

**EVALUATION OF AGROFORESTRY SYSTEMS FOR THEIR
CARBON AND NITROGEN POOLS IN MID-HILLS OF
HIMACHAL PRADESH**

Thesis

by

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(F-2021-14-M)**

submitted to



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This is to certify that the thesis entitled, “**Evaluation of agroforestry systems for their carbon and nitrogen pools in mid-hills of Himachal Pradesh**” submitted in partial fulfillment of the requirements for the award of degree of **Master of Science** in the discipline of **Forestry (Silviculture and Agroforestry)** of Dr Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan (H.P.),173220 is a bonafide research work carried out by **Ms. Sakshi Tomar (F-2021-14-M)** daughter of Shri Shiv Gopal Singh under my supervision and that no part of this thesis has been submitted for any other degree or diploma.

The assistance and help received during the course of investigation has been fully acknowledged.

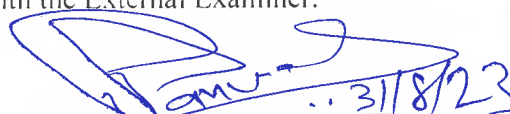
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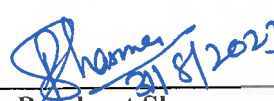


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LIST OF ABBREVIATIONS

%	:	Per cent
&	:	And
@	:	At the rate of
AAC	:	Aggregated associated Carbon
AC	:	Active Carbon
AF	:	Agroforestry
AFs	:	Agroforestry Systems
AN	:	Ammonical Nitrogen
ANOVA	:	Analysis of Variance
BL	:	Barren Land
CD	:	Critical difference
C_{frac1}	:	Carbon fraction 1
C_{frac2}	:	Carbon Fraction 2
C_{frac3}	:	Carbon Fraction 3
C_{frac4}	:	Carbon fraction 4
CL	:	Cultivated Land
cm	:	Centimeter
cm^2	:	square centimetre
CMI	:	Carbon Management Index
C_{mic}	:	Microbial Biomass Carbon
C_{oc}	:	Organic Carbon
CPI	:	Carbon Pool Index
CR	:	Recalcitrant Carbon
C_{tot}	:	Total Carbon
CV	:	Coefficient of Variation
D	:	Depth
e.g	:	for example
<i>et al</i>	:	Co-workers
Fig	:	Figure
FL	:	Fallow Land
g	:	grams
GHG	:	Green House Gas

GL	:	Grassland
H.P.	:	Himachal Pradesh
ha	:	Hectare
i.e.	:	That is
Kg	:	Kilogram
LC	:	Labile Carbon
LDN	:	Land Degradation Neutrality
LI	:	Lability Index
LLC	:	Less Labile Carbon
LUS	:	Land Use System
MC	:	Mineralizable Carbon
Mg	:	Mega gram
mg	:	Milligrams
mm	:	Millimetres
N	:	Nitrogen
NLC	:	Non Labile Carbon
NN	:	Nitrate Nitrogen
NPP	:	Net Primary Productivity
°C	:	Degree Centigrade
OP	:	Open Pasture
PC	:	Passive Carbon
POC	:	Particulate Organic Carbon
RF	:	Rainfed Cultivation
SDG	:	Sustainable Development Goal
SE	:	Standard Error
SOC	:	Soil Organic Carbon
SP	:	Silvipasture
T	:	Treatment
TN	:	Total Nitrogen
TOC	:	Organic Carbon
TLC	:	Total Labile Carbon
VLC	:	Very Labile Carbon

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Chapter-1

INTRODUCTION

In recent years, one of the most debated subjects has been the struggle against climate change, with a focus on the significant potential that soils have to stabilise the climate (McClellan *et al.*, 2015; FAO, 2019). In order to reduce greenhouse gas (GHG) emissions, management practices that aim to store soil organic carbon and improve soil quality in agroecosystems have been applied (Schleifer and Sun, 2020). Due to their advantages in terms of output and the environment, agroforestry systems are now recognised on a global scale as an integrated strategy for more sustainable land use. Agroforestry (AF) is the practice of raising multipurpose trees with agricultural crops or pastures on the same piece of land. It is one of the main source for bringing about the prosperity of the poor, who suffer from hunger, malnutrition, extreme poverty, and environmental degradation in the regions that have been left out of the Green Revolution. Trees and agroforestry can indeed play a crucial role in global carbon flux and contribute to carbon storage (Ramesh *et al.*, 2015). According to Gordon *et al.* (1997), there are interactions between many components in agroforestry systems that are both ecological and economic and thus contribute in sustainability of system. The inclusion of agroforestry systems can have a significant impact on carbon (C) sequestration due to their increased contribution of organic matter to the soil. Through litter accumulation, agroforestry (AF) is thought to increase soil organic carbon (SOC), reduce soil erosion, improve land productivity, and diversify agricultural revenue (Nair *et al.*, 2010). The significance of organic carbon for soil quality in terms of its physical, chemical, and biological aspects is widely acknowledged. Nevertheless, assessing soil quality solely based on total organic carbon measurements may not provide accurate indicators of changes. Instead, employing techniques that selectively extract the more readily decomposable fraction could offer a more practical method for evaluating variations in soil organic carbon resulting from diverse soil types.

Even with considerable studies related to potential of Agroforestry system to store carbon, significant gaps still remain in the study of their ability to store Carbon in different forms like active and passive pool. Earlier this was practiced by farmers to meet their basic needs but the role of agroforestry in dealing with climatic change is also catching the

attraction of ecologists to deal with changing climatic patterns all over the globe. In recent years, interest in sustainable farming practices like agroforestry has grown.

In India, 28.427 million ha, or 8.65% of the total geographical area is under agroforestry (Raza *et al.*, 2022). In hilly regions, multipurpose trees of farmland not only provide fodder, fuel, fiber, and fruits, but also reduces soil erosion and landslide, protect crops from unfavourable weather conditions, conserve moisture, and improve soil quality through nitrogen fixation and organic matter in the form of leaf fall, among other things. The amount of carbon dioxide in the atmosphere has risen to 412 ppm. Many experts suggested agroforestry as a powerful tool for reducing climate change and reaping financial rewards. To slow down climate change, the Indian government is also promoting a tree-based land management system that helps to reach the target of 33% of the geographical area as forest cover.

The core concept supporting agroforestry is spatial or temporal arrangements that result in greater structural complexity compared to monoculture production (Jose, 2009). In the mid-hills of Himachal Pradesh, agroforestry is a popular technique where farmers keep specific trees and shrubs in their crop production systems to replenish soil fertility depleted by cropping. Agroforestry systems, such as agrisilviculture, agrihorticulture, silvopastoral, etc. are more prevalent in Himachal Pradesh and give farming systems stability and sustainability from a production and soil quality maintenance point of view.

Carbon stored in the earth and plants are lost as a result of climate change, land degradation, and desertification. The main contributors to soil organic matter are nitrogen and soil organic carbon. In addition to being crucial for sustainability and production, their dynamics offer ways to lessen the enrichment of atmospheric carbon dioxide (Lal, 2004). The fundamental idea behind achieving Land Degradation Neutrality (LDN) is to reroute atmospheric carbon (C) into the soil system because soil organic carbon (SOC) contains the key to stopping the process of land degradation. The two main measures or indices for the rehabilitation of degraded lands are the accretion of soil organic C and its fractions and the increase in Net Primary Productivity (NPP) (Chappell *et al.*, 2019). Any managerial strategy that enables both would therefore be the key to success.

One of the major causes of soil quality deterioration in the world is increasing anthropogenic disturbances, especially in land use and cover change. Soil organic carbon

significantly affects the physical, chemical, and biological aspects of the soil, due to which it has prominently gained importance in the assessment of soil quality. Although SOC is an indicator of soil quality, the evaluation of different soil fractions of carbon can be used to detect even the slightest changes in land use management as different land use types influence the carbon fluxes in an ecosystem through different mechanisms *viz.*, litter quality, litter deposition and turnover rate, *etc.* According to Chen *et al.* (2004), the dynamics of soil carbon is crucial to the carbon cycle and the viability of terrestrial ecosystems.

The main contributors to soil organic carbon are nitrogen and soil organic carbon. In addition to being crucial for productivity and sustainability, their dynamics offer ways to lessen the enrichment of atmospheric CO₂ (Lal, 2004). The partitioning of SOC into pools with various turnover rates based on biological lability has been one method utilised to understand SOC dynamics (Benbi *et al.*, 2012; Majumder *et al.*, 2007 and Ramesh *et al.*, 2015). Based on the decomposition turnover time, soil organic carbon (SOC) is categorised into two main pool that are categorised into labile or active pool and the passive pool. The passive pool is least impacted by management practices and does not show significant variation, whereas the active pool is more vulnerable to changes in management practices and displays more variability among treatments. In order to sustain soil quality and production, the active or labile C pool, which has a quick turnover rate, is a crucial energy source for the soil food web. As roots are the primary source of belowground carbon, soil depth is an important consideration in SOC stock investigations (Brunn *et al.*, 2023). It is widely acknowledged that plant roots and their exudates, dissolved organic matter, and bioturbation activities significantly contribute organic matter to the subsurface horizons (Rumpel and Kogel-Knabner, 2011). Furthermore, because carbon stored in the subsurface is less affected by disturbances brought on by changes in land use, subsoil carbon is sometimes regarded as being more significant than topsoil carbon in terms of source vs sink relations for CO₂ (Batjes, 1996; Lorenz and Lal, 2005).

The relative proportion of various soil carbon fractions determines the pattern of mineralization and soil quality (Ghosh *et al.*, 2012). A comprehensive understanding of these fractions in any land-use system will help to determine the sustainability and quality of the soil. In spite of the existence of a large number of studies that integrate the different carbon pools/fractions into the Carbon Management Index (CMI) as a way to assess the capacity of land use management systems to promote soil quality. Different indices like the Lability

Index (LI) and Carbon Pool Index (CPI) can also be derived from various SOC pools that further help to determine the suitability of land use for sustainable development.

Similar to this, there are many sources of nitrogen (N), such as ammonia and nitrate N, which are crucial for delivering N to plants and regulating the rate of mineralization. It takes time for biological N to be mineralized into ammonium ($\text{NH}_4^+\text{-N}$). It is the primary form in which N is made available for crops and takes place through microbial transformation activities. The process of N-mineralization is an essential component of N cycling in an ecosystem (Hojjati *et al.*, 2021). According to Neve *et al.* (2003), microbial activity, which is indirectly influenced by soil temperature, moisture content, and accessible pore space, controls the N-mineralization process. The importance of agroforestry trees in the accumulation of nutrient pools and their transformations into an ecosystem resembling a forest is now well known (Das and Chaturvedi, 2008; Rodrigues *et al.*, 2011), however, little is known about how well agroforestry trees can accumulate and mineralize nitrogen (Pandey *et al.*, 2000, 2007). Land-use decisions, cultural activities, and management strategies all have a significant role in the nitrogen cycle through influencing nutrient buildup, turnover, and transportation (Laganier *et al.*, 2010). Predicting soil nutrient dynamics under various land-use changes will be made easier by evaluating the impact of land-use pattern on N-mineralization. Agri-horti-silviculture, agri-silviculture, and agrihorticulture are some of the traditional agroforestry systems that have been used in the Himalayan belt (Parihaar *et al.*, 2015; Bargali *et al.*, 2019), and they are among the most widely used systems (Padalia *et al.*, 2018). The main tree/shrub species and floristic composition may be significantly altered by changes in land use, such as the conversion of forest to grassland or the use of agroforestry, which will then have an impact on the soil structure and soil processes. According to Nyadzi *et al.* (2003), research on the cycling of nitrogen and other nutrients can be used to both identify and reap the potential benefits of agroforestry systems. In addition to modifying soil organic matter stability, consequences linked to changes in land use also impact nitrogen availability (Glaser *et al.*, 2001).

In the biosphere, soil plays a significant role in carbon sequestration and has a greater capacity to store carbon in vegetation than atmosphere (Bellamy *et al.*, 2005). In an agroforestry system, soil carbon is influenced because of inputs from litter production and turnover in conjunction with various stabilization processes occurring in the soil. The fundamental mechanism by which SOC is retained in soil is soil aggregation (Carter, 1996).

The type of soil aggregation also affects the amount of soil C retention in soils, among other factors (Carter, 1996; Haile *et al.*, 2008, and Takimoto *et al.*, 2008a). Many significant features are still incompletely studied, including the amount of carbon (C) sequestration in soils under agroforestry systems (AFS) in relation to soil types and vegetation structure. It can be held for extended periods of time in particle size 53-250 μm or for short periods of time in particle size 250-2000 μm , including the generally recognised stability of C stored in the smallest size class, the silt and clay size fraction (<53 μm) (Six *et al.* 2002). Particle size 250-2000 μm show higher SOC concentration than particle size 53-250 μm and silt and clay fractions (<53 μm). At the same time, particle size 250-2000 μm are more sensitive to the effects of land-use changes. SOC stored in the silt and clay (<53 μm) is securely held and is physically protected from the effects of land-use changes. Tree-based land use systems can improve nutrient cycling and enhance soil structure, increase SOC stocks depending upon the quantity and quality of litter reaching the soil surface and the rate of litter decomposition and nutrient release (Aguiar *et al.*, 2010). It is very important to study the dynamics of SOC through its fractions, which differ in their residence time, soil function, and control factors (Solomon *et al.* 2000). The finding that particle size 250-2000 μm is frequently more labile than SOC in the clay and silt fractions (<53 μm) is the fundamental premise for soil size fractionation (Tiessen and Stewart, 1983). Given the importance of size fractions in SOC storage, several studies on the potential for C sequestration in soils under AFS have emphasized the importance of determining the extent of C storage in different aggregate classes at deeper soil depths up to 1 m (Haile *et al.*, 2008). These studies suggest that a variety of site-specific variables, such as soil type, land use, and soil depth class, as well as their potent interactions have impact on amount of soil C stored in land use system. To draw conclusions on the significance of AFS in soil C storage, it is crucial to expand such studies across a wide range of land-use regimes.

There are a number of studies that are available on soil C storage under different land use types prevalent in Himachal Pradesh. But very less study has been conducted so far related to the evaluation of different soil carbon fractions stored in soils under different newly established agroforestry systems, particularly in mid-hills agro-ecosystems of the north-western Himalayas. Predicting the permanence and functionality of sequestered SOC requires a thorough understanding of how carbon inputs are distributed among the various SOC fractions (Zhang *et al.*, 2022). Additionally, it advances knowledge on the mechanisms

underlying SOM's synthesis, stabilisation, and resistance to degradation (Lavallee *et al.*, 2020). Therefore, it is crucial to research various SOC compartments and how various land-use and management techniques affect them (Lavallee *et al.*, 2020). Therefore, the present study focuses on the long-term effects of various agroforestry systems on the distribution of soil carbon and nitrogen pools with varying lability and oxidisability, as well as the distribution of organic carbon in different soil-sized fractions under the given land-use systems. This study will be helpful in establishing appropriate sustainable land use and soil management system and practices in the mid-hill ecological region of the north-western Himalayas, particularly in Himachal Pradesh. Therefore, the present study entitled “Evaluation of agroforestry systems for their carbon and nitrogen pools in mid-hills of Himachal Pradesh” was undertaken with below mentioned objectives:

- i. To estimate soil carbon and nitrogen pools of different agroforestry systems in mid-hills of Himachal Pradesh.
- ii. Estimation of carbon storage in relation to soil-size fractions under different agroforestry systems in mid-hills of Himachal Pradesh.

Chapter – 2

REVIEW OF LITERATURE

Agroforestry is a major practice around the globe but recently this practice is catching the eye of researchers as this system is more or less sustainable land use management and has a good impact on the environment. Tree components of agroforestry systems store carbon in their root and shoot biomass and also have powerful effects in storing carbon in different pools. These pools serve as crucial markers of a variety of soil functions. Similarly, trees also have a good impact on the mineralization of nitrogen and these nitrogen pools further play an important role in the sustainability of the land use system. Carbon stored in different soil size fractions determines the ability of the system to store carbon for different time duration. Therefore, in this chapter, the relevant information related to the present study entitled **“Evaluation of agroforestry systems for their carbon and nitrogen pools in mid-hills of Himachal Pradesh”** has been reviewed under the following heads:

2.1 Soil carbon pools

2.2 Soil nitrogen pools

2.3 Carbon storage in relation to soil-size fractions

2.1 Soil carbon pools

Carbon storage in different agroforestry systems is rapidly progressing because agroforestry is emerging as a boon to mitigate climate change and also to fulfil the need of people. But there is a dearth of knowledge on carbon pools, and how the management practices and tree-based land use system affects these pools as these pools are representative of soil health and sequestration capacity of atmospheric carbon in soil. Higher values of the CMI indicate that there has been a greater regeneration of soil carbon. Lesser numbers show that the system is not properly managed. Therefore, it is crucial to comprehend how this agroforestry system affects the various carbon pools and CMI and how these pools further help in achieving SDG 13 (sustainable development goal for climate change).

Blair *et al.* (1995) analysed soil samples (cropped and uncropped) from three sites in northern and central New South Wales, Australia and stated that Labile carbon is a more

sensitive indication of the carbon dynamics of the system since it decays and regenerates more quickly than non-labile carbon or total carbon.

Zhang *et al.* (2014) studied four land-use systems i.e., *Deyeuxia angustifolia* wetland, upland forest, and two farmlands (cultivated for 9 and 15 years, respectively) and concluded that in *Deyeuxia angustifolia* wetland, the labile fraction organic C levels declined considerably with increasing soil depth. However, the labile fraction organic C contents decreased much less with increasing soil depth in the upland forest, abandoned cultivated, and cultivated soils.

The relationship between soil carbon and land use in sloping land of Thailand was investigated by Aumtong *et al.* (2009). They observed that fruit tree plantations and wetland rice fields, which are primarily anoxic, exhibited the highest fraction of oxidizable carbon but low levels of water and hot water-soluble carbon. Conversely, fallow agricultural land and secondary woods have high concentrations of water-soluble carbon and very low concentrations of oxidizable carbon.

Barreto *et al.* (2011) evaluate different C fractions i.e., labile fraction, moderate labile fraction, low labile fraction and a recalcitrant fraction under cacao agroforestry systems. They found that C fractions generally decreased as soil depth increased and the labile and moderate labile fractions were 50% greater on the upper layer (0–5 and 5–10 cm).

Jiao *et al.* (2020) conducted an experiment to identify the most accurate indicator of soil quality (CMI) of Arable land, grassland, and forest land Yellow River Delta (YRD), China. The CMI in arable land was lowest in the top 50 cm of soil and declined as soil depth increased. The CMI in grassland was greater than 100 at depths of 10-20 cm and 20-30 cm, indicating that it was higher than the CMI on forest land (the reference soil).

Benbi *et al.* (2012) studied the impact of three different land-use systems viz., poplar-based agroforestry involving wheat-legume rotation, rice-wheat and maize-wheat agroecosystems, on dynamics of total organic C (TOC), oxidisable soil organic C (SOC), very labile, labile, less labile, and recalcitrant C fractions in the semi-arid subtropical India. In comparison to the rice-wheat system, the maize-wheat and agroforestry systems had 65-88% larger SOC stores and were characterised by primarily labile C. In comparison to 37% in rice-wheat rotation, around 56–60% of the total organic C in maize–wheat and agroforestry

systems occurred as labile and highly labile C. However, in rice-wheat soils, the majority of the organic C (63%) was stabilised in less labile and resistant forms. Further, they also conducted the same type of study in 2014 by taking the sugarcane field as the additional plot for the study.

Goswami *et al.* (2014) in the mid-hills of the Himalayan region evaluated the total C pool and found that in the 0–20 cm soil layer, abandoned land had the highest total C pool (86.75 Mg ha⁻¹) followed by silvipasture (63.54 Mg ha⁻¹), while C pool in agrisilvihorticulture, agrihortisilviculture, agrisilviculture and agrihorticulture systems were statistically similar. The statistically lowest C pool was observed in pure agriculture, i.e., 35.93 Mg ha⁻¹. The behaviour of the C pool in 20–40 cm remained the same as in the 0–20 cm soil layer in Brazil. Similarly,

Kalambukattu *et al.* (2013) conducted an experiment in the Almora region of Central Himalaya to assess total organic carbon (TOC), and labile carbon (LC) and measured the carbon management index (CMI). The soil with the highest TOC concentration was found in undisturbed forests (45.4 g kg⁻¹) and the soil with the lowest TOC content was found in arid areas (18.4 g kg⁻¹). Under a forest, the CMI was highest, while on arid ground, it was lowest. They also showed that the pools of soil organic carbon have drastically decreased as a result of cultivating Himalayan soils.

Benbi *et al.* (2015) also evaluated the impact of agroforestry consisting of poplar with wheat, rice–wheat, maize–wheat and sugarcane agro-ecosystems on total organic carbon (TOC) and labile pools. In contrast to uncultivated soils, soils under rice-wheat and maize-wheat systems, and soils under agroforestry systems, they discovered that soils under sugarcane and sugarcane systems had very labile C. On the other hand, uncultivated soils and those planted with maize-wheat and rice-wheat both had more organic C in recalcitrant fractions.

Further, Sharma *et al.* (2014) also assessed the impact of different land use systems on labile C pools and soil organic carbon stocks in the foothill Himalayas. They found that Agriculture and degraded areas had comparable levels of soil organic carbon. For agricultural, horticultural, forest, and degraded areas, the labile C in the surface layer ranged from 304.7 to 1494.7, 473.5 to 2026.9, 205.9 to 1011.2, and 145.7 to 1140.6 mg kg⁻¹ soil,

respectively. Forest soils had the highest levels of labile carbon (957.9 mg kg⁻¹ soil) followed by agricultural, horticultural, and degraded areas. Forest soils had the highest sub-surface labile carbon concentration followed by horticulture soils and then agriculture.

Cardozo *et al.* (2016) investigated five pasture production systems, including an agroforestry system, a native vegetation plot, and four monoculture systems with forage grasses such as *Andropogon*, *Brachiaria*, *Panicum*, and *Cynodon*. The *Andropogon* system showed higher C lability during the dry and wet seasons, and during the dry season in *Cynodon* while CMI was < 100 in all plots.

Naik *et al.* (2016) investigated the dynamics of total soil organic carbon (C_{tot}), oxidizable organic carbon (C_{oc}), very labile carbon (C_{frac1}), labile carbon (C_{frac2}), less labile carbon (C_{frac3}), non-labile carbon (C_{frac4}), microbial biomass carbon (C_{mic}), and SOC sequestration in 6-year-old fruit orchards. Mango, guava, and litchi orchards induced 17.2%, 12.6% and 11% enrichment of C_{tot} above the control, respectively. The mango orchard showed the greatest significant increase in C_{frac1} , C_{frac2} , and C_{frac4} over control i.e., 20.7%, 13.5% and 17.4%, respectively. All the C fractions had accumulated more in 0-30 cm. The maximum total active carbon pool in the mango orchard was 36.2 Mg C ha⁻¹ which is 1.2 times higher than the control. The amount of carbon in the passive pool, which made up 42.4% of C_{tot} was highest in the mango orchard. The carbon management index also showed an increase of 1.13 (guava and litchi orchard) and 1.2 (mango orchard) fold over control. The highest carbon build rate was recorded in a mango orchard (1.53 Mg C ha⁻¹) with a 17.3% increase in carbon buildup above the control.

Moharana *et al.* (2017) evaluated different systems, like barley-fallow, mustard-moth bean, and chickpea-groundnut. Except for the Barley-fallow system, all other systems followed the order NLC > LLC > LC > VLC in terms of the magnitude of the various fractions of oxidizable organic C, namely, very labile C (VLC), labile C (LC), less labile C (LLC), and non-labile C (NLC).

Kaur *et al.* (2018) in the alluvial plain of Haryana, India observed that agroforestry had the highest concentration of labile C (LC) at 1626 mg C kg⁻¹, followed by forestry at 755 mg C kg⁻¹, grassland at 705 mg C kg⁻¹, and cropland at 418 mg C kg⁻¹. However, in the

alluvial plains of Punjab, India cropland (1420 mg C kg⁻¹), forestry (1540 mg C kg⁻¹), and agroforestry (806.66 mg C kg⁻¹), all had much higher values than grassland (1963 mg C kg⁻¹).

Kaushik *et al.* (2018) investigated C and N pools under agriculture and horticulture-based land use system. The amount of total nitrogen was found to be higher in the horticulture land use system than in other land use systems, with the maximum level (1365.6 mg kg⁻¹) being found in a guava orchard. sugarcane-sugarcane pearl millet-wheat (zero tillage system had the highest concentration of ammonia nitrogen (245.8 mg kg⁻¹), whereas guava had the second-highest concentration (234.6 mg kg⁻¹). The maximum concentration (9.72 g kg⁻¹) of total organic carbon was discovered in guava orchards, while the lowest concentration (4.84 g kg⁻¹) was identified in pearl millet-wheat land use systems. The highest levels of light fraction and heavy fraction carbon, respectively 238.14 mg kg⁻¹, 1.76 g kg⁻¹, and 7.51 g kg⁻¹, were found under guava orchards.

Meena *et al.* (2018) studied the labile and non-labile carbon in various LUS, using Indian mid-Himalayan barren land (BL), cultivated land (CL), grassland (GL), and forest land (FL). The LUS and soil depth from 0-15, 15-30, and 30-45 cm soil depth of Indian mid-Himalaya considerably affected the WBC and LOC concentrations from arid land, farmed land, grassland, and forest land. At the depths of 0, 15, 30, and 45 cm, respectively, labile carbon substantially varied with soil depth, ranging from 0.09-0.18 C kg⁻¹, 0.10-0.26 C kg⁻¹, and 0.09-0.34 C kg⁻¹. In all land-use regimes, the amount of labile C increases noticeably as soil depth increases.

Similarly, Raza *et al.* (2006) suggested that grassland land use had the highest levels of very labile and labile carbon, with mean values of 16.10 and 5.26 g kg⁻¹ in the top layer (0–15 cm) of soil, while forest land use had the highest levels of less labile and nonlabile carbon, with mean values of 7.93 and 78.08 g kg⁻¹, respectively.

Sahoo *et al.* (2019) studied the total soil organic carbon (TOC) in seven distinct land use regimes in northeast India to determine the active and passive carbon pools. The TOC dropped with increasing depth in the various pools of lability, with grassland having the lowest TOC (1.31%) and natural forest having the greatest TOC (2.75%). Across various land use systems, the Very Labile Carbon (VLC) proportion ranged from 36.11 to 42.74% of TOC. Wet rice cultivation had the highest active carbon (AC) pool (61.64%), whereas natural

forests had the lowest (58.71%). Further, Babu *et al.* (2020) found the greatest organic carbon (OC, 145.8 Mg ha⁻¹), active carbon (AC, 73.7 Mg ha⁻¹), and passive carbon (PC, 72.1 Mg ha⁻¹) pools in undisturbed forest soil.

Pandher *et al.* (2020) reported that in comparison to the other three cropping systems (maize-wheat, agro-horticulture and agroforestry (3 and 6-year plantation) land use systems, the surface soils of the 6-year agroforestry plantation had considerably greater levels of labile carbon (LC), aggregate associated carbon (AAC), particulate organic carbon (POC), and mineralizable carbon (MC).

Also, Rekwar *et al.* (2022) studied different carbon pools under Bamboo fields, tea plantations and rainfed rice. At 0–15 cm, rainfed rice had significantly more very labile carbon in the soil than tea plantations and bamboo fields, but at 15–30 cm, tea plantations had significantly more very labile C than bamboo fields and rainfed rice. However, under 30-60 and 60-100 cm depths, respectively, bamboo fields and tea plantations exhibited Very labile C that was much higher than rainfed rice. Labile carbon pool (CL) was significantly greater in bamboo fields at all levels, ranging from 1.01 to 1.67 g kg⁻¹, while less labile carbon pool (LLC) was significantly higher in bamboo fields at depths of 0- 15, 15-30, and 30-60 cm than in tea plantations and rainfed rice soils. The recalcitrant carbon (CR) pool, however, did not significantly differ between various LUS.

Additionally, Singh *et al.* (2021) also studied the long-term effects of agroforestry systems on carbon and nitrogen pools in Punjab, India. They found that at the depth of 0–15 cm, poplar with fodder–wheat rotation (87.9%) and eucalyptus with fodder-wheat rotation (70.6%) had higher soil organic carbon than sole fodder–wheat rotation; while poplar with citrus (37.4 %) and eucalyptus with citrus (30.2%) had higher SOC than sole citrus. At all soil depths, SOC was lowest under fallow land and decreased with depth. The soil carbon pools (very labile, labile, less labile and recalcitrant carbon) were highly positively correlated with SOC and were higher in poplar with fodder–wheat rotation and eucalyptus with fodder–wheat rotation than in other land-use systems. The carbon management index was found to be significantly higher in poplar with fodder–wheat rotation and eucalyptus with fodder–wheat rotation than other systems. While,

Kaushal *et al.* (2022) ascertained the impact of different bamboo species on labile and non-labile carbon fractions and observed that in 0-15 cm layer, *Bambusa nutans* had the highest

very labile C (7.65 g kg^{-1}), this indicated the positive influence of bamboo in soil C build-up in the top 0-15 cm soil layer. Amongst the different species of bamboo evaluated in this study, *Dendrocalamus strictus* accumulated the highest active C pool in the 0-30 cm soil layer followed by *B. vulgaris*. Of the total organic C in the 0–30 cm soil depth, the majority (55-60%) was contributed by the passive C pool comprising the less labile and the non-labile fraction of SOC.

Nitrogen pools:

Agroforestry systems (AFSs) represent a key alternative since adequate tree management promotes an effective cycling of nitrogen pools and contribute to sustainable management of land use system. Understanding how mineralization of the nitrogen soil are influenced under agroforestry is important because different inorganic pools (e.g., NH_4^+ , NO_3^-) are crucial in supplying nitrogen to plants and in determining the rate of organic matter decomposition.

Walia *et al.* (1998) revealed that due to the ongoing mineralization of more organic matter, exchangeable NH_4^+ -N which is the predominant type of mineral nitrogen, contributed around 70% of the total mineral nitrogen and was higher in most of the surface layers than the soils of underlying strata.

Issac *et al.* (2005) estimated carbon and nitrogen dynamics in a twenty-five-year chronosequence of cacao (*Theobroma cacao* Linn.) plantations in Ghana, West Africa. Three treatments were selected as on-farm research sites i.e., 2, 15 and 25-year-old plantations. Total soil nitrogen in the top 15 cm varied from $1.09 \text{ Mg N ha}^{-1}$ and $1.25 \text{ Mg N ha}^{-1}$ but no significant differences were noted between treatments; while soil nitrification rates and litter fall increased significantly with treatment age.

Sacramento *et al.* (2013) in the semiarid region of Brazil studied the relationship between inadequate management of cropping systems and low plant biomass production, which was the main reason for the reduction of soil carbon (C) and nitrogen (N) stocks. The goal of this study was to assess the changes in soil C and N stocks brought about by traditional agricultural practices (slash-and-burn clearing and cultivation for two and three years) and agroforestry (agrosilvopastoral and silvopastoral) and to compare these practices with the native Caatinga vegetation after 13 years of cultivation. They found that the conventional farming method resulted in decreases of 58.87 Mg ha^{-1} and 9.57 Mg ha^{-1} of total N and the total N values were highest in agrosilvopastoral, and silvopastoral systems.

Santiago *et al.* (2013) in oil palm-based agroforestry systems with different species diversity investigated soil nitrogen forms (microbial-N, nitrate N, ammonical N) as well as soil carbon concentration, and compared them with an adjacent 13-year-old secondary forest. Nitrate concentration was found to be higher in the high-diversity AFS than in other vegetation types, while soil C (15.6 mg g^{-1}) was found to be substantially higher in the high-diversity AFS than in the secondary forest (13.0 mg g^{-1}).

On the contrary, Xue *et al.* (2013) conducted an experiment in China and compare nitrogen pools under different land use systems i.e., natural grassland, shrubland, abandoned farmland, orchard, farmland, and man-made grassland. They concluded that Ammonium nitrogen levels were reduced in man-made grassland, shrubland, farmland, abandoned farmland, and orchard soils by 7, 29, 240, 253, and 406%, respectively, in comparison to the natural grassland soil while soil nitrate nitrogen contents in the man-made grassland, abandoned farmland, farmland, and orchard dropped by 101, 158, 208, and 235%, respectively, in comparison to the natural grassland areas. Compared to the natural grassland, the total N content showed decreases in the shrubland, abandoned farmland, orchard, man-made grassland and farmland of 39, 50, 60, 89 and 126 %, respectively. Also,

Heman *et al.* (2016) estimated the total nitrogen (TN), mineralized nitrogen (nitrate nitrogen (NN) and ammonium nitrogen (AN) in different soil depths (0-5, 5-10, 10-20, 20-30, 30-40, and 40-50 cm) in farmland and adjacent natural grassland. They concluded that as soil depth increased, the concentration of nitrate N in Tibet's farms and grassland declined. The farmland's nitrate N concentrations in the 0-5cm and 40-50 cm layers were $28.56\text{-}27.23 \text{ mg kg}^{-1}$ and $5.90\text{-}5.97 \text{ mg kg}^{-1}$, respectively, reflecting a reduction of 79.34 %. This reduction was significantly more pronounced in total nitrogen content.

Hussain *et al.* (2016) concluded that exchangeable $\text{NH}_4\text{-N}$ content in soil at various layers varied from 5.0 to 25.5 mg kg^{-1} in the apple-growing soils of the Pulwama region of Kashmir Valley. In terms of exchangeable $\text{NH}_4\text{-N}$ content, surface soils are richer than subsoils and account for 1.75 to 12.6% of all nitrogen. Similarly,

Bashir *et al.* (2022) also studied nitrogen pool in different land use and found the order of total N content in the surface layer (0–15 cm) as follow: horticulture, agriculture, forest, and fallow areas while Agriculture (0.6 g kg^{-1}), horticulture (0.55 g kg^{-1}), forestry (0.5 g kg^{-1}) and fallow (0.3 g kg^{-1}) were the land uses with the highest recorded amounts of total

soil nitrogen in the 30-60 cm range. The largest concentration of soil ammonium nitrogen was found in the top layer (0–15 cm), which was rated as follows: agricultural land use, horticultural land use, forest land use, and fallow land use and in comparison, to other land uses, agricultural and horticultural soils had higher nitrate-nitrogen concentrations (0–15 cm). Horticulture had the highest concentration of nitrate nitrogen in the 10–30 cm layer, followed by agricultural >forest and fallow land uses.

Carbon storage in relation to soil-size fractions

Agroforestry systems (AFS) have the potential to capture more soil carbon than traditional systems. The amount of tree litter and tree roots incorporated into the soil is a significant source of C input to AFS but its storage for long or short time depends on the aggregate size and fraction percentage of aggregates in soil. Aggregates are secondary particles created when mineral particles are mixed with organic and inorganic materials. The retention of carbon in soil is known to be significantly influenced by soil aggregates and size fractions and therefore it is crucial to more focus on the dynamics of soil under different agroforestry systems and their relationships with different popular fast-growing species used in different agroforestry systems.

Christensen *et al.* (1985) investigated five surface soils (0-20 cm) with different amounts of fine particles i.e., clay-, silt- and three sand-size fractions. The clay and silt fractions were enriched in C and N relative to whole soil contents, whereas all of the sand fractions were deficient. Less than 10% of the soil C was present in the sand-size fraction, while between 49% and 69 % was present in the clay and between 22 % and 38% was present in the silt.

Guggenberger *et al.* (1994) reported that total C from the spruce forest, deciduous woodland, permanent grassland, and arable agriculture were 84, 59, 73, and 25 g C/kg, respectively. The C concentration decreased for all sites in the following order: clay (2 μm), silt (2-20 μm), and sand (20-2000 μm). Arable cropland had much lower carbon concentrations of clay and silt and C linked with sand as compared to spruce forest, deciduous forest, and permanent grassland. Similarly,

Hassink (1997) investigated the amount of C linked with different soil size fractions and he found that in coarse-textured soils, the amount of C linked with the clay and soil fraction was less than 10 g kg⁻¹ soil and up to 37 g kg⁻¹ soil in fine-textured soils.

John *et al.* (2005) conducted a study in Japan to characterise SOC storage in different soil size fractions under wheat, maize, grassland and spruce land-use systems. SOC concentration was lowest in the fraction <53 μm within a horizon. The SOC concentration order found was (<53 μm) > microaggregates > macro aggregates.

Don *et al.* (2007) did a study in grassland at two distinct locations *i.e.* Mehrstedt and Kaltenborn, the SOC stocks at the clay-rich Mehrstedt site were nearly twice as high as those at the sand-filled Kaltenborn site. In the top 60 cm of soil, the clay soil had an average carbon content of 123 C t ha⁻¹.

Haile *et al.* (2008) in an experiment based on the Silvopastoral system studied soil C contents at six soil depths *i.e.*, 0-5 cm, 5-15 cm, 15-30 cm, 30-50 cm, 50-75 cm, and 75-125 cm in silvopastoral agroforestry system of slash pine (*Pinus elliottii*) + bahiagrass (*Paspalum notatum*) and in an adjacent open pasture with Bahia grass at four sites, representing Spodosols and Ultisols order of soil, in Florida. The C contents in each of the three classes (250-2000 μm , 53-250 μm and 53 μm) of soil samples from each layer were calculated. In comparison to nearby open pastures, the total soil organic Carbon content was higher in silvopasture next to trees by 33% and in the alleys between tree row by 28%. In the biggest fraction size (250-2000 μm), it was greater in the alley between tree row by 39% and in silvopasture close to trees by 20% than in open pastures, and by 12.3 and 18.8%, respectively in the intermediate size fraction (53-250 μm).

Saha *et al.* (2010) investigated soil C storage in home gardens, natural forests, and single-species stands of coconut (*Cocos nucifera*), rice (*Oryza sativa*)-paddy and rubber (*Hevea brasiliensis*) in Kerala, India in different size fractions. Soil samples of a depth of one metre were fractionated into three size classes (250-2000 μm , 53-250 μm , <53 μm). The results showed storage of higher amounts of C in the <53 μm fractions and the most stable form of C in soil up to one-metre depth in land use systems with a high density of trees such as forests and home gardens.

Similarly, Gama-Rodrigues *et al.* (2010) also conducted a study to characterize the SOC storage in relation to soil fraction-size classes in cacao (*Theobroma cacao* L.) based agroforestry systems and compared it with an adjacent natural forest in reddish-yellow Oxisols in Bahia, Brazil. They concluded that total SOC stock did not vary among systems

(mean: 302 Mg ha⁻¹). On average, 72 % of SOC was in macroaggregate size, 20% in micro aggregate size, and 8% in silt-and-clay size fractions in soil.

Kukal *et al.* (2014) conducted a study in a mixed vegetation cover watershed with forest, grass, cultivated and eroded lands in the degraded Shiwaliks of the lower Himalayas to assess land-use effects on profile SOC distribution and storage and to quantify the SOC fractions in water-stable macro aggregates (WSA) and micro aggregates. With larger macro-aggregates (> 2 mm) and diverse land uses, the SOC changed dramatically with macro aggregates. It was in the order of grassland > forest > cultivated > degraded soils. The SOC was 54.1, 49, and 26.6 per cent lower in the WSA > 2 mm from the degraded soils, respectively. The difference in SOC diminished as the stable aggregate size was reduced to micro-aggregates (WSA 0.25 mm).

Shang *et al.* (2014) also studied SOC in lighter fractions under four forest vegetation-land use types ranging from 1.4 to 13.1 C g kg⁻¹. The SOC was maximum in the fine fraction in the chestnut forest while C in the coarse fraction were more in the evergreen broad-leaf, pine, and bamboo forests as compared to the chestnut forest.

Gelaw *et al.* (2015) conducted an experiment in Ethiopia to study the relationship between particle-associated SOC and depth (0 to 10 cm and 10 to 20 cm) under five land uses viz. rainfed cultivation (RF), agroforestry (AF), open pasture (OP), silvopasture (SP), and irrigation (IR). Under all land uses, macroaggregates had higher SOC than micro aggregates in both levels. SOC associated with micro aggregates was highest in AF (2.6 g kg⁻¹) and lowest in SP (2.3 g kg⁻¹), showing that AF has a greater capacity to stabilise SOC than other land uses. Uncultivated habitats had the highest levels of sand-associated SOC and TN. Further evidence that grass-based and tree-based systems are rich in stable SOC was provided by the greater SOC concentrations associated with clay particles in soils under OP, SP, and AF. This is because clay-related SOC has a longer residence period than that associated with sand or silt fractions. Also,

Fornara *et al.* (2018) performed soil physical fractionation analyses to calculate the C pool of various aggregate fractions for three land use types- permanent grassland, planted woodland with ash trees, and a silvopastoral system with ash trees that was established in 1989 at Loughgall, Northern Ireland, UK. Results reveal that soil C (and N) stocks (0–20 cm depth) did not differ significantly among the three land use types 26 years after permanent grassland was converted to either silvopastoral or forest systems. However, permanent

grassland soils had significantly greater soil C pools of the macro-aggregate fraction (>2 mm), but silvopastoral and forest systems had significantly higher soil C pools of the micro-aggregate (53-250 μm) and silt & clay (53 μm) fractions.

Fujisaki *et al.* (2018) reported that maximum SOC in tropical soils of fine fraction (53 g C/kg fine fraction). In forest soils compared to agriculture, the F<20 μm C fraction was closer to SOC saturation. Especially in sandy soils (41.3%), SOC content in the coarser fraction (>50 μm micrometres) considerably contributed to the total SOC and was independent of soil texture. As there was a correlation between the overall SOC content and the mass of F<20 μm , they also discovered a pattern of textural control of SOC retention.

Chatterjee *et al.* (2019a) reported that Total SOC contained in the macroaggregates was 116.1 C Mg ha⁻¹, 84.4 C Mg ha⁻¹, 71.6 C Mg ha⁻¹, 78.3 C Mg ha⁻¹, and 63 C Mg ha⁻¹) in the forest, organic Terminalia, conventional Erythrina, organic Erythrina, and sun coffee treatments, respectively. Forest organic had the highest quantity of SOC, whereas Organic Terminalia had the highest microaggregates. The largest amount of the total C was kept by the macro aggregates. In particular, in the topmost soil layer, 0–10 cm, the SOC levels in the silt+clay fraction were higher under the two AFS systems (Coffee treatment and Organic Terminalia) with Terminalia as the shade tree. On the other hand,

Chatterjee *et al.* (2019b) also evaluated soil carbon stock in shaded perennial agroforestry systems in Koppa, Karnataka, India at various depths (0-10, 10-30, 30- 60 and 60-100 cm). Coffee (*Coffea canephora*) was grown under *Grevillea robusta* trees (Coffee + Grevillea), tea (*Camellia sinensis*) was grown under *Grevillea robusta* trees (Tea + Grevillea), a traditional small-holder farm with several crops was grown together (Homegarden), and a native moist deciduous forest. The stock of soil organic carbon (SOC) was calculated for the entire soil as well as three soil aggregate sections (2000-250 μm , 250-53 μm and 53 μm). The SOC stock to one-metre depth was 172.3 C Mg ha⁻¹ under Forest, 142.4 C Mg ha⁻¹ under Coffee + Grevillea, and 89.3 C Mg ha⁻¹ under Homegarden. Under Forest and other shaded AFS, there were no significant variations in SOC within the silt + clay fraction (>53 μm) beyond 60 cm depth.

Kumar *et al.* (2020) investigated different Carbon fractions, viz. very labile (C1 frac), labile (C2 frac), less labile (C3 frac) and non-labile (C4 frac) at 0–15 and 15–30 cm soil depth under *Terminalia chebula*. The study concluded that C1 frac (13.8%), C2 frac (4.8%),

C3 frac (8.3%) and C4 frac (11.1%) were higher under agroforestry as compared to open systems.

Yan *et al.* (2022) concluded in their experiment that silt particles had the lowest carbon content in grassland and abandoned cropland, and it was much lower than clay particles in the Cropland grassland sites. Additionally, they noticed that in woodlands, the carbon content of each particle rose as particle size decreased. The researchers also discovered that the carbon content of clay particles was much higher in Woodland than that of sand and that Cropland had the highest (24.26 g kg⁻¹) and lowest (6.40 g kg⁻¹) carbon content for sand particles. In comparison to other sites, Woodland had the highest carbon concentration in silt and clay particles, measuring 23.56 g kg⁻¹ and 28.62 g kg⁻¹, respectively.

Mir *et al.* (2023) analysed the impact of significant land uses and soil depth on the pools of soil organic carbon in the northwestern Himalayas of India. Up to a depth of 1 m (0-30, 30-60, 60-90 cm), soil samples from five different land uses—forest, pasture, apple, saffron, and paddy oilseed were taken. The findings showed that all carbon pools varied considerably ($p \leq 0.05$) among the investigated land use systems, with maximum values found under forest soils and lowest under paddy-oilseed soils, regardless of soil depth. Additionally, when the effects of soil depth were assessed, all of the carbon pools showed a significant decline and variance with the highest values recorded in the top (0–30 cm) soils and the lowest in the subsurface (60–90 cm) layers. And CMI was higher in forest soils (100), while lowest in paddy-oilseed (28.29) at surface soil.

Chapter – 3

MATERIALS AND METHODS

The present study entitled “**Evaluation of agroforestry systems for their carbon and nitrogen pools in mid-hills of Himachal Pradesh**” was conducted in the mid-hill zone of Himachal Pradesh during 2022-23. The description of the study, techniques and methodology put into use in the present study is given below:

SITE DESCRIPTION

3.1.1 Site and location:

The study was carried out at the experimental farm of the Department of Silviculture and Agroforestry, Dr Y. S. Parmar University of Horticulture and Forestry, Nauni, Solan (H.P.) and adjoining area during the year 2022-23. This experimental area is located in the mid-hill zone of Himachal Pradesh, 13 km away from Solan town. The coordinates are 30.8600° N, 77.1730°E and it is at 1300 meters above mean sea level

3.1.2 Climatic and edaphic factors:

The experimental site lies in the sub-humid mid-hill zone of Himachal Pradesh and it is a transition zone between sub-tropical and sub-temperate zone. As per the data available with the Department of Environment Sciences, YSPUHF, Nauni this site experiences hot summers and cold winters with average minimum and maximum temperatures of 3°C (January) and 32°C (June) respectively. However, the average annual temperature is between 17-19 °C. Rainfall varies from 1000 mm - 1400 mm with an average of 64 rainy days. This region receives most of the rainfall in the month of July to September with few pre-monsoon showers, along with limited winter rains, received in January and February. Soil is mainly clayey loam of inceptisol order. This area witness humidity of 58-87 % in the month of monsoons and wind speed of 2.24 m/sec.

3.1.3 Agroforestry system

Agroforestry is the integration of crops, livestock, or fish production with woody perennials like trees and shrubs to produce advantages for the environment, the economy, and society. There are numerous types of agroforestry systems that fall within the silvopastoral,

agrosilvicultural, or agrosilvopastoral categories. There are different types of agroforestry system adopted by farmers of Himachal Pradesh. Different system selected for studies are Sole cropping, Natural Forest, Agri-silvi-horticulture system, Agrisilviculture, Fruit based agroforestry system, Fodder tree-based agroforestry system, Bamboo based agroforestry system, Melia based agroforestry system, Poplar based agroforestry system, Silvipasture system.

Table 1: Tree-crop combination under different agroforestry systems during the time of study

S. No.	Agroforestry System	Tree-crop combination	Plot size (ha)	Area under tree (ha ⁻¹)	Area under crop/grass (ha ⁻¹)
1	T ₁ - Sole cropping	Red chilies-Wheat/Pea	0.1		0.1
		Cabbage-Garlic			
		Cauliflower-Onion			
2	T ₂ - Natural Forest	-	-	-	-
3	T ₃ -Agri-silvi-horticulture system	Apricot + Celtis + Tomato -Wheat	0.1	0.03	0.07
		Toona + Pear + Maize – W heat			
		Toona + Plum + Maize - Garlic			
4	T ₄ -Agrisilviculture	Toona + Soyabean - Mustard	0.1	0.02	0.08
		Toona + Grewia - Wheat			
		Toona + Bauhinia + Soyabean- Pea			
5	T ₅ - Fruit based agroforestry system	Apricot + Peach + Okra - Wheat	0.1	0.04	0.06
		Plum + Pear + Cabbage – Potato			
		Plum + Pear + Soyabean - Linseed			
6	T ₆ - Fodder tree based agroforestry system	Grewia + Capsicum - Potato	0.1	0.03	0.07
		Grewia + Soyabean - Linseed			
		Morus + Maize - Chickpea			
7	T ₇ - Bamboo based agroforestry system	Bamboo + Soyabean - Ginger	0.1	0.04	0.06
		Bamboo + Capsicum - Mustard			
		Bamboo + Turmeric - Mustard			
8	T ₈ - Melia based agroforestry system	Melia + Cabbage - Garlic	0.1	0.04	0.06
		Melia + Cauliflower - Raddish			
		Melia + Soyabean - Mustard			
9	T ₉ - Poplar based agroforestry system	Poplar + Turmeric - Pea	0.1	0.04	0.06
		Poplar + Capsicum - Mustard			
		Poplar + Turmeric - Wheat			
10	T ₁₀ - Silvipasture system	Leucaena + Grewia + Grasses	0.1	0.08	0.02
		Grewia + Morus + Grasses			
		Bauhinia + Grewia + Grasses			



LOCATION:-
 30° 51' N Latitude
 76° 11' E Longitude

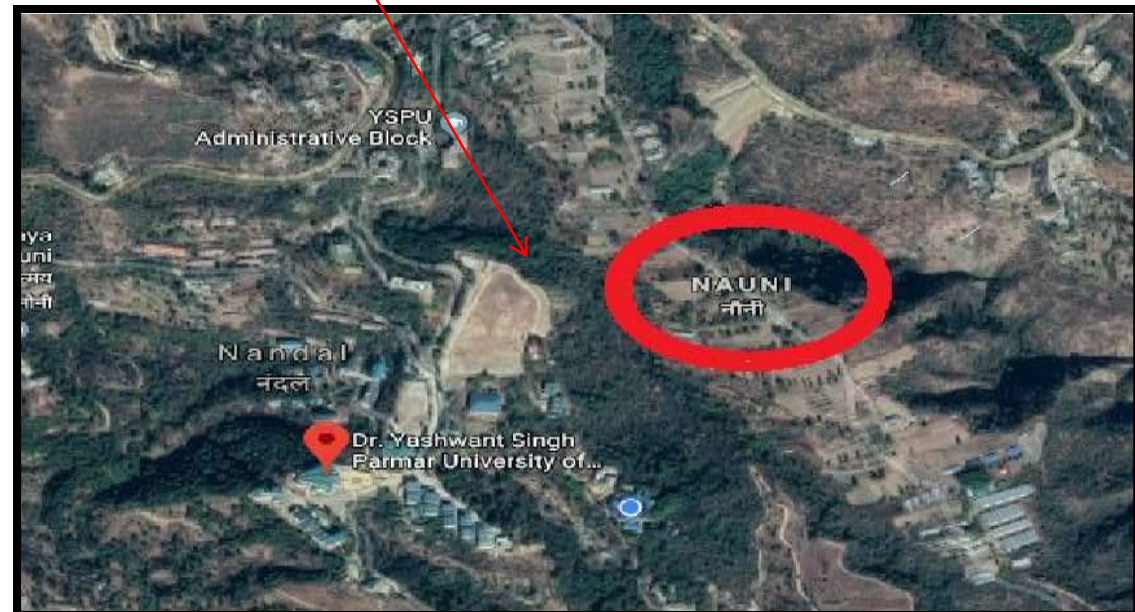


Plate1. Site and location of study



Plate 2. Sole cropping



Plate 3. Natural forest



Plate 4. Agri-silvi-horticulture system



Plate 5. Agrisilviculture system



Plate 6. Fruit tree based agroforestry system



Plate 7. Fodder tree based agroforestry system



Plate 8. Bamboo based agroforestry system



Plate 9. Melia based agroforestry system



Plate 10. Poplar based agroforestry system



Plate 11. Silviculture system

Table 2: Year of establishment and age of trees under different agroforestry systems during the time of study

S. No	Agroforestry System	Year of establishment	Average age of trees	Total vegetation biomass (Mg ha ⁻¹)	Spacing (m x m)	Number of trees per hectare	Leaf litter biomass (Mg ha ⁻¹)
1	T ₁ - Sole cropping	-	-	7.89	-	-	0.04
2	T ₂ - Natural Forest	-	-	-	-	-	-
3	T ₃ - Agri-silvi-horticulture system	2005	17	43.65	8 x 2	625	0.25
4	T ₄ - Agrisilviculture	2007	15	37.24	8 x 2	625	0.12
5	T ₅ - Fruit based agroforestry system	2006	16	30.48	9 x 5	222	0.16
6	T ₆ - Fodder tree based agroforestry system	2006	16	66.11	9 x 3	370	0.13
7	T ₇ - Bamboo based agroforestry system	2006	16	35.83	9 x 5	222	0.23
8	T ₈ - Melia based agroforestry system	2006	16	106.09	9 x 5	222	0.30
9	T ₉ - Poplar based agroforestry system	2003	19	130.87	9 x 5	222	0.33
10	T ₁₀ - Silvipasture system	2001	21	87.72	10 x 1	1000	0.15

3.2. METHODOLOGY

Experiment I: To estimate soil carbon pools, nitrogen pools and carbon storage in relation to soil-size fractionsof agroforestry systems in mid-hills of Himachal Pradesh

(A) Agroforestry systems

T₁- Sole cropping

T₂- Natural Forest

T₃- Agri-silvi-horticulture system

T₄- Agrisilviculture

- T₅- Fruit based agroforestry system
- T₆- Fodder tree based agroforestry system
- T₇- Bamboo based agroforestry system
- T₈- Melia based agroforestry system
- T₉- Poplar based agroforestry system
- T₁₀- Silvipasture system

(B) Soil depths

D ₁	:	0-20cm
D ₂	:	20-40cm
D ₃	:	40-60cm
Design	:	Two way ANOVA
No. of treatment combination	:	30 {10 (Agroforestry system) x 3 (Soil depths)}
Replication	:	3

3.3 Observations Recorded:

3.3.1 SOIL SAMPLING:

Bulk soil samples were collected from randomly selected plots during the year 2022. Soil samples were collected from three soil depths 0–20 cm, 20–40 cm and 40-60 cm with the help of an auger. For each plot, soil samples were collected from six random locations in each agroforestry system and mixed to obtain a composite sample of about 1000 g. There were total 90 samples (10 Agroforestry system × 3 replications × 3 depths). The soil samples were air-dried in shade, ground and sieved for the analysis of various C fractions. Soil samples for all 10 agroforestry system were analyzed for the various soil carbon fractions. The sole cropping plot was a site taken as a control plot and it was free from canopy interferences, this served as the control plot or reference for comparison of the impact of the different treatments on the soil C fractions.

3.3.2 Carbon fraction and Carbon Management Index (CMI) under different agroforestry systems

SOC was calculated using the fast titration method developed by Walkley and Black. This method was used to digest 2 g of soil with K₂Cr₂O₇ and H₂SO₄, then titrate against ferrous ammonium sulphate to note the end point from violet to green and compare it to a control.

1. Fraction 1 (VLP) – Very labile:

Soil Organic Carbon (SOC) fraction 1 was determined by the Modified Walkley and Black method using 20ml of 12 N concentrated sulphuric acid (H_2SO_4) (Chan et al. 2001, Ghosh et al., 2012). It was that C which was oxidizable under 12 NH_2SO_4 .

2. Fraction 2 (LP) – Labile:

It was determined by estimating the difference in oxidizable organic C extracted between 18 N and 12 N H_2SO_4 and soil Organic Carbon (SOC) was determined by the Modified Walkley and Black method i.e.

Fraction 2 (LP) = oxidizable organic C extracted by 18 N H_2SO_4 – Oxidizable organic C extracted by 12 N H_2SO_4

3. Fraction 3 (LLP) – Less Labile:

This C fraction was calculated by getting difference in oxidizable organic C extracted between 24 N and 18 N H_2SO_4 and C at each concentration was determined with the help of Walkley and Black Method.

Fraction 3 (LLP) = oxidizable organic C extracted by 24 N H_2SO_4 – Oxidizable organic C extracted by 18 N H_2SO_4

4. Fraction 4 (NLP) – Non labile:

For this fraction, C was determined by subtracting organic C extracted with 24 N H_2SO_4 and TOC determined by CHN analyzer Fraction 4 (LLP) = TOC determined by CHN analyser – Oxidizable organic C extracted by 24 N H_2SO_4

5. Active Pool (AP):

The ACP is the summation of Fraction 1 and Fraction 2 which is the easily oxidisable/labile/active part as the name suggests.

Active Pool = VLP + LP (Unstable/labile)

6. Passive Pool (PP):

The passive C pool is the stable/recalcitrant/less reactive pool which is oxidised and extracted with more difficulty (Fraction 3 and 4).

Passive Pool = LLP + NLP (Stable/non labile)

7. Lability index for the organic carbon (LI):

The Lability Index mainly throws light on the nature or oxidisability of the SOC fractions and it was determined by using formula:

Labiality index for the organic carbon (LI) = [(C fraction 1 / TOC) x 3 + (C fraction 2 / TOC) 0x 2 + (C fraction 3 / TOC) x 1]

8. Carbon Pool Index (CPI):

It was determined with the help of given formula:

Carbon Pool Index (CPI) = Sample total C (mg kg⁻¹) / reference total C (mg kg⁻¹)

Where,

Reference total carbon is the total carbon content (mg kg⁻¹) of control plots

9. Carbon Management Index (CMI):

The CMI is widely accepted as an indicator of soil degradation or improvement in response to land use changes (Sainepo *et al.*, 2018). It takes into account both the quality and quantity of SOC and effectively monitors short-term changes in soil C pools (Blair *et al.*, 1995; Sodhi *et al.*, 2009) and it was determined by using formulae, as below:

CMI = CPI × LI × 100

10. Bulk Density

Bulk density of soil sample was determined in the laboratory by using core tube method in the field. It was calculated using the formula:

Using the formula

$$\rho_b = \frac{M_{soil}}{V_t}$$

3.3.3 Different nitrogen pools in soil

Following collection and bulking, the soil samples underwent shade drying processing before being finely powdered and sieved through a 2.0 mm sieve.

1. Total Nitrogen (%):

It was determined by using CHNS analyser.

2. Ammonical Nitrogen (mg kg⁻¹):

The ammonical nitrogen was extracted using the Kjeldahl distillation process. The soil samples were shaken with 2 N KCl for 2 h and samples were filtered. The distillation process was carried out with MgO.

3. Nitrate Nitrogen (mg kg⁻¹):

The Nitrate nitrogen was also extracted by the Kjeldahl distillation process. The soil samples were shaken with 2 N KCl for 2 h and samples were filtered. The distillation process was carried out with MgO and Devarda's alloy together.

4. Total nitrogen density

It was determined by using given formula:

TN density (Mg ha⁻¹) = TN (%) × Bulk density of respective soil depth (Mg m⁻³) × soil depth (m) × area (10⁴ m²) × 10⁻²

3.3.4 Carbon storage in different soil size fractions

Composite soil samples from all the land use systems were collected from three soil depths i.e., 0-20, 20-40 and 40-60 cm. The soil samples were wet-sieved through a succession of two sieve sizes (250 and 53 μm) to physically separate them into three fraction size classes: macro (250-2000 μm), micro (53-250 μm), and silt- and clay-sized fraction (53 μm). In order to release the air that has been trapped inside the soil pores, a subsample of 100 g of the composite soil sample was first placed on top of a 250μm sieve after being immersed in a 500-ml beaker of deionized water for around 5 min. The sieving was carried out by hand. The proportion that was left after passing through a 250-2000 μm sieve was collected in a hard plastic pan, dried in an oven at 65°C, and weighed. A 53-250μm sieve was used to filter 250 μm of water and soil, and the process was repeated. A micro-sized fraction of 53 to 250 μm, a silt + clay fraction of size <53 μm, and a water-stable, macrosized fraction of 250 to 2000 μm were all produced by the whole technique.

$$\text{C storage} = \text{C concentration} \times \text{BD} \times \text{Soil depth} \times \text{Fraction weight}$$

Where,

C storage = C expressed in Mg ha⁻¹ in each fraction class for a given depth

C concentration = C in fraction size, g per Kg of soil of that fraction size
BD = Bulk density, Mgm⁻³

Depth = Depth of soil profile, cm, and

Fraction weight = % weight of the fraction in the whole soil

Statistical analysis:

Two-way analysis of variance (ANOVA) was used to compare the effects of various agroforestry systems on SOC fractions and various indices, including LI and CMI, and the Least Significant Difference (LSD) test for factorial randomised complete block design (RCBD) was used to compare means in posthoc analysis. Packages like readxl, agricolae, doebioresearch, openxlsx, etc were used during analysis. Using Pearson's correlation coefficient approach, correlation analysis was also performed between the various soil C fractions, LI, and CMI. All graphs were plotted with the help of excel and r software.

Chapter - 4

RESULT AND DISCUSSION

The present study entitled “**Evaluation of agroforestry systems for their carbon and nitrogen pools in mid-hills of Himachal Pradesh**” was carried out at the experimental field of the Department of Silviculture and Agroforestry, Dr Y S Parmar University of Horticulture and Forestry, Nauni, Solan (HP) during years 2022-2023. The investigations were aimed at determining the role of commercial agroforestry systems and soil depth on the carbon and nitrogen pools and also the carbon stored in different soil particle size fractions i.e., 250-2000 μm , 53-250 μm , <53 μm . The results thus obtained during the course of study are described and discussed here under the following heads and subheads:

4.1 Bulk density (g cm^{-3})

4.2 Soil carbon pools

4.2.1 Carbon Fraction 1 (Very Labile Carbon) (mg g^{-1})

4.2.2 Carbon Fraction 2 (Labile Carbon) (mg g^{-1})

4.2.3 Carbon Fraction 3 (Less Labile Carbon) (mg g^{-1})

4.2.4 Carbon Fraction 4 (Non-Labile Carbon) (mg g^{-1})

4.2.5 Active Carbon Pool (mg g^{-1})

4.2.6 Passive Carbon Pool (mg g^{-1})

4.2.7 Lability Index

4.2.8 Carbon Pool Index

4.2.9 Carbon Management Index

4.3 Soil nitrogen pools

4.3.1 Ammonical nitrogen (mg kg^{-1})

4.3.2 Nitrate nitrogen (mg kg^{-1})

4.3.3 Total nitrogen (%)

4.3.4 Total nitrogen density (Mg ha⁻¹)

4.4 Soil carbon stored in different soil particle size fraction

4.4.1 Soil size fraction (%) of particle size 250-2000µm

4.4.2 Soil size fraction (%) of particle size 53-250µm

4.4.3 Soil size fraction (%) of particle size <53 µm

4.4.4 Soil organic carbon (mg g⁻¹) of particle size 250-2000µm

4.4.5 Soil organic carbon (mg g⁻¹) of particle size 53-250µm

4.4.6 Soil organic carbon (mg g⁻¹) of particle size <53 µm

4.4.7 Total organic carbon (%)

4.4.8 Carbon density of 250-2000 µm soil size fraction (Mg ha⁻¹)

4.4.9 Carbon density of 53-250µm soil size fraction (Mg ha⁻¹)

4.4.10 Carbon density of <53m soil size fraction (Mg ha⁻¹)

4.4.11 Average carbon density (Mg ha⁻¹)

4.4.12 Total carbon density (Mg ha⁻¹) different agroforestry system

4.1 BULK DENSITY (g cm⁻³)

Bulk density is one of the most important physical property of soil that affects quality of soil and further affects the fertility of soil.

The Bulk density of soil was determined and it is given in Table 3. Bulk density of sole cropping (T₁) and agri-silvi-horticulture system (T₃) are statistically at par and also have the maximum value of bulk density which is 1.27 g cm⁻³ in both while natural forest (T₂) had mean minimum value i.e. (0.93 g cm⁻³). It may be because of the addition of organic matter through leaf fall and litter. The bulk density results indicate a relative relationship between the soil's organic carbon content and the number of trees or leaf fall in particular agroforestry system soils. These findings are in line with the study of Matos *et al.* (2020) who concluded that the bulk densities of soils in eight-year-old agroforestry systems were more as compared to nearby pastures. Increased soil strength brought on by increased bulk density results in

decreased soil aeration, which negatively impacts root growth. Bulk densities, particularly in tree plantations, can favourably affect root development. According to Berhe *et al.* (2013), the soil outside of tree canopies has larger bulk densities than soil beneath tree canopies because of litter addition to the soil, a higher concentration of tree roots close to the tree's base, and exposure to direct sunshine. Additionally, the lower bulk densities may benefit root growth, particularly in tree plantations. These findings are entirely consistent with earlier research conducted in Peru under cacao-based agroforestry systems by Gardini *et al.* (2015), who came to the conclusion that increased vegetation cover increases fresh organic matter and decreases the bulk density of soils because the components of decomposing organic matter are less dense than mineral components.

Table 3: Effect of agroforestry system, soil depth and their interaction on Bulk Density (g cm^{-3})

Agroforestry system (T)	Soil depth D)			Mean
	D ₁	D ₂	D ₃	
T ₁ - Sole cropping	1.20 ^{ef}	1.23 ^{de}	1.36 ^a	1.27 ^a
T ₂ - Natural Forest	0.91 ^k	0.92 ^j	0.96 ^j	0.93 ^f
T ₃ - Agri-silvi-horticulture system	1.21 ^{de}	1.21 ^{def}	1.37 ^a	1.27 ^a
T ₄ - Agrisilviculture	1.18 ^{efg}	1.20 ^{ef}	1.26 ^{cd}	1.22 ^b
T ₅ - Fruit based agroforestry system	1.11 ^{de}	1.11 ⁱ	1.41 ^{bc}	1.22 ^b
T ₆ -Fodder tree based agroforestry system	0.95 ^j	1.13 ^{hi}	1.20 ^{ef}	1.10 ^e
T ₇ -Bamboo based agroforestry system	1.14 ^{ghi}	1.17 ^{fgh}	1.21 ^{def}	1.18 ^c
T ₈ - Melia based agroforestry system	0.99 ^j	1.17 ^{fgh}	1.22 ^{de}	1.13 ^d
T ₉ - Poplar based agroforestry system	1.12 ^{hi}	1.21 ^{ab}	1.34 ^{def}	1.23 ^b
T ₁₀ - Silvipasture system	1.20 ^{ef}	1.20 ^{ef}	1.24 ^{de}	1.22 ^b
Mean	1.10 ^c	1.16 ^b	1.26 ^a	
Factors	SE(d)	CD at 5%		
Soil Depth (D)	0.008	0.016		
AFS (T)	0.015	0.030		
Interaction (T×D)	0.026	0.052		

Significant difference exists between the mean values in the same row that are denoted by a distinct letter (^{a, b, c, ...})

Depth wise average bulk density varies greatly at the surface soil layer, but in all agroforestry systems, the variance tends to decline as the soil layers descend. Bulk density was 1.10 g cm^{-3} in $D_1(0-20\text{cm})$, 1.16 g cm^{-3} in $D_2(20-40\text{cm})$ and 1.26 g cm^{-3} in $D_3(40-60\text{cm})$, it is mainly because of decrease in organic matter content with increase in soil depth. These findings concur with those of Bargali and Bargali (2020), who estimated the bulk densities of the surface and sub-surface layers to range between 0.62 and 1.16 g cm^{-3} and 0.79 g cm^{-3} and 1.22 g cm^{-3} , respectively. In each layer, the bulk densities under tree-based systems were lower than those under sole cropping (T_1). These findings are also supported by Gardini *et al.* (2015). Further, as an interaction effect, maximum value was recorded in T_1D_3 (1.36 g cm^{-3}), while minimum was recorded in T_2D_1 (0.91 g cm^{-3}).

4.2 Effect of Agroforestry system and soil depth on soil carbon pools

Total soil organic carbon (TSOC) stock is divided into different pools based on their cycling rates and stability. These pools include the labile or actively cycling pool, the slow pool, and the stable or passive recalcitrant pool, each with varying residence times. Different Agroforestry systems (AFSs) were studied to determine the dynamics of soil organic carbon stock. All Carbon pools have been recorded and presented in following subsections:

4.2.1 Carbon Fraction 1 (Very Labile Carbon) (mg g^{-1})

Data for very labile carbon is presented in Table 4. It reveals that most of the agroforestry systems (AFSs) were statistically different, average data for agrisilviculture (T_4) (0.74 mg g^{-1}) and bamboo-based agroforestry systems (T_7) (0.71 mg g^{-1}) were statistically at par. Sole cropping (T_1) had a minimum value of very labile carbon i.e., 0.62 mg g^{-1} while natural forest (T_2) had a maximum i.e., 3.24 mg g^{-1} and all the tree-based systems showed more storage of very labile carbon than sole cropping (T_1). These results were in consonance with the findings of Bayer *et al.*, (2006) who concluded that the lower values of labile C in the cropping systems can be associated with aggregate disruption and greater organic matter oxidation in conventional agricultural systems due to ploughing and harrowing, as these practices results in the mechanical disturbance of the soil, which lead to the breakdown of soil aggregates. Soil aggregates provide pore spaces and stability to the soil, promoting water infiltration, root penetration, and air exchange so their disruption causes a lower value of very labile carbon because when the soil aggregates are disrupted, very labile carbon becomes more susceptible to oxidation and microbial breakdown. While the higher value of very labile

carbon concentration observed under natural forests (T_2) and other AFSs compared to sole cropping (T_1), which can be attributed to several factors, including the accretion of carbon through litter fall and root biomass. Trees shed leaves, twigs, and other plant materials, which contribute to the organic matter input on the forest floor. The decomposition of this litter adds to the very labile carbon pool in the soil. Additionally, it has been noted that fast-growing trees, such as Poplar trees established in the area, contribute 2.9–3.3 Mg ha⁻¹ of litter fall each year and supply 2.3 Mg C ha⁻¹ y⁻¹ through their roots and leaves (Ralhan *et al.*, 1992; Tandon *et al.*, 1991). Trees also have large and more extensive root systems compared to annual crops. The greater root biomass contributes to increased organic carbon inputs into the soil through root exudates, root turnover, and the subsequent decomposition of fine roots (Singh *et al.*, 2009).

Very labile carbon differed significantly among different layers (Table 4). The layer of D_1 (0-20cm), D_2 (20-40cm) and D_3 (40-60cm) displayed average value of 1.76 mg g⁻¹, 1.54 mg g⁻¹, 1.16 mg g⁻¹, respectively. The greater percentage of C in the upper soil layer (0–20 cm) can be attributed to the litter material present in this layer, which enhances the availability and provision of mineralizable and easily hydrolysable carbon, resulting in higher activity and population of microorganisms (Kaur *et al.*, 2008; Benbi *et al.*, 2015). Rangel *et al.* (2008) and Andrade *et al.* (2008) also observed a pronounced reduction of levels of very labile carbon with an increase in depth.

In layer D_1 (0-20 cm), this carbon fraction varied from 0.62 to 3.87 mg g⁻¹ in sole cropping (T_1) and natural forest (T_2), respectively. In D_2 (20-40 cm), sole cropping (T_1) exhibited higher carbon fraction than agrisilviculture (T_4) and silvipasture (T_{10}), most likely as a result of C input from the application of farmyard manure to sole cropping. Benbi *et al.* (1998) also emphasized upon the beneficial effects of manure application on SOC build-up under sole cropping in semi-arid India. In D_3 (40-60cm), very labile carbon was maximum in natural forest (T_2) (2.77 mg g⁻¹) followed by bamboo-based agroforestry system (T_7) (1.98 mg g⁻¹) and minimum in sole cropping (T_1) (0.28 mg g⁻¹). The higher value of very labile carbon in aforesaid AFSs than other AFSs can be attributed to the spread of deep and extensive root systems of T_2 & T_7 and annual addition and decomposition. Further, as the roots penetrate the soil, they create channels that facilitate the movement of water through the soil profile. This movement of water can lead to the leaching of dissolved organic carbon from the topsoil to the lower profile of soils. Additionally, the fine mesh-like root system of

bamboo can help in binding soil aggregates together, enhancing soil stability and reducing erosion. By preventing soil erosion, bamboo plantations can help retain the organic carbon within the soil rather than losing it through surface runoff. The aforementioned factors improve the capacity of bamboo species to efficiently build up soil organic carbon (Kaushal *et al.*, 2020 a,b). Moreover, as an interaction effect, greatest value was recorded in T₁D₁ (3.87 mg g⁻¹), while lowest value was recorded in T₁D₃ (0.62 mg g⁻¹).

Table 4: Effect of agroforestry system, soil depth and their interaction on Carbon fraction1 (Very Labile) (mg g⁻¹)

Agroforestrysystem (T)	Soil depth (D)			Mean
	D ₁	D ₂	D ₃	
T ₁ - Sole cropping	0.62 ^{op}	0.94 ^m	0.28 ^q	0.62 ⁱ
T ₂ - Natural Forest	3.87 ^a	3.07 ^b	2.77 ^{cd}	3.24 ^a
T ₃ - Agri-silvi-horticulture system	1.64 ^{gh}	1.38 ^j	1.33 ^j	1.46 ^d
T ₄ - Agrisilviculture	1.10 ^{kl}	0.63 ^{op}	0.49 ^p	0.75 ^h
T ₅ - Fruit basedagroforestry system	2.58 ^e	2.63 ^{de}	1.74 ^g	2.32 ^c
T ₆ - Fodder tree based agroforestry system	1.68 ^{gh}	1.48 ^{ij}	0.63 ^{op}	1.27 ^e
T ₇ - Bamboo basedagroforestry system	2.81 ^c	2.49 ^e	1.98 ^f	2.43 ^b
T ₈ - Melia basedagroforestry system	1.56 ^{hi}	1.17 ^k	0.73 ^{no}	1.16 ^f
T ₉ - Poplar basedagroforestry system	0.88 ^{mn}	0.92 ^m	0.95 ^{lm}	0.92 ^g
T ₁₀ - Silvipasture system	0.84 ^{mn}	0.63 ^{op}	0.65 ^o	0.71 ^h
Mean	1.76 ^a	1.54 ^b	1.16 ^c	
Factors	SE(d)	CD at 5%		
Soil Depth (D)	0.036	0.049		
AFS (T)	0.066	0.090		
Interaction (T×D)	0.114	0.156		

Significant difference exists between the mean values in the same row that are denoted by a distinct letter (a, b, c, ...)

4.2.2 Carbon Fraction 2 (Labile Carbon) (mg g⁻¹)

A perusal of data in Table 5 indicate that labile carbon is maximum in a fruit-based agroforestry system (T₅) (1.85 mg g⁻¹) followed by agri-silvi-horticulture (T₃) (1.43 mg g⁻¹), sole cropping (T₁) (1.15 mg g⁻¹) and natural forest (T₂) (1.05 mg g⁻¹). Seneviratne *et al.* (2009) postulated that the application of balanced fertilizers along with organic manure increased polysaccharides in the soil resulting in the production of a higher amount of labile

carbon fraction. Labile organic C are more readily influenced by management practices like tillage, use of fertilizer and manure than the recalcitrant pools (Biederbeck *et al.*, 1994; Meena *et al.*, 2018). The labile carbon responds rapidly to the changes in organic matter inputs and is considered to be a better indicator of land use (Gregorich *et al.*, 1994). Labile carbon decreased along with depth i.e., 1.30 mg g⁻¹, 1.09 mg g⁻¹, 0.73 mg g⁻¹ in D₁, D₂ and D₃, respectively. Gleixner *et al.* (2001) also observed higher content of labile carbon fraction in surface soil and linked it to litterfall addition and its decomposition and transformation products have a shorter residence time in soil due to different chemical recalcitrance. At all soil depth, fruit-based agroforestry systems show higher value while interaction effect shows that maximum value in T₅D₁ (2.04 mg g⁻¹) and minimum in T₇D₃ (0.22 mg g⁻¹).

Table 5: Effect of agroforestry system, soil depth and their interaction on Carbon fraction2 (Labile) (mg g⁻¹)

Agroforestry system (T)	Soil depth (D)			Mean
	D ₁	D ₂	D ₃	
T ₁ - Sole cropping	1.54 ^{de}	1.34 ^{gh}	0.55 ^{rs}	1.15 ^c
T ₂ - Natural Forest	1.45 ^{efg}	1.19 ⁱ	0.51 ^{rst}	1.05 ^d
T ₃ - Agri-silvi-horticulture system	1.63 ^{cd}	1.49 ^{ef}	1.16 ^{ij}	1.43 ^b
T ₄ - Agrisilviculture	1.37 ^{tgh}	1.05 ^{kl}	0.41 ^{tu}	0.95 ^e
T ₅ - Fruit based agroforestry system	2.04 ^a	1.66 ^{cd}	1.83 ^b	1.85 ^a
T ₆ - Fodder tree-based agroforestry system	1.31 ^h	1.04 ^{kl}	0.78 ^{op}	1.05 ^d
T ₇ - Bamboo based agroforestry system	1.05 ^{kl}	0.92 ^{mn}	0.22 ^v	0.73 ^f
T ₈ - Melia based agroforestry system	0.99 ^{lm}	0.72 ^{pq}	0.61 ^{qr}	0.78 ^f
T ₉ - Poplar based agroforestry system	1.11 ^{ijk}	1.07 ^{jkl}	0.84 ^{no}	1.01 ^{de}
T ₁₀ - Silvipasture system	0.49 st	0.41 ^{tu}	0.38 ^u	0.43 ^g
Mean	1.30 ^a	1.09 ^b	0.73 ^c	
Factors	SE(d)	CD at 5%		
Soil Depth (D)	0.018	0.035		
AFS (T)	0.032	0.064		
Interaction (T×D)	0.056	0.112		

Significant difference exists between the mean values in the same row that are denoted by a distinct letter (a, b, c, ...)

4.2.3 Carbon Fraction 3 (Less Labile Carbon) (mg g⁻¹)

A critical examination of the data enumerated in Table 6 reveals that less labile carbon is significantly different among AFSs. It was found maximum in the agri-silvi-

horticulture system (T₃) (3.81 mg g⁻¹), while minimum in silvipasture (T₁₀) (0.35 mg g⁻¹). It was also observed that sole cropping (T₁) showed higher less labile carbon than some tree-based agroforestry systems. Less labile carbon also decreased with depth i.e., 3.44 mg g⁻¹, 2.32 mg g⁻¹, and 2.24 mg g⁻¹ in D₁, D₂ and D₃ respectively. Smaller variation of less labile carbon with increase in depth of the soil was also reported by Barreto *et al.* (2011), who suggested that across the entire soil profile, these fractions are less responsive to variations in C quality. Interaction study shows higher and lower value of less labile carbon in T₁D₁ (5.28 mg g⁻¹) and T₁₀D₃ (0.24 mg g⁻¹) respectively.

Table 6: Effect of agroforestry system, soil depth and their interaction on Carbon fraction3 (Less Labile Carbon) (mg g⁻¹)

Agroforestry system (T)	Soil depth (D)			Mean
	D ₁	D ₂	D ₃	
T ₁ - Sole cropping	5.28 ^a	1.95 ⁿ	0.95 ^p	2.73 ^e
T ₂ - Natural Forest	2.45 ^{jk}	1.91 ^{no}	1.72 ^o	2.03 ^h
T ₃ - Agri-silvi-horticulture system	4.60 ^b	3.34 ^{fg}	3.45 ^{ef}	3.81 ^a
T ₄ - Agrisilviculture	4.51 ^{bc}	3.03 ^h	2.31 ^{kl}	3.29 ^c
T ₅ - Fruit based agroforestry system	3.59 ^e	2.75 ⁱ	3.21 ^{gh}	3.19 ^c
T ₆ - Fodder tree-based agroforestry system	4.31 ^{cd}	3.22 ^{gh}	3.41 ^{efg}	3.65 ^b
T ₇ - Bamboo based agroforestry system	2.43 ^k	2.01 ^{mn}	2.05 ^{mn}	2.17 ^g
T ₈ - Melia based agroforestry system	2.52 ^{ijk}	2.18 ^{lm}	2.67 ^{ij}	2.46 ^f
T ₉ - Poplar based agroforestry system	4.13 ^d	2.49 ^{jk}	2.43 ^k	3.02 ^d
T ₁₀ - Silvipasturesystem	0.51 ^q	0.29 ^{qr}	0.24 ^r	0.35 ⁱ
Mean	3.44 ^a	2.32 ^b	2.24 ^c	
Factors	SE(d)	CD at 5%		
Soil Depth (D)	0.036	0.072		
AFS (T)	0.066	0.132		
Interaction (T×D)	0.144	0.228		

Significant difference exists between the mean values in the same row that are denoted by a distinct letter (a, b, c, ...)

4.2.4 Carbon Fraction 4 (Non-Labile Carbon) (mg g⁻¹)

A perusal of Table 7 implies that mean non-labile carbon fraction is maximum in silvipasture (T₁₀) (11.06 mg g⁻¹), which is statistically at par with natural forest (T₂) (10.98

mg g⁻¹) followed by melia based agroforestry system (T₈) (8.73 mg g⁻¹) which was statistically at par with bamboo based agroforestry system (T₇) (8.49 mg g⁻¹). The higher value of silvipasture system (T₁₀) and natural Forest (T₁₀) than other system can be owed due to lack of intercultural practices coupled with long lived trees prevalent in these systems because over time, labile carbon fractions in organic materials can transform into less labile and recalcitrant carbon fractions, primarily due to the increased presence of compounds such as lignin, suberin, cutins, and tannins and these compounds are highly resistant to microbial degradation and can persist in the environment for longer periods (Sharma *et al.*, 2015). Minimum non-labile carbon observed in fruit based agroforestry system (T₅) (2.89 mg g⁻¹), while it has been also observed that like less labile carbon, non-labile carbon of sole cropping of value 5.63 mg g⁻¹ (T₁) had higher value than some of tree-based agroforestry system.

Table 7: Effect of agroforestry system, soil depth and their interaction on Carbon fraction 4 (Non Labile) (mg g⁻¹)

Agroforestry system (T)	Soil depth (D)			Mean
	D ₁	D ₂	D ₃	
T ₁ - Sole cropping	3.88 ^m	5.54 ^{kl}	7.46 ^g	5.63 ^{de}
T ₂ - Natural Forest	11.70 ^b	10.49 ^c	10.73 ^c	10.98 ^a
T ₃ -Agri-silvi horticulture system	4.18 ^m	4.14 ^m	3.87 ^m	4.07 ^f
T ₄ - Agrisilviculture	5.08 ^l	5.83 ^{jk}	6.33 ^{ij}	5.75 ^d
T ₅ - Fruit based agroforestry system	2.94 ^{no}	3.21 ⁿ	2.50 ^o	2.89 ^g
T ₆ - Fodder tree based agroforestry system	5.52 ^{kl}	5.26 ^{kl}	5.40 ^{kl}	5.40 ^e
T ₇ - Bamboo based agroforestry system	9.07 ^d	8.26 ^{ef}	8.11 ^f	8.49 ^b
T ₈ - Melia based agroforestry system	10.59 ^c	8.78 ^{de}	6.80 ^{hi}	8.73 ^b
T ₉ - Poplar based agroforestry system	7.28 ^{gh}	7.75 ^{fg}	7.31 ^{gh}	7.45 ^c
T ₁₀ - Silvipasture system	12.48 ^a	10.38 ^c	10.30 ^c	11.06 ^a
Mean	7.27 ^a	6.97 ^b	6.88 ^b	
Factors	SE(d)	CD at 5%		
Soil Depth (D)	0.092	0.184		
AFS (T)	0.168	0.336		
Interaction (T×D)	0.291	0.582		

Significant difference exists between the mean values in the same row that are denoted by a distinct letter (^{a, b, c, ...})

Along the depth, there was slight variation in non-labile carbon that ranges from 6.88 mg g⁻¹ to 7.27 mg g⁻¹ only, which suggests that these fractions are also less sensitive to changes in C quality across the soil profile. Similar results were also reported by Barreto *et*

al. (2011). In D₁(0-20cm), (12.48 mg g⁻¹) silvopasture showed more non-labile carbon while in both D₂(0-20cm) and D₃(0-20cm) silvopasture (T₁₀) (10.38 mg g⁻¹ and 10.30 mg g⁻¹) and natural forest (T₁₀) (10.49 mg g⁻¹ and 10.73 mg g⁻¹) were statistically at par. Further, interaction effect shows maximum value in T₁₀D₁ (12.48 mg g⁻¹) and minimum in T₅D₃ (2.50 mg g⁻¹).

4.2.5 Active Carbon Pool (mg g⁻¹)

Active carbon pool followed the trend: Natural Forest > Fruit based agroforestry system > Tree-based agroforestry system > sole cropping (Table 8). The trend of increasing active fractions of C in forest and plantation soils followed the expected lines (Aumtong *et al.*, 2009; Kaur *et al.*, 2000). Smith (2007) which concluded that land use determines the amount of carbon being contributed to the soil and forest systems tend to have the largest input of C to the soil. Natural forest (T₂) (4.30 mg g⁻¹) had a maximum active carbon pool which was statistically at par with fruit-based agroforestry system (T₅) (4.17 mg g⁻¹) and minimum active carbon pool i.e., 1.14 (mg g⁻¹) was detected in silvopasture (T₁₀) i.e., 1.14 (mg g⁻¹), which is nearly 3.8 times smaller than the highest recorded value of natural forest (T₂). The higher active carbon pool in a fruit based agroforestry system (T₅) as compared to other AFSs may be attributed to the fact that root biomass and leaf-litters of this system decomposed into tannins and lignin components, which shielded the carbon from rapid degradation and maintained it in the aggregates (Kalambukattu *et al.*, 2013). Vesterdal *et al.* (2008) also reported that fresh litterfall and root residues are indeed primary sources of soil organic carbon (SOC) in fruit based agroforestry systems, contributing to the increased amount of very labile carbon and labile carbon fractions. These results are also in agreement with Kumar *et al.* (2020), who reported that in comparison to open land, there was a significant active carbon pool in tree-based AFSs. Other researchers also noted that due to the continuous delivery of massive volumes of litter and larger concentrations of fine roots, tree species help to boost the soil's organic carbon content (Munoz and Beer, 2001; Singh, 2005). Further, many workers reported that lack of biomass addition to soil, crop residue removal, and conventional tillage practices in agricultural production systems enhance carbon losses from the soil (Baker *et al.*, 2007; Lal and Kimble, 1997; Smith, 2007 and Yang *et al.*, 2004).

Among all AFSs, a relatively higher proportion of the active carbon pool was found in D₁(0-20cm), whereas it was found to decrease significantly with increasing soil depth ranging from 3.06 (mg g⁻¹) to 1.89 (mg g⁻¹). This was due to gradient in supply and the availability of

additional mineralisable and readily hydrolysable carbon resulting in higher microbial activity in surface layers (Kaur *et al.*, 2008).

Table 8: Effect of agroforestry system, soil depth and their interaction on Active Carbon Pool (mg g^{-1})

Agroforestry system (T)	Soil depth (D)			Mean
	D ₁	D ₂	D ₃	
T ₁ - Sole cropping	2.17 ^{jk}	2.29 ^{ij}	0.84 ^o	1.77 ^f
T ₂ - Natural Forest	5.32 ^a	4.26 ^c	3.28 ^e	4.30 ^a
T ₃ - Agri-silvi-horticulture system	3.27 ^f	2.87 ^g	2.50 ^{hi}	2.89 ^c
T ₄ - Agrisilviculture	2.48 ^{hi}	1.68 ^m	0.91 ^o	1.69 ^f
T ₅ - Fruit based agroforestry system	4.63 ^b	4.30 ^c	3.58 ^e	4.17 ^a
T ₆ - Fodder tree based agroforestry system	3.00 ^g	2.52 ^{hi}	1.42 ⁿ	2.32 ^d
T ₇ - Bamboo based agroforestry system	3.86 ^d	3.42 ^{ef}	2.20 ^{jk}	3.17 ^b
T ₈ - Melia based agroforestry system	2.55 ^h	1.90 ^{lm}	1.35 ⁿ	1.94 ^e
T ₉ - Poplar based agroforestry system	1.99 ^{kl}	2.00 ^{kl}	1.79 ^{lm}	1.93 ^e
T ₁₀ - Silvipasture system	1.34 ⁿ	1.04 ^o	1.03 ^o	1.14 ^g
Mean	3.06 ^a	2.63 ^b	1.89 ^c	
Factors	SE(d)	CD at 5%		
Soil Depth (D)	0.038	0.076		
AFS (T)	0.070	0.139		
Interaction (T×D)	0.121	0.241		

Significant difference exists between the mean values in the same row that are denoted by a distinct letter (^{a, b, c, ...})

In contrast to D₁(0-20cm) and D₃(40-60cm) which showed a lower value of active carbon pool than most agroforestry systems, the active carbon pool in D₂ (20-40 cm) in sole cropping (T₁) showed a higher active carbon pool in comparison to some tree-based agroforestry systems. A similar trend was observed by Pandher *et al.* (2020). This might be due to the addition of root debris from agricultural crops contributing to the transformation of active carbon fractions into less labile and recalcitrant carbon fractions in the soil. The root systems of these crops are typically concentrated in the topsoil layer, where they release organic compounds into the soil during root exudation and decomposition. The active carbon fractions of soil organic carbon (SOC) are often the most sensitive to changes resulting from different crop types and nutrient management practices in agricultural systems (Chan *et al.*, 2001). This demonstrated the need for monitoring the effectiveness of various management techniques in maintaining active pools of C,

which play a significant role in the cycling of nutrients. Maximum active carbon pool was recorded in treatment combination T₂D₁ (5.32 mg g⁻¹) while minimum in T₁D₃ (0.84 mg g⁻¹).

4.2.6 Passive Carbon Pool (mg g⁻¹)

Passive carbon pool is generally less influenced by short-term alterations in land use management practices compared to labile carbon fractions. This is because recalcitrant carbon compounds are more resistant to microbial degradation and have longer turnover times in the soil (Sainepo *et al.*, 2018). As demonstrated in Table 9, a higher value of passive carbon pool was observed in natural forest (T₂) i.e., 13.01 mg g⁻¹, which is almost double that of the lowest passive carbon pool stored in a fruit based agroforestry system (T₅). The passive carbon pool in a bamboo-based agroforestry system (T₇) (10.65 mg g⁻¹) was higher than its active carbon pool and these results are of utmost significance and demonstrate the importance of bamboo based land use systems in climate change mitigation and sustainability of the system. Further, Kaushal *et al* (2021) who also found the same range of passive carbon pool i.e. 13.27 mg g⁻¹ to 11.21 mg g⁻¹ and this may be due to bamboo plants producing phytolith-occluded carbon (PhytOC), which are microscopic silica structures that are formed within plant tissues and is a form of recalcitrant carbon that can remain in the soil for long periods of time. The high stability of PhytOC is attributed to the protective nature of the silica matrix, which shields the carbon from microbial degradation and other environmental factors (Huang *et al.*, 2014). Further, poplar based agroforestry system (T₉) also demonstrated a higher passive carbon pool as compared to its active carbon pool. These results are in alignment with Sierra *et al.* (2013) who also found that poplar plantations had a higher concentration of passive carbon pool, which is explained by the presence of aromatic compounds in the lignin and other refractory chemicals. Significant recalcitrance is added to soil organic matter by the incorporation of phenolic moieties into SOM fractions as a result of delayed lignin degradation (Olk *et al.*, 1996).

Passive carbon pool also followed the same trend as less labile and non-labile fractions of carbon and it decreased with depth but with slight variation within depth (10.71 mg g⁻¹ to 9.13 mg g⁻¹), these results are in consonance with the findings of Naik *et al* (2016). It is also clear from the data that passive carbon pools (less labile and more non labile carbon fractions) contributed more to total soil organic pools. Passive carbon pool contributes about ~60 per cent of total organic carbon in the soil system and similar observations have been made by Kaushal *et al* (2021). These carbon fractions are protected from microbial action and least degraded because they are tightly bonded to the mineral matrix of the soil (Dwivedi *et*

al., 2019). In each layer, the natural forest (T₂) had a higher value because of the deep tap root system that contributes to carbon, while minimum in a fruit-based agroforestry system (T₅). Maximum passive carbon pool was recorded in treatment combination T₂D₁ (14.15 mg g⁻¹) while minimum in T₅D₃ (5.72 mg g⁻¹).

The magnitude of different fractions of oxidizable organic C viz., very labile, labile, less labile and non-labile under a gradient of oxidising conditions was followed the order: NLC > LLC > LC > VLC. Data revealed that long-term cultivation of different crops had significantly higher build-up in passive pools and cover barren land and similar results were also depicted by Moharana *et al.* (2017).

Table 9: Effect of agroforestry system, soil depth and their interaction on Passive Carbon Pool (mg g⁻¹)

Agroforestry system (T)	Soil depth (D)			Mean
	D ₁	D ₂	D ₃	
T ₁ - Sole cropping	9.17 ^{kl}	7.50 ^p	8.41 ^o	8.36 ^e
T ₂ - Natural Forest	14.15 ^a	12.41 ^c	12.46 ^c	13.01 ^a
T ₃ - Agri-silvi-horticulture system	8.79 ^{mn}	7.49 ^p	7.33 ^p	7.87 ^f
T ₄ - Agrisilviculture	9.60 ^j	8.87 ^{lm}	8.64 ^{mno}	9.04 ^d
T ₅ -Fruit based agroforestry system	6.53 ^q	5.96 ^r	5.72 ^r	6.08 ^g
T ₆ - Fodder tree based agroforestry system	9.84 ^{ij}	8.48 ^{no}	8.82 ^{lmn}	9.05 ^d
T ₇ - Bamboo based agroforestry system	11.51 ^d	10.28 ^{gh}	10.16 ^{hi}	10.65 ^c
T ₈ -Melia based agroforestry system	13.12 ^b	10.97 ^e	9.47 ^{jk}	11.19 ^b
T ₉ - Poplar based agroforestry system	11.42 ^d	10.24 ^{gh}	9.74 ^j	10.47 ^c
T ₁₀ - Silvipasture system	12.99 ^b	10.68 ^{ef}	10.54 ^{fg}	11.41 ^b
Mean	10.71 ^a	9.29 ^b	9.13 ^c	
Factors	SE(d)	CD at 5%		
Soil Depth (D)	0.060	0.119		
AFS (T)	0.109	0.218		
Interaction (T×D)	0.188	0.377		

Significant difference exists between the mean values in the same row that are denoted by a distinct letter (^{a, b, c, ...})

4.2.7 Lability Index (LI)

From Table 10 it can be depicted that the fruit based system (T₅) had a higher LI value i.e., 1.35 and the lowest value in silvipasture system (T₁₀) i.e., 0.24. This pattern

showed that a fruit based system (T₅) provided a more oxidative environment, and there is less physical protection of soil organic matter (SOM), which favour a higher proportion of labile carbon compared to total SOC (TSOC). This is because a more oxidative environment, typically characterized by higher oxygen availability, which enhances the decomposition rate and oxidation processes of organic matter (Blair *et al.*, 1995). Contrarily, silvipasture systems have less lability means less oxidative conditions and hence desirable from environment conservation point view. However, there was a very slight variation in LI among AFSs. There is also not much variation in the lability index among the studied AFSs at three depth of soil profile. These results are in consonance with the findings of Naik *et al.* (2016) and Kaushal *et al.* (2016) who observed little variation among different soil depth. Moreover, treatment combination is maximum in T₅D₁ (1.38) and minimum in T₁₀D₃ (0.19).

Table 10: Effect of agroforestry system, soil depth and their interaction on Lability Index (LI)

Agroforestrysystem (T)	Soil depth (D)			Mean
	D ₁	D ₂	D ₃	
T ₁ - Sole cropping	0.90 ^{de}	0.76 ^{gh}	0.31 ⁿ	0.66 ^d
T ₂ - Natural Forest	0.87 ^{def}	0.81 ^{fg}	0.70 ^{hi}	0.80 ^c
T ₃ - Agri-silvi-horticulture system	1.06 ^b	1.01 ^{bc}	0.99 ^{bc}	1.02 ^b
T ₄ - Agrisilviculture	0.87 ^{def}	0.66 ^{ijk}	0.48 ^m	0.68 ^d
T ₅ - Fruit basedagroforestry system	1.38 ^a	1.36 ^a	1.30 ^a	1.35 ^a
T ₆ - Fodder tree based agroforestry system	0.93 ^{cd}	0.88 ^{def}	0.67 ^{ijk}	0.83 ^c
T ₇ - Bamboo based agroforestry system	0.84 ^{efg}	0.82 ^{efg}	0.68 ^{hij}	0.79 ^c
T ₈ - Melia based agroforestry system	0.58 ^{kl}	0.55 ^{lm}	0.56 ^{lm}	0.57 ^e
T ₉ - Poplar based agroforestry system	0.67 ^{ijk}	0.60 ^{jkl}	0.60 ^{jkl}	0.63 ^d
T ₁₀ - Silvipasture system	0.28 ⁿ	0.25 ^{no}	0.19 ^o	0.24 ^f
Mean	0.84 ^a	0.77 ^b	0.65 ^c	
Factors	SE(d)	CD at 5%		
Soil Depth (D)	0.014	0.028		
AFS (T)	0.026	0.052		
Interaction (T×D)	0.045	0.089		

Significant difference exists between the mean values in the same row that are denoted by a distinct letter (^{a, b, c, ...})

4.2.8 Carbon Pool Index (CPI)

It is evident from the data given in Table 11 that the highest CPI value of 2.74 is in natural forest (T₁), which is statistically at par with the Melia based agroforestry system (T₈)

of value 2.60; while all other studied systems varied statistically. As a whole, CPI increased in all the systems over sole cropping (T₁) and similar results was also reported by Naik *et al.* (2016). CPI also decrease with an increase in soil profile depth and there was only a slight variation value that differs by 0.1 only. The CPI value was also higher in silvipasture (T₁₀) throughout the depth of the soil profile highlighting the high potential of silvipasture system (T₁₀) in restoring the original soil organic C stocks. The CPI value obtained at each depth is minimum in sole cropping only. Interaction effect shows higher CPI in T₂D₁ (2.83) which is statistically at par with T₈D₁ (2.83).

Table 11: Effect of agroforestry system, soil depth and their interaction on Carbon Pool Index (CPI)

Agroforestry system (T)	Soil depth (D)			Mean
	D ₁	D ₂	D ₃	
T ₁ - Sole cropping	1.00 ^{ij}	1.00 ^{ij}	1.00 ^{ij}	1.00 ^g
T ₂ - Natural Forest	2.83 ^a	2.59 ^{abc}	2.79 ^{ab}	2.74 ^a
T ₃ - Agri-silvi-horticulture system	1.31 ^h	1.14 ^{hij}	1.14 ^{hij}	1.20 ^f
T ₄ - Agri silviculture	1.34 ^{gh}	1.19 ^{hi}	0.97 ^{ij}	1.17 ^f
T ₅ - Fruit based agroforestry system	1.06 ^{ij}	1.05 ^{ij}	0.90 ^j	1.01 ^g
T ₆ -Fodder tree based agroforestry system	1.59 ^g	1.37 ^{gh}	1.32 ^h	1.43 ^c
T ₇ - Bamboo based agroforestry system	2.11 ^{ef}	2.03 ^f	2.00 ^f	2.05 ^c
T ₈ - Melia based agroforestry system	2.83 ^a	2.56 ^{bcd}	2.39 ^{cd}	2.60 ^a
T ₉ - Poplar based agroforestry system	1.90 ^f	1.88 ^f	1.88 ^f	1.89 ^d
T ₁₀ - Silvipasture system	2.10 ^{ef}	2.33 ^{de}	2.56 ^{bcd}	2.33 ^b
Mean	1.81 ^a	1.71 ^b	1.70 ^c	
Factors	SE(d)	CD at 5%		
Soil Depth (D)	0.040	0.079		
AFS (T)	0.072	0.144		
Interaction (T×D)	0.125	0.250		

Significant difference exists between the mean values in the same row that are denoted by a distinct letter (a, b, c, ...)

4.2.9 Carbon Management Index (CMI)

Table 12 demonstrated that CMI varied significantly with the AFSs, soil depth and interaction between them. The values among different AFSs ranged from 66.13 to 184.08. A management system is considered sustainable if the value of CMI is greater than 100, in this

context all the commercial AFSs except agrisilviculture system and silvipasture system and natural forest fits well. The observed trend of CMI was natural forest (T₂) > bamboo-based agroforestry system (T₇) > Melia based agroforestry system (T₈) > fruit-based agroforestry system (T₅) > agrisilviculture (T₃) > Fodder based agroforestry system (T₆) > Poplar based agroforestry system (T₉) > agrisilviculture agroforestry (T₄) > silvipasture (T₁₀) > sole cropping (T₁). The results of the present investigation are in agreement with the findings of Kalambukattu *et al.* (2013) who also reported that forests had a higher value of CMI than sole cropping. The higher the Carbon Management Index (CMI) values, the greater the potential for storing soil carbon (C) and reducing carbon losses. A higher CMI indicates improved soil quality, including enhanced physical and chemical properties and microbial dynamics in the soil, which contribute to better carbon sequestration and reduced carbon losses (Blair, 2000).

Table 12: Effect of agroforestry system, soil depth and their interaction on Carbon Management Index (CMI).

Agroforestry system (T)	Soil depth (D)			Mean
	D ₁	D ₂	D ₃	
T ₁ - Sole cropping	90.50 ^k	76.42 ^k	31.46 ⁿ	66.13 ^g
T ₂ - Natural Forest	183.25 ^{ab}	189.08 ^a	179.91 ^{ab}	184.08 ^a
T ₃ - Agri-silvi-horticulture system	139.14 ^{efg}	115.05 ^{ij}	113.90 ^j	122.70 ^e
T ₄ - Agri silviculture	117.64 ^{hij}	78.55 ^k	47.44 ^{mn}	81.21 ^f
T ₅ - Fruit based agroforestry system	146.54 ^{def}	143.24 ^{efg}	117.54 ^{hij}	135.78 ^d
T ₆ -Fodder tree based agroforestry system	149.08 ^{cde}	122.65 ^{ghij}	89.11 ^k	120.29 ^e
T ₇ - Bamboo based agroforestry system	178.27 ^{ab}	169.54 ^{abc}	136.75 ^{efgh}	161.53 ^b
T ₈ - Melia based agroforestry system	166.48 ^{bcd}	143.05 ^{efg}	135.22 ^{efghi}	148.26 ^c
T ₉ - Poplar based agroforestry system	126.67 ^{fghij}	115.46 ^{ij}	114.01 ^{ij}	118.71 ^e
T ₁₀ - Silvipasture system	72.67 ^{kl}	71.96 ^{kl}	54.22 ^{lm}	66.29 ^g
Mean	137.02 ^a	122.50 ^b	101.96 ^c	
Factors	SE(d)	CD at 5%		
Soil Depth (D)	3.355	6.716		
AFS (T)	6.125	12.261		
Interaction (T×D)	10.609	21.237		

Significant difference exists between the mean values in the same row that are denoted by a distinct letter (^{a, b, c, ...})

The Carbon Management Index (CMI) is a tool used to quantify soil carbon restoration and assess changes in soil carbon levels over time. The absolute value of the CMI is not as important as the differences observed between different land uses or management practices (Blair *et al.*, 1995). To measure how quickly SOC changes in response to changes in the agricultural system and soil management, CMI is utilised as a more sensitive indicator (Whitbread *et al.*, 1998). Therefore, SOC pools have a direct impact on the physical, chemical, and biological characteristics of soil as well as its ability to self-organize (Addiscott *et al.*, 1995). The value of CMI significantly decreased with increasing depth i.e., 137.02 in D₁, 122.50 in D₂ and 101.96 in D₃. Further, treatment combination T₂D₂ (189.08) shows maximum value and T₄D₃ (47.44) shows minimum value.

4.3 Soil nitrogen pools

The different pools of soil nitrogen, including total nitrogen (TN), ammonium nitrogen and nitrate nitrogen play crucial roles in nitrogen supply and organic matter decomposition rates in the soil and level of atmospheric nitrogen. Different Agroforestry systems were studied to determine the dynamics of the soil nitrogen pool. The Nitrogen pools- total nitrogen, ammonical nitrogen and nitrate nitrogen have been recorded and given as below:

4.3.1 Ammonical nitrogen (mg kg⁻¹)

A higher ammonification rate in all systems can promote the growth of heterotrophic microorganisms in the soil. This, in turn, can lead to increased microbial immobilization of nitrogen, serving as a conservation strategy and contributing to the formation of a labile nutrient pool in the soil. Microbial immobilization refers to the process where microorganisms assimilate and temporarily retain nitrogen from the soil, making it less available for plant uptake. Maithani *et al.* (1998) also provide more specific insights into the factors contributing to the variation in inorganic-N pools among agroforestry systems. Understanding these factors is crucial for effective nutrient management in agroforestry systems, as it allows for the development of strategies to optimize nitrogen availability, minimize losses, and maintain soil fertility.

It is evident from the Table 13 that ammonical N varied significantly due to AFS, soil depth and interaction between them. Maximum ammonical nitrogen was obtained in natural

forest (6.93 mg kg^{-1}) followed by sole cropping (T_7) (5.91 mg kg^{-1}), while minimum value of ammonical nitrogen (1.70 mg kg^{-1}) obtained in silvipasture system (T_{10}). Ammonical nitrogen reported in fruit based agroforestry system was more than agrisilviculture and similar results were also reported by Karki *et al.* (2021a). Ammonical nitrogen is higher in natural forests (T_2) because of the high microbial population that breakdown organic matter into ammonia.

Ammonia content was also found higher under sole cropping systems than other tree-based AFSs because this nitrogen fraction being described here is more closely linked to the application of fertilizers and manures rather than the organic matter input from litter fall. Dominguez *et al.* (2016) also observed that the concentration of this nitrogen fraction was lower in uncultivated soils compared to cultivated soils. These findings are in line with those of Bertiller *et al.* (2006), who discovered that continuous cropping with a different tillage strategy had a significant impact on the dynamic of soil organic N. The application of an organic nutrient source affected the rate of N mineralization, which ultimately aids in the accumulation of NH_4^+ -N in the soil. AFSs can affect soil N cycling by altering abiotic and biotic factors as well as litter quality (Mendham *et al.*, 2004).

In conformity with the previous study (Chen *et al.*, 2005), ammonification and nitrification rates generally decreased with increasing soil depth in our study. With the increase in soil profile depth, it decreased from 6.02 mg kg^{-1} to 3.09 mg kg^{-1} which was almost half in D_3 (40-60 cm) as compared to the top layer- D_1 (0-20 cm). Higher level of ammonical nitrogen pool at the surface level than at the sub-surface can be owed to continuous accretion of leaf-litter and its decomposition at the surface layer. Karki *et al.* (2021a) also reported a decrease in the mineral N-pool with increase in the soil depth. This shows that N-mineralization conditions become unfavourable in deep soil layers, which can be attributed to the declining soil N with increasing soil depth that adversely influenced N-mineralization. Pandey *et al.* (2000) also reported that under *Acacia nilotica* N pool sizes were the highest in the surface layer which declined with depth. Irrespective of land use systems, in soil depths, D_1 (0-20 cm), D_2 (20-40 cm) and D_3 (40-60cm) values maximum values were recorded in the natural forest (T_2) and minimum in silvipasture system (T_{10}) and in bamboo-based agroforestry system (T_7). Treatment combination T_2D_1 (9.08 mg kg^{-1}) shows maximum ammonical nitrogen while T_7D_3 (0.18 mg kg^{-1}) shows minimum value.

Table 13: Effect of agroforestry system, soil depth and their interaction on Ammonical Nitrogen (mg kg^{-1})

Agroforestry system (T)	Soil depth (D)			Mean
	D ₁	D ₂	D ₃	
T ₁ - Sole cropping	6.88 ^c	5.58 ^{fg}	5.25 ^{gh}	5.91 ^b
T ₂ - Natural Forest	9.08 ^a	6.22 ^{de}	5.48 ^{fg}	6.93 ^a
T ₃ - Agri-silvi-horticulture system	6.67 ^{cd}	4.45 ^{ij}	3.26 ^{lm}	4.80 ^e
T ₄ - Agrisilviculture	5.16 ^{gh}	3.39 ^l	1.83 ^o	3.46 ^h
T ₅ -Fruit based agroforestry system	7.54 ^b	5.34 ^g	3.48 ^{kl}	5.46 ^c
T ₆ - Fodder tree based agroforestry system	6.01 ^{ef}	4.35 ^{ij}	3.35 ^l	4.57 ^f
T ₇ - Bamboo based agroforestry system	4.70 ^{hi}	2.66 ^{mn}	0.18 ^q	2.51 ⁱ
T ₈ - Melia based agroforestry system	6.44 ^{cde}	4.96 ^{ghi}	3.69 ^{kl}	5.03 ^d
T ₉ - Poplar based agroforestry system	5.30 ^{gh}	4.04 ^{jk}	3.39 ^l	4.25 ^g
T ₁₀ - Silvipasture system	2.56 ⁿ	1.51 ^{op}	1.03 ^p	1.70 ^j
Mean	6.02 ^a	4.25 ^b	3.09 ^c	
Factors	SE(d)	CD at 5%		
Soil Depth (D)	0.069	0.101		
AFS (T)	0.179	0.184		
Interaction (T×D)	0.311	0.319		

Significant difference exists between the mean values in the same row that are denoted by a distinct letter (^{a, b, c, ...})

4.3.2 Nitrate nitrogen (mg kg^{-1})

Trend obtained in nitrate nitrogen (Table 14) is: natural forest (T₂) > fruit-based agroforestry system (T₅) > Bamboo based agroforestry system (T₇) > melia based agroforestry system (T₈) > agri-sivli-horticulture based system (T₃) > fodder-based agroforestry system (T₆) > poplar-based agroforestry system (T₉) > agrisilviculture system (T₄) > silvipasture system (T₁₀) > sole cropping (T₁). Value among AFSs ranged from 0.86 mg kg^{-1} to 4.34 mg kg^{-1} . Maximum nitrate nitrogen in natural forest (T₂) i.e., 4.34 mg kg^{-1} can be attributed to the fact that the quantity and quality of the vegetation's litter has an impact on N-mineralization (Bargali *et al.*, 1993, 2015). Indeed, vegetation cover and related factors have a significant impact on soil nitrogen content, organic matter quality, microbial activity, and subsequently, the rate of nitrogen mineralization. The type, density, and diversity of plant species comprising the vegetation cover play a crucial role in determining the amount and quality of organic matter returned to the soil. Different plant species have varying

nutrient requirements and produce varying amounts and types of organic residues through litter fall and root exudation and that's why there was a significant difference in nitrate nitrogen of all studied systems. Our findings are also supported by Singh and Kashyap (2007).

Variation among different depths of soil profile was also significantly different i.e., 3.52 mg kg⁻¹, 2.75 mg kg⁻¹ and 1.88 mg kg⁻¹ in D₁(0-20cm), D₂(20-40cm), D₃(40-60cm), respectively and there was sharp fall in nitrate nitrogen with soil depth i.e., ~50% from D₁ to D₃. Our results are also supported by Hussain *et al.* (2016) and Guo *et al.* (2020) who reported the same trend of nitrate nitrogen with an increase in depth.

Table 14: Effect of agroforestry system, soil depth and their interaction Nitrate Nitrogen (mg kg⁻¹)

Agroforestry system (T)	Soil depth (D)			Mean
	D ₁	D ₂	D ₃	
T ₁ - Sole cropping	1.02 ^{opq}	0.83 ^{pq}	0.73 ^q	0.86 ^l
T ₂ - Natural Forest	5.11 ^b	4.05 ^{cde}	3.84 ^{defg}	4.34 ^a
T ₃ - Agri-silvi-horticulture system	3.03 ^{hi}	2.80 ^{hijk}	2.59 ^{ijkl}	2.81 ^e
T ₄ - Agrisilviculture	2.88 ^{hij}	2.00 ^{lm}	1.13 ^{nopq}	2.01 ^h
T ₅ -Fruit based agroforestry system	4.51 ^{bcd}	3.88 ^{def}	3.26 ^{fghi}	3.89 ^b
T ₆ - Fodder tree based agroforestry system	3.42 ^{efgh}	2.20 ^{klm}	1.94 ^{lm}	2.52 ^f
T ₇ - Bamboo based agroforestry system	6.30 ^a	4.72 ^{bc}	3.10 ^{efgh}	3.74 ^c
T ₈ -Melia based agroforestry system	3.80 ^{defg}	3.49 ^{efgh}	2.12 ^{klm}	3.14 ^d
T ₉ -Poplar based agroforestry system	3.15 ^{ghi}	1.84 ^{mn}	1.60 ^{mno}	2.20 ^g
T ₁₀ - Silvipasture system	1.86 ^{lm}	1.72 ^{mno}	1.54 ^{mnop}	1.71 ⁱ
Mean	3.52 ^a	2.75 ^b	1.88 ^c	
Factors	SE(d)	CD at 5%		
Soil Depth (D)	0.115	0.080		
AFS (T)	0.209	0.147		
Interaction (T×D)	0.363	0.254		

Significant difference exists between the mean values in the same row that are denoted by a distinct letter (^{a, b, c, ...})

In D₁(0-20cm) and D₂(20-40cm) natural forest (T₁) showed the greatest value (6.30 mg kg⁻¹ and 4.72 mg kg⁻¹ respectively) while in D₃(40-60cm), Bamboo based agroforestry system (T₇) obtained higher value i.e., 3.84 mg kg⁻¹ in contrast to natural

forest (T₂) (0.10 mg kg⁻¹). High level of nitrate nitrogen at D₃ can be ascribed detritus pool continuously added at deeper soil layer and its decomposition.

The ammonification rate was higher than the nitrification rate in all AFSs. Similar findings in northeast India's *Areca catechu*-based agroforestry system and Indian subtropical humid forests were reported by Tanjang *et al.* (2010) and Das *et al.* (1997), respectively. Maintaining N loss through leaching would benefit from lower rates of nitrification than ammonification (Das *et al.*, 1997). Treatment combination T₇D₁ (6.30 mg kg⁻¹) shows maximum while T₁D₃ (0.73 mg kg⁻¹) shows minimum nitrate nitrogen.

4.3.3 Total nitrogen (%)

Total nitrogen content among AFSs varied from 0.26 % to 0.06 %. The content of Total nitrogen did not register large variation among AFSs. Maximum value obtained in natural forest (T₂) (0.26 %) followed by bamboo based agroforestry system (T₇) (0.15 %); while minimum (0.06 %) value was obtained in sole cropping (T₁) i.e., which is statistically at par with fruit based AFS. The level of Total nitrogen is a function of inputs of organic matter, rate of decomposition, cultural practices, leaching and gaseous losses as well as runoff and erosion, etc (Palm *et al.*, 1996; Paul and Clark, 1996). Due to a larger return of litter in the soil, tree-based agroforestry systems were shown to have a higher content of total nitrogen than agriculture land use systems. Similar results were founded by Liding *et al.* (2010) who reported higher content of total nitrogen in orchards than in sole crops.

Total nitrogen followed the same trend as ammonical and nitrate nitrogen that it decreases with depth. However, the decrease within the soil profile layer was ~ 50%. In comparison to all land uses, the total N content decreased by every metre of soil depth and these results are in consonance with the study of Bashir *et al.* (2022) who also reported the same trend of decline in the value of total nitrogen in depth. A declining trend of total nitrogen with increasing soil depths was also reported by Tiwari *et al.* (2013). In a tropical moist forest in eastern Nepal, Gautam and Mandal (2013) also reported a declining trend of SOC and nitrogen with deeper soil layers. Song *et al.* (2016) also reported that the total nitrogen decreased with depth, and the greatest concentration was in the topsoil in selected forests of China. Mao and Zeng (2010) found that total N and potentially mineralizable N rates decreased initially following afforestation and then

increased with stand development suggesting increased mineralization in higher-age plantations that would provide more nutrients to plants making poplar based agroforestry a viable option for production as well as maintaining soil fertility and productivity and this was the reason that total nitrogen in silvipasture system (T₁₀) (0.12%) was more than some of tree-based agroforestry system. In each layer of soil profile maximum value was obtained in natural forest (T₂) and minimum in sole cropping (T₁).

Table 15: Effect of agroforestry system, soil depth and their interaction Total Nitrogen (%)

Agroforestry system (T)	Soil depth (D)			Mean
	D ₁	D ₂	D ₃	
T ₁ - Sole cropping	0.06 ^{mn}	0.06 ^{no}	0.04 ^p	0.06 ^h
T ₂ - Natural Forest	0.27 ^a	0.26 ^a	0.24 ^b	0.26 ^a
T ₃ -Agri-silvi- horticulture system	0.09 ^{jk}	0.07 ^{lm}	0.05 ^o	0.08 ^g
T ₄ - Agrisilviculture	0.09 ^k	0.07 ^{lm}	0.05 ^o	0.08 ^g
T ₅ -Fruit based agroforestry system	0.07 ^{lm}	0.06 ^{no}	0.03 ^p	0.06 ^h
T ₆ - Fodder tree based agroforestry system	0.11 ^{gh}	0.08 ^l	0.06 ^{mn}	0.09 ^f
T ₇ - Bamboo based agroforestry system	0.17 ^c	0.14 ^d	0.13 ^{ef}	0.15 ^b
T ₈ - Melia based agroforestry system	0.17 ^c	0.12 ^{fg}	0.10 ^{hij}	0.13 ^c
T ₉ - Poplar based agroforestry system	0.13 ^{de}	0.11 ^{hi}	0.081 ^l	0.11 ^e
T ₁₀ - Silvipasture system	0.13 ^{de}	0.11 ^{hi}	0.10 ^{ij}	0.12 ^d
Mean	0.13 ^a	0.11 ^b	0.09 ^c	
Factors	SE(d)	CD at 5%		
Soil Depth (D)	0.002	0.003		
AFS (T)	0.003	0.006		
Interaction (T×D)	0.005	0.010		

Significant difference exists between the mean values in the same row that are denoted by a distinct letter (^{a, b, c, ...})

It is also observed in Table 15 that total nitrogen was significantly affected by soil depth. Trees in agroforestry systems may help to maintain soil N pools and consequently increase the availability of N (Zaia *et al.* 2012; Rathore *et al.*, 2013 and Bargali *et al.*, 2019). The lowermost layer displayed the lowest total nitrogen content, which ranged

from 0.03 to 0.24 %. Interaction effects shows greater value in T₂D₁ (0.27%) and lower in T₅D₃ (0.03%).

4.3.4 Total nitrogen density (Mg ha⁻¹)

As indicated in Table 16 natural forest (T₂) shows a higher value of total nitrogen density followed by bamboo-based agroforestry system (T₇). Higher value of total nitrogen density was obtained in natural forest and bamboo-based agroforestry system was 4.93 Mg ha⁻¹ and 3.56 Mg ha⁻¹ respectively. Total nitrogen density has also been reported to be correlated with polyphenols (Seneviratne *et al.*, 2009) which are the compounds affecting the stability of carbon.

Table 16: Effect of agroforestry system, soil depth and their interaction Total Nitrogen Density (Mg ha⁻¹)

Agroforestry system (T)	Soil depth (D)			Mean
	D ₁	D ₂	D ₃	
T ₁ - Sole cropping	1.64 ^{kl}	1.492 ^{kl}	1.17 ^{mn}	1.44 ^f
T ₂ - Natural Forest	4.93 ^a	5.04 ^a	4.80 ^a	4.93 ^a
T ₃ - Agri-silvi-horticulture system	2.44 ^{gh}	1.78 ^{ijk}	1.49 ^{kl}	1.91 ^e
T ₄ - Agrisilviculture	2.32 ^h	1.77 ^{ijke}	1.38 ^{lm}	1.83 ^e
T ₅ - Fruit based agroforestry system	1.90 ^j	1.39 ^{lm}	0.98 ⁿ	1.43 ^f
T ₆ - Fodder tree based agroforestry system	2.26 ^h	1.84 ^{ij}	1.66 ^{kl}	1.93 ^e
T ₇ - Bamboo based agroforestry system	3.98 ^b	3.48 ^c	3.21 ^{cde}	3.56 ^b
T ₈ - Melia based agroforestry system	3.37 ^{cd}	2.94 ^{ef}	2.67 ^{fg}	3.00 ^c
T ₉ - Poplar based agroforestry system	3.13 ^{de}	3.05 ^e	1.97 ⁱ	2.72 ^d
T ₁₀ - Silvipasture system	3.36 ^{cd}	2.73 ^f	2.68 ^{fg}	2.93 ^c
Mean	2.93 ^a	2.55 ^b	2.20 ^c	
Factors	SE(d)	CD at 5%		
Soil Depth (D)	0.045	0.091		
AFS (T)	0.083	0.166		
Interaction (T×D)	0.144	0.287		

Significant difference exists between the mean values in the same row that are denoted by a distinct letter (a, b, c, ...)

The data on less labile and recalcitrant carbon support this fact and it might have resulted in increased total N content. The accumulation of organic constituents and their decomposition increased nitrogen accumulation under tree biomass in comparison to systems without trees.

Results reported that there were significant differences along the depth and values ranged from 2.93 Mg ha⁻¹ to 2.20 Mg ha⁻¹. Similar results were also obtained by Singh *et al.* (2021). The availability of total nitrogen density may be increased by trees in AFSs by maintaining soil N pools by continuous addition of organic matter that also promotes the microbial population further leading to a high value of total nitrogen density (Zaia *et al.* (2012), Rathore *et al.* (2013) and Bargali *et al.* (2019). Higher and lower value obtained in all three depths of soil in natural forest (T₂) and sole cropping (T₁), respectively. Moreover high value of total nitrogen density found in treatment combination T₂D₃ (4.80 Mg ha⁻¹) while minimum in T₁D₃ (1.17 Mg ha⁻¹).

4.4 Soil carbon stored in different soil particle size fraction

To better understand the connection between the stability and decomposition of the soil organic matter and its location and state, soil organic carbon collected through soil particle-size grouping is a helpful starting point. Carbon stored in different soil particle size fractions has been recorded and given here below:

4.4.1 Soil size fraction (%) of particle size 250-2000µm

Data in Table 17 demonstrate that sole cropping (T₁) (58.06%) had a higher percentage of 250-2000µm particle size and a lower percentage (49.96%) was observed in natural forest (T₂). This fraction of soil size was more abundant as compared to other particle sizes. These findings are in consonance with the observations of Gama Rodrigue *et al.* (2010). Variation within soil profile is not very profound and as values differed by 2.88% only. Similarly, Munny *et al.* (2021), Mandal and Sharad (2013), Arevalo *et al.* (2009) and Walker and Desanker. (2004) also recorded very less variation among different soil profiles in their respective studies. Difference in 250-2000µm particle size fraction within each depth layer was not significant yet a higher value was obtained at all depths in sole cropping (T₁) and lowest in the natural forest (T₂) ecosystem. Interaction effect signifies that T₁D₁ (59.37%) shows maximum 250-2000µm particles soil size fraction and minimum in T₂D₃ (49.41%).

Table 17: Variation of soil size fraction (%) of particle size 250-2000 μ m in agroforestry system, and within soil depth

Agroforestry system (T)	Soil depth (D)			Mean
	D ₁	D ₂	D ₃	
T ₁ - Sole cropping	59.37 ^a	58.48 ^{ab}	56.32 ^{bcdefg}	58.06 ^a
T ₂ - Natural Forest	53.24 ^{ijkl}	49.24 ^{no}	47.41 ^o	49.96 ^c
T ₃ - Agri-silvi-horticulture system	57.12 ^{abcd}	56.64 ^{bcde}	56.17 ^{bcdefg} _h	56.64 ^{ab}
T ₄ - Agrisilviculture	56.50 ^{bcdef}	56.18 ^{bcdefgh}	53.90 ^{ghijk}	55.53 ^b
T ₅ - Fruit based agroforestry system	54.10 ^{fghijk}	53.37 ^{ijkl}	52.28 ^{klm}	53.25 ^{cd}
T ₆ - Fodder tree based agroforestry system	54.89 ^{drfghi}	54.01 ^{ghijk}	52.96 ^{ijklm}	53.95 ^c
T ₇ - Bamboo based agroforestry system	53.47 ^{ijkl}	52.88 ^{ijklm}	51.10 ^{lmn}	52.48 ^d
T ₈ - Melia based agroforestry system	54.01 ^{ghijk}	53.84 ^{hijk}	50.51 ^{mn}	52.79 ^{cd}
T ₉ - Poplar based agroforestry system	54.38 ^{efghijk}	53.91 ^{ghijk}	49.76 ^{no}	52.68 ^{cd}
T ₁₀ - Silvipasture system	58.11 ^{abc}	57.73 ^{abc}	55.93 ^{cdefgh} _i	57.26 ^a
Mean	55.51 ^a	54.62 ^b	52.63 ^c	
Factors	SE(d)	CD at 5%		
Soil Depth (D)	0.391	0.782		
AFS (T)	0.713	1.428		
Interaction (T×D)	1.236	2.474		

Significant difference exists between the mean values in the same row that are denoted by a distinct letter (^{a, b, c, ...})

4.4.2 Soil size fraction (%) of particle size 53-250 μ m

The distribution of 53-250 μ m particle size among different land use systems and the depths is given in Table 18. It is clear from the table that all tree-based system had more 53-250 μ m particle size fraction as compared to the sole cropping (T₁) having a value of 24.63%. In land-use systems with no tillage, the absence of mechanical disturbance through tillage practices promotes a slow turnover of 250-2000 μ m soil size particles. This slower turnover rate allows for the accumulation and formation of fine occluded particulate organic matter. Over time, these organic particles become encrusted with microbial products, leading to the formation of particles of size 53-250 μ m and this is the reason that 250-2000 μ m soil size particles are more in all tree-based agroforestry systems. These findings are in line with the observation of John *et al.* (2005). With increasing depth, it was observed that percentage

fraction of 53-250 μ m particle size also increased from 26.69% to 28.85%. In D₁(0-20cm), poplar-based agroforestry system (T₉) and fruit-based agroforestry system (T₅) showed higher value and both are statistically at par. In D₂(20-40cm) and D₃(40-60cm), natural forest (T₂) and poplar-based agroforestry systems (T₉) showed higher values, while minimum value of percentage fraction was observed in sole cropping (T₁) at all three layer i.e., 23.30%, 24.60%, 25.91% in D₁(0-20cm), D₂(20-40cm) and D₃(40-60cm), respectively. Treatment combination T₂D₃ (31.20%) have greater value while T₁D₁ (23.30%) have minimum value.

Table 18: Variation of soil size fraction (%) of particle size 53-250 μ m in agroforestry system, and within soil depth

Agroforestry system (T)	Soil depth (D)			Mean
	D ₁	D ₂	D ₃	
T ₁ - Sole cropping	23.30 ^l	24.60 ^k	25.91 ^{ijk}	24.63 ^f
T ₂ - Natural Forest	26.85 ^{hi}	30.96 ^{ab}	31.20 ^a	29.67 ^{abc}
T ₃ - Agri-silvi-horticulture system	25.84 ^{ijk}	26.35 ^{hi}	26.52 ^{hi}	26.24 ^e
T ₄ - Agrisilviculture	24.71 ^k	26.10 ^{hij}	26.77 ^{hi}	25.86 ^e
T ₅ - Fruit based agroforestry system	28.79 ^{def}	29.72 ^{cde}	29.88 ^{bcde}	29.46 ^{bc}
T ₆ - Fodder tree based agroforestry system	27.28 ^{gh}	28.85 ^{def}	28.96 ^{cdef}	28.36 ^d
T ₇ - Bamboo based agroforestry system	28.16 ^{fg}	29.11 ^{cdef}	30.02 ^{abcd}	29.10 ^c
T ₈ - Melia based agroforestry system	28.18 ^{fg}	30.14 ^{abc}	31.11 ^{ab}	29.81 ^{ab}
T ₉ - Poplar based agroforestry system	28.78 ^{ef}	30.98 ^{ab}	31.16 ^a	30.31 ^a
T ₁₀ -Silvipasture system	25.01 ^{jk}	26.26 ^{hi}	26.98 ^{ghi}	26.08 ^e
Mean	26.69 ^c	28.31 ^b	28.85 ^a	
Factors	SE(d)	CD at 5%		
Soil Depth (D)	0.195	0.389		
AFS (T)	0.355	0.711		
Interaction (T×D)	0.615	1.232		

Significant difference exists between the mean values in the same row that are denoted by a distinct letter (^{a, b, c, ...})

4.4.3 Soil size fraction (%) of particle size <53 μ m

Data depicted in the Table 19 that the fraction of silt and clay is maximum (20.37%) in natural forest (T₂) and the minimum (16.66%) in silvipasture system. It may be attributed release

of root exudates and acidic substances that break larger particles into smaller ones. Further, microorganisms associated with the roots are also responsible for this.

The percentage of silt and clay increased with an increase in soil depth and values were in the descending order of 17.79% in D₁(0-20cm), 17.05% in D₂(20-40cm) and 18.51% in D₃(40-60cm), respectively. Datta *et al.* (2015) opined that the transfer of finer particles from the surface layers and subsequent illuviation in sub-surface horizons may be the cause of the higher finer particle (silt plus clay) content in the lower soil layer. No significant differences were observed in the percentage fraction among different layers. Further, analysis of interaction shows that T₂D₃ (21.39%) have maximum percentage of silt and clay particle while minimum in T₉D₂ (15.11%).

Table19: Variation of soil size fraction (%) of particle size <53 µm in agroforestry system, and within soil depth

Agroforestry system (T)	Soil depth (D)			Mean
	D ₁	D ₂	D ₃	
T ₁ - Sole cropping	17.33 ^{hijklm}	16.84 ^m	17.77 ^{ghijk}	17.31 ^{cd}
T ₂ - Natural Forest	19.91 ^b	19.80 ^{bc}	21.39 ^a	20.37 ^a
T ₃ - Agri-silvi-horticulture system	17.04 ^{klm}	17.01 ^{lm}	17.31 ^{ijklm}	17.12 ^d
T ₄ - Agrisilviculture	18.79 ^{def}	17.72 ^{ghijkl}	19.33 ^{bcd}	18.61 ^b
T ₅ - Fruit based agroforestry system	17.11 ^{jklm}	16.91 ^m	17.84 ^{ghij}	17.29 ^{cd}
T ₆ - Fodder tree based agroforestry system	17.83 ^{ghij}	17.14 ^{ghij}	18.08 ^{jklm}	17.68 ^c
T ₇ - Bamboo based agroforestry system	18.37 ^{efg}	18.01 ^{ghi}	18.88 ^{de}	18.42 ^b
T ₈ - Melia based agroforestry system	17.81 ^{ghij}	16.02 ⁿ	18.38 ^{efg}	17.40 ^{cd}
T ₉ - Poplar based agroforestry system	16.84 ^m	15.11 ^o	19.08 ^{cde}	17.01 ^{de}
T ₁₀ - Silvipasture system	16.88 ^m	16.01 ⁿ	17.09 ^{jklm}	16.66 ^e
Mean	17.79 ^b	17.05 ^c	18.51 ^a	
Factors	SE(d)	CD at 5%		
Soil Depth (D)	0.119	0.238		
AFS (T)	0.217	0.434		
Interaction (T×D)	0.376	0.752		

Significant difference exists between the mean values in the same row that are denoted by a distinct letter (^{a, b, c, ...})

4.4.4 Soil organic carbon (mg g⁻¹) of particle size 250-2000µm

The data for soil organic carbon of particle size 250-2000µm is presented in Table 20. It reveals that natural forest (T₂) stored 4.65 mg g⁻¹ which was followed by bamboo

based AFS (T₇), while the minimum was in fruit based agroforestry system (T₅) i.e., 2.30 mg g⁻¹. Soil C concentration maximum in the 250-2000µm size fraction under natural forests (T₂) may be due to continuous accretion of subsurface biomass through root exudation, litterfall, and plant residue addition (Zhang *et al.*, 2014). SOC concentration in the coarse fraction was also high in the bamboo-based agroforestry system (T₇) (3.50 mg g⁻¹) compared to the other tree-based AFSs, which can be owed to annual addition of leaf-litter, twigs and root exudates in bulk. These results are aligned with the study of Shang *et al.* (2014). Amelung *et al.* (1998) concluded that the higher the sand concentrations, the more the dilution of the SOC concentrations will take place. This pool is susceptible to changes in the dynamics of organic matter as it comprises recently deposited carbon in the soil (Carter 1996).

Table 20: Effect of agroforestry system, soil depth and their interaction on soil organic carbon (mg g⁻¹) of particle size 250-2000µm

Agroforestry system (T)	Soil depth (D)			Mean
	D ₁	D ₂	D ₃	
T ₁ - Sole cropping	5.41 ^b	3.58 ^h	1.35 ^q	3.45 ^b
T ₂ - Natural Forest	6.46 ^a	4.31 ^e	3.18 ^j	4.65 ^a
T ₃ - Agri-silvi-horticulture system	2.77 ^l	2.73 ^l	1.90 ^o	2.47 ^f
T ₄ - Agrisilviculture	3.81 ^{fg}	2.29 ^{mn}	1.59 ^p	2.57 ^e
T ₅ – Fruit based agroforestry system	3.37 ⁱ	2.44 ^m	1.09 ^r	2.30 ^g
T ₆ - Fodder tree based agroforestry system	3.92 ^{fg}	2.86 ^l	0.93 ^s	2.58 ^e
T ₇ - Bamboo based agroforestry system	5.32 ^{bc}	3.35 ⁱ	1.82 ^o	3.50 ^b
T ₈ - Melia based agroforestry system	5.21 ^c	3.93 ^f	0.77 ^t	3.31 ^c
T ₉ - Poplar based agroforestry system	3.77 ^g	3.03 ^k	1.58 ^p	2.80 ^d
T ₁₀ - Silvipasture system	4.60 ^d	2.28 ⁿ	0.73 ^t	2.54 ^{ef}
Mean	4.46 ^a	3.08 ^b	1.50 ^c	
Factors	SE(d)	CD at 5%		
Soil Depth (D)	0.023	0.047		
AFS (T)	0.043	0.086		
Interaction (T×D)	0.074	0.149		

Significant difference exists between the mean values in the same row that are denoted by a distinct letter (a, b, c, ...)

A sharp decline of organic carbon stored in particle size 250-2000 μm was observed within the soil profile and its value remained only $\sim 33\%$ as compared to the topmost layer of soil i.e., 4.46 mg g^{-1} in $D_1(0-20\text{cm})$, 3.08 mg g^{-1} in $D_2(20-40\text{cm})$ while only 1.50 mg g^{-1} in $D_3(40-60\text{cm})$, which is in conformity with the finding of Saha *et al.* (2010).

In each depth carbon stored in particle size 250-2000 μm was higher in natural forest (T_2), while the lowest value of stored carbon varied with the system in each depth. In $D_1(0-20\text{cm})$, agri-silvi-horticulture system (T_3) displayed minimum value i.e., 2.77 mg g^{-1} while silvipasture system (T_{10}) stored minimum stored carbon value (2.28 mg g^{-1} and 0.73 mg g^{-1}) in both $D_2(20-40\text{cm})$ and $D_3(40-60\text{cm})$ layer of soil, respectively. In general, in the restored soil types, the organic carbon that can be bound by the soil particle size 250-2000 μm was greater than that of the particles size 53-250 μm . Maximum carbon stored in particles size 53-250 μm reported in T_2D_1 (6.46 mg g^{-1}) and minimum in $T_{10}D_3$ (0.73 mg g^{-1}).

4.4.5 Soil organic carbon (mg g^{-1}) of particle size 53-250 μm

Carbon stored in 53-250 μm soil size fraction is demonstrated in Table 21. A higher value (4.24 mg g^{-1}) was found in natural forest (T_2) and lower in sole cropping (2.13 mg g^{-1}). It may be due to the impact of regular deposition of high organic matter and microbial decomposition in natural forest (T_2) ecosystems. 53-250 μm soil size fraction have a relatively passive SOC pool that is better protected. Saha *et al.* (2010) also gives similar outcomes and concluded that due to significant biochemical interaction. The difference obtained in stored carbon in 53-250 μm soil size fraction was significant and it decreased from 4.39 mg g^{-1} in $D_1(0-20\text{cm})$ to 1.43 mg g^{-1} in D_3 (40-60cm). These studies are aligned with the results of Haile *et al.* (2008) who also observed the same trend.

Among all the studied AFSs in relation with each depth found greater carbon storage in forest in all studied i.e., 5.80 mg g^{-1} in $D_1(0-20\text{cm})$, 3.90 mg g^{-1} in $D_2(20-40\text{cm})$ and 3.01 mg g^{-1} in $D_3(40-60\text{cm})$. Lower value found in sole cropping (T_1) (2.51 mg g^{-1}) in $D_1(0-20\text{cm})$ and while silvipasture system (T_{10}) showed lower value (1.58 mg g^{-1} , 1.02 mg g^{-1} in D_2 (20-40cm), D_3 (40-60cm) respectively). Moreover, T_2D_1 have greater value i.e., 5.80 mg g^{-1} while $T_{10}D_3$ have lower value i.e., 1.02 mg g^{-1} .

Table 21: Effect of agroforestry system, soil depth and their interaction on soil organic carbon (mg g^{-1}) of particle size 53-250 μm

Agroforestry system (T)	Soil depth (D)			Mean
	D ₁	D ₂	D ₃	
T ₁ - Sole cropping	2.51 ¹	2.32 ^j	1.54 ^{lm}	2.13 ^g
T ₂ - Natural Forest	5.80 ^a	3.90 ^t	3.01 ^g	4.24 ^a
T ₃ -Agri-silvi-horticulture system	4.49 ^c	1.43 ^{mn}	1.18 ^{pq}	2.37 ^e
T ₄ - Agrisilviculture	4.22 ^{de}	1.39 ^{no}	1.28 ^{op}	2.30 ^{ef}
T ₅ -Fruitbased agroforestry system	4.17 ^e	2.64 ^h	1.58 ^l	2.80 ^c
T ₆ -Fodder tree-based agroforestry system	4.32 ^d	2.27 ^j	1.29 ^{op}	2.63 ^d
T ₇ - Bamboo basedagroforestry system	4.22 ^{de}	2.53 ^{hi}	1.06 ^r	2.61 ^d
T ₈ -Melia based agroforestry system	5.19 ^b	2.29 ^j	1.12 ^{qr}	2.87 ^b
T ₉ - Poplar based agroforestry system	3.82 ^t	1.96 ^k	1.28 ^{op}	2.36 ^e
T ₁₀ - Silvipasture system	4.22 ^{de}	1.58 ^l	1.02 ^r	2.28 ^t
Mean	4.30 ^a	2.23 ^b	1.43 ^c	
Factors	SE(d)	CD at 5%		
Soil Depth (D)	0.019	0.039		
AFS (T)	0.035	0.071		
Interaction (T×D)	0.061	0.123		

Significant difference exists between the mean values in the same row that are denoted by a distinct letter (^{a, b, c, ...})

4.4.6 Soil organic carbon (mg g^{-1}) of particle size <53 μm

Soil organic carbon in silt plus clay (<53 μm) is depicted in Table 22. Natural forest (T₂) reported maximum value, while silvipasture system (T₁₀) (7.73 mg g^{-1}) and bamboo based agroforestry system (T₇) (7.71 mg g^{-1}) were statistically alike. This can be owed to their extensive root system, which increases soil aeration, microbial decomposition and leads to release of carbon. Yan *et al.* (2022) suggested that clay particles in forests or less disturbed soil are able to provide good physical protection for the soil organic matter and thus higher organic carbon in this soil size fraction. Christensen (1992) also deduced that the clay fraction binds the mobile and labile fractions of C, resulting in the creation of passive SOC pools with slow down turnover times and thus making tree-based land use system more sustainable and environment friendly. Further, workers, like Jenkinson (1977), Spain (1990), Schimel (1994), and Bird *et al.* (2000) also opined that clay and organic molecules combine to create organo-mineral complexes, which reduce the accessibility of the organic matter to

decomposers. Hassink *et al.* (1997) also reported that silt and clay have more ability to store more carbon as compared to other fraction sizes.

Soil organic carbon shows a positive correlation with depth and it also increased with an increase in the depth of the soil profile. Organic carbon recorded in D₁, D₂ and D₃ were 5.01 mg g⁻¹, 6.60 mg g⁻¹ and 8.80 mg g⁻¹. Similarly, Saroa and Lal. (2003), Tiessen and Stewart (1983), Anderson and Paul (1984) and Christensen and Sorensen (1986) observed the ability of this size fraction to get stored in deeper layer. The variation observed within each soil depth was significantly different. Further, interaction study depicts that T₁₀D₃ (9.82 mg g⁻¹) shows higher value and T₁D₁ (3.44 mg g⁻¹) shows lower value.

Table 22: Effect of agroforestry system, soil depth and their interaction on soil organic carbon (mg g⁻¹) of particle size <53 µm

Agroforestry system (T)	Soil depth (D)			Mean
	D ₁	D ₂	D ₃	
T ₁ - Sole cropping	3.44 ^q	3.90 ^p	6.31 ^j	4.55 ^h
T ₂ - Natural Forest	7.21 ^g	8.45 ^e	9.55 ^b	8.41 ^a
T ₃ - Agri-silvi-horticulture system	4.80 ⁿ	6.20 ^j	6.75 ^{hi}	5.92 ^f
T ₄ - Agrisilviculture	4.04 ^p	6.85 ^h	6.68 ^{hi}	5.86 ^f
T ₅ - Fruit based agroforestry system	3.62 ^q	5.18 ^m	6.62 ⁱ	5.15 ^g
T ₆ -Fodder tree based agroforestry system	4.59 ^o	5.86 ^k	8.00 ^f	6.16 ^e
T ₇ - Bamboo based agroforestry system	5.83 ^k	7.82 ^f	9.48 ^b	7.71 ^b
T ₈ -Melia based agroforestry system	5.26 ^m	6.64 ⁱ	8.92 ^c	6.95 ^d
T ₉ -Poplar based agroforestry system	5.81 ^k	7.24 ^g	8.67 ^d	7.24 ^c
T ₁₀ -Silvipasture system	5.51 ^l	7.85 ^f	9.82 ^a	7.73 ^b
Mean	5.01 ^c	6.60 ^b	8.08 ^a	
Factors	SE(d)	CD at 5%		
Soil Depth (D)	0.031	0.063		
AFS (T)	0.057	0.115		
Interaction (T×D)	0.099	0.199		

Significant difference exists between the mean values in the same row that are denoted by a distinct letter (a, b, c, ...)

4.4.7 Organic carbon (%)

Table.23 represents crops under different AFS on percent organic carbon (OC%) in soil. It is quite evident that natural forest (T₂) had higher OC% value 1.73% while all tree-

based agroforestry system showed more OC% as compared to sole cropping (T₁) (1.01%). Higher OC% in natural forest (T₂) may be attributed due to the significant annual addition of organic matter in the form of leaf litter, which stays in the soil due to the lack of disturbance, forest soil has a higher OC content. Results reported by Haynes (2005) also supported our study. He also concluded that the environment may experience low temperatures brought on by the high altitude, which could impede or stop the decomposition of residues, raising the carbon values (Haynes, 2005).

Table 23: Effect of agroforestry system, soil depth and their interaction on organic carbon (%)

Agroforestry system (T)	Soil depth (D)			Mean
	D ₁	D ₂	D ₃	
T ₁ - Sole cropping	1.13 ^{lm}	0.98 ^r	0.92 ^t	1.01 ^h
T ₂ - Natural Forest	1.94 ^a	1.66 ^b	1.57 ^c	1.73 ^a
T ₃ - Agri-silvi-horticulture system	1.20 ^j	1.03 ^{pq}	0.98 ^r	1.08 ^g
T ₄ - Agrisilviculture	1.20 ^j	1.05 ^p	0.95 ^s	1.07 ^g
T ₅ - Fruit based agroforestry system	1.11 ^{mn}	1.02 ^q	0.93 ^t	1.02 ^h
T ₆ - Fodder tree based agroforestry system	1.28 ^h	1.10 ^{no}	1.02 ^q	1.14 ^f
T ₇ - Bamboo based agroforestry system	1.53 ^d	1.37 ^f	1.23 ⁱ	1.38 ^b
T ₈ - Melia based agroforestry system	1.56 ^c	1.28 ^h	1.08 ^o	1.31 ^c
T ₉ - Poplar based agroforestry system	1.34 ^g	1.22 ^{ij}	1.15 ^{kl}	1.24 ^e
T ₁₀ -Silvipasture system	1.43 ^e	1.17 ^k	1.15 ^{kl}	1.26 ^d
Mean	1.37 ^a	1.19 ^b	1.10 ^c	
Factors	SE(d)	CD at 5%		
Soil Depth (D)	0.004	0.007		
AFS (T)	0.007	0.013		
Interaction (T×D)	0.012	0.023		

Significant difference exists between the mean values in the same row that are denoted by a distinct letter (^{a, b, c, ...})

OC% decreased with an increase in depth from 1.73% to 1.10% and it suggests that there was very less variation within the depth. A similar trend was also revealed by Jobbagy and Jackson (2000) and Wang *et al.* (2010). Analysis of AFS within each depth showed that not only in D₁(0-20cm) but at all depths OC% was higher in natural forest (T₂). Fruit based

system (T₅) showed lowest value in D₁(0-20cm) in contrast OC% in D₂(20-40cm) and D₃(40-60cm) reported in sole cropping (T₁) with value 0.92% and 0.98%. further, T₂D₁ (1.94%) have maximum OC% while minimum value obtained in T₁D₃ (0.92%).

4.4.8 Carbon density of 250-2000 µm soil size fraction (Mg ha⁻¹)

The carbon density in particles size 250-2000 µm was maximum in natural forest (T₂) (8.68 Mg ha⁻¹) and minimum in fodder tree-based agroforestry system (T₅) (5.53 Mg ha⁻¹) as indicated in Table 24. Observed value in D₁, D₂ and D₃ were 9.84 Mg ha⁻¹, 7.20 Mg ha⁻¹ and 3.62 Mg ha⁻¹ respectively. In D₁(0-20cm), sole cropping (T₁) (13.06 Mg ha⁻¹) had greater value followed by bamboo based agroforestry system (T₇) (12.14 Mg ha⁻¹) while lower value in agri-silvi-horticulture system (T₃) (6.80 Mg ha⁻¹).

Table 24: Effect of agroforestry system, soil depth and their interaction on carbon density of 250-2000µm soil size fraction (Mg ha⁻¹).

Agroforestry system (T)	Soil depth (D)			Mean
	D ₁	D ₂	D ₃	
T ₁ - Sole cropping	13.06 ^a	8.84 ^{fg}	3.68 ^o	8.53 ^a
T ₂ - Natural Forest	11.63 ^c	8.25 ^{hi}	6.14 ^l	8.68 ^a
T ₃ - Agri-silvi-horticulture system	6.80 ^k	6.65 ^k	5.18 ^m	6.21 ^e
T ₄ - Agrisilviculture	9.07 ^f	5.52 ^m	4.04 ^{no}	6.21 ^e
T ₅ - Fruit based agroforestry system	8.29 ^{hi}	5.45 ^m	2.84 ^p	5.53 ^f
T ₆ - Fodder tree based agroforestry system	7.49 ^j	6.49 ^{kl}	2.26 ^q	5.42 ^f
T ₇ - Bamboo based agroforestry system	12.14 ^b	7.85 ^{ij}	4.44 ⁿ	8.15 ^b
T ₈ -Melia based agroforestry system	10.34 ^e	9.24 ^f	1.90 ^q	7.16 ^c
T ₉ -Poplar based agroforestry system	8.52 ^{gh}	8.17 ^{hi}	3.86 ^o	6.85 ^d
T ₁₀ -Silvipasture system	11.11 ^d	5.52 ^m	1.83 ^q	6.16 ^e
Mean	9.84 ^a	7.20 ^b	3.62 ^c	
Factors	SE(d)	CD at 5%		
Soil Depth (D)	0.078	0.156		
AFS (T)	0.142	0.285		
Interaction (T×D)	0.246	0.494		

Significant difference exists between the mean values in the same row that are denoted by a distinct letter (^{a, b, c, ...})

In D₂(20-40cm), Melia based agroforestry system (T₈) (9.24 Mg ha⁻¹) and fruit based agroforestry system (T₅) (5.45 Mg ha⁻¹) reported maximum and minimum value, respectively. In D₃(40-60cm), natural forest (T₂) (6.14 Mg ha⁻¹) had more value as compared to all studied

systems and Melia-based system (T₈) had lowest (1.90 Mg ha⁻¹). Treatment combination T₁D₁ (13.06 Mg ha⁻¹) showed greater value of carbon density while T₁₀D₃ showed lower value which is statistically at par with T₈D₃ (1.90 Mg ha⁻¹).

4.4.9 Carbon density of 53-250µm soil size fraction (Mg ha⁻¹)

Table 25 indicated that tree-based system had more carbon density than sole cropping (T₁) and the difference between the maximum and minimum observed values was 2.58 Mg ha⁻¹. Natural forest (T₂) reported 7.91 Mg ha⁻¹ while sole cropping (T₁) reported 5.33 Mg ha⁻¹ which was higher and the lower value respectively. Nearly a variation of 63% was observed in the lower soil layer as compared to the top layer.

Table 25: Effect of agroforestry system, soil depth and their interaction on carbon density of 53-250µm soil size fraction (Mg ha⁻¹)

Agroforestry system (T)	Soil depth (D)			Mean
	D ₁	D ₂	D ₃	
T ₁ - Sole cropping	6.06 ^g	5.73 ^{gh}	4.19 ^j	5.33 ^f
T ₂ - Natural Forest	10.45 ^b	7.46 ^t	5.81 ^g	7.91 ^a
T ₃ - Agri-silvi-horticulture system	11.04 ^a	3.48 ^{kl}	3.22 ^l	5.92 ^{cd}
T ₄ - Agrisilviculture	10.04 ^{cd}	3.36 ^l	3.24 ^l	5.55 ^{ef}
T ₅ - Fruit based agroforestry system	10.27 ^{bc}	5.89 ^g	4.13 ^j	6.77 ^b
T ₆ - Fodder tree based agroforestry system	8.26 ^e	5.15 ⁱ	3.13 ^{lm}	5.52 ^{ef}
T ₇ - Bamboo based agroforestry system	9.64 ^d	5.93 ^g	2.58 ⁿ	6.05 ^c
T ₈ -Melia based agroforestry system	10.28 ^g	5.38 ^{hi}	2.76 ^{mn}	6.15 ^c
T ₉ -Poplar based agroforestry system	8.63 ^{bc}	5.30 ⁱ	3.11 ^{lm}	5.69 ^{de}
T ₁₀ - Silviculture system	10.20 ^c	3.83 ^{jk}	2.53 ⁿ	5.53 ^{ef}
Mean	9.49 ^a	5.15 ^b	3.47 ^c	
Factors	SE(d)	CD at 5%		
Soil Depth (D)	0.065	0.130		
AFS (T)	0.118	0.237		
Interaction (T×D)	0.205	0.410		

Significant difference exists between the mean values in the same row that are denoted by a distinct letter (^{a, b, c, ...})

In D₁(0-20cm) agrisilvihorticulture system (T₃) showed higher value (11.04 Mg ha⁻¹) while in D₂(20-40cm) and D₃(40-60cm) natural forest (T₂) showed maximum effect in carbon density (7.46 Mg ha⁻¹ and 5.81 Mg ha⁻¹ respectively). Minimum value reported in D₁(0-20cm) was in sole cropping (T₁) (6.06 Mg ha⁻¹) and in D₂ and D₃ silviculture system (T₁₀)

had lowest value i.e., 3.83 Mg ha⁻¹, 2.53 Mg ha⁻¹. Further, T₃D₁ have maximum carbon density of microaggregate particles i.e., 11.04 Mg ha⁻¹ while lower in T₁₀D₃ (2.53 Mg ha⁻¹).

4.4.10 Carbon density of <53µm soil size fraction (Mg ha⁻¹)

Table 26 reveals that carbon density of <53µm soil size fraction was greater in silvipasture system (T₁₀) (18.88 Mg ha⁻¹) followed by poplar-based agroforestry system (T₉) (17.91 Mg ha⁻¹). Lower value observed in sole cropping i.e. (T₁) (11.70 Mg ha⁻¹). It increased with an increase in soil profile from a value of 11.05 Mg ha⁻¹ to 19.80 Mg ha⁻¹. In each depth, the carbon density of silt and clay was reported higher in tree-based land use system than sole cropping (T₁). Table 26 also indicated that T₁₀D₃ (24.36 Mg ha⁻¹) shows higher value while lower in T₁D₁ (8.3 Mg ha⁻¹).

Table 26: Effect of agroforestry system, soil depth and their interaction on carbon density of <53 µm soil size fraction (Mg ha⁻¹).

Agroforestry system (T)	Soil depth (D)			Mean
	D ₁	D ₂	D ₃	
T ₁ - Sole cropping	8.30 ^o	9.61 ^{mn}	17.17 ^g	11.70 ^h
T ₂ - Natural Forest	12.98 ^k	16.20 ^{hi}	18.44 ^f	15.88 ^c
T ₃ -Agri-silvi-horticulture system	11.82 ^l	15.09 ^j	18.37 ^f	15.10 ^d
T ₄ - Agrisilviculture	9.61 ^{mn}	16.50 ^{gh}	16.91 ^{gh}	14.35 ^e
T ₅ -Fruit based agroforestry system	8.90 ^{no}	11.58 ^l	17.32 ^g	12.61 ^g
T ₆ - Fodder tree based agroforestry system	8.78 ^{no}	13.28 ^k	19.32 ^e	13.80 ^f
T ₇ - Bamboo based agroforestry system	13.31 ^k	18.32 ^f	23.08 ^b	18.24 ^b
T ₈ - Melia based agroforestry system	10.44 ^m	15.59 ^j	21.93 ^c	15.99 ^c
T ₉ - Poplar based agroforestry system	13.12 ^k	19.52 ^e	21.07 ^d	17.91 ^b
T ₁₀ - Silvipasturesystem	13.29 ^k	18.99 ^{ef}	24.36 ^a	18.88 ^a
Mean	11.05 ^c	15.47 ^b	19.80 ^a	
Factors	SE(d)	CD at 5%		
Soil Depth (D)	0.133	0.266		
AFS (T)	0.243	0.486		
Interaction (T×D)	0.421	0.842		

Significant difference exists between the mean values in the same row that are denoted by a distinct letter (^{a, b, c, ...})

4.4.11 Average carbon density (Mg ha⁻¹)

From the Table 27. It can be concluded that natural forest (T₂) and tree-based agroforestry system showed more storage of carbon as compared to solecropping (T₁). Value ranged from 24.73

Mg ha⁻¹ to 32.47 Mg ha⁻¹ in sole cropping (T₁) and natural forest (T₂) respectively. Chatterjee *et al.* (2019) also observed the similar findings. Average carbon density in D₁(0-20cm), D₂(20-40cm) and D₃(40-60cm) were in the order of: 30.39 Mg ha⁻¹, 27.83 Mg ha⁻¹ and 26.89 Mg ha⁻¹. Our findings are strongly supported by Kafle (2019) who concluded that the higher organic carbon percentage in the top layer of soil can be attributed to the rapid decomposition of forest litter in a favorable environment. Forest litter, such as fallen leaves, branches, and other organic debris, contains a significant amount of organic carbon. When these materials decompose, they release carbon into the soil, contributing to the organic carbon content. Soils with rich organic carbon levels are generally considered highly fertile. Organic carbon serves as a source of energy and nutrients for soil microorganisms and promotes their activity. Pandey and Bhusan (2016) and Ghimire *et al.* (2018) in the *Shorea robusta*-dominated tropical community forest of Nepal found similar findings on the drop of SOC stocks with the increase in soil depth.

Table 27: Effect of agroforestry system, soil depth and their interaction on average carbon density (Mg ha⁻¹)

Agroforestrysystem (T)	Soil depth (D)			Mean
	D ₁	D ₂	D ₃	
T ₁ - Sole cropping	27.43 ^{ghi}	24.19 ^{lm}	25.05 ^l	25.56 ^{ef}
T ₂ - Natural Forest	35.07 ^a	31.92 ^{bc}	30.40 ^d	32.47 ^a
T ₃ -Agri-silvi-horticulture system	29.67 ^{def}	25.23 ^{kl}	26.78 ^{hij}	27.23 ^d
T ₄ - Agrisilviculture	28.72 ^{efg}	25.40 ^{kl}	24.19 ^{lm}	26.11 ^e
T ₅ -Fruit based agroforestry system	27.47 ^{ghi}	22.93 ^m	24.30 ^{lm}	24.90 ^{fg}
T ₆ - Fodder tree based agroforestry system	24.54 ^l	24.92 ^l	24.72 ^l	24.73 ^g
T ₇ - Bamboo basedagroforestry system	35.10 ^a	32.11 ^{bc}	30.12 ^{de}	32.45 ^a
T ₈ - Melia based agroforestry system	31.07 ^{cd}	30.21 ^d	26.60 ^{ijk}	29.30 ^c
T ₉ - Poplar based agroforestry system	30.28 ^d	33.00 ^b	28.04 ^{gh}	30.45 ^b
T ₁₀ - Silvipasturesystem	34.61 ^a	28.35 ^{fg}	28.73 ^{efg}	30.57 ^b
Mean	30.39 ^a	27.83 ^b	26.89 ^c	
Factors	SE(d)	CD at 5%		
Soil Depth (D)	0.222	0.445		
AFS (T)	0.406	0.812		
Interaction (T×D)	0.703	1.406		

Significant difference exists between the mean values in the same row that are denoted by a distinct letter (^{a, b, c, ...})

Within each layer, average carbon density found maximum in natural forest (T₂) while minimum value in D₁(0-20cm) was observed in fodder tree-based agroforestry system (T₆) (24.54 Mg ha⁻¹), fruit-based agroforestry system (T₅) (22.93 Mg ha⁻¹) and agrisilviculture system (T₄) (24.19 Mg ha⁻¹) showed lower value in D₂(20-40cm) and D₃(40-60cm)

respectively. T₇D₁ (35.10 Mg ha⁻¹) have higher value and T₄D₃ (24.19 Mg ha⁻¹), T₅D₃ (24.30 Mg ha⁻¹) have lowest value and are at statistically at par.

4.4.12 Total carbon density (Mg ha⁻¹) different agroforestry system

The data enumerated in table 28 reveals that the natural forest (T₂) (97.40 Mg ha⁻¹) and bamboo-based agroforestry system (T₇) (97.34 Mg ha⁻¹) showed higher value and both are statistically at par. It can also be concluded from the table that there was no large variation in total carbon density among different AFS. These results are aligned with the observation of Sharma *et al.* (2009), Srinivas and Sundarapandian (2019), and Paul *et al.* (2002) who suggested that this increase in total carbon density under the tree-based system may be brought on by the addition of tree leaves to the soil, decreased soil erosion, and altered microclimates. Paul *et al.* (2002) also concluded that surface soils are typically drier and cooler under plantations than sole cropping because of shade and high evaporation. This element could lead to slower rates of degradation and thus increase total carbon density in tree-based land use systems.

Table 28: Total carbon density (Mg ha⁻¹) of different agroforestry system in 0-60cm depth

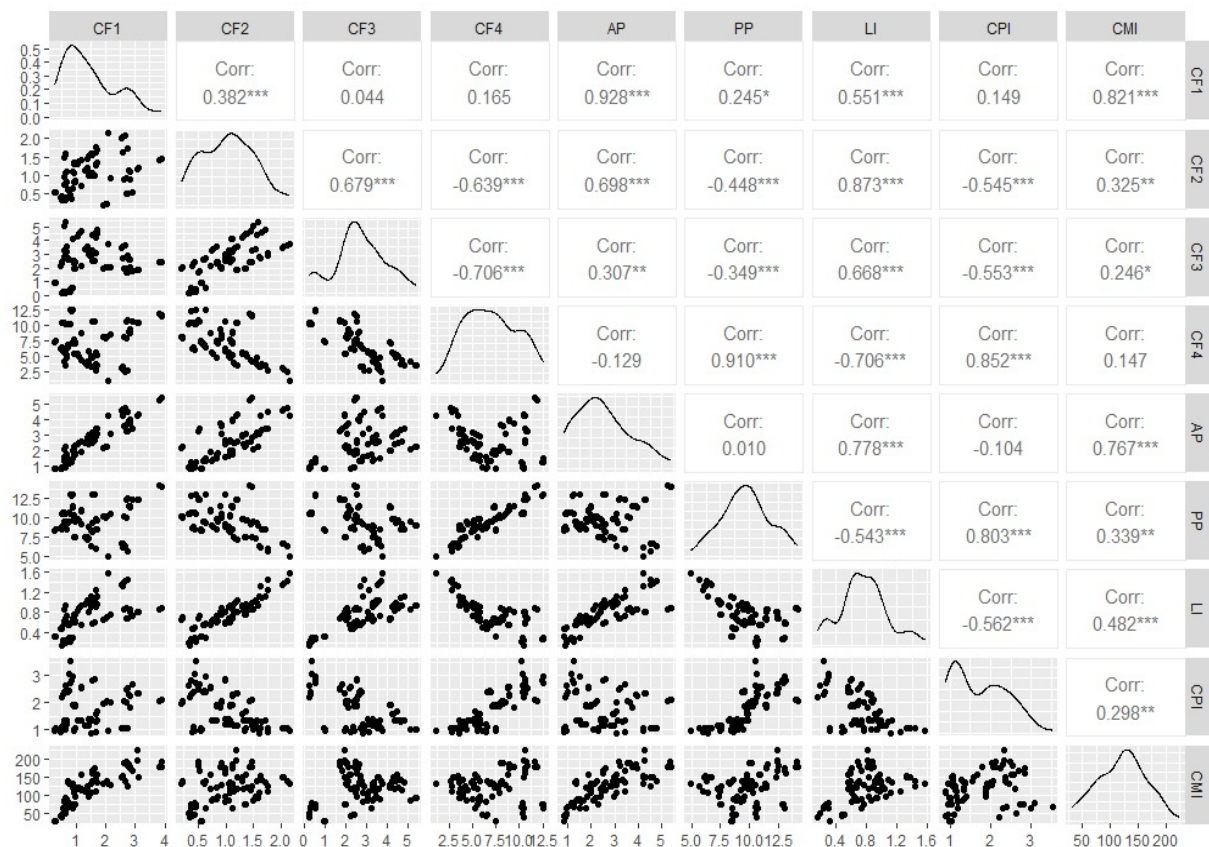
Agroforestry system (T)	Mean
T1- Sole cropping	76.68 ^{cd}
T2- Natural Forest	97.40 ^a
T3- Agri-silvi-horticulture system	81.69 ^c
T4- Agrisilviculture	78.32 ^{cd}
T5- Fruit based agroforestry system	74.71 ^d
T6- Fodder tree based agroforestrysystem	74.20 ^d
T7- Bamboo based agroforestry system	97.34 ^a
T8- Melia based agroforestry system	87.89 ^b
T9- Poplar based agroforestry system	91.34 ^{ab}
T10- Silvipasture system	91.70 ^{ab}
SE(d)	1.780
CD at 5%	0.090

Significant difference exists between the mean values in the same row that are denoted by a distinct letter (^{a, b, c, ...})

Correlation analysis of different pools of Carbon:

As shown in figure 1, Active carbon pool shows negative correlation with carbon fraction 4 (Non labile). Carbon fraction 4 (Non labile) and passive pool are also strongly

correlated with each other. Lability index is also strongly correlated with carbon fraction 2 (Labile) while significantly correlated with carbon fraction 1 (Very labile) and active pool, Passive carbon pool is strongly positive correlated with CPI. Similarly, passive pool has a significantly positive correlation with CMI but not with LI. Moreover, Carbon fraction 2 (Labile) and carbon fraction 4 (Non labile) is negatively correlated with each other. The carbon management index and carbon fraction 1 (Very labile) also have a strong positive correlation with one another.

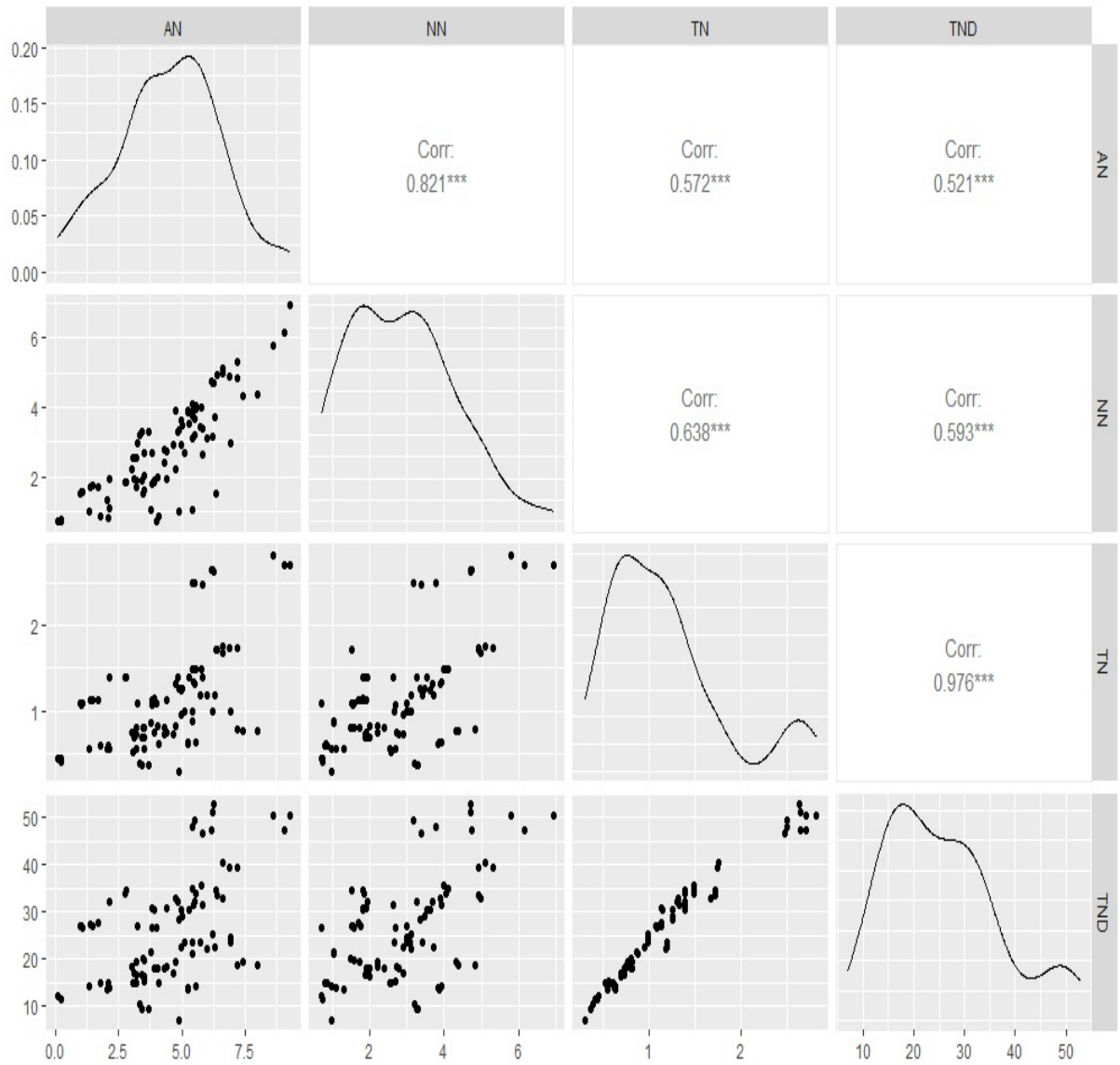


CF1 –Very Labile Carbon, CF2-Labile Carbon, CF3- Less Labile Carbon, CF4-Non Labile Carbon, AP-Active Pool, PP-Passive Pool, LI-Lability Index,CPI-Carbon Pool Index, CMI- Carbon Management Index

Fig 1. Correlation analysis of different pools of Carbon

Correlation analysis of different pools of Nitrogen:

Analysis from figure 2 shows that nitrate nitrogen is positively correlated with all the studied variables of nitrogen i.e., ammonical nitrogen, total nitrogen and total nitrogen density. Total nitrogen shows significant correlation with ammonical nitrogen while strong positive correlation with total nitrogen density. Total nitrogen density also shows significant correlation with ammonical nitrogen.



AN- Ammonical Nitrogen, NN- Nitrate Nitrogen, TN- Total Nitrogen, TND- Total Nitrogen Density

Fig 2. Correlation analysis of different pools of Nitrogen

Chapter-5

SUMMARY AND CONCLUSION

The work done on “**Evaluation of agroforestry systems for their carbon and nitrogen pools in mid-hills of Himachal Pradesh**” was carried out in the laboratory and experimental farm of the Department of Silviculture and Agroforestry, Dr Y S Parmar University of Horticulture and Forestry, Nauni, Solan, Himachal Pradesh during the year 2022-2023. The current study aimed to evaluate different agroforestry systems in the mid-hills of Himachal Pradesh for their carbon and nitrogen pools and also to determine the carbon stored in different soil size fractions. Each experiment was carried out on a Factorial Randomized Complete Block Design, the results of the study are summarized in this chapter, as below:

5.1 Bulk density

- The bulk density of sole cropping and agrisilvihorticulture system both reach a maximum value of 1.27 g cm^{-3} , but natural forest had a minimum value of 0.93 g cm^{-3} .

5.1 Soil carbon pools

Soil carbon pools have four types of fractions of carbon i.e., very labile carbon, labile carbon, less labile carbon and non-labile carbon that further form active and passive carbon pools. These pools were studied under ten lands use systems, each at three depths.

- All the fractions of carbon decrease with an increase in depth.
- Natural forest had significantly maximum (3.24 mg g^{-1}) amount of very labile carbon, while all tree-based systems had higher levels of very labile carbon storage than sole cropping (0.62 mg g^{-1}).
- Fruit-based agroforestry systems has the highest level of labile carbon (1.85 mg g^{-1}), followed by agrisilvihorticulture (1.43 mg g^{-1}), solo cropping (1.15 mg g^{-1}) and natural forest (1.05 mg g^{-1}), respectively.
- AFSs differed greatly in respect of less labile carbon. The maximum concentration was in the agri-silvi-horticulture system (3.81 mg g^{-1}), while the lowest was in the

silvipasture (2.03 mg g^{-1}). It was also noted that compared to other tree-based agroforestry systems, sole cropping displayed higher levels of less labile carbon.

- The highest non-labile carbon fraction was found in silvipasture (11.06 mg g^{-1}), which was statistically at par with natural forest (10.98 mg g^{-1}), and is followed by a melia-based agroforestry system, which was statistically at par with bamboo-based agroforestry system (8.49 mg g^{-1}). The least amount of non-labile carbon was found in the fruit-based agroforestry system (2.89 mg g^{-1}).
- The active carbon pool followed the trend: Natural Forest > Fruit-based agroforestry system > Tree-based agroforestry system > sole cropping. A minimum active carbon pool of 1.14 mg g^{-1} was found in silvipasture, which is nearly 3.8 times smaller than the highest recorded value of natural forest (4.30 mg g^{-1}). As very labile and labile carbon decrease with depth.
- The passive carbon pool declined with depth although with a minor variance within depth (10.71 mg g^{-1} to 9.13 mg g^{-1}), following the same trend as the less labile and non-labile fractions of carbon. At all depths natural forests showed greater value than all studied systems while, and fruit-based agroforestry system had the least value.
- The silvipasture system had the lowest value of LI (0.24), and the fruit-based system (T₅) had the highest of LI value (1.35).
- The natural forest has the highest CPI value i.e., 2.74 while sole cropping has the least value.
- The observed trend of CMI was natural forest > bamboo-based agroforestry system > Melia based agroforestry system > fruit-based agroforestry system > agrisilvihorticulture > Fodder based agroforestry system > Poplar based agroforestry system > agrisilviculture agroforestry > silvipasture > sole cropping. With increasing depth (137.02 in D₁, 122.50 in D₂, and 101.96 in D₃), the value of CMI declined significantly.

5.2 Soil nitrogen pools

Ammonical nitrogen, nitrate nitrogen, total nitrogen and total nitrogen density of different soil samples collected from different land use systems were studied within different layers of soil profile and summarised results of studies are given below:

- Sharp decline in nitrogen pool was found with increasing soil depth in all the studied land use systems.
- Natural forests (6.93 mg kg^{-1}) and sole cropping (T_1 , 5.91 mg kg^{-1}) had the highest value of ammonical nitrogen, while silvipasture systems (1.70 mg kg^{-1}) had the lowest levels. Regardless of the type of land use, the natural forest (T_2) had the highest ammonical nitrogen values for all depths.
- The value of nitrate nitrogen for all studied AFSs ranged from 0.86 mg kg^{-1} to 4.34 mg kg^{-1} , Nitrate nitrogen was found maximum in natural forest followed by fruit-based agroforestry system and bamboo-based agroforestry system; while minimum was in sole cropping.
- The total nitrogen concentration of AFSs ranged from 0.26% to 0.06%. The maximum value was attained in natural forest (0.26%), followed by bamboo-based agroforestry system (0.15%), and least value (0.06%) was in sole cropping, which was statistically comparable to fruit-based AFS.
- Natural forest is followed by agroforestry system based on bamboo in respect of total nitrogen density. In natural forests and sole cropping, higher and lower values, respectively for all three soil depths.

5.3 Soil carbon stored in different soil particle size fraction

Soil carbon stored in different soil particle size fractions along with fraction percentage of soil fraction classes were recorded in ten land use systems for three depths of soil. A compendium of study is discussed here:

- Study suggests that fraction percentage of particles shows a positive correlation with carbon stored in them.
- Carbon stored in soil particle ($250\text{-}2000\mu\text{m}$) under different agroforestry systems was observed maximum in natural forest with a value of 4.65 mg g^{-1} followed by bamboo-based agroforestry system (3.50 mg g^{-1}), which was statistically at par with sole cropping (3.47 mg g^{-1}) and also total carbon density of this size fraction found maximum in natural forest (32.47 Mg ha^{-1}).
- Lowest values (2.13 mg g^{-1}) and highest values (4.24 mg g^{-1}) of carbon stored in microaggregate particles ($53\text{-}250\mu\text{m}$) were recorded in sole cropping and natural

forest, respectively. AFSs within each depth follow the same pattern as stored carbon in macroaggregate particles (250-2000 μm).

- The largest value of carbon stored in silt and clay particle (<53 μm) was recorded by the natural forest (8.41 mg g^{-1}), while the silvipasture system (7.73 mg g^{-1}) and the bamboo-based agroforestry system (7.71 mg g^{-1}) were statistically equal and other systems also did not exhibit more variation among themselves.
- As all fractions of carbon were maximum in natural forest so OC% and total carbon density also exhibited a higher value. With depth also these parameters showed a positive correlation with different fractions of carbon.

CONCLUSIONS

- Natural forests had a favourable effect on both the active and passive C pools. We can therefore draw the following conclusions in answer to the research questions posed at the start of the study that
- Natural forest ecosystems have higher values of active carbon pool, passive carbon pool, carbon pool index, carbon management index, and lability index.
- The various SOC fractions were significantly positively impacted by all trees, particularly bamboo, poplar, and melia.
- Among the commercial AFSs, bamboo-based systems, poplar-based systems, melia based systems emerged as promising systems for better soil health and in amelioration of climate change.
- Fruit-based land systems have higher lability and thus have highest level of sustainability but were poor from climate mitigation.
- From a climate change mitigation point of view silvipasture systems are best among all the land-used systems of mid-hills of the northwestern Himalayas as they store carbon in the passive pool, which is less in equilibrium with the atmosphere.
- Hence, among all the studied systems, all tree-based agroforestry systems except agrisilviculture system and silvipasture system have CMI values greater than 100 which shows that these systems are healthy and sustainable. Silvipasture system and

sole cropping have poor carbon management index and there is an urgent need to manage these systems for carbon.

- All tree-based systems are promising for both sustainability as well as climate change mitigation in North-western Himalayas as they store more carbon in smallest soil size fraction ($< 50 \mu\text{m}$), which have a potential to stores carbon for a long period of time.

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APPENDIX-I

Effect of agroforestry system, soil depth and their interaction on Bulk Density

Source of Variation	d.f.	Sum of Squares	Mean Squares	F _{calculated}
Replications	2	0.0004	0.0002	0.1930
Depth	2	0.2121	0.1060	105.1713
Systems	9	0.7976	0.0886	87.8894
Depth * Systems	18	0.2156	0.0120	11.8770
Error	58	0.0585	0.0010	0.0000
Total	89	0.2121		

APPENDIX-II

Effect of agroforestry system, soil depth and their interaction on Carbon fraction1 (Very labile)

Source of Variation	d.f.	Sum of Squares	Mean Squares	F _{calculated}
Replications	2	0.02	0.01	1.27
Depth	2	5.57	2.79	307.02
Systems	9	63.44	7.05	776.84
Depth * Systems	18	3.34	0.19	20.47
Error	58	0.53	0.01	0.00
Total	89	72.35		

APPENDIX-III

Effect of agroforestry system, soil depth and their interaction on Carbon fraction 2 (Labile)

Source of Variation	d.f.	Sum of Squares	Mean Squares	F _{calculated}
Replications	2	0.02	0.01	2.31
Depth	2	4.97	2.48	532.26
Systems	9	12.26	1.36	291.88
Depth * Systems	18	2.07	0.11	24.63
Error	58	0.27	0.00	0.00
Total	89	19.29		

APPENDIX-IV

Effect of agroforestry system, soil depth and their interaction on Carbon fraction3 (Less labile)

Source of Variation	d.f.	Sum of Squares	Mean Squares	F _{calculated}
Replications	2	0.06	0.03	1.51
Depth	2	26.77	13.39	687.89
Systems	9	81.99	9.11	468.16
Depth * Systems	18	25.07	1.39	71.58
Error	58	1.13	0.02	0.00
Total	89	133.84		

APPENDIX-V

Effect of agroforestry system, soil depth and their interaction on Carbon fraction 4 (Non labile)

Source of Variation	d.f.	Sum of Squares	Mean Squares	F _{calculated}
Replications	2	0.34	0.17	1.32
Depth	2	2.52	1.26	9.96
Systems	9	622.59	69.18	545.87
Depth * Systems	18	55.34	3.07	24.26
Error	58	7.35	0.13	0.00
Total	89	680.45		

APPENDIX-VI

Effect of agroforestry system, soil depth and their interaction on Active Carbon Pool

Source of Variation	d.f.	Sum of Squares	Mean Squares	F _{calculated}
Replications	2	0.09	0.04	2.04
Depth	2	21.06	10.53	483.03
Systems	9	92.68	10.30	472.39
Depth * Systems	18	6.24	0.35	15.89
Error	58	1.26	0.02	0.00
Total	89	119.98		

APPENDIX-VII

Effect of agroforestry system, soil depth and their interaction on Passive Carbon Pool

Source of Variation	d.f.	Sum of Squares	Mean Squares	F _{calculated}
Replications	2	0.12	0.06	1.15
Depth	2	45.55	22.77	427.92
Systems	9	330.44	36.72	689.87
Depth * Systems	18	13.28	0.74	13.86
Error	58	3.09	0.05	0.00
Total	89	389.26		

APPENDIX-VIII

Effect of agroforestry system, soil depth and their interaction on Lability Index

Source of Variation	d.f.	Sum of Squares	Mean Squares	F _{calculated}
Replications	2	0.01	0.01	2.00
Depth	2	0.56	0.28	92.80
Systems	9	6.86	0.76	254.38
Depth * Systems	18	0.49	0.03	9.13
Error	58	0.17	0.00	0.00
Total	89	7.91		

APPENDIX-IX

Effect of agroforestry system, soil depth and their interaction on Carbon Pool Index

Source of Variation	d.f.	Sum of Squares	Mean Squares	F _{calculated}
Replications	2	0.48	0.24	8.81
Depth	2	0.11	3.89	3.16
Systems	9	4.00	147.46	2.05
Depth * Systems	18	0.05	1.95	1.78
Error	58	0.03	0.00	0.00
Total	89	37.19		

APPENDIX-X

Effect of agroforestry system, soil depth and their interaction on Carbon Management Index

Source of Variation	d.f.	Sum of Squares	Mean Squares	F _{calculated}
Replications	2	1343.62	671.81	3.98
Depth	2	18628.68	9314.34	55.17
Systems	9	127590.33	14176.70	83.97
Depth * Systems	18	8187.23	454.85	2.69
Error	58	9792.70	168.84	0.00
Total	89	154406.23		

APPENDIX-XI

Effect of agroforestry system, soil depth and their interaction on Ammonical Nitrogen

Source of Variation	d.f.	Sum of Squares	Mean Squares	F _{calculated}
Replications	2	0.94	0.47	3.26
Depth	2	130.06	65.03	449.42
Systems	9	198.48	22.05	152.41
Depth * Systems	18	15.82	0.88	6.07
Error	58	8.39	0.14	0.00
Total	89	344.35		

APPENDIX-XII

Effect of agroforestry system, soil depth and their interaction Nitrate Nitrogen

Source of Variation	d.f.	Sum of Squares	Mean Squares	F _{calculated}
Replications	2	1.69	0.84	4.29
Depth	2	25.17	12.58	63.83
Systems	9	123.71	13.75	69.73
Depth * Systems	18	10.09	0.56	2.84
Error	58	11.43	0.20	0.00
Total	89	158.97		

APPENDIX-XIII

Effect of agroforestry system, soil depth and their interaction Total Nitrogen (%)

Source of Variation	d.f.	Sum of Squares	Mean Squares	F _{calculated}
Replications	2	0.0004	0.0002	0.0005
Depth	2	0.0002	0.0001	0.0003
Systems	9	0.0003	0.0003	0.0008
Depth * Systems	18	0.0003	0.0001	0.0004
Error	58	0.0002	0.0003	0.0000
Total	89	0.0003		

APPENDIX-XIV

Effect of agroforestry system, soil depth and their interaction Total Nitrogen Density

Source of Variation	d.f.	Sum of Squares	Mean Squares	F _{calculated}
Replications	2	0.009	0.005	0.152
Depth	2	8.044	4.022	130.016
Systems	9	97.790	10.866	351.256
Depth * Systems	18	2.057	0.114	3.694
Error	58	1.794	0.031	0.000
Total	89	107.890		

APPENDIX-XV

Effect of agroforestry system, soil depth and their interaction on soil size fraction (%) of particle size 250-2000 μ m

Source of Variation	d.f.	Sum of Squares	Mean Squares	F _{calculated}
Replications	2	5.80	2.90	1.27
Depth	2	130.93	65.47	28.58
Systems	9	522.61	58.07	25.35
Depth * Systems	18	40.64	2.26	0.99
Error	58	132.85	2.29	0.00
Total	89	694.19		

APPENDIX-XVI

Effect of agroforestry system, soil depth and their interaction on soil size fraction (%) of particle size 53-250 μ m

Source of Variation	d.f.	Sum of Squares	Mean Squares	F _{calculated}
Replications	2	2.01	1.00	1.77
Depth	2	75.98	37.99	66.91
Systems	9	338.02	37.56	66.15
Depth * Systems	18	19.93	1.11	1.95
Error	58	32.93	0.57	0.00
Total	89	433.94		

APPENDIX-XVII

Effect of agroforestry system, soil depth and their interaction on soil size fraction (%) of particle size <53 μm

Source of Variation	d.f.	Sum of Squares	Mean Squares	F _{calculated}
Replications	2	0.25	0.12	0.59
Depth	2	31.89	15.94	75.24
Systems	9	96.21	10.69	50.44
Depth * Systems	18	17.18	0.95	4.50
Error	58	12.29	0.21	0.00
Total	89	145.27		

APPENDIX-XVIII

Effect of agroforestry system, soil depth and their interaction on soil organic carbon (mg g^{-1}) of particle size 250-2000 μm

Source of Variation	d.f.	Sum of Squares	Mean Squares	F _{calculated}
Replications	2	0.02	0.01	1.13
Depth	2	132.30	66.15	8005.89
Systems	9	41.99	4.67	564.59
Depth * Systems	18	19.83	1.10	133.32
Error	58	0.48	0.01	0.00
Total	89	194.12		

APPENDIX-XIX

Effect of agroforestry system, soil depth and their interaction on soil organic carbon (mg g^{-1}) of particle size 53-250 μm

Source of Variation	d.f.	Sum of Squares	Mean Squares	F _{calculated}
Replications	2	0.03	0.01	2.59
Depth	2	130.89	65.44	11620.48
Systems	9	29.74	3.30	586.81
Depth * Systems	18	13.79	0.77	136.06
Error	58	0.33	0.01	0.00
Total	89	174.42		

APPENDIX-XX

Effect of agroforestry system, soil depth and their interaction on soil organic carbon (mg g^{-1}) of particle size <53 μm

Source of Variation	d.f.	Sum of Squares	Mean Squares	F _{calculated}
Replications	2	0.08	0.04	2.82
Depth	2	141.36	70.68	4773.25
Systems	9	124.34	13.82	933.00
Depth * Systems	18	14.24	0.79	53.43
Error	58	0.86	0.01	0.00
Total	89	279.94		

APPENDIX-XXI

Effect of agroforestry system, soil depth and their interaction on organic carbon (%)

Source of Variation	df	Sum of Squares	Mean Squares	F _{calculated}
Replications	2	0.66	0.33	0.44
Depth	2	197.20	98.60	133.14
Systems	9	746.42	82.94	111.99
Depth * Systems	18	132.25	7.35	9.92
Error	58	42.95	0.74	0.00
Total	89	1075.87		

APPENDIX-XXII

Effect of agroforestry system, soil depth and their interaction on carbon density of 250-2000 μ m soil size fraction

Source of Variation	d.f.	Sum of Squares	Mean Squares	F _{calculated}
Replications	2	0.03	0.02	0.17
Depth	2	586.32	293.16	3228.26
Systems	9	117.06	13.01	143.22
Depth * Systems	18	114.98	6.39	70.34
Error	58	5.27	0.09	0.00
Total	89	818.35		

APPENDIX-XXIII

Effect of agroforestry system, soil depth and their interaction on carbon density of 53-250 μ m soil size fraction

Source of Variation	d.f.	Sum of Squares	Mean Squares	F _{calculated}
Replications	2	0.15	0.08	1.21
Depth	2	578.21	289.11	4597.29
Systems	9	49.21	5.47	86.94
Depth * Systems	18	79.84	4.44	70.54
Error	58	3.65	0.06	0.00
Total	89	707.26		

APPENDIX-XXIV

Effect of agroforestry system, soil depth and their interaction on carbon density of <53 μ m soil size fraction

Source of Variation	d.f.	Sum of Squares	Mean Squares	F _{calculated}
Replications	2	1.02	0.51	1.92
Depth	2	1147.06	573.53	2161.49
Systems	9	470.98	52.33	197.22
Depth * Systems	18	113.17	6.29	23.70
Error	58	15.39	0.27	0.00
Total	89	1731.21		

APPENDIX-XXV

Effect of agroforestry system, soil depth and their interaction on average carbon density

Source of Variation	d.f.	Sum of Squares	Mean Squares	F _{calculated}
Replications	2	0.0003	0.0002	0.8266
Depth	2	1.1883	0.5941	2950.4257
Systems	9	3.8428	0.4270	2120.3061
Depth * Systems	18	0.1409	0.0078	38.8848
Error	58	0.0117	0.0002	0.0000
Total	89	5.1721		

APPENDIX-XXVI

Total carbon density (Mg ha⁻¹) of different agroforestry system in 0-60cm depth

Source of Variation	d.f.	Sum of Squares	Mean Squares	F _{calculated}
Replications	2	1.968	0.984	0.373
Systems	9	2239.271	248.808	94.363
Error	18	47.461	2.637	0.000
Total	29			

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ABSTRACT

The present investigation entitled “Evaluation of agroforestry systems for their carbon and nitrogen pools in mid-hills of Himachal Pradesh” was carried out during 2022-23. In the present study, agroforestry systems, viz., sole cropping, natural forest, agrisilvihorticulture, agrisilviculture, fruit based agroforestry system, fodder based agroforestry system, melia based agroforestry system, poplar based agroforestry system, bamboo based agroforestry system, silvipasture system along with three depth (0-20cm, 20-40cm, 40-60cm) with 3 replication of each factor were explored for different pools of carbon and nitrogen as well as carbon stored in different soil size fraction viz., 250-2000 μ m particle size, 53-250 μ m particle size and clay and silt (<53 μ m). This experiment was laid out in a Factorial Randomized Complete Block Design. The results of study revealed that active carbon was greater in natural forest (4.30 mg g⁻¹) followed by fruit based system (4.17 mg g⁻¹) while maximum passive pool was found in natural forest (13.01 mg g⁻¹) followed by silvipasture system (11.41 mg g⁻¹). The maximum CMI was reported in natural forest (184.08) followed by bamboo based agroforestry system (161.35). Both ammonical nitrogen and nitrate nitrogen were reported maximum in natural forest i.e., 6.93 mg kg⁻¹ and 4.34 mg kg⁻¹ respectively. On an average, carbon pool and nitrogen pool declined with increase in soil depth irrespective of the land use. Moreover, the maximum organic carbon stored in particle size 250-2000 μ m as well as 53-250 μ m particle size were observed maximum in natural forest with a value of 4.65 mg g⁻¹ and 4.24 mg g⁻¹, respectively. Clay and silt particles stored maximum carbon under natural forest (8.41 mg g⁻¹) while minimum under silvipasture system (7.73 mg g⁻¹). Overall, the study findings suggest that different commercial agroforestry systems like bamboo, melia, and poplar-based systems stand out as beneficial options, positively influencing both soil health and climate change mitigation. The fruit-based system, while enhancing soil health (greater lability index), may require additional measures for effective climate change mitigation. Silvipasture system demonstrated great potential as climate change mitigation strategies (higher passive C pool), though careful carbon management practices are required to ensure sustainable carbon sequestration, minimize carbon loss and increase carbon management index.

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