	40	430.35
5	50	537.94
6	60	645.53
7	70	753.12
8	80	860.71
9	90	968.29
10	100	1075.88

Table 4.35 Land suitability criteria for afforestation and suitable area

Level	Land characteristics/qualities	Suitable Area (ha)	Potential increase in carbon stock (tonnes/year)
Highly suitable	0–5% slopes, Good water holding capacity, Sandy loam to loam texture, High soil moisture, moderate runoff,	261.84 (55%)	589.14
Moderately suitable	High slopes with small plain land (5-15%), Thick soils depth, Clay texture, Modest water holding capacity, Medium soil moisture, Moderate runoff	126.19 (26%)	283.92
Marginally suitable	>15% slope, Thin soils depth, Loam soil texture, Less water holding capacity, Less soil moisture, High runoff, Low accessibility nutrients	90.14 (19%)	202.81
			(Kadam *et al.*, 2020)

In addition to the benefits of carbon sequestration, afforestation can also provide other benefits such as soil conservation, biodiversity conservation, wood and non-timber forest products, recreation and tourism, and climate regulation. Therefore, implementing afforestation in the watershed, in combination with soil and water conservation measures, is a very prudent approach for increasing carbon stock levels and promoting sustainable development. It is crucial to note that afforestation efforts need to be done carefully, with proper planning and management, to avoid unintended negative impacts on local ecosystems and biodiversity. For example, planting non-native tree species can disrupt local ecosystems by outcompeting native species for resources such as sunlight and water. Non-native tree species can also attract non-native insects and pathogens that can harm native plants and animals. Therefore, it is important to carefully plan and manage afforestation efforts to minimize negative impacts on local ecosystems and biodiversity. This can include using native tree species that are adapted to local environmental conditions, considering the potential impact on local hydrology and soil conditions and monitoring the effects of afforestation over time to assess and mitigate any negative impacts. Overall, afforestation can play a vital role in mitigating climate change and promoting sustainable development, making it an important strategy for addressing global environmental challenges.

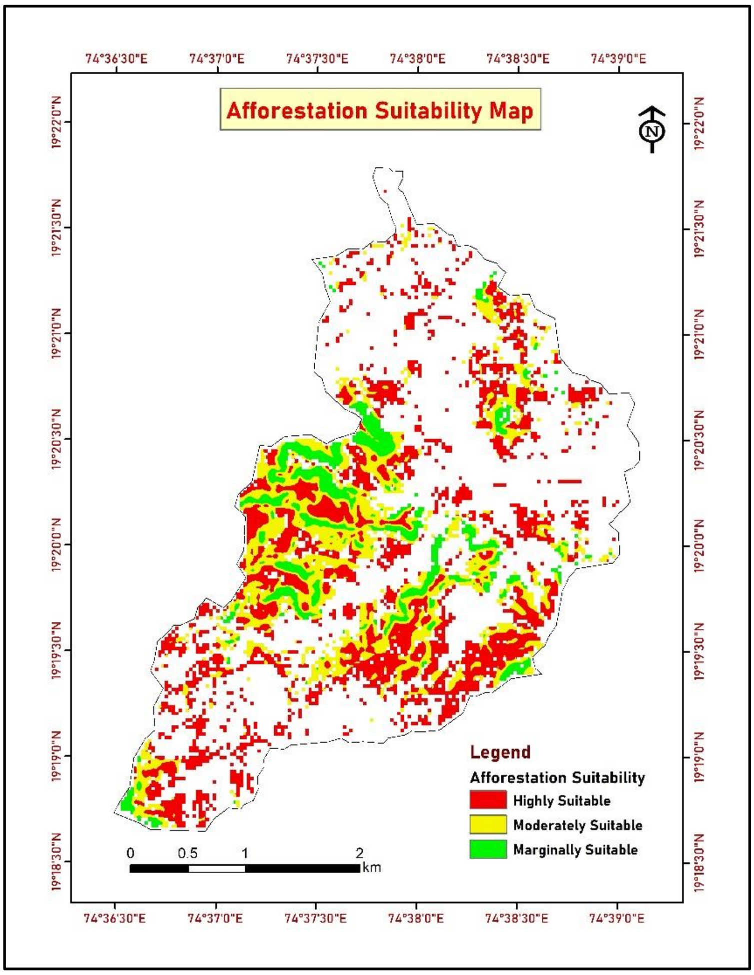

Figure 4.34 Afforestation suitability map of the watershed

Agroforestry is an integrated land use management practice that combines trees and crops or livestock on the same land area. This approach offers many benefits, including increased carbon sequestration in soils and biomass, enhanced soil fertility, and improved crop yields. Planting trees alongside agricultural crops or livestock, agroforestry can help capture and store carbon in the soil, while also providing additional environmental benefits (Jose *et al.*, 2021).

Agroforestry practices can help in mitigating climate change by sequestering carbon in soils and biomass. The amount of carbon sequestered depends on the species of trees, soil type and management practices. According to studies, agroforestry systems can sequester up to 30% more carbon than conventional agricultural systems (Lorenz and Lal, 2018). The carbon sequestration potential of agroforestry systems can be enhanced by using trees with deep root systems that can store carbon deeper in the soil. According to a study published by the Indian Council of Agricultural Research (ICAR), the carbon sequestration rate in agroforestry systems ranges from 0.83 to 2.52 t/ha/yr, with an average of 1.54 t/ha/yr (AICRP-AR, 2022). Implementing agroforestry practices in the barren areas of the watershed can make a significant contribution to the carbon stock of the area. Applying agroforestry to half of the barren land in the watershed can result in an additional 368.19 tonnes of C sequestration per year, while implementing it in the entire barren land can add 736.38 tonnes of C per year. Table 4.36 provided shows the potential increase in carbon stock through agroforestry by converting different percentages of barren land. Remote sensing and GIS techniques were employed to classify the barren land in the watershed according to its suitability for agroforestry, using the criteria listed in table 4.37. The land suitability map for agroforestry is given in Fig. 4.35. The results showed that 25% of the total barren land in the watershed (118.25 ha) was found to be highly suitable for agroforestry, while 54% (256.48 ha) and 21% (103.44 ha) were moderately and marginally suitable, respectively. This indicates that there is potential for integrating agriculture and forestry practices in the watershed to promote sustainable land use and increase carbon sequestration. However, it is important to note that appropriate management practices and conservation measures must be implemented to ensure that the agroforestry systems are productive, resilient, and environmentally sustainable. The conversion of barren land into agroforestry land can potentially provide benefits such as food security, biodiversity conservation and climate change mitigation. By providing shade and windbreaks, agroforestry can also help reduce the effects of extreme weather conditions, such as drought or heatwaves, on crops and livestock.

Table 4.36 Agroforestry on different percentage of barren land and potential carbon stock increase

Sr. No.	Agroforestry on barren land (%)	Potential increase in carbon stock (tonnes)
1	10	73.64
2	20	147.28
3	30	220.91
4	40	294.55
5	50	368.19
6	60	441.83
7	70	515.47
8	80	589.11
9	90	662.74
10	100	736.38

Table 4.37 Land suitability criteria for agroforestry and suitable area

Level	Land characteristics/qualities	Suitable Area (ha)	Potential increase in carbon stock (tonnes/year)
Highly suitable	0–2% slopes, Relatively very high moisture content, High soil depth, Adequate soil nutrient availability, loamy texture soil, Low runoff velocity	118.25 (25%)	182.10
Moderately suitable	2-15% slope, High moisture content, Moderate soil depth, Modest water holding capacity Moderate runoff velocity	256.48 (54%)	394.97
Marginally suitable	15-35% slope, Low moisture content, Less water holding capacity, High runoff velocity, Low nutrient availability	103.44 (21%)	159.29
			(Ahmad *et al.*, 2018)

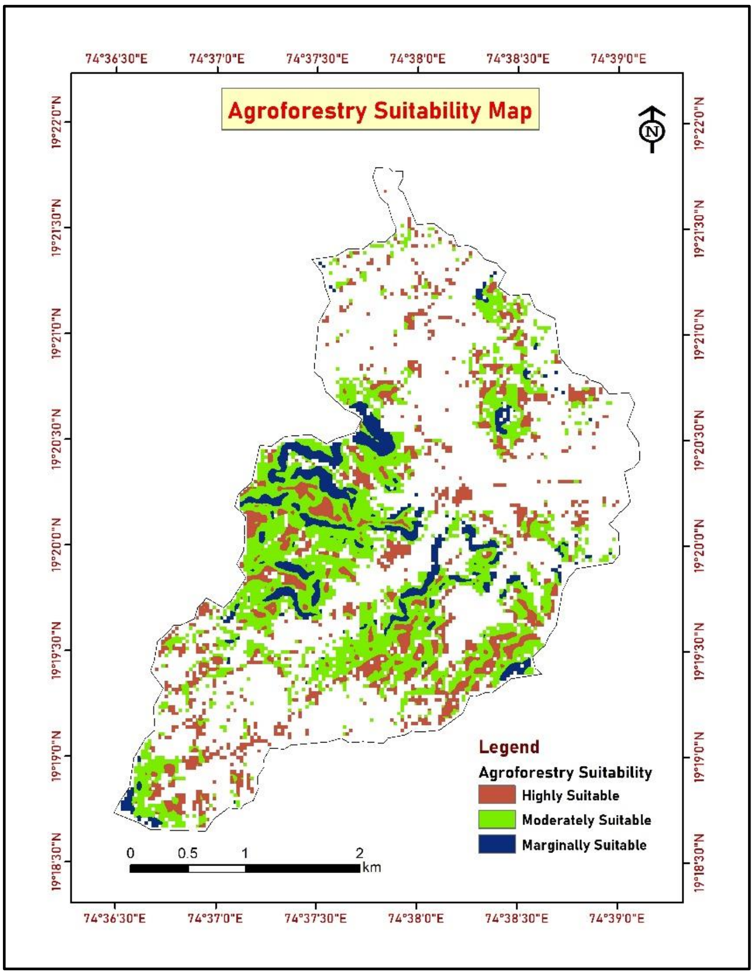

Figure 4.35 Agroforestry suitability map of the watershed

4.6.3 Agricultural Practices to Improve Carbon Sequestration

Sustainable agricultural practices can play a crucial role in enhancing soil carbon sequestration. Some agricultural practices that can improve soil carbon sequestration include reducing soil tillage, planting cover crops, incorporating crop residues into the soil and using organic fertilizers. Reducing tillage can increase soil organic matter content, which leads to greater carbon storage in the soil. Planting cover crops, such as legumes, can fix atmospheric nitrogen and increase soil organic matter content. Incorporating crop residues back into the soil can enhance soil fertility and carbon storage, while using organic fertilizers can improve soil structure and nutrient content, leading to greater carbon storage.

Agricultural area in the watershed is 230 ha i.e., 18% of the watershed area. Implementing sustainable agricultural practices on this area will further improve the soil carbon sequestration rate from these areas. There are several sustainable agricultural practices that have proven their role in increasing soil carbon sequestration. These includes crop residues management, mulches, cover crops, no tillage and crop rotation. The agronomical practices and their carbon sequestration rates are given in the table 4.38.

The implementation of crop residue management in the entire agricultural area of the watershed can lead to an increase in soil carbon stock of 103.5 tonnes per year. Likewise, the implementation of mulching, cover crops, no tillage and crop rotation on the entire agricultural area can increase carbon stock by 129.95, 95.22, 51.52 and 79.35 tonnes per year, respectively. The adoption of sustainable agricultural practices in the watershed will significantly increase the carbon sequestration rate from agricultural lands. In addition to carbon sequestration, these practices can also provide other benefits such as reduced soil erosion, improved soil moisture, and better nutrient management. Thus, alongside drainage line and land area treatment, the implementation of sustainable agricultural practices can further enhance the carbon sequestration capacity of the watershed. By adopting these practices, farmers can improve the productivity and resilience of their farms. It will also contribute in mitigating climate change by sequestering atmospheric carbon in the soil. Therefore, promoting the adoption of these practices in agricultural systems in the watershed can have positive impacts on both the environment and agricultural productivity. It is important to note that the adoption of these practices can not only contribute to carbon sequestration in the watershed but also improve the soil quality, making it more sustainable for future generations.

Table. 4.38 Agronomical practices and soil carbon sequestration rates

Agricultural Practice	**Soil Carbon Sequestration Rates (kg C/ ha/yr) (World Bank Report, 2012)**
Crop residues management	450
Mulches	565
Cover Crops	414
No Tillage	224
Crop Rotation	345

A sustainable plan for optimal land utilization within the watershed was proposed, which involves the conversion of barren land into agriculture, agroforestry, or afforestation based on land suitability criteria. To prioritize the barren land areas, farmers' income and productivity were given top priority. Agricultural land was given the highest priority since it is the primary source of income for farmers and generates employment opportunities. Agroforestry was given second priority on land where agriculture is not feasible, while afforestation was given third priority because it has a wider suitability range.

The study found that 25% (118.25 ha) of the barren land area in the watershed is highly suitable for agriculture, 54% (256.48 ha) is suitable for agroforestry and 21% (103.44 ha) is suitable for afforestation. The proposed land suitability map of the watershed is shown in Fig. 4.36. The Indian Council of Agricultural Research (ICAR) estimated that the carbon sequestration rate of agriculture with conservation agricultural practices in India is between 0.44 to 1.32 tonnes of C per hectare per year, with a mean of 0.88 tonnes of C/ha/year (Kaur *et al.*, 2023). Thus, converting 24% of the barren land into agriculture with conservation agriculture practices can increase the average carbon stock in the watershed by 104.06 tonnes of C/year.

Similarly, converting 54% and 21% of the barren land into agroforestry and afforestation, respectively, can increase the carbon stock in the watershed by 394.98 and 232.74 tonnes of C/year. By implementing these three recommended land covers with appropriate soil and water conservation measures can significantly contribute to soil loss reduction and improve carbon sequestration in the watershed.

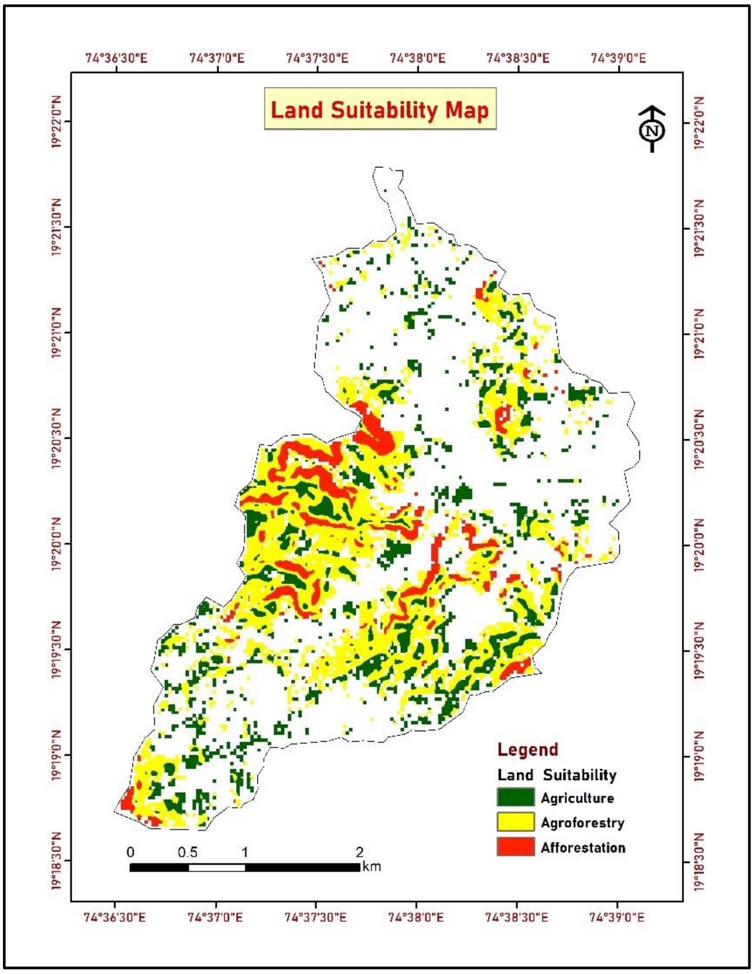

Figure 4.36 Land suitability map of the watershed

The proposed land utilization plan has the potential to significantly increase the overall carbon stock in the watershed by 731.78 tonnes of C/year, which is a remarkable increase over the current carbon levels in the watershed. This will help in balancing carbon emissions of the watershed with carbon sequestration and developing a carbon-neutral watershed.

Implementation of recommended soil and water conservation (SWC) measures, combined with afforestation, agroforestry and sustainable agricultural practices, can provide a sustainable solution to natural resource management and improve carbon sequestration in watersheds. This, in turn, can lead to the development of carbon-neutral watersheds. Achieving carbon neutrality in a watershed can have significant positive impacts on the environment, such as mitigating climate change, enhancing soil fertility and water holding capacity, conserving biodiversity and improving the resilience of local communities to extreme weather conditions. By adopting sustainable watershed management practices, we can promote the development of carbon-neutral watersheds, which in turn can contribute to achieving global climate goals and a sustainable future for all.

The gist is that, the development of carbon-neutral watersheds through sustainable watershed management practices is clairvoyant approach towards mitigating climate change and achieving a sustainable future. By adopting these practices, we can improve natural resource management, enhance the resilience of ecosystems and communities to extreme weather events and help to secure a more sustainable future for generations to come.

5. SUMMARY AND CONCLUSIONS

Climate change is considered one of the biggest threats facing humanity and the planet. The Earth's climate is changing at an unprecedented rate due to human activities, such as burning fossil fuels, deforestation and other industrial activities that release greenhouse gases into the atmosphere. The consequences of climate change include rising temperatures, more frequent and extreme weather events like heat waves, droughts, floods and storms, melting glaciers and ice caps, rising sea levels and ocean acidification. These changes pose significant risks to human health, biodiversity, ecosystems and economies around the world. Moreover, climate change can exacerbate global problems such as poverty, hunger and political instability. Therefore, it is crucial to take immediate and effective actions to mitigate and adapt to climate change in order to ensure a sustainable future for ourselves and future generations.

Sustainable strategies are necessary to address the global challenge of climate change, and one such strategy in natural resource management is carbon sequestration. Carbon sequestration is the process of capturing carbon dioxide (CO_2) from the atmosphere and storing it in long-term sinks, such as soil, oceans, forests or underground geological formations. This process helps to mitigate the negative consequences of climate change by reducing the amount of CO_2 in the atmosphere, which is one of the main contributors to global warming. Carbon sequestration can be achieved through a variety of techniques, including afforestation and reforestation, ocean fertilization and carbon capture and storage (CCS) technologies. One of the most accessible methods is terrestrial carbon sequestration, which involves storing carbon in plants and soils. This can be achieved by planting more trees and other vegetation or adopting sustainable land management practices that enhance the capacity of soil to absorb and store carbon.

Land degradation, particularly through soil erosion, can exacerbate the impacts of climate change. It is just one of many factors that must be addressed in order to combat global threat of climate change. Soil erosion cause significant loss of soil organic carbon, which aids to climate change. Soil organic carbon is an important component of healthy soils and it plays a critical role in carbon sequestration. When soil erosion occurs, it leads to the loss of topsoil, which is typically the most fertile and carbon-rich layer of soil. This loss can result in a reduction in the amount of soil organic carbon, as well as a decrease in the soil's ability to sequester carbon from the atmosphere. Therefore, efforts to combat soil erosion and promote healthy soils are an important part of sustainable land management and climate change mitigation strategies. Effective action to mitigate and adapt to climate change will require a multifaceted approach that addresses a range of interconnected issues, from sustainable land management practices to renewable energy development and more.

Soil conservation is of utmost importance to ensure a balanced climate cycle and healthy agricultural production. Effective control of soil erosion and restoration of degraded soils can contribute to carbon sequestration, which can be achieved through soil and water conservation (SWC) measures. The effectiveness of SWC techniques in preserving soil quality and fertility as well as soil moisture improvement has been widely investigated and acknowledged worldwide. However, their role in carbon sequestration needs to be studied further. Therefore, there is a need for scientific approach to demonstrate the significance of SWC measures in the global carbon cycle and carbon sequestration. Scientific research on the effectiveness of SWC measures in carbon sequestration can provide a sustainable and cost-effective solution to combat climate change, especially in countries with limited resources for climate change mitigation. This valuable information can be applied in the planning of carbon-neutral watersheds since watersheds provide ideal planning units for integrated soil and water resource management. Accordingly, the present study was undertaken to investigate the role of SWC measures in climate change mitigation.

The study was conducted in the “Central MPKV Campus Watershed” located in Rahuri Taluka in Ahmednagar District of Maharashtra State, India. The study area covers 1260 ha with an elevation ranging from 441 to 542 m above mean sea level. The region has a unimodal rainfall pattern, with the primary rainy season occurring from late June to early September and the annual rainfall varying from 313 to 948 mm with average rainfall of 592 mm. The Central MPKV Campus watershed is treated with various scientifically planned soil and water conservation (SWC) measures. The implementation of watershed development activities through state government funded project of Adarsh Gaon Yojana began in 2017 in the study area, and by 2019, nearly half of the watershed was treated with both land area and drainage line treatments covering a total of 545 ha. The land area treatments in the watershed include deep continuous contour trenches (DCCT) and compartment bunding, while drainage line treatments include earthen nala bunds, loose boulder structures and percolation tank.

Implementation of the SWC measures significantly affected land use in the watershed, with increases in agriculture, natural forest, horticultural, settlement and waterbody land cover classes and decreases in barren and current fallow land. SWC measures led to rapid increases in water availability, which in turn led to the conversion of barren and fallow land to agricultural production. The increase in agricultural area and decrease in barren and fallow land suggests that the SWC measures have helped in increase in food production and employment opportunities in the area. The increase in settlement area suggests that the population in the watershed has grown, possibly due to improved living standards. The water conservation measures implemented in the watershed resulted in an augmentation of the watershed's water storage capacity by 123.4 thousand cubic meter (TCM). The increase in water availability has not only benefited agriculture, but also helped increase vegetation and replenish groundwater. It was observed that the implementation of SWC measures not only helped conserve natural resources, but also improved the socio-economic status of people living in the watershed.

The estimation of the total terrestrial carbon stock in the watershed involved assessing both the biomass and soil carbon stocks across various land cover types. The biomass carbon stock was estimated using a regression equation specifically developed for tropical regions, while the soil carbon stock was estimated using the soil organic carbon content, bulk density and soil coarse fraction from collected soil samples. It was found that the central MPKV campus watershed has a total terrestrial carbon stock of 39191.74 tonnes, with 45% stored in vegetation biomass and 55% stored in the soil. The high proportion of carbon stored in the soil of the watershed highlights the importance of protecting and managing soil health for both environmental and agricultural benefits. Natural forest land was found to have the largest carbon content, comprising 56% of the total terrestrial carbon stock, followed by barren land (17%), agricultural land (14%) and horticultural land (13%). The barren land in the watershed area constitutes the highest proportion, accounting for 38% of the total area. However, it only contains 17% of the total carbon in the watershed, highlighting the potential for carbon sequestration through restoration efforts in this land cover type. The high carbon content in natural forest land was attributed to the presence of plant biomass and continuous generation and decomposition of litter biomass, which increases the soil organic carbon content. Understanding the distribution of carbon stock across different land cover types is crucial for designing effective strategies to enhance the carbon storage potential of a watershed.

The impact of SWC measures on carbon sequestration was analysed by assessing soil carbon sequestration (SCS) rates in treated and untreated areas. It was observed that soil and SWC measures have a significant impact on soil carbon sequestration (SCS) rates in treated areas. The implementation of compartment bunding in agricultural land has resulted in a higher soil carbon sequestration rate of 343 kg C/ha/yr, as compared to untreated agricultural lands with a rate of 190 kg C/ha/yr. Likewise, natural forest, horticulture and barren lands treated with DCCT had higher SCS rates of 470, 382 and 211 kg C/ha/yr, respectively, compared to similar untreated land covers with rates of 270, 213 and -112 kg C/ha/yr. It is noteworthy that untreated barren lands without any SWC measures were found to be a net source of carbon emissions due to the continuous deterioration of the topsoil resulted from severe soil erosion. However, appropriately managed barren land with SWC measures act as natural carbon sinks. In untreated areas, appropriate SWC measures, plantation and agroforestry practices are required to reduce carbon loss from the soil and increase SCS rates. The findings suggest that the implementation of scientifically planned SWC measures can play a crucial role in mitigating climate change by enhancing terrestrial carbon storage.

The study evaluated the impact of soil erosion on carbon loss by estimating the soil loss and associated carbon loss from the watershed before and after the adoption of conservation measures. The USLE model was used to estimate soil loss from the watershed, while carbon loss was estimated using factors such as soil loss, carbon enrichment ratio and soil organic carbon content. The results showed that the average annual soil loss from the watershed decreased from 18.68 t/ha/yr to 9.41 t/ha/yr after the adoption of conservation measures, a reduction of 50% and well below the tolerable soil loss limit of 11 t/ha/yr. This indicates that the rate of soil formation is higher than the rate of soil loss in the watershed. Similarly, the average annual carbon loss decreased from 348.71 kg C/ha/yr to 190.52 kg C/ha/yr with a reduction of 45% after the adoption of conservation measures. After adopting conservation measures, the watershed saw reductions in soil carbon loss and CO_2 emissions of upto 218.95 tonnes of C/year and 802.88 tonnes of CO_2/year, respectively, compared to the initial levels of 398.46 tonnes of C/year and 1461.15 tonnes of CO_2/year. It was found that adoption of scientifically planned SWC measures in the watershed mitigate climate change by reducing soil loss rates and carbon emissions, while increasing soil carbon sequestration. These measures can serve as both climate change mitigation and adaptation strategies.

About half of the watershed area still lacks SWC measures, highlighting the potential for further reducing soil loss and associated carbon loss. Therefore, additional conservation strategies are recommended for these untreated parts of the watershed to further reduce soil erosion, carbon emissions and increase carbon sequestration. The proposed drainage line treatments for the watershed include 109 structures, such as earthen nala bunds (12), cement nala bunds (3), percolation tanks (1), check dams (4), loose boulder structures (87) and Kolhapur Type weirs (2). In addition, recommended land area treatments for the watershed include compartment bunding (304 ha), contour bunding (192 ha), DCCT (89 ha) and bench terraces (130 ha). Implementation of these recommended conservation measures is expected to result in an average annual soil loss rate of 6.17 t/ha/yr, which will be 35% reduction compared to the current soil loss rate. Similarly, it is anticipated that the average annual carbon loss rate will decrease from the current rate of 190.52 kg C/ha/yr to 125.64 kg C/ha/yr. If these measures are implemented, the stock of soil organic carbon in the watershed can increase by 192 tonnes of C per year. It is a significant improvement compared to the 84 tonnes of C per year increase for untreated land. Converting entire barren land into natural vegetation cover through afforestation can increase the watershed's carbon stock by 1075.88 tonnes of carbon per year, while applying agroforestry to entire barren land can result in an additional 736.38 tonnes of C per year. Furthermore, implementing crop residue management, mulches, cover crops, no tillage and crop rotation in the entire agricultural lands of the watershed can increase the carbon stock by 103.5, 129.95, 95.22, 51.52 and 79.35 tonnes per year, respectively.

The study has proposed a sustainable plan for optimal land utilization within the watershed, focusing on the conversion of barren land into agriculture, agroforestry or afforestation based on land suitability criteria, with priority given to farmers' income and productivity. The proposed land suitability map showed that 25%, 54% and 21% of the barren land area were suitable for agriculture, agroforestry and afforestation, respectively. By implementing these recommended land covers with appropriate soil and water conservation measures, the proposed plan has the potential to significantly increase the overall carbon stock in the watershed by 731.78 tonnes of C/year, contributing to soil loss reduction and improved carbon sequestration.

The adoption of recommended soil and water conservation (SWC) measures, in combination with afforestation, agroforestry and sustainable agricultural practices, will play a crucial role in developing carbon neutral climate smart watershed. Adopting these practices will improve natural resources of the watershed, enhance the resilience of ecosystems and communities to extreme weather events and secure a more sustainable future for generations to come.

Thus, the following specific conclusions are drawn from the present study;

1. The study highlights the crucial role of soil health in providing environmental and agricultural benefits, as the soil stores a significant proportion (55%) of the carbon in the watershed. Therefore, it is essential to implement sustainable soil management practices to maintain the soil's capacity to function as a carbon sink and provide other ecosystem services.
2. Natural forest land cover is the most efficient in carbon sequestration and storage, as it stores the largest amount of total terrestrial carbon (56%). This highlights the importance of preserving natural forest areas to maintain a balance of carbon emissions and sequestration.
3. Barren land constitutes a substantial proportion (38%) of the watershed area but stores only 17% of the total carbon in the watershed. This indicates the untapped potential of barren land for carbon sequestration through restoration activities.
4. Scientifically planned SWC measures implemented in the watershed have resulted in a 50% reduction in soil loss rate and a 40% reduction in carbon loss rate. Additionally, the treated area showed a 1.5-fold higher rate of soil carbon sequestration compared to the untreated area. These findings highlight the significance of SWC measures as a crucial strategy for mitigating and adapting to the adverse impacts of climate change by promoting carbon storage and decreasing emissions from watersheds while conserving natural resources.
5. The study proposes a sustainable plan for land utilization in the watershed that identifies the suitability of barren land for agriculture, agroforestry and afforestation. The proposed plan has the potential to significantly increase the carbon stock in the watershed, with the potential of achieving a 3.5-fold increase compared to the current annual soil carbon sequestration rate of barren land. The proposed plan offers a viable

solution for enhancing the carbon sequestration potential of the watershed while supporting the economic well-being of local farmers.

6. The study recommends additional SWC measures to further reduce soil and carbon loss in untreated areas of the watershed by 35% each. This will aid in minimizing carbon emissions and promoting the development of a carbon neutral climate smart watershed.

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7. APPENDICES

Appendix –A

Yearly rainfall and rainfall erosivity

Year	Rainfall (mm)	Rainfall Erosivity (MJ-mm/ha-hr-yr)
1995	549	402.25
1996	636	563.59
1997	590	474.14
1998	637	565.64
1999	842	1078.38
2000	616	522.57
2001	579	454.12
2002	325	140.13
2003	313	132.32
2004	575	446.98
2005	465	278.09
2006	796	947.24
2007	746	813.98
2008	671	637.89
2009	686	671.38
2010	886	1212.54
2011	589	472.29
2012	513	345.24
2013	502	329.24
2014	426	231.10
2015	381	184.96
2016	541	388.28
2017	622	535.58
2018	240	98.29
2019	589	471.56
2020	949	1417.74
2021	726	765.80

Appendix –B

Tree Diameter and Hight Measurements of Plantations

Sr. No.	Coconut			Eucalyptus			Gliricidia		
	Diameter (cm)	Height (m)	Biomass (kg/tree)	Diameter (cm)	Height (m)	Biomass (kg/tree)	Diameter (cm)	Height (m)	Biomass (kg/tree)
1	28.03	18.10	375.25	32.48	11.20	547.22	25.80	5.00	166.88
2	28.66	18.20	394.99	16.24	9.20	128.36	20.70	4.60	103.31
3	29.30	18.30	415.39	13.38	8.80	86.35	21.66	4.70	114.44
4	30.57	18.40	452.86	24.84	10.10	304.51	14.33	4.40	50.57
5	33.12	18.50	527.23	24.52	10.00	294.70	11.15	3.90	28.57
6	35.67	18.80	621.55	27.39	10.20	367.45	23.57	4.80	136.22
7	34.08	18.40	547.77	16.88	9.30	139.10	21.02	4.50	104.12
8	35.35	18.60	597.93	14.01	8.70	93.05	32.80	5.30	273.37
9	41.72	19.60	894.89	30.57	11.30	493.70	28.98	5.20	214.10
10	33.12	18.20	509.01	31.53	11.20	518.10	28.66	5.10	206.11
11	38.85	19.50	781.22	19.43	9.40	181.73	27.39	5.00	186.23
12	32.48	18.70	521.50	27.07	10.40	366.12	22.93	4.60	124.60
13	33.44	18.80	555.03	16.56	9.30	134.33	22.29	4.70	120.68
14	36.31	19.00	655.91	16.24	9.40	130.91	18.47	4.50	82.17
15	28.98	18.00	393.26	28.03	10.80	403.86	28.98	5.10	210.32
16	34.39	18.60	569.88	18.47	9.50	167.31	17.83	4.40	75.49
17	30.89	18.10	445.14	27.39	10.50	377.34	19.11	4.60	89.22
18	40.45	19.30	819.86	22.93	10.30	267.74	30.89	5.30	244.90
19	37.58	19.20	712.68	21.97	10.20	245.46	27.71	5.10	193.70
20	39.81	19.40	806.26	10.83	8.60	57.41	16.24	4.30	62.28
21	38.54	19.30	753.14	30.25	11.10	476.46	18.47	4.60	83.85
22	36.31	19.10	663.36	33.12	11.30	571.67	21.02	4.70	108.35
23	29.30	18.10	405.68	22.61	10.40	263.29	23.57	4.70	133.62
24	36.94	19.10	683.91	21.97	10.10	243.25	16.24	4.40	63.60
25	34.71	18.90	599.45	18.47	9.60	168.92	14.97	4.30	53.62
26	31.21	18.30	464.06	23.57	10.40	284.03	14.33	4.20	48.46
27	34.08	18.50	554.19	29.94	10.90	459.60	21.66	4.80	116.67
28	34.71	18.50	572.49	27.71	10.70	392.14	31.21	5.20	245.23
29	34.71	18.40	565.85	26.11	10.60	348.83	20.70	4.60	103.31
30	31.53	18.20	466.87	23.57	10.30	281.52	28.98	5.20	214.10
31	35.67	18.80	621.55	14.01	8.70	93.05	28.66	5.10	206.11
32	34.08	18.40	547.77	30.57	11.30	493.70	27.39	5.00	186.23
33	35.35	18.60	597.93	31.53	11.20	518.10	22.93	4.60	124.60
34	41.72	19.60	894.89	19.43	9.40	181.73	22.29	4.70	120.68
35	33.12	18.20	509.01	27.07	10.40	366.12	18.47	4.50	82.17
36	38.85	19.50	781.22	16.56	9.30	134.33	28.98	5.10	210.32
37	32.48	18.70	521.50	16.24	9.40	130.91	17.83	4.40	75.49
38	33.44	18.80	555.03	28.03	10.80	403.86	21.02	4.70	108.35

39	36.31	19.00	655.91	18.47	9.50	167.31	23.57	4.70	133.62
40	28.98	18.00	393.26	27.39	10.50	377.34	16.24	4.40	63.60
41	34.39	18.60	569.88	22.93	10.30	267.74	14.97	4.30	53.62
42	33.12	18.20	509.01	21.97	10.20	245.46	21.02	4.50	104.12
43	38.85	19.50	781.22	15.32	9.60	57.41	20.18	4.80	273.37
44	32.48	18.70	521.50	21.97	10.20	245.46	19.45	5.20	214.10
45	33.44	18.80	555.03	13.22	8.70	57.41	28.66	5.10	206.11
46	36.31	19.00	655.91	30.25	11.10	476.46	21.33	5.00	186.23
47	28.98	18.00	393.26	33.12	11.30	571.67	22.93	4.60	124.60
48	34.39	18.60	569.88	22.61	10.40	263.29	22.29	4.70	120.68
49	36.31	19.00	655.91	21.97	10.10	243.25	20.70	4.60	103.31
50	28.98	18.20	393.26	18.47	9.60	168.92	28.98	5.20	214.10
51	34.39	18.60	569.88	23.57	10.40	284.03	28.66	5.10	206.11
52	30.89	18.10	445.14	29.94	10.90	459.60	27.39	5.00	186.23
53	31.32	18.10	819.86	27.71	10.70	392.14	22.93	4.60	124.60
54	37.58	19.20	712.68	26.11	10.60	348.83	22.29	4.70	120.68
55	39.81	19.40	806.26	23.57	10.30	281.52	18.47	4.50	82.17
56	38.54	19.30	753.14	14.01	8.70	93.05	28.98	5.10	210.32
57	36.31	19.10	663.36	30.57	11.30	493.70	17.83	4.40	75.49
58	29.30	18.10	405.68	31.53	11.20	518.10	21.02	4.70	108.35
59	36.94	19.10	683.91	22.21	9.40	181.73	23.57	4.70	133.62
60	34.71	18.90	599.45	27.07	10.40	366.12	16.24	4.40	63.60
61	31.21	18.30	464.06	26.56	9.70	134.33	14.97	4.30	53.62
62	34.08	18.50	554.19	16.24	9.40	130.91	21.02	4.50	104.12
63	34.71	18.50	572.49	28.03	10.80	403.86	30.32	5.30	273.37
64	34.71	18.40	565.85	18.47	9.50	167.31	25.45	5.20	214.10
65	31.53	18.20	466.87	32.48	11.20	547.22	28.66	5.10	206.11
66	35.67	18.80	621.55	16.24	9.40	128.36	24.25	5.00	186.23
67	34.08	18.40	547.77	13.38	8.80	86.35	25.80	5.00	166.88
68	35.35	18.60	597.93	26.42	10.10	304.51	20.70	4.60	103.31
69	35.23	19.10	894.89	24.52	10.00	294.70	21.66	4.70	114.44
70	33.12	18.20	509.01	27.39	10.20	367.45	14.33	4.40	50.57
71	38.85	19.50	781.22	19.23	9.30	139.10	11.15	3.90	28.57
72	32.48	18.70	521.50	14.01	8.70	93.05	23.57	4.80	136.22
73	32.48	18.70	521.50	30.57	11.30	493.70	21.02	4.50	104.12
74	33.44	18.80	555.03	14.01	8.70	93.05	32.80	5.30	273.37
75	36.31	19.00	655.91	30.57	11.30	493.70	21.35	4.70	214.10
76	28.98	18.30	393.26	31.53	11.20	518.10	23.57	4.70	133.62
77	34.39	18.60	569.88	19.43	9.40	181.73	16.24	4.40	63.60
78	30.89	18.10	445.14	27.07	10.40	366.12	14.97	4.30	53.62
79	35.21	18.30	819.86	16.56	9.60	134.33	21.02	4.50	104.12
80	37.58	19.10	712.68	16.24	9.40	130.91	32.80	5.30	273.37
81	39.81	19.40	806.26	28.03	10.80	403.86	28.98	5.20	214.10
82	38.54	19.30	753.14	18.47	9.70	167.31	19.85	4.50	206.11
83	36.31	19.10	663.36	33.45	11.20	547.22	26.45	5.00	186.23
84	29.30	18.10	405.68	16.24	9.40	128.36	25.80	4.80	166.88

85	36.94	19.10	683.91	13.38	8.80	86.35	20.70	4.60	103.31
86	34.71	18.90	599.45	24.84	10.10	304.51	21.66	4.70	114.44
87	31.21	18.30	464.06	24.52	10.00	294.70	14.33	4.40	50.57
88	34.08	18.50	554.19	27.39	10.20	367.45	11.15	3.90	28.57
89	34.71	18.50	572.49	20.54	9.90	139.10	23.57	4.80	136.22
90	34.71	18.40	565.85	18.31	8.70	93.05	21.02	4.30	104.12
91	31.53	18.20	466.87	30.57	11.30	493.70	16.21	4.50	273.37
92	35.67	18.80	621.55	31.53	11.20	518.10	22.29	4.70	120.68
93	28.03	18.10	375.25	19.43	9.40	181.73	20.70	4.60	103.31
94	28.66	18.20	394.99	27.07	10.40	366.12	28.98	5.20	214.10
95	29.30	18.30	415.39	16.56	9.30	134.33	28.66	5.10	206.11
96	30.57	18.40	452.86	24.35	11.20	130.91	27.39	4.80	186.23
97	33.12	18.50	527.23	28.03	10.80	403.86	22.93	4.40	124.60
98	35.67	18.80	621.55	18.47	9.50	167.31	22.29	4.70	120.68
99	34.08	18.50	547.77	27.39	11.10	377.34	18.47	4.30	82.17
100	37.35	18.80	597.93	22.93	10.40	267.74	24.21	5.10	210.32

Sr. No.	**Hardwickia**			**Mango**			**Neem**		
	Diameter (cm)	**Height (m)**	**Biomass (kg/tree)**	**Diameter (cm)**	**Height (m)**	**Biomass (kg/tree)**	**Diameter (cm)**	**Height (m)**	**Biomass (kg/tree)**
1	34.39	14.70	810.05	33.44	6.00	278.56	22.93	5.40	152.07
2	22.61	11.50	300.00	22.61	5.40	123.51	21.34	5.30	131.02
3	28.66	13.20	525.58	33.76	6.10	287.76	15.29	4.70	63.71
4	24.84	12.00	370.57	26.43	5.60	169.98	27.07	5.60	213.09
5	21.97	11.30	280.16	37.58	6.30	360.74	12.42	4.30	40.14
6	19.11	10.60	204.54	36.94	6.20	344.53	24.20	5.30	165.05
7	31.21	13.80	639.84	27.07	5.70	180.46	20.06	5.30	117.05
8	31.21	13.80	639.84	41.40	6.70	455.77	13.06	4.40	44.93
9	26.11	12.60	424.68	34.08	6.30	301.54	27.07	5.40	206.11
10	23.25	11.80	323.20	37.58	6.40	365.98	25.48	5.50	187.57
11	24.52	12.30	370.19	44.59	6.60	514.90	17.52	4.90	84.94
12	26.43	12.80	440.53	19.43	5.10	88.75	23.57	5.20	154.46
13	26.75	12.70	447.08	36.31	6.30	338.66	19.11	5.00	101.48
14	33.44	14.20	745.30	32.80	6.20	277.12	14.97	4.50	58.91
15	29.94	13.70	588.88	33.44	6.20	287.05	23.89	5.30	161.09
16	27.71	12.70	476.76	35.35	6.40	327.19	22.61	5.30	145.70
17	17.20	10.80	171.55	38.85	6.50	394.60	23.89	5.40	163.88
18	21.66	11.30	272.77	32.48	6.10	268.18	20.70	5.10	119.65
19	16.88	10.40	160.14	38.85	6.50	394.60	14.33	4.60	55.50
20	22.29	11.80	299.28	32.48	6.20	272.21	22.93	5.20	146.90
21	20.70	11.30	251.13	35.35	6.30	322.51	15.29	4.60	62.47
22	18.15	10.60	186.19	34.08	6.30	301.54	20.70	5.10	119.65
23	28.34	13.40	522.07	28.03	5.70	192.30	23.57	5.30	157.18
24	19.75	11.00	224.70	39.49	6.60	412.25	21.34	5.00	124.21

25	22.93	12.20	324.90	37.58	6.70	381.67	28.03	5.60	227.07
26	21.34	12.10	282.63	43.31	6.80	501.81	24.20	5.20	162.20
27	26.75	13.30	466.39	27.39	5.60	181.41	24.52	5.30	169.05
28	26.43	13.70	468.82	34.39	6.30	306.72	17.52	4.80	83.35
29	31.53	14.40	677.77	26.75	5.50	170.91	24.84	5.40	176.08
30	23.57	12.20	341.63	37.58	6.60	376.45	26.75	5.50	205.11
31	30.25	13.30	584.33	38.54	6.60	394.17	13.06	4.40	44.93
32	31.85	13.60	655.15	35.35	6.50	331.87	27.07	5.40	206.11
33	22.29	11.60	294.63	38.54	6.60	394.17	25.48	5.50	187.57
34	30.57	13.70	612.03	21.66	5.40	114.12	17.52	4.90	84.94
35	20.70	11.10	247.05	33.12	5.80	265.35	23.57	5.20	154.46
36	23.89	11.90	342.24	21.66	5.20	110.24	19.11	5.00	101.48
37	26.43	12.70	437.37	33.76	5.80	274.77	14.97	4.50	58.91
38	23.57	11.80	331.36	35.67	6.30	327.85	23.89	5.30	161.09
39	30.57	13.60	607.94	18.79	4.80	78.98	22.61	5.30	145.70
40	25.48	12.50	402.95	38.22	6.50	382.83	23.89	5.40	163.88
41	29.94	13.40	577.05	44.59	6.80	529.17	20.70	5.10	119.65
42	28.34	13.40	522.07	45.54	6.80	550.13	14.33	4.60	55.50
43	33.76	14.40	768.14	24.84	5.20	141.74	22.93	5.20	146.90
44	30.89	13.80	627.93	42.99	6.70	488.39	15.29	4.60	62.47
45	23.57	11.80	331.36	42.04	6.60	462.28	20.70	5.10	119.65
46	28.03	13.00	497.37	33.44	5.90	274.30	23.57	5.30	157.18
47	22.29	11.60	294.63	42.68	6.70	481.79	21.34	5.00	124.21
48	24.52	12.20	367.43	39.81	6.60	418.36	28.03	5.60	227.07
49	23.57	12.10	339.06	42.36	6.70	475.22	24.20	5.20	162.20
50	32.17	14.00	685.15	38.54	6.60	394.17	24.52	5.30	169.05
51	30.25	13.80	604.42	44.27	6.50	501.12	17.52	4.80	83.35
52	28.34	13.20	514.93	40.76	6.60	436.94	22.61	5.30	145.70
53	35.35	14.90	862.36	41.72	6.70	462.21	23.89	5.40	163.88
54	24.84	12.20	376.22	34.71	6.10	302.86	20.70	5.10	119.65
55	21.34	11.10	261.16	42.68	6.60	475.20	15.32	4.60	55.50
56	32.48	14.30	711.31	30.89	5.70	229.86	22.93	5.20	146.90
57	26.11	12.50	421.59	35.67	5.50	289.50	15.29	4.60	62.47
58	23.25	11.60	318.18	30.89	5.20	211.32	20.70	5.10	119.65
59	28.03	13.30	507.88	43.95	6.70	508.46	23.57	5.30	157.18
60	26.11	12.70	427.77	38.85	6.10	372.30	21.34	5.00	124.21
61	31.21	13.80	639.84	35.35	6.30	322.51	28.03	5.60	227.07
62	26.11	12.60	424.68	34.08	6.30	301.54	24.20	5.20	162.20
63	23.25	11.80	323.20	28.03	5.70	192.30	24.52	5.30	169.05
64	24.52	12.30	370.19	39.49	6.60	412.25	17.52	4.80	83.35
65	26.43	11.80	440.53	37.58	6.70	381.67	20.70	5.10	119.65
66	26.75	12.70	447.08	43.31	6.80	501.81	18.42	4.60	55.50
67	33.44	14.20	745.30	27.39	5.60	181.41	22.93	5.20	146.90
68	29.94	13.70	588.88	34.39	6.30	306.72	15.29	4.60	62.47
69	30.25	13.40	604.42	26.75	5.50	170.91	20.70	5.10	119.65
70	28.34	13.20	514.93	37.58	6.60	376.45	23.57	5.30	157.18

71	35.35	14.90	862.36	38.54	6.60	394.17	21.34	5.00	124.21
72	24.84	12.20	376.22	35.35	6.50	331.87	28.03	5.60	227.07
73	21.34	11.10	261.16	38.54	6.60	394.17	24.20	5.20	162.20
74	32.48	14.30	711.31	21.66	5.40	114.12	24.52	5.30	169.05
75	26.11	12.50	421.59	33.12	5.80	265.35	17.52	4.60	83.35
76	23.25	11.60	318.18	39.81	6.60	418.36	22.61	5.20	145.70
77	21.34	13.30	507.88	42.36	6.70	475.22	23.89	5.40	163.88
78	26.11	12.70	427.77	38.54	6.60	394.17	20.70	5.10	119.65
79	31.21	13.50	639.84	44.27	6.50	501.12	17.22	4.60	55.50
80	26.11	12.30	424.68	40.76	6.60	436.94	22.93	5.20	146.90
81	23.25	11.80	323.20	41.72	6.70	462.21	15.29	4.60	62.47
82	24.52	12.30	370.19	34.71	6.10	302.86	20.70	5.10	119.65
83	25.41	12.60	440.53	42.68	6.60	475.20	23.57	5.30	157.18
84	31.85	13.60	655.15	30.89	5.70	229.86	21.34	5.00	124.21
85	22.29	11.60	294.63	35.67	5.50	289.50	21.34	5.30	131.02
86	30.57	13.70	612.03	30.89	5.20	211.32	15.29	4.70	63.71
87	20.70	11.10	247.05	43.95	6.70	508.46	27.07	5.50	213.09
88	23.89	11.90	342.24	38.85	6.10	372.30	12.42	4.30	40.14
89	26.43	12.70	437.37	35.35	6.30	322.51	24.20	5.30	165.05
90	23.57	11.50	331.36	34.08	6.30	301.54	20.06	5.30	117.05
91	23.42	13.60	607.94	28.03	5.70	192.30	13.06	4.40	44.93
92	25.48	11.50	402.95	39.49	6.60	412.25	27.07	5.20	206.11
93	20.14	11.40	577.05	37.58	6.70	381.67	25.48	5.50	187.57
94	28.34	13.40	522.07	42.26	6.50	501.81	17.52	4.30	84.94
95	25.48	14.10	768.14	27.39	5.60	181.41	23.57	5.20	154.46
96	23.20	12.20	627.93	34.39	6.30	306.72	22.61	5.30	145.70
97	23.57	11.80	331.36	26.75	5.50	170.91	23.89	5.40	163.88
98	28.03	12.80	497.37	33.12	5.80	265.35	20.70	5.10	119.65
99	22.29	11.60	294.63	21.66	5.20	110.24	14.33	4.60	55.50
100	24.52	11.90	367.43	33.76	5.80	274.77	22.93	5.20	146.90

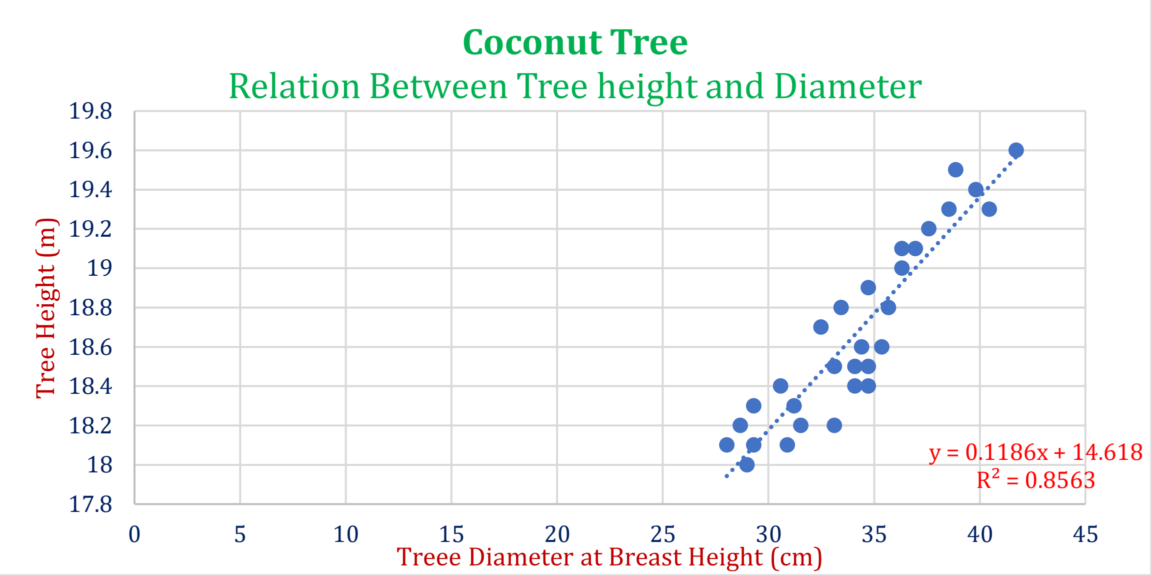
Sr. No.	**Senegalia Catechu**			**Tamarind**		
	Diameter (cm)	**Height (m)**	**Biomass (kg/tree)**	**Diameter (cm)**	**Height (m)**	**Biomass (kg/tree)**
1	21.66	4.50	139.27	34.08	5.20	406.35
2	27.39	5.10	240.16	32.80	5.30	385.63
3	28.98	5.00	261.57	28.34	4.80	269.47
4	30.89	5.10	299.41	18.47	3.90	101.68
5	19.75	4.40	115.19	26.11	4.60	223.05
6	20.06	4.50	121.09	29.94	4.70	292.16
7	24.20	4.70	177.69	14.01	4.10	64.17
8	28.66	5.00	256.32	21.97	4.50	159.34
9	26.75	4.90	221.75	23.57	4.60	184.81
10	26.11	4.80	208.20	29.94	4.80	297.85
11	24.20	4.70	177.69	28.98	4.70	275.31
12	31.21	5.20	310.56	14.65	4.30	72.72
13	28.34	5.10	255.73	19.75	4.60	133.65

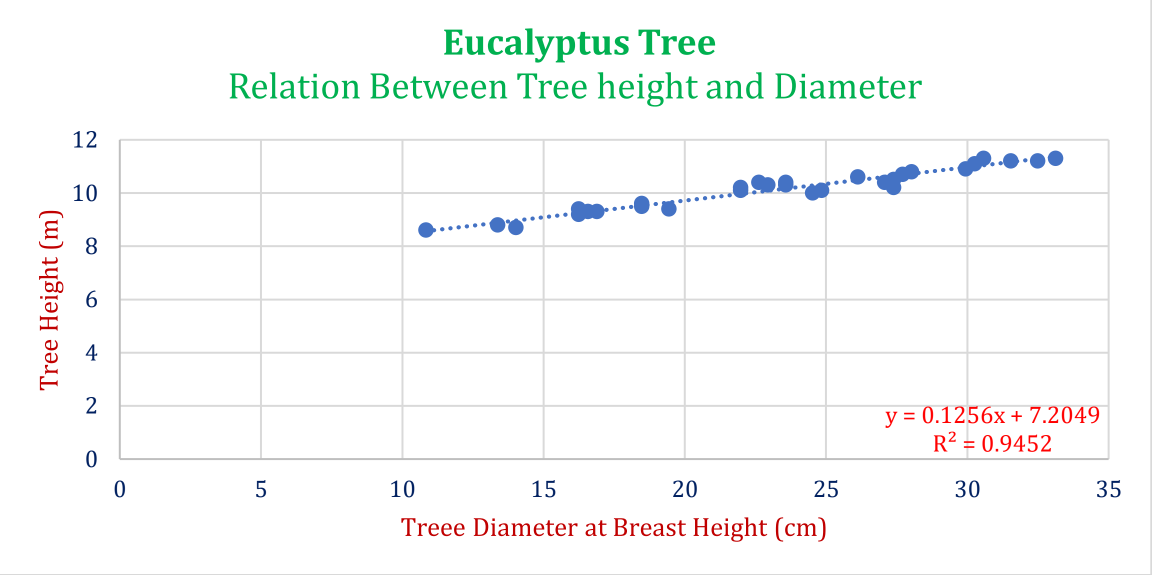
14	27.71	4.90	236.47	13.38	4.20	60.24
15	32.80	5.20	340.20	25.16	4.50	204.18
16	35.35	5.30	397.03	13.38	3.90	56.29
17	28.34	5.00	251.13	30.89	4.90	321.51
18	24.52	4.70	181.99	21.66	4.40	151.98
19	29.62	5.10	277.18	34.39	5.20	413.34
20	31.85	5.20	322.27	29.94	5.10	314.86
21	31.21	5.10	305.08	18.15	4.40	110.00
22	32.48	5.30	340.06	30.57	4.80	309.57
23	29.30	4.90	261.96	13.38	4.20	60.24
24	24.20	4.70	177.69	28.34	4.90	274.61
25	22.61	4.70	156.86	33.44	5.20	392.55
26	27.39	4.80	227.18	20.06	4.50	134.88
27	20.70	4.60	130.83	14.33	4.20	68.36
28	21.66	4.60	142.10	28.03	4.60	253.86
29	28.03	5.10	250.49	13.69	4.40	65.63
30	30.57	5.20	299.05	17.83	4.60	110.91
31	24.20	4.70	177.69	19.75	4.60	133.65
32	28.66	5.00	256.32	13.38	4.20	60.24
33	26.75	4.90	221.75	25.16	4.50	204.18
34	26.11	4.80	208.20	13.38	3.90	56.29
35	24.20	4.70	177.69	30.89	4.90	321.51
36	31.21	5.20	310.56	21.66	4.40	151.98
37	28.34	5.10	255.73	34.39	5.20	413.34
38	27.71	4.90	236.47	29.94	5.10	314.86
39	32.80	5.20	340.20	18.15	4.40	110.00
40	35.35	5.30	397.03	30.57	4.80	309.57
41	28.34	5.00	251.13	13.38	4.20	60.24
42	24.52	4.70	181.99	28.34	4.90	274.61
43	29.62	5.10	277.18	33.44	5.20	392.55
44	31.85	5.20	322.27	20.06	4.50	134.88
45	31.21	5.10	305.08	14.33	4.20	68.36
46	32.48	5.30	340.06	28.03	4.60	253.86
47	29.30	4.90	261.96	13.69	4.40	65.63
48	24.20	4.70	177.69	17.83	4.60	110.91
49	24.52	4.70	181.99	34.08	5.20	406.35
50	29.62	5.10	277.18	32.80	5.30	385.63
51	31.85	5.20	322.27	28.34	4.80	269.47
52	31.21	5.10	305.08	18.47	3.90	101.68
53	32.48	5.30	340.06	26.11	4.60	223.05
54	29.30	4.90	261.96	29.94	4.70	292.16
55	24.20	4.70	177.69	14.01	4.10	64.17
56	22.61	4.70	156.86	21.97	4.50	159.34
57	27.39	4.80	227.18	23.57	4.60	184.81
58	20.70	4.60	130.83	29.94	4.80	297.85
59	21.66	4.60	142.10	28.98	4.70	275.31
60	28.03	5.10	250.49	14.65	4.30	72.72
61	30.57	5.20	299.05	19.75	4.60	133.65
62	24.20	4.70	177.69	13.38	4.20	60.24
63	28.66	5.00	256.32	25.16	4.50	204.18

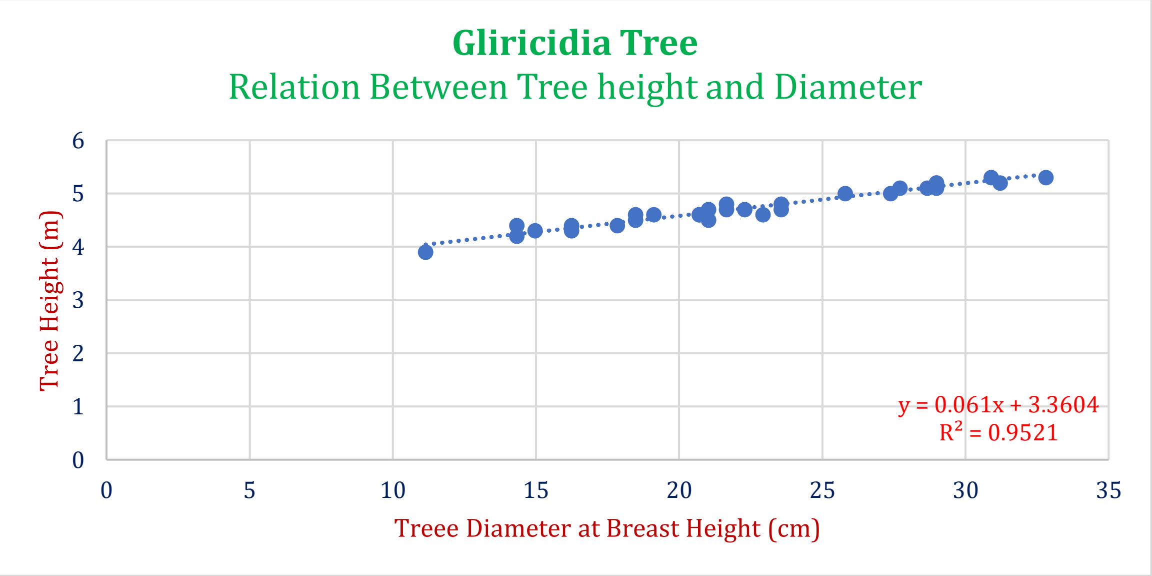
64	26.75	4.90	221.75	13.38	3.90	56.29
65	26.11	4.80	208.20	34.39	5.20	413.34
66	24.20	4.70	177.69	29.94	5.10	314.86
67	22.24	4.70	310.56	18.15	4.40	110.00
68	23.25	4.80	255.73	31.40	4.80	309.57
69	27.71	4.90	236.47	13.38	4.20	60.24
70	32.80	5.20	340.20	28.34	4.90	274.61
71	35.35	5.30	397.03	33.44	5.20	392.55
72	28.34	5.00	251.13	20.06	4.50	134.88
73	24.52	4.70	181.99	14.33	4.20	68.36
74	29.62	5.10	277.18	28.03	4.60	253.86
75	20.70	4.60	130.83	13.69	4.40	65.63
76	21.66	4.60	142.10	17.83	4.60	110.91
77	28.03	5.10	250.49	34.08	5.20	406.35
78	20.41	4.60	299.05	32.80	5.30	385.63
79	24.20	4.70	177.69	28.34	4.80	269.47
80	28.66	5.00	256.32	18.47	3.90	101.68
81	26.75	4.90	221.75	28.03	4.60	253.86
82	26.11	4.80	208.20	13.69	4.40	65.63
83	24.20	4.70	177.69	17.83	4.60	110.91
84	21.44	4.80	310.56	34.65	5.20	406.35
85	28.34	5.10	255.73	32.80	5.30	385.63
86	27.71	4.90	236.47	28.34	4.80	269.47
87	32.80	5.20	340.20	18.47	3.90	101.68
88	25.21	4.80	397.03	26.11	4.60	223.05
89	28.34	5.00	251.13	30.40	4.70	292.16
90	24.52	4.70	181.99	14.01	4.10	64.17
91	24.32	4.60	277.18	21.97	4.30	159.34
92	26.36	4.80	322.27	23.57	4.60	184.81
93	27.71	4.90	236.47	29.94	4.80	297.85
94	32.80	5.20	340.20	28.98	4.70	275.31
95	34.32	5.30	397.03	14.65	4.30	72.72
96	28.34	5.00	251.13	19.75	4.60	133.65
97	24.52	4.70	181.99	13.38	4.20	60.24
98	29.62	5.10	277.18	33.45	5.30	385.63
99	20.70	4.60	130.83	28.34	4.80	269.47
100	21.66	4.60	142.10	18.47	3.90	101.68

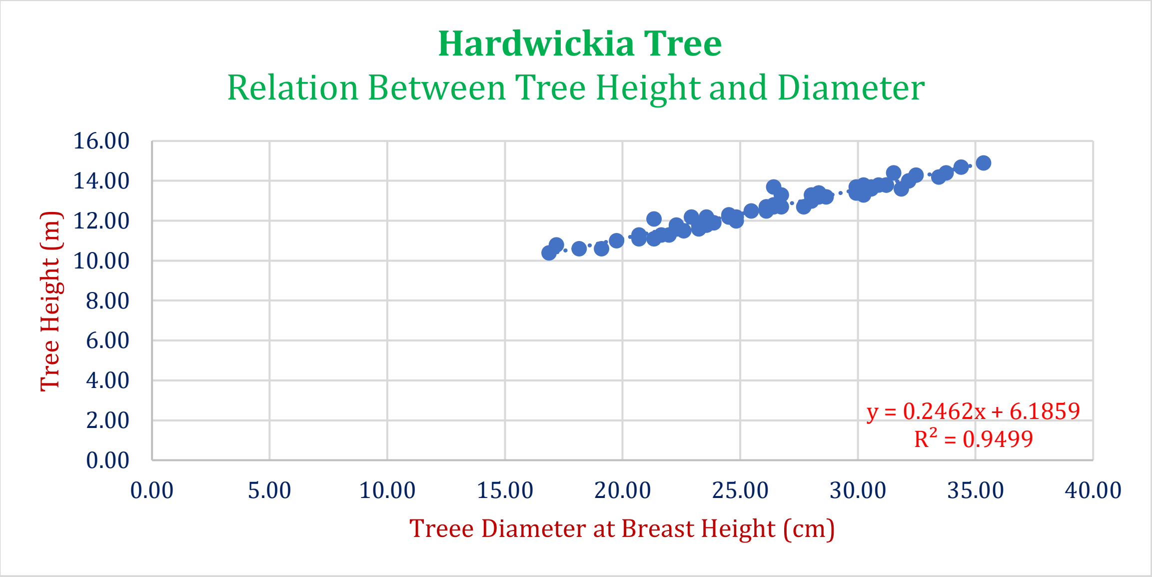
Appendix –C

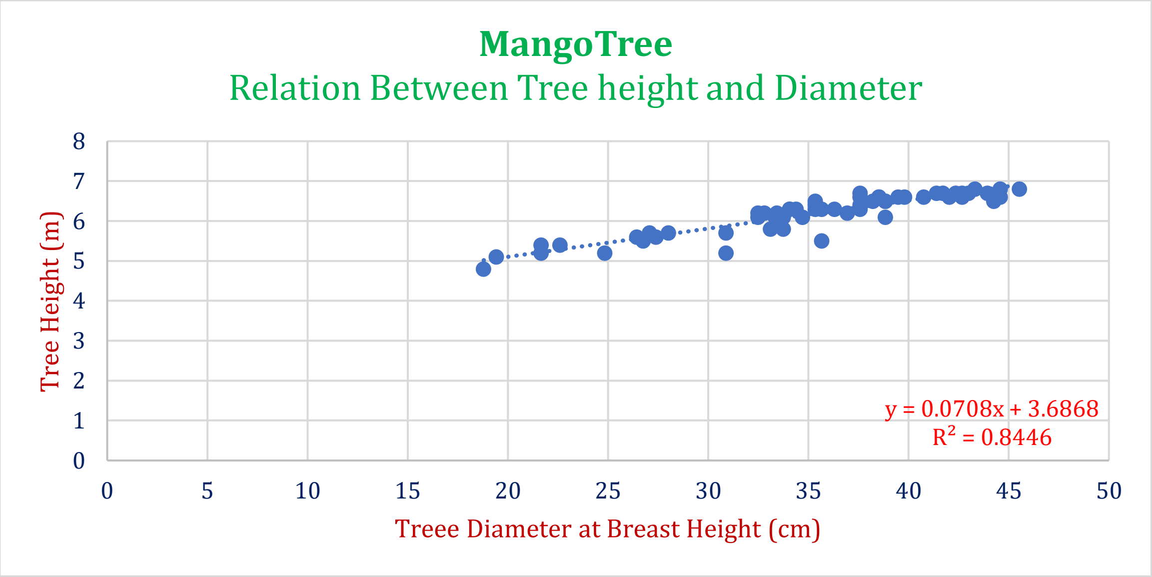
Relation between tree height and diameter for plantations in the watershed

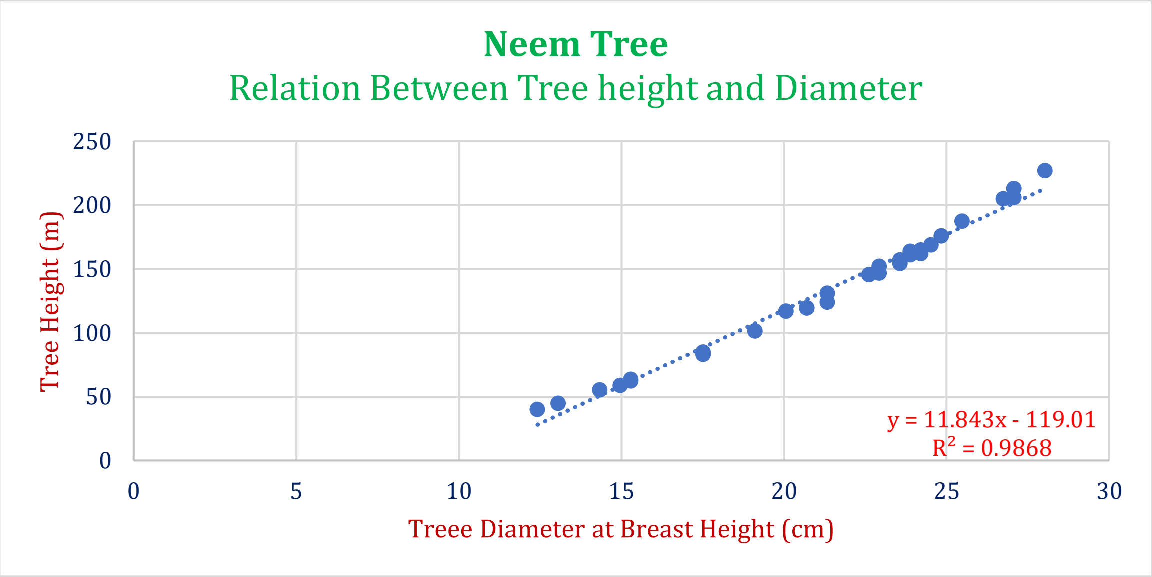


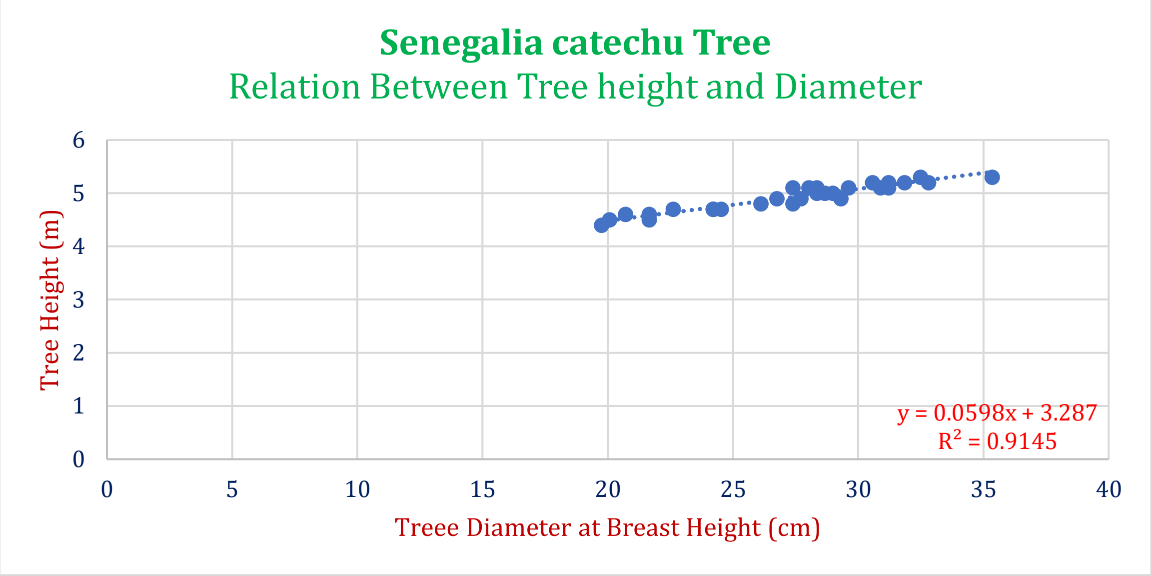


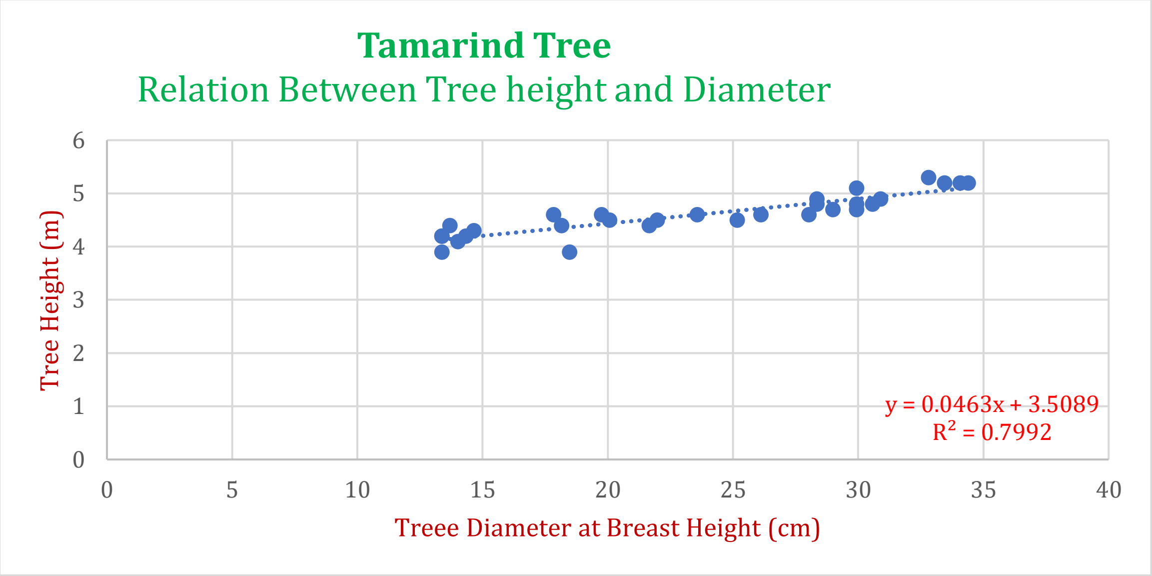



Hardwickia Tree
Relation Between Tree Height and Diameter
Tree Height (m)
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
Treee Diameter at Breast Height (cm)
y = 0.2462x + 6.1859
R² = 0.9499


MangoTree
Relation Between Tree height and Diameter
Tree Height (m)
8
7
6
5
4
3
2
1
0
0
5
10
15
20
25
30
35
40
45
50
Treee Diameter at Breast Height (cm)
y = 0.0708x + 3.6868
R² = 0.8446

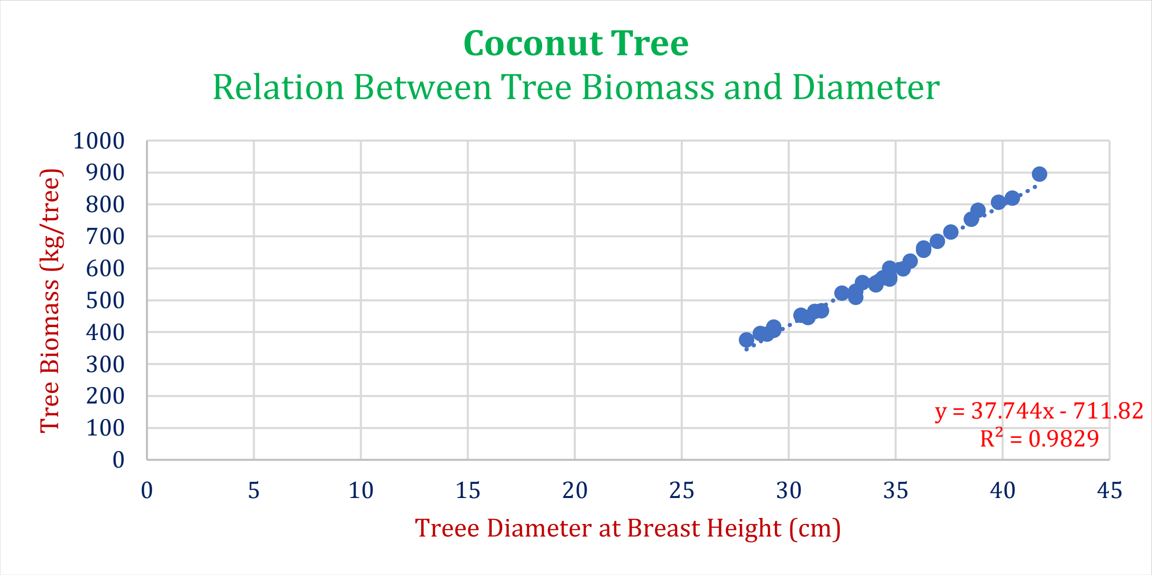

Neem Tree
Relation Between Tree height and Diameter
Tree Height (m)
250
200
150
100
50
0
0
5
10
15
20
25
30
Treee Diameter at Breast Height (cm)
y = 11.843x - 119.01
R² = 0.9868

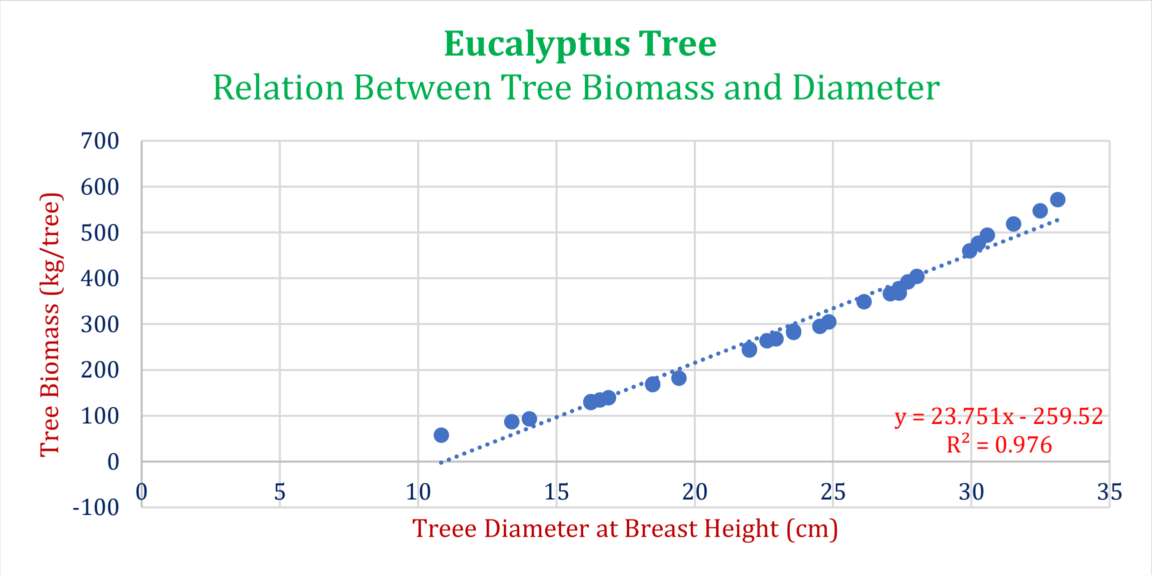

Senegalia catechu Tree
Relation Between Tree height and Diameter
Tree Height (m)
0
1
2
3
4
5
6
0
5
10
15
20
25
30
35
40
Treee Diameter at Breast Height (cm)
y = 0.0598x + 3.287
R² = 0.9145

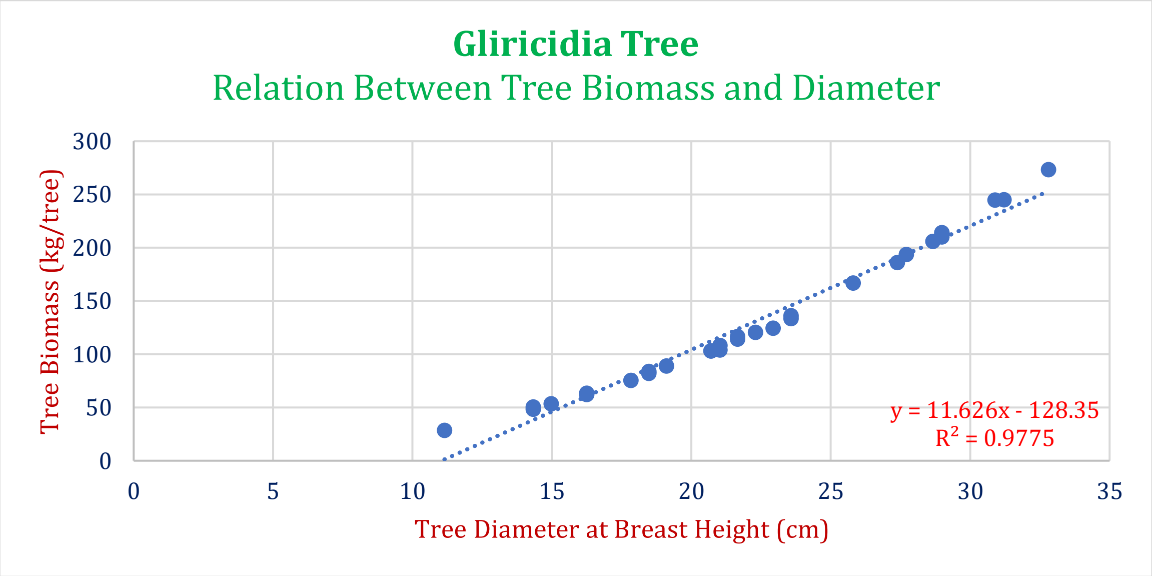

Tamarind Tree
Relation Between Tree height and Diameter
Tree Height (m)
0
1
2
3
4
5
6
0
5
10
15
20
25
30
35
40
Treee Diameter at Breast Height (cm)
y = 0.0463x + 3.5089
R² = 0.7992

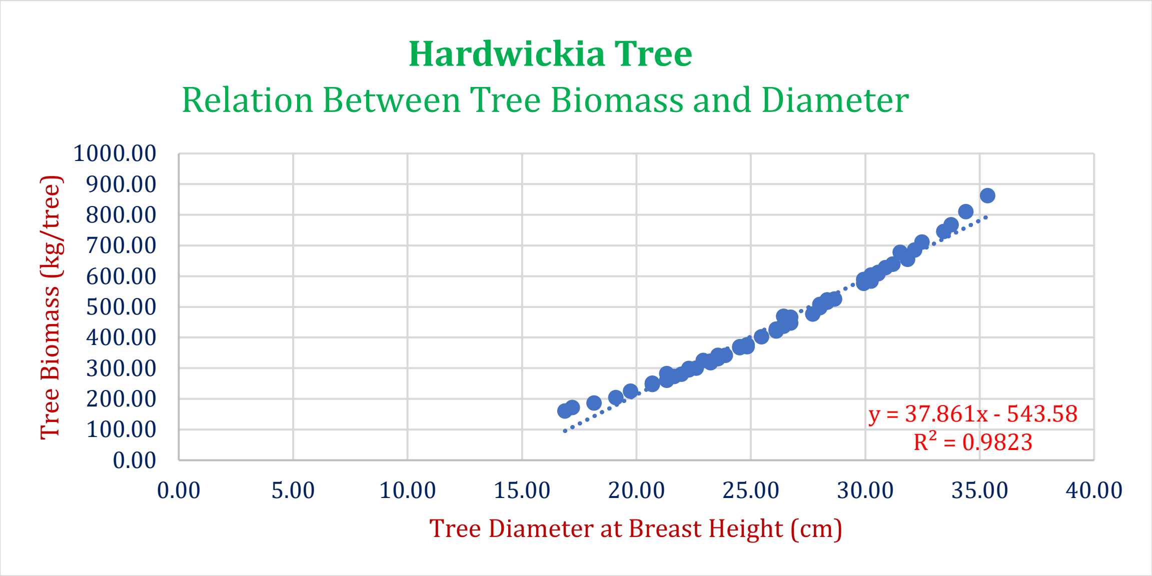
Appendix –D

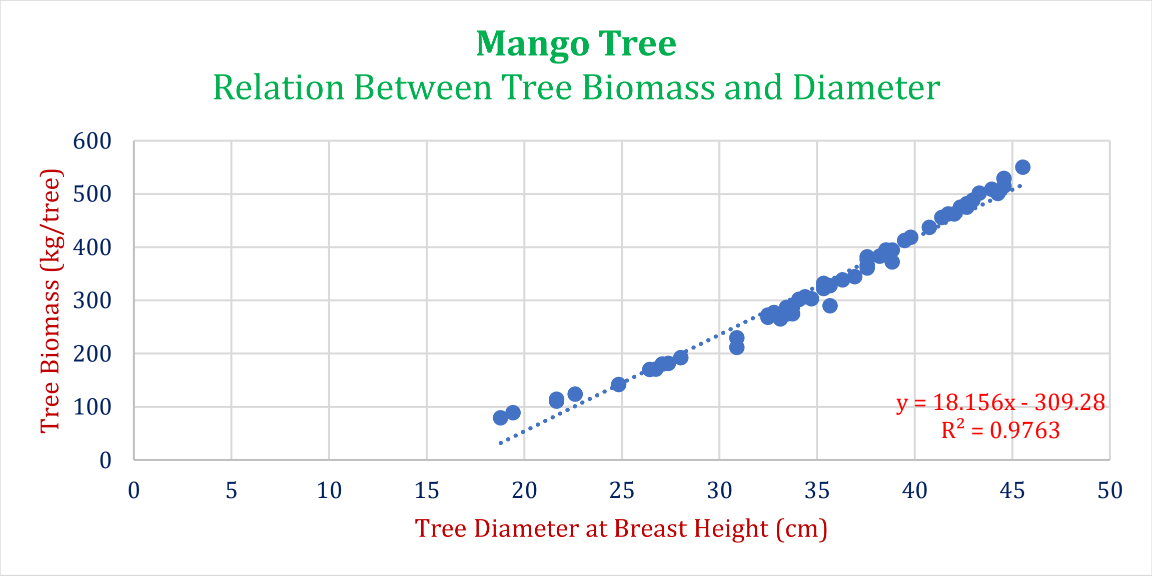
Relation between tree biomass and diameter for plantations in the watershed

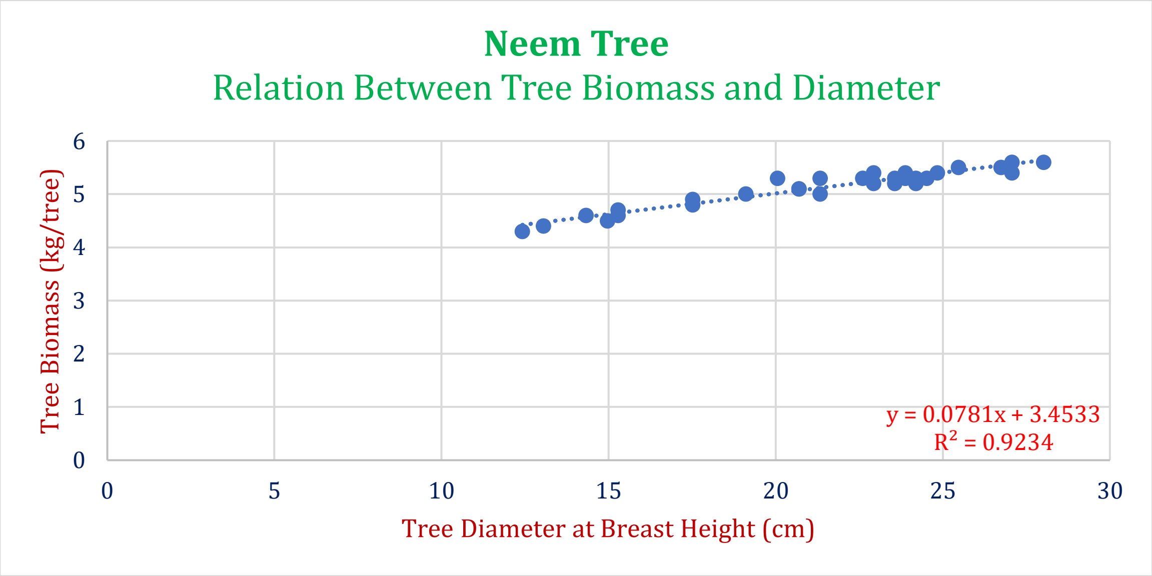


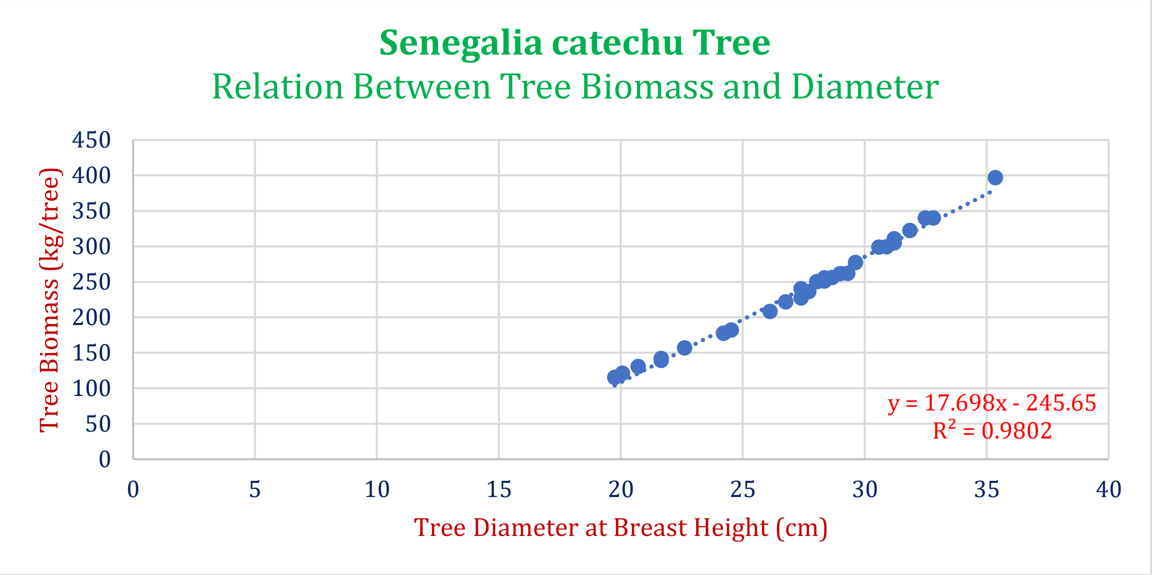


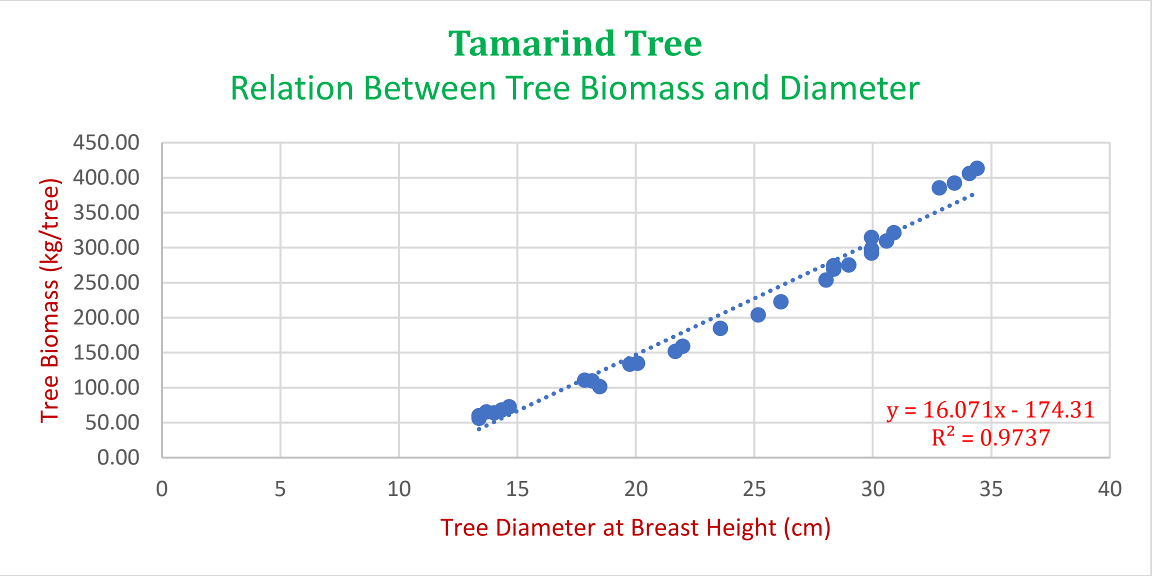



Hardwickia Tree
Relation Between Tree Biomass and Diameter
Tree Biomass (kg/tree)
1000.00
900.00
800.00
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
Tree Diameter at Breast Height (cm)
y = 37.861x - 543.58
R² = 0.9823


Mango Tree
Relation Between Tree Biomass and Diameter
Tree Biomass (kg/tree)
600
500
400
300
200
100
0
0
5
10
15
20
25
30
35
40
45
50
Tree Diameter at Breast Height (cm)
y = 18.156x - 309.28
R² = 0.9763


Neem Tree
Relation Between Tree Biomass and Diameter
Tree Biomass (kg/tree)
6
5
4
3
2
1
0
0
5
10
15
20
25
30
Tree Diameter at Breast Height (cm)
y = 0.0781x + 3.4533
R² = 0.9234


Senegalia catechu Tree
Relation Between Tree Biomass and Diameter
Tree Biomass (kg/tree)
450
400
350
300
250
200
150
100
50
0
0
5
10
15
20
25
30
35
40
Tree Diameter at Breast Height (cm)
y = 17.698x - 245.65
R² = 0.9802


Tamarind Tree
Relation Between Tree Biomass and Diameter
Tree Biomass (kg/tree)
450.00
400.00
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
0
5
10
15
20
25
30
35
40
Tree Diameter at Breast Height (cm)
y = 16.071x - 174.31
R² = 0.9737

Appendix –E

Soil properties of three consecutive sampling years (SOC, BD and SOC density)

Sr. No.	Latitude	Longitude	SOC (%)		Bulk density (g/cm^3)		SOC density (t/ha)	
			0-15	15-30	0-15	15-30	0-15	15-30
1	19.3850	74.8331	0.68	0.60	1.41	1.42	10.55	9.41
2	19.3944	74.7750	0.45	0.38	1.45	1.47	7.42	6.34
3	19.3194	74.3000	0.34	0.30	1.48	1.49	4.87	4.33
4	19.4183	74.6828	0.15	0.12	1.54	1.55	2.83	2.28
5	19.5711	74.6925	0.41	0.25	1.46	1.51	6.54	4.11
6	19.5383	74.6778	0.20	0.18	1.52	1.53	3.05	2.76
7	19.5467	74.8747	0.94	0.80	1.36	1.38	15.31	13.25
8	19.3789	74.7294	0.41	0.40	1.46	1.47	7.25	7.09
9	19.6178	74.8086	0.86	0.53	1.24	1.44	12.28	8.76
10	19.4661	74.6683	0.91	0.62	1.37	1.42	10.59	7.49
11	19.4917	74.6525	0.98	0.83	1.36	1.38	14.67	12.65
12	19.5144	74.7806	0.82	0.73	1.38	1.40	12.67	11.41
13	19.5344	74.7878	0.76	0.71	1.39	1.40	12.79	12.03
14	19.5506	74.7931	0.18	0.17	1.53	1.53	2.84	2.69
15	19.4989	74.8053	0.78	0.74	1.39	1.40	12.80	12.21
16	19.5006	74.8928	0.16	0.15	1.54	1.54	2.81	2.64
17	19.4639	74.8494	0.67	0.61	1.41	1.42	9.87	9.06
18	19.4797	74.8353	0.89	0.85	1.37	1.38	13.12	12.60
19	19.3958	74.8353	0.19	0.16	1.53	1.54	3.20	2.71
20	19.3850	74.8353	0.85	0.63	1.38	1.42	14.68	11.19
21	19.5706	74.2586	0.59	0.38	1.42	1.47	10.29	6.84
22	19.9586	74.4058	0.85	0.57	1.38	1.43	13.27	9.23
23	19.2669	74.4339	0.63	0.52	1.42	1.44	9.50	7.96
24	19.0419	74.5203	0.41	0.20	1.46	1.52	6.14	3.12
25	19.9708	74.5692	0.93	0.82	1.36	1.38	12.10	10.81
26	19.9458	74.8533	0.67	0.23	1.41	1.51	11.34	4.18
27	19.0450	74.1247	1.03	0.83	1.35	1.38	16.15	13.32
28	19.0458	74.1267	0.57	0.55	1.43	1.43	9.00	8.71
29	19.0486	74.9547	0.76	0.65	1.39	1.41	12.27	10.65
30	19.2372	74.8914	0.43	0.31	1.46	1.49	6.82	5.02

31	29.3872	74.8511	0.78	0.67	1.39	1.41	12.31	10.72
32	19.5247	74.6350	0.61	0.43	1.42	1.46	10.34	7.49
33	19.5369	74.2336	0.76	0.35	1.39	1.48	11.08	5.42
34	19.4961	74.4503	1.02	0.93	1.35	1.36	14.57	13.42
35	19.5375	74.1078	0.17	0.13	1.55	1.60	2.97	2.34
36	19.5242	74.4239	0.33	0.26	1.48	1.50	5.97	4.77
37	19.5483	74.2189	0.59	0.50	1.42	1.44	9.27	7.96
38	19.0231	74.4567	0.95	0.81	1.36	1.38	15.15	13.14
39	19.0308	74.4747	0.81	0.76	1.38	1.39	13.72	12.95
40	19.0483	74.5058	0.76	0.61	1.39	1.42	11.48	9.40
41	19.7336	74.3747	1.10	0.95	1.32	1.36	16.45	14.63
42	19.4503	74.1753	0.41	0.36	1.46	1.48	5.99	5.30
43	19.3836	74.4506	0.76	0.70	1.39	1.40	12.47	11.58
44	19.0086	74.9122	0.91	0.83	1.37	1.38	13.31	12.25
45	19.2242	74.9431	0.81	0.75	1.38	1.39	11.82	11.03
46	19.2039	74.8053	0.72	0.68	1.40	1.41	10.97	10.41
47	19.4869	74.8058	0.76	0.62	1.39	1.42	10.90	9.06
48	19.7197	74.1928	0.90	0.52	1.37	1.44	15.24	9.26
49	19.4339	74.7478	0.78	0.71	1.39	1.40	13.08	12.01
50	19.3197	74.3003	0.51	0.43	1.44	1.46	8.33	7.11

Sr. No.	**Latitude**	**Longitude**	**SOC (%)**		**Bulk density (g/cm^3)**		**SOC density (t/ha)**	
			0-15	**15-30**	**0-15**	**15-30**	**0-15**	**15-30**
1	19.3850	74.8331	0.75	0.62	1.39	1.42	11.53	9.70
2	19.3944	74.7750	0.48	0.40	1.45	1.47	7.88	6.65
3	19.3194	74.3000	0.37	0.31	1.47	1.49	5.28	4.47
4	19.4183	74.6828	0.25	0.15	1.51	1.54	4.61	2.83
5	19.5711	74.6925	0.47	0.26	1.45	1.50	7.43	4.26
6	19.5383	74.6778	0.31	0.20	1.49	1.52	4.62	3.05
7	19.5467	74.8747	0.80	0.81	1.38	1.38	13.25	13.40
8	19.3789	74.7294	0.47	0.41	1.45	1.46	8.23	7.25
9	19.6178	74.8086	0.68	0.52	1.41	1.44	11.01	8.61
10	19.4661	74.6683	0.94	0.67	1.36	1.41	10.90	8.04
11	19.4917	74.6525	1.06	0.86	1.34	1.37	15.72	13.06
12	19.5144	74.7806	0.84	0.74	1.38	1.40	12.95	11.55

13	19.5344	74.7878	1.06	0.76	1.34	1.39	17.22	12.79
14	19.5506	74.7931	0.20	0.17	1.52	1.53	3.14	2.69
15	19.4989	74.8053	0.82	0.52	1.38	1.44	13.39	8.84
16	19.5006	74.8928	0.18	0.17	1.53	1.53	3.15	2.98
17	19.4639	74.8494	0.70	0.63	1.40	1.42	10.27	9.33
18	19.4797	74.8353	0.93	0.85	1.36	1.38	13.65	12.60
19	19.3958	74.8353	0.42	0.16	1.46	1.54	6.77	2.71
20	19.3850	74.8353	0.87	0.65	1.37	1.41	14.99	11.52
21	19.5706	74.2586	0.60	0.46	1.42	1.45	10.45	8.18
22	19.9586	74.4058	0.88	0.56	1.37	1.43	13.69	9.08
23	19.2669	74.4339	0.65	0.53	1.41	1.44	9.77	8.10
24	19.0419	74.5203	0.42	0.24	1.46	1.51	6.28	3.71
25	19.9708	74.5692	0.95	0.85	1.36	1.38	12.34	11.17
26	19.9458	74.8533	0.68	0.33	1.41	1.48	11.49	5.88
27	19.0450	74.1247	1.13	0.86	1.33	1.37	17.53	13.76
28	19.0458	74.1267	0.60	0.55	1.42	1.43	9.44	8.71
29	19.0486	74.9547	0.72	0.67	1.40	1.41	11.69	10.95
30	19.2372	74.8914	0.45	0.36	1.45	1.48	7.12	5.78
31	29.3872	74.8511	0.74	0.68	1.40	1.41	11.74	10.87
32	19.5247	74.6350	0.63	0.46	1.42	1.45	10.65	7.97
33	19.5369	74.2336	0.70	0.36	1.40	1.48	10.28	5.56
34	19.4961	74.4503	1.06	0.90	1.34	1.37	15.07	13.04
35	19.5375	74.1078	0.20	0.14	1.52	1.54	3.43	2.43
36	19.5242	74.4239	0.40	0.26	1.47	1.50	7.15	4.77
37	19.5483	74.2189	0.62	0.57	1.42	1.43	9.71	8.99
38	19.0231	74.4567	0.93	0.82	1.36	1.38	14.87	13.29
39	19.0308	74.4747	0.85	0.78	1.38	1.39	14.32	13.26
40	19.0483	74.5058	0.79	0.63	1.39	1.42	11.88	9.68
41	19.7336	74.3747	0.80	0.94	1.38	1.36	12.55	14.49
42	19.4503	74.1753	0.60	0.35	1.42	1.48	8.51	5.16
43	19.3836	74.4506	0.78	0.70	1.39	1.40	12.77	11.58
44	19.0086	74.9122	0.93	0.80	1.36	1.38	13.57	11.85
45	19.2242	74.9431	0.83	0.78	1.38	1.39	12.09	11.43
46	19.2039	74.8053	0.76	0.71	1.39	1.40	11.51	10.83
47	19.4869	74.8058	0.78	0.64	1.39	1.41	11.16	9.33

48	19.7197	74.1928	0.63	0.53	1.42	1.44	11.04	9.42
49	19.4339	74.7478	0.80	0.73	1.38	1.40	13.38	12.32
50	19.3197	74.3003	0.53	0.45	1.44	1.45	8.63	7.42

Sr. No.	**Latitude**	**Longitude**	**SOC (%)**		**Bulk density (g/cm^3)**		**SOC density (t/ha)**	
			0-15	**15-30**	**0-15**	**15-30**	**0-15**	**15-30**
1	19.3850	74.8331	0.75	0.62	1.39	1.42	11.47	9.70
2	19.3944	74.7750	0.48	0.40	1.41	1.46	7.70	6.64
3	19.3194	74.3000	0.37	0.31	1.47	1.44	5.25	4.34
4	19.4183	74.6828	0.25	0.15	1.47	1.54	4.50	2.83
5	19.5711	74.6925	0.47	0.26	1.44	1.50	7.37	4.25
6	19.5383	74.6778	0.31	0.20	1.41	1.52	4.38	3.05
7	19.5467	74.8747	0.80	0.81	1.38	1.38	13.20	13.35
8	19.3789	74.7294	0.47	0.41	1.44	1.46	8.16	7.22
9	19.6178	74.8086	0.68	0.52	1.41	1.43	11.05	8.56
10	19.4661	74.6683	0.94	0.67	1.36	1.41	10.89	8.02
11	19.4917	74.6525	1.06	0.86	1.35	1.37	15.78	13.06
12	19.5144	74.7806	0.84	0.74	1.37	1.39	12.89	11.52
13	19.5344	74.7878	1.06	0.76	1.34	1.38	17.22	12.73
14	19.5506	74.7931	0.20	0.17	1.51	1.52	3.12	2.67
15	19.4989	74.8053	0.82	0.52	1.37	1.43	13.31	8.76
16	19.5006	74.8928	0.18	0.17	1.52	1.53	3.13	2.98
17	19.4639	74.8494	0.70	0.63	1.40	1.41	10.23	9.31
18	19.4797	74.8353	0.93	0.85	1.36	1.37	13.62	12.56
19	19.3958	74.8353	0.42	0.16	1.45	1.53	6.74	2.70
20	19.3850	74.8353	0.87	0.65	1.37	1.40	14.94	11.41
21	19.5706	74.2586	0.60	0.46	1.42	1.45	10.40	8.18
22	19.9586	74.4058	0.88	0.56	1.37	1.42	13.66	9.03
23	19.2669	74.4339	0.65	0.53	1.42	1.43	9.81	8.07
24	19.0419	74.5203	0.42	0.24	1.45	1.50	6.25	3.69
25	19.9708	74.5692	0.95	0.85	1.36	1.37	12.34	11.16
26	19.9458	74.8533	0.68	0.33	1.41	1.48	11.49	5.86
27	19.0450	74.1247	1.13	0.86	1.33	1.37	17.54	13.71
28	19.0458	74.1267	0.60	0.55	1.41	1.42	9.37	8.63

29	19.0486	74.9547	0.72	0.67	1.39	1.40	11.60	10.88
30	19.2372	74.8914	0.45	0.36	1.45	1.47	7.12	5.75
31	29.3872	74.8511	0.74	0.68	1.39	1.41	11.72	10.87
32	19.5247	74.6350	0.63	0.46	1.41	1.45	10.58	7.96
33	19.5369	74.2336	0.70	0.36	1.40	1.47	10.24	5.52
34	19.4961	74.4503	1.06	0.90	1.34	1.36	15.01	12.98
35	19.5375	74.1078	0.20	0.14	1.52	1.54	3.43	2.43
36	19.5242	74.4239	0.40	0.26	1.46	1.49	7.11	4.73
37	19.5483	74.2189	0.62	0.57	1.42	1.43	9.69	9.00
38	19.0231	74.4567	0.93	0.82	1.33	1.38	14.51	13.24
39	19.0308	74.4747	0.85	0.78	1.37	1.38	14.27	13.18
40	19.0483	74.5058	0.79	0.63	1.38	1.41	11.87	9.61
41	19.7336	74.3747	0.80	0.94	1.38	1.36	12.55	14.44
42	19.4503	74.1753	0.60	0.35	1.37	1.48	8.18	5.15
43	19.3836	74.4506	0.78	0.70	1.38	1.40	12.71	11.53
44	19.0086	74.9122	0.93	0.80	1.35	1.38	13.41	11.81
45	19.2242	74.9431	0.83	0.78	1.38	1.38	12.10	11.40
46	19.2039	74.8053	0.76	0.71	1.39	1.40	11.49	10.80
47	19.4869	74.8058	0.78	0.64	1.39	1.42	11.16	9.34
48	19.7197	74.1928	0.63	0.53	1.41	1.43	11.03	9.38
49	19.4339	74.7478	0.80	0.73	1.38	1.39	13.33	12.27
50	19.3197	74.3003	0.53	0.45	1.43	1.45	8.58	7.41

Appendix – F

Sample Calculations

Amount of CO_2 sequestered by tree

Diameter = 30 cm

Height = 5.2 m

Wood density = 0.59 g/cm^3

Age = 30 years

Above ground biomass = $AGB = 0.112 \times (\rho D^2 H)^{0.916}$

$$= 0.112 \times (0.59 \times 30^2 \times 5.2)^{0.916}$$

= 158.95 kg/tree

Below ground biomass = AGB×0.26 = 158.95×0.26 = 41.32 kg/tree

Total biomass = AGB + BGB = 158.95 +14.32 = 200.28 kg/tree

Total carbon stock = Total Biomass ×0.5 =200.28 × 0.5 = 100.14 kg C/tree

The biomass carbon stock of a tree is 100.14 kg C/tree

CO_2 sequestered by tree = 100.14 × 3.667 = 367.21 kg of CO_2/tree

CO_2 sequestration rate of a tree = 367.21/30 =12.24 kg of CO_2/year

Amount of CO_2 sequestered by soil

Bulk density = 1.42 gm/cc

Soil organic carbon = 0.70%

Coarse fraction = 25%

$$Corrected\ Bulk\ density = Bulk\ density\ \times \frac{(100 - Coarse\ Farction)}{100}$$

$$= 1.42\ \times \frac{(100 - 25)}{100}$$

= 1.06

$$SOC\ density = \frac{SOC}{100} \times Corrected\ Bulk\ density \times Soil\ Sampling\ depth \times 10^4$$

$$= \frac{0.70}{100} \times 1.06 \times 0.15 \times 10^4$$

=11.13 tonnes/ha

Total carbon stored in soil = SOC density ×Area

=11.13 ×1260

= 14023.8 tonnes

Appendix – G

Plates

Plate: Measurement of tree parameters (DBH and Height)

Plate: Grass sample collection

Plate: Shrub sample collection

Plate: Soil sample collection and analysis

Plate: Soil sample analysis

8. VITAE

SHELAR RAHUL SANJAY

DOCTOR OF PHILOSOPHY (AGRICULTURAL ENGINEERING)

IN

SOIL AND WATER CONSERVATION ENGINEERING

2023

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