EVALUATION OF ESTABLISHED AGROFORESTRY SYSTEMS FOR THEIR CARBON SEQUESTRATION AND SOIL ENRICHMENT POTENTIAL IN MID-HILLS OF HIMACHAL PRADESH

Thesis

by

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CERTIFICATE- I

This is to certify that the thesis titled, **“Evaluation of established Agroforestry systems for their Carbon sequestration and Soil enrichment potential in mid-hills of Himachal Pradesh”** submitted in partial fulfilment of the requirements for the award of the degree of **MASTER OF SCIENCE (FORESTRY)** in the discipline of **AGROFORESTRY** to Dr. Yashwant Singh Parmar University of Horticulture and Forestry, (Nauni) Solan (H.P.) – 173230 is a bonafide research work carried out by **Mr. TARUN VERMA (F-2019-21-M),** son of Shri Virender Kumar Verma 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 this investigation have been fully acknowledged.

Place: Nauni (Solan)
Dated:

Dr. D.R. Bhardwaj
Chairman
Advisory Committee

C E R T I F I C A T E – II

This is to certify that the thesis entitled **“ Evaluation of Established Agroforestry System for their Carbon Sequestration and Soil Enrichment Poiential in Mid-Hills of Himachal Pradesh”** submitted by Mr Tarun Verma [F-2019-21-M] son of Sh Virender Kumar Verma to the Dr Yashwant Singh Parmar University of Horticulture and Forestry, Nauni [Solan] HP-173230 India in partial fulfillment of the requirements for the degree of **Master of Science Forestry [Agroforestry]** has been approved by the students’ advisory committee after an oral examination of the students in collaboration with the external examiner

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Place: Nauni, Solan
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CONTENTS

LIST OF ABBREVIATIONS

%	Per cent
AH	Agrihorticulture
ASH	Agrisilvihorticulture
ANOVA	Analysis of variance
AS	Agri-silviculture
ASH	Agri-silvi-horticulture
BEF	Biomass expansion factor
C	Carbon
C: N	Carbon nitrogen ratio
Ca	Calcium
CD	Critical difference
CDM	Clean development mechanism
cm	Centimeter
Cfu g^{-1}	Colony forming unit per unit gram of soil
CO_2	Carbon dioxide
Cu	Copper
D	Depth
DBH	Diameter at breast height
EC	Electrical conductivity
et al.	And others
g	Gram
GHGs	Green house gases
GPS	Global positioning unit
Gt	Giga tonnes
Fe	Iron
H.P.	Himachal Pradesh
HGs	Home gardens
ha	Hectare
i.e.	That is
IPCC	Intergovernmental panel on climate change
K	Potassium
K&M	Knight’s and Munaier’s media

Kg	Kilogram
Km^2	Square kilometer
Kgha-1	Kilogram per hectare
Mha	Million hectares
MT	Metric tonnes
a.m.s.l.	Above mean sea level
MAT	Mean annual temperature
Mg	Megagram
Mg Cha^{-1}	Megagram carbon per hectare
Mg Cha^{-1} yr^{-1}	Megagram carbon per hectare per year
Mg ha^{-1}	Megagram per hectare
Mg ha^{-1} yr^{-1}	Megagram per hectare per year
Mg kg^{-1}	Miligram per kilogram
Mn	Manganese
N	Nitrogen
NA	Nutrient Agar
OC	Organic carbon
^{o}C	Degree Celsius
P	Phosphorus
PDA	Potato Dextrose Agar
Pg	Petagram
pH	Negative logarithm of hydrogen ion
ppm	Parts per million
RBD	Randomized block design
RBA	Relative basal area
R: S	Root shoot ratio
S	Sulphur
SOC	Soil organic carbon
T ha^{-1}	Tonne per hectare
UHF	University of horticulture and forestry
VOB	Volume over bark
WD	Wood density
Zn	Zinc

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Chapter-1

INTRODUCTION

Agroforestry is a land use management system in which woody perennials are deliberately grown around or along with agricultural food crops and pasturelands. Theoretically, agroforestry is based on ecology or agro ecology which comprehends various applications, such as: improved nutrient and carbon cycling, better water conservation and optimum utilization, biodiversification of habitats, improved soil nutrients, etc. Agroforestry is a new concept although it has been practiced in India for thousands of years (Puri and Nair, 2004). It is recognized as one of the important means to reduce CO_2 emissions as well as enhancing carbon sinks. Globally, agroforestry is estimated to be practiced over around 1.6 billion hectares, having more than 10 per cent tree cover (Nair and Garrity, 2012). It is the major land use activity after agriculture and forestry in India, covering approximately 25.32 million hectares *i.e.* about 8.2 per cent of the total geographical area (Dhyani *et al*., 2013), which can further be increased up to 80 million hectares (FSI, 2013). In 2014, the Indian government created the National Agroforestry Policy, recognizing the potential of agroforestry as a pro-poor, multi-benefit land management strategy.

Various agroforestry systems have the potential to produce 100 m^3 timber/ pulpwood for industrial and domestic use (Chavan *et al*., 2015). It is capable of satiating 65 per cent of the country’s timber demand, 70 per cent of small timber demand, 70–80 per cent of plywood demand and 60 per cent raw material demand for paper pulp. In addition, it is capable of producing 150 million tonnes equivalent of firewood which fulfills half of country’s firewood demand. Likewise, 9-11 per cent of the green fodder requirements are met from the trees grown on the farms *i.e.* through agroforestry (Singh and Pandey, 2011). Eighty seven per cent of the Indian farmers belong to small and marginal categories. They could be highly benefitted by the famous 6 Fs: food, fruit, fiber, fodder, fertilizer and fuel, all in same place at the same time (Chavan *et al*., 2015). A report of Indian Council of Agricultural Research (ICAR) in 2010, suggested that agroforestry has been capable of safeguarding nearly 120.7 million hectares of land from different forms of soil degradation. The trees have deep, spreading roots and are capable of taking up nutrients from deeper soil profile and eventually depositing on the surface layers through litter-fall and other mechanisms, referred to as nutrient pumping by trees. They increase the supply of nutrients within the rooting zone of crops and reduce nutrient loss by leaching and erosion (Roland *et al.*, 1996). Addition of nutrients through litter decomposition, dead root biomass and nitrogen fixation increases importance of tree species in soil nutrient status improvement. Trees affect the environment for soil organisms, stimulate microbial activity and contribute to nutrient inputs and synergistic symbiosis *i.e.* nitrogen fixing bacteria and leguminous trees (Barrios *et al.*, 2002). It improves soil biota, soil health, as they play a role in soil organic matter decomposition, nutrient cycling, influencing physical and chemical properties of soil which ultimately determines the soil fertility and long-term sustainability. Further, by joining the carbon credit markets, the landowners could also sell the carbon sequestered by their agroforestry trees (Takimoto, 2007).

Therefore, a lot counts on agroforestry for its vast applications and utility in varied contexts. The inclusion of trees *i.e.* nitrogen fixing, may specifically enhance SOC storage in agroforestry systems. An Intergovernmental Panel on Climate Change (IPCC) report (2000) estimated at least 630 Mha of futile cropland, worldwide could be converted to agroforestry with an additional sequestering of about 500 MT carbon by 2040. In India, by 2050, there is a scope of increasing the area under agroforestry by another 28.0 Mha and thus, a total of 53.23 Mha or 17.5 per cent of the area under agroforestry (CAFRI, 2015).

In addition to climate benefits, agroforestry can deliver benefits for rural development. In line to this, India has announced the landmark National Agroforestry Policy in 2014 that will mainstream the growing of trees on farms to meet a wide range of developmental and environmental goals, especially in arid agro-ecosystems which cover a large number of areas in India (Chavan *et al.*, 2015). India has also become the first country in the world to develop and declare a National Agroforestry Policy which has to be promulgated whole-heartedly to reduce the pressure on forest areas for fuel wood, diversify agriculture, and most importantly, aid carbon sequestration. The CO_2 reduction in atmosphere can only be achieved by shifting from lower biomass land uses (e.g. grasslands, crop fallows etc.) to tree-based systems such as agroforestry, forests, and plantation forests (Roshetko *et al.*, 2007) which revealed a general trend of increasing soil carbon sequestration (SCS) in agroforestry as compared to other land-use practices (with the exception of forests). An agroforestry system that incorporates trees, agricultural crops, and/or animals has the ability to improve soil fertility, minimize erosion, improve water quality, boost biodiversity, improve aesthetics, and absorb carbon (Nair *et al*., 2009). It has long been recognized that agroforestry methods provide services and benefits on a variety of geographical and temporal dimensions (Izac, 2003). With focus on more and more carbon sequestration worldwide, emphasis is being laid on forest plantation which is a herculean task. A much feasible approach, therefore, is the planting of trees in fallow lands, urban areas, public places, farms and agricultural lands, etc. Of all these options, special attention is being paid on planting trees on agriculture lands because of its outnumbering of the benefits compared to other plantations. Agroforestry multitasks by sequestering carbon, improving microclimate, providing additional incomes and improving soil nutrient status simultaneously.

Agroforestry can also play a vital role in achieving Sustainable Development Goals (SDGs) set forth by the United Nations Development Program (UNDP). More than half of the seventeen UNDP SDGs are attainable, if agroforestry is practiced scientifically in rural areas. Natural cycling of nutrients from soil to plants, animals and back, has been a part of earth’s history since life appeared on earth. Agroforestry`s potential to improve soil quality has been widely recognized as a major benefit, due to its inherent nature as a rejuvenator of soil nutrient cycling which makes agroforestry far sustainable than other counterpart land use systems. It enriches the soil with various nutrients for overall enhancement of soil properties, character and form (Young, 1989; Nair, 2011). Soil biology, nutrient dynamics and degradation resistance are highly influenced by soil organic matter which is added by woody perennials in agroforestry systems (Lal, 2002). Further, the floral diversity of agroforestry systems creates suitable conditions for soil microbes, which play a major role in litter decomposition and release of nutrients (Kumar, 2011). Although agroforestry systems store less carbon per unit area than forests or tree plantations, the land available for agroforestry is vast across the world.

Carbon in the earth system is transported between four major reservoirs: fossil and geological formations, oceans, atmosphere and terrestrial ecosystems such as forests (Siegenthaler and Sarmiento, 1993 and Prentice *et al.*, 2001). The movement of carbon from one reservoir in the system to another is termed accumulation, whereas an additional transfer of carbon from the atmosphere into a reservoir of the agroforestry system is termed sequestration. This process is a genuine contribution to climate change mitigation (Powlson *et al.*, 2011). Agroforestry is now a well-established science for carbon sequestration which is simply the seizing and storing of the elemental carbon (atmospheric CO_2) by forests, agro-ecosystems, oceans, etc. During photosynthesis with most terrestrial carbon storage in tree trunks, branches, foliage and roots commonly known as biomass. Because they store significant amounts of carbon in plant, detritus, and soil, and exchange large amounts of carbon with the atmosphere through photosynthesis and respiration, forest ecosystems play a critical role in regional and global terrestrial carbon cycles (Dixon et al., 1994). Same goes for the agroforestry tree species too as average yields from clonal plantations in agroforestry have proven to be 20 to 25 times more than the average productivity of forests in India (Tahir *et al*., 2017). Carbon sequestration is a long term capture. The removal of CO_2 from atmosphere occurring via various routes: biological processes (in peat lands, forests, wetlands, agriculture, bamboo farming, etc.), physical processes (biomass burial, ocean storage, geological sequestration etc.) and chemical processes (mineral carbonation, industrial use of carbon, etc.). Out of all the carbon emitted by humans, nearly 30% is absorbed by the oceans, 45% remains in the atmosphere and rest is incorporated into the terrestrial ecosystems.

The above-ground woody biomass of agroforestry trees is comprised of majority of carbon sequestered in the system (Chauhan *et al.*, 2015). But with the advancement of mankind, the burden on our forest resources has also been on constant rise. The total carbon stock in forests in India is estimated at 7,124.6 million tonnes, 42.6 million tonnes increase as compared to the India State of Forest Report (ISFR), 2017 and a lot can be attributed to agroforestry which covers more than 25 million hectares (8.2 per cent) of the total geographic area of the country. India also aims at increasing this total carbon stock in forests from 7.1 billion tonnes to 10 billion tonnes by 2030 as per the Paris Agreement (ISFR, 2019).

Soil is the biggest carbon reservoir on the planet, storing almost three times the amount of C found in plants and roughly double that found in the atmosphere (Eswaran *et al*., 1993). The top one metre of soil stores between 1,500 and 1,600 Pg C (Post *et al*., 1982; Batjes, 1996; Guo and Gifford, 2002), while the upper 3 m stores around 2,350 Pg C (Jobbágy and Jackson 2000). As a result, soil plays an important part in the global carbon budget and can have a significant influence on carbon emissions in a climate change scenario (Lal *et al*., 1995).

The capacity for carbon sequestration is determined by biological productivity, which itself is determined by interactions among land use type, species, climate, management techniques, stand age and edaphic variables (Pregitzer and Euskirchen, 2004). As a result, carbon density and sequestration potential vary by location, type of agroforestry system, and must be calculated on a regional and species-by-species basis. Furthermore, different ecosystem components (vegetation, detritus, and soil) react to changes in these regulating variables in different ways (Gower *et al*., 1997; Law *et al*., 2003; Martin *et al*., 2005). As a result, knowing the factors that influence carbon storage and distribution in distinct agroforestry system components is critical for forecasting carbon balance responses to climate change and mending agroforestry practices.

India's annual per capita CO_2 emission has doubled in almost 50 years and increased from 0.6 MT in 1950 to 1.2 MT in 2004 (Sharma *et al.*, 2006). Sequestering CO_2 from point sources or atmosphere through natural techniques (afforestation, reforestation, natural regeneration of forests and the adaptive agriculture, etc.) is economically and ecologically sound in increasing the carbon storage capacity of the terrestrial ecosystems. Hence; increased tree plantation surface on wasteland, as well as increased tree density on farmland, have long been suggested as ways to slow the rate of CO_2 buildup in the atmosphere (Dyson, 1977). For two reasons, a realistic estimation of carbon density at any given time is critical, firstly, to tell if plant has the ability to absorb carbon or not and secondly, determining net carbon flux to and from soils using time series of carbon stock in vegetation (Goodale *et al*., 2002). It is important to assess the practical potential of Carbon Sequestration (CS) by agroforestry systems as globally, 630 Mha area is expected to be available for agro-forestry, which has the potential to sequester 586 MT of carbon per year by 2040 (Watson *et al.*, 2000). Agroforestry systems are considered to provide a variety of ecosystem services, but there has been little evidence in the literature to back up these claims. Three prospective ecosystem services and environmental advantages of agroforestry are: (1) Carbon sequestration, (2) biodiversity preservation, and (3) soil enrichment. Agroforestry is a good balance since it improves carbon storage on land while also potentially improving agricultural productivity.

Although, agroforestry systems (AFS) are not primarily designed for carbon sequestration, there are many recent studies to substantiate the evidence that agroforestry systems can play a major role in storing carbon in Above-ground biomass (Murthy *et al.*, 2013) as well as in below ground biomass (Nair *et al.*, 2009). The carbon sequestration potential of agroforestry land use system has quite recently drawn attention especially since the recognition of agroforestry by the Kyoto protocol as a viable option for alleviating greenhouse gas emissions and climate change. Various researches have proven the might of agroforestry in retaining carbon in above and below ground as compared to the tree-less land use systems.

Given, future greenhouse/climate change forecasts, the balance between carbon sequestration (storage) in various sinks such as soil and vegetation versus that released to the atmosphere as carbon dioxide (CO_2) is currently a matter of contention. Although studies have been conducted to work out the carbon sequestration potential of various plantations (Sharma and Singh, 2010; Shah *et al.*, 2013; Devi *et al.*, 2013 and Kaur and Kaur, 2016) and traditional agroforestry systems (Goswami *et al.*, 2013; Rajput *et al.*, 2016; Gupta *et al.*, 2017; Singh *et al.*, 2017) of the north-western Himalayas. Therefore, different land use patterns in Himachal Pradesh's mid-hill and sub-humid regions might well be potential carbon sequestration sources which sequester carbon and provide numerous ecosystem services, economic and environmental gains at different levels.

The Department of Silviculture and Agroforestry has carried out a lot of tree species plantation and agroforestry model development operations in the University campus since the 2000s. But, as of now, no systematic attempts have been made to analyze the newly developed agroforestry systems for their carbon sequestration and soil enrichment potential vis-à-vis traditional agroforestry systems of the region. In the present study, precedence was given to such agroforestry systems which are farmer oriented *viz.*, fruit based, fodder based, fire wood based and silvipastures. Hence, the present study “Evaluation of established Agroforestry systems for their carbon sequestration and soil enrichment potential in mid-hills of Himachal Pradesh” will be carried out with the below mentioned objectives:

i) To quantify the biomass production and carbon sequestration potential of different agroforestry ecosystems in mid-hill zone of Himachal Pradesh;
ii) To assess the soil enrichment potential of the different agroforestry systems.

Chapter-2

REVIEW OF LITERATURE

Agroforestry is a major practice around the globe but, has come in limelight recently for the role it can and will play in mitigating all the global climatic threats being faced by the world since past few decades. Apart from agriculture, the farming community has adopted diversified land use systems, of which, agroforestry systems appear most appealing because agroforestry products are substitutes for similar products obtained from natural forests and several other benefits, along with sequestering carbon. A lot of studies have been conducted on the prowess of agroforestry systems as modus operandi for carbon storage, soil enrichment and economic feasibility. To promote this multi-faceted practice among the masses, further advancements need to be encouraged, for which, the prior studies need to be taken cognizance of. Therefore, an attempt has been made to examine previous works on carbon sequestration and soil enrichment potential in this chapter, and available literature pertaining to the present study have been reviewed under the following subheads:

2.1 Carbon sequestration potential
  2.1.1 Biomass and carbon stock in different components of systems
  2.1.2 Carbon sequestration by systems
2.2 Soil enrichment potential
  2.2.1 Soil physico-chemical properties
  2.2.2 Soil microbiological properties

2.1 CARBON SEQUESTRATION POTENTIAL

Carbon sequestration studies are rapidly progressing worldwide because of the increasing concentrations of atmospheric carbon dioxide (CO_2) which is leading to problems *viz*. climate change, global warming, seasonal changes affecting agriculture and natural environmental cycles, etc. To check these issues and avert further damage, sequestration of greenhouse gases (GHGs) especially CO_2 is very necessary. Therefore, carbon sequestration studies are of great significance with respect to trees and have been studied widely throughout the globe, especially since past three to four decades.

2.1.1 Biomass and carbon stock in different components

Carbon stock in terrestrial pools include the above ground plant biomass, such as timber, fuel wood and Below-ground biomass such as roots, soil microorganisms, and all the forms of organic and inorganic C in soils including deep root zone.

a). Vegetation

Samra *et al.* (1999) studied various silvipastoral systems on boulder marginal lands in Doon valley needing rehabilitation and simultaneously meeting the biomass requirements of poor farmers. Four tree species: *Albizia lebbeck*, *Bauhinia purpurea, Grewia optiva, Leucaena leucocephala* and two grass species *i.e. Chrysopogon fulvus* and *Eulaliopsis binata* were analysed. It was observed that biomass production was highest in case of grass with *Bauhinia purpurea* (2,929 Kg ha^{-1}) and then, *Grewia optiva* (2,372 Kg ha^{-1}), both appearing to be most suitable tree species with *Eulaliopsis binata*.

Rao *et al.* (2000) at Acharya NG Ranga Agricultural University, Rajendranagar campus, Andhra Pradesh, carried out an experiment on 11 multipurpose tree species was undertaken on red sandy loam soils (India) *Acacia albida*, *A. auriculiformis*, *A. nilotica*, *A. tortilis*, *Albizia lebbeck*, *Azadirachta indica*, *Dalbergia sissoo, Leucaena leucocephala*, *Dendrocalamus strictus*, *Eucalyptus camaldulensis* and *Tamarindus indica*. *Dalbergia sissoo* produced the most biomass (214.6 MT ha^{-1}), followed by *L. leucocephala* (187.8 MT ha^{-1}) and *A. auriculiformis* (162.4 MT ha^{-1}). Similar trend was observed for highest maximum mean annual biomass production: *D. sissoo* (23.8 MT ha^{-1}) followed by *L. leucocephala* (20.9 MT ha^{-1}) and *A. auriculiformis* (18.0 MT ha^{-1}). Whereas, in case of foliage output, *L. leucocephala* (16.8 MT ha^{-1}) stood first, followed by *A. auriculiformis* (12.0 MT ha^{-1}) and *E. camaldulensis* (9.9 MT ha^{-1}).

Carbon sequestration in Indian agroforestry varies from 19.56 Mg Cha^{-1} in north Indian state of Uttar Pradesh to a carbon pool of 23.46–47.36 Mg Cha^{-1} in tree-bearing arid agro-ecosystems of Rajasthan, as observed by Pandey (2002).

Nair *et al.* (2009) showed that the carbon sequestration potential of agroforestry systems was remarkable than single-species crop or pasture systems because of their apparent capacity to collect and use growth resources (light, nutrients, and water). The amount of carbon stored in AFS is estimated to be between 0.29 and 15.21 Mg ha^{-1} yr^{-1} Above-ground and 30 to 300 Mg ha^{-1} yr^{-1} in the soil up to a depth of one metre. Thus, tree-based agricultural systems stored more carbon in deeper soil layers near the tree than treeless systems; higher soil organic carbon content was linked to better species diversity and tree abundance.

Singh and Lodhiyal (2009) conducted studies in eight-year-old *Populus deltoides* agroforestry plantations in Terai region of Central Himalayas. They observed a total biomass of 202.59 MT ha^{-1}, of which, 78.68 per cent was Above-ground and 21.32 per cent was the below ground biomass.

Singh and Rai (2012) studied biomass production of 30 bamboo species in a bamboosetum. Among all the species, *Bambusa bambos*, *B. balcooa*, *B. cacharensis*, *B. nutans, B. pallida, B. tulsa*, *Dendrocalamus giganteus*, *D. hookeri*, *D. sikkimensis*, etc. are the world's highest biomass producer 494.67 ± 260.36 MT ha^{-1}. In most bamboos, the culms constituted more than 90 per cent of the total biomass such as in *Arundinaria hirsuta, A. mannii*, *B. bambos* and *B. balcooa*. The leaves and the branches of *S. polymorphum* constituted around 40 per cent of the total biomass. The total biomass production in bamboo showed a significant positive correlation with the height and thickness of the culms, the leaf length and number of internodes per culm.

Gaur and Gupta (2012) studied carbon storage in soil plant systems in relation to site conditions under *Populus deltoides* based agroforestry system. Top layer of the soil was analyzed and the soil organic carbon (SOC) pool under *Populus deltoides* agroforestry system was higher at Kalesar at 22.31-20.28 Mg Cha^{-1} against 19.63-30.11 Mg Cha^{-1} at Salimpur. The Carbon storage varied from 18.92 to 71.02 Mg Cha^{-1} at Kalesar and 14.78 to 56.91 Mg Cha^{-1} at Salimpur. Agroforestry system with wheat crop was 3.70-3.5 3 Mg Cha^{-1} in Salimpur and 3.84-3.68 Mg Cha^{-1} in Kalesar.

Zhuang *et al.* (2015) analysed Moso bamboo (*Phyllostachys pubescens*) stands in the forests and concluded that total carbon biomass was 14 Kg culm^{-1}. The total biomass carbon storage on an average, was approximated at 54.6 Mg ha^{-1} with soil Carbon storage being 90.6 Mg ha^{-1} up to 60 cm soil depth. The total Carbon storage estimated was 145.3 Mg Cha^{-1}. The removal of annual yield by harvest was recorded around 3.97 Mg ha^{-1} *i.e.* 7.3 per cent of the total bamboo biomass Carbon.

b). Soil

Schimel (1995) stated that at global level, the amount of carbon stored in soil may be almost equivalent to the amount stored in vegetation and in the atmosphere combined. A substantial portion of carbon fixed by vegetation is transferred to the soil annually (Raich and Nadelhoffer, 1989), a portion of which is refractory material with very slow rate of replacement, the rest decomposes relatively rapidly and is returned to the atmosphere as CO_2 (Falloon and Smith, 2000).

Sanneh (2007) studied the various land use systems for their soil organic carbon storage potential and concluded the forest land system to be displaying the maximum value of soil organic carbon stock, 108.99 Mg Cha^{-1} followed by agrihorticulture with 105.46 Mg Cha^{-1}, agrisilviculture 40.40 Mg Cha^{-1}, grasslands 36.37 Mg Cha^{-1} and silvipastoral 33.54 Mg Cha^{-1} in the top layer of soil up to 40 cm deep. The organic carbon was much higher in the top 0-20 cm layer compared to the 20-40 cm deep layer.

Nair *et al.* (2010) reported that studies on carbon sequestration in soils of India and rest of the world revealed a general trend of increasing SCS in agroforestry as compared to other land-use practices (with the exception of forests). Overall, in terms of SOC content, the land-use systems were ranked in the order: forests > agroforests > tree plantations > arable crops.

Chauhan *et al.* (2011) investigated the carbon sequestration capacity of poplar block plantations for one to six years. They found that litter and roots in the surface layer of soil (0-15 cm) under poplar blocks increased soil organic carbon levels when compared to open areas with just wheat crops. From treeless site up to five year old planting, the total organic carbon concentrations varied from 6.91 to 8.44 Mg ha^{-1}, an increase of 22.14 % under fifth-year planting compared to the tree-free control plot.

Gupta *et al.* (2013) worked in Indo-gangetic plains conducting a stimulation study for carbon sequestration and soil organic carbon (SOC) of agroforestry systems. They concluded carbon sequestration potential of agroforestry systems increased with increasing tree density per hectare and soil organic carbon in the baseline ranging from 8.13 to 9.12 Mg Cha^{-1} and could be increased up to 24.51 Mg Cha^{-1} in Dinajpur and Ludhiana district, respectively. Further, carbon sequestration in soil was determined on the basis of CO_2 FIX models. It was observe that agroforestry systems with 37.95 trees of Poplar/Eucalyptus ha^{-1} in Ludhiana were able to sequester 0.513 Mg Cha^{-1} yr^{-1} in soil. Similar results, outside India reported by Post and Kwon (2006) inferred that the average rate of SCS under tree-based systems ranged between 0-3 Mg Cha^{-1} yr^{-1}.

A study was conducted by Kanime *et al.* (2013) on biomass production and carbon sequestration in several tree-based systems in the Central Himalayan tarai region, found the highest soil organic carbon stock (48.99 Mg ha^{-1}) under *Dalbergia sissoo*. . The larger accumulation of leaf litter, organic carbon, and reduced bulk density of soil in the system were linked to the highest carbon stock under *Dalbergia sissoo*.

Goswami *et al.* (2013) investigated biomass and carbon sequestration in several agroforestry systems in a Western Himalayan watershed, found that the total C pool on disused soils (0–40 cm) was the greatest, followed by silvipasture and agrisilvihorticulture systems. For the agrihortisilviculture system, silvipasture, agrisilvihorticulture, and agrisilviculture systems, C stocks in soil (0–40 cm) surpassed C stocks in plants by a ratio of 15.81, indicating a greater C mitigation potential of 1.71, 1.52, and 1.43 Mg Cha^{-1} yr^{-1}, respectively.

Mangalassery *et al.* (2014) investigated carbon sequestration in agroforestry and pasture systems in arid northwestern India, found that silvipastoral systems (*Acacia tortilis* + *Cenchrus ciliaris*, *Acacia tortilis* + *Cenchrus setigerus*, *Azadirachta indica* + *Cenchrus ciliaris*, *Azadirachta indica* + *Cenchrus setigerus*) sequestered 36.3 percent to 60.0 percent more soil organic carbon stock in contrast to tree systems (*Acacia tortilis*, *Azadirachta indica*) and 27.1-70.8 per cent more compared to pasture systems (*Cenchrus ciliaris*, *Cenchrus setigerus*), indicating that silvipastoral systems can help in better carbon sequestration than tree or pasture systems.

2.1.2 Carbon sequestration by systems

Agroforestry, according to Pandey (2002), is an important land use system in the context of the global carbon cycle for two primary reasons: the tree component in agroforestry systems fixes carbon from the atmosphere and stores it until they are cut or die and helps to reduce pressure on natural forests by supplementing some of the products obtained in natural forests. He also stated that agroforestry systems may absorb 0.2 to 3.1 Mg Cha^{-1} yr^{-1} and have the potential to sequester 7 Gt of carbon globally between 1995 and 2050.

Albrecht and Kandji (2003) analysed carbon storage data in some tropical agroforestry systems to discuss the role they can play in reducing CO_2 in the atmosphere. The Carbon sequestration potential of agroforestry systems was estimated between 12 and 228 Mg ha^{-1} with an average value of 95 Mg ha^{-1}. Therefore, based on earth`s area suitable for practising agroforestry (585-1,215 x 10^6 ha), 1.1-2.2 BT carbon could be stored in the terrestrial ecosystems over the next 50 years.

Central Agroforestry Research Institute (CAFRI) Jhansi has been working on carbon sequestration potential of various agroforestry systems since 2000 and released its official document “Vision 2025” in 2007 and “Vision 2050” in 2013. CAFRI as a partner in ICAR scheme NICRA (National Innovations on Climate Resilient Agriculture) is assessing the carbon sequestration potential of selected AFS in the country. The survey (32 districts of 12 states) for existing trees on farmers’ fields in these districts varied from 2 to 204 ha^{-1}. The standing biomass in the tree component varied from 0.58 to 113.12 Mg $DMha^{-1}$, whereas, the total biomass (tree and crop) ranged from 4.96 to 123.58 Mg $DMha^{-1}$. The soil organic carbon ranged from 4.28 to 24.13 Mg Cha^{-1}. The CSP of existing AFS at district level has been estimated to range from 0.05 to 2.78 Mg Cha^{-1} yr^{-1}. Based on this study, estimated value of trees per ha was 19.44 and average CSP of existing AFS at country level was 0.34 Mg Cha^{-1} yr^{-1}or equivalently AFS in India has the potential to mitigate 1.245 Mg Cha^{-1} yr^{-1}.

Kaul *et al.* (2010) used a dynamic growth model (CO_2FIX) for estimating the carbon sequestration potential of *Eucalyptus*, poplar, sal and teak forests in India. The results indicated that long-term total carbon storage ranged from 101 to 156 Mg Cha^{-1} yr^{-1}, with the largest carbon stock in the living biomass of long rotation sal forests (82 Mg Cha^{-1}). The net annual carbon sequestration rates were achieved for fast growing poplar (8 Mg Cha^{-1} yr^{-1}) and *Eucalyptus* plantations (6 Mg Cha^{-1} yr^{-1}) followed by moderate growing teak forests (2 Mg Cha^{-1} yr^{-1}) and slow growing long rotation sal forests (1 Mg Cha^{-1} yr^{-1}). Due to fast growth rate, short rotation plantations, in addition to carbon storage rapidly produce biomass for energy and contribute to reduced greenhouse gas emissions.

Nair *et al.* (2010) analyzed that the CSP of trees varies with species, structure, age and spatial distribution. The tree density ranged from 312–800 trees ha^{-1} (usually preferred by the farmers in planted AFS), the CSP varied in the range of 0.25 to 19.14 Mg Cha^{-1} yr^{-1}. The world scenario of carbon stored in AFSs ranged from 0.29 to 15.21 Mg Cha^{-1} yr^{-1} in above ground, and 30–300 Mg Cha^{-1} yr^{-1} up to a depth of 1 m in the soil (the age varied from 4 to 35 years).

Luedeling *et al.* (2011) stated that agroforestry can raise carbon stocks of agricultural systems which can potentially be sold as CO_2 emission offsets. Biophysical, technical, economical and practical information about agroforestry systems such as live fences, parklands and home gardens was collected and it was found that they had substantial carbon stocks and accumulated 0.2-0.8 Mg Cha^{-1} yr^{-1}. It was observed that rotational woodlots and improved fallow lands sequestered C faster, but only during fallow phases.

Pathak *et al.* (2011) compiled the information on carbon sequestration potential of different cropping systems of Indian agriculture studied through different long term experiments (LTE's) in different agro-climatic zones of India and reported that C sequestration rate varied from 0.02 Mg Cha^{-1} yr^{-1} (in NPK treatment for soybean-wheat cropping systems over the 28 years duration at Jabalpur in Madhya Pradesh) to 1.2 Mg Cha^{-1} yr^{-1} (in NPK+FYM treatment for cassava based systems over 13 years duration at Trivandrum, Kerala) and 0.59 Mg Cha^{-1} yr^{-1} carbon sequestration potential of rice-wheat cropping system in no-tillage conditions. The CSP of 30 year duration pure crop based LTE's ranged from 0.02 to 0.10 Mg Cha^{-1} $yr^{-1}$with an average value of 0.062 Mg Cha^{-1} yr^{-1}. However, majority of published reports assents that carbon sequestration in pure cropping systems is only feasible, when some organic matter (FYM, green manure, straw, and some other tree material used for growing crops) is used.

Pragasan and Karthick (2013) estimated the potential of carbon stock sequestered *Eucalyptus* plantation (EP) and mixed species plantation (MP) in Bharathiar University campus at Coimbatore, India. Total carbon stock (TCS) of all live trees was determined by non-destructive method. Tree density and total biomass were 320 & 468 stems ha^{-1} and 48.05 & 39.64 MT ha^{-1} sites EP and MP, respectively. Total carbon stock sequestered by the two plantations was 27.72 and 22.25 MT ha^{-1} respectively. This reveals that TCS increases with increase in tree density and biomass, results show that the carbon sequestration potential of the fast-growing Eucalyptus plantation is 11 per cent higher than the mixed species plantation.

Wang *et al.* (2014) studied the carbon sequestration in different forest categories between 2004 and 2008 to evaluate the average carbon storage to be 360 Mg Cha^{-1} with 300

Mg Cha^{-1} in vegetation and 59 Mg Cha^{-1} in top layer of the soil (0-1m). The total carbon sequestered ranged from 20 Mg Cha^{-1} in bamboo forest to 110 Mg Cha^{-1} in broad-leaved forest, during the study period.

Tanwar *et al.* (2019) analysed carbon sequestration potential of eight land-use systems of arid western Rajasthan. The biomass C stock was recorded maximum in farm forestry of *Acacia tortilis* (31.4 Mg Cha^{-1}) followed by *Prosopis cineraria* and *Hardwickia binata* based silvoarable systems (8.8 and 10.6 Mg Cha^{-1}). Soil C stock was also maximum in farm forestry (47.6 Mg Cha^{-1}) followed by *Ziziphus* based systems (32.5–33.9 Mg Cha^{-1}). The total C sequestered (biomass plus soil) over a period of nineteen years was in the order: farm forestry (49.80 Mg Cha^{-1})> silvoarable systems (11.0–13.3 Mg Cha^{-1})> hortipastural system (8.3 Mg Cha^{-1})> agrihorticulture system (5.5 Mg Cha^{-1})> silvopasture (5.4 Mg Cha^{-1}) and sole pastures (5.3 Mg Cha^{-1}) compared to (–1.0 Mg Cha^{-1}) in sole cropping.

2.2 SOIL ENRICHMENT POTENTIAL

Although, agroforestry community has long been convinced of its soil health benefits, it remains to be fully accepted by the mainstream agriculture community, thus, large number of studies have been carried out world over to establish the soil enriching character of agroforestry. Soil improvement under trees and agroforestry systems is in great part related to increases in organic matter, whether in the form of surface litter or soil carbon. Therefore, besides their role in above-ground carbon sequestration, agroforestry systems also have a great potential to increase carbon stocks in the soil and for mitigation of greenhouse gas emissions to reduce climate change. Increases in organic matter, whether in the form of surface litter or soil carbon, are closely linked to soil improvement beneath trees and agroforestry systems.

2.2.1 Soil physico-chemical properties

Evans and Rombold (1984) observed that *Melia azederach* has the potential to improve soil by adding organic carbon and nitrogen along with improving soil aeration. Its roots had the potential to retrieve nutrients leached below the root zone.

Hazra *et al.* (1990) tested silvipastoral systems with various tree species, *viz.*, *Leucaena leucocephala, Acacia nilotica, Albizia lebbeck* and *Albizia procera* against open grasslands without trees for 7 years and reported that *Leucaena leucocephala* significantly decreased soil pH and EC (Electric conductivity) and increased the nutrient status of the soil as compared to the open grasslands.

Dhyani *et al.* (1990) studied the effects of five tree species *viz., Bauhinia purpurea, Grewia optiva, Leucaena leucocephala, Eucalyptus tereticornis* and *Ougenia oojeinensis* on the nutrient status in 0-15cm soil depth and concluded that N, available P_2O_5, available K_2O, exchangeable Ca and Mg were higher in the soil under the tree species compared to treeless areas.

Szott *et al.* (1991) studied the nature of soil constraints in the humid and semi-arid tropics and how these limitations affect plant/soil interactions related to nutrient additions, losses and cycling via litter-soil organic matter (SOM) pathways in agroforestry systems and concluded that the ability of agroforestry systems to enhance nutrient availability of infertile soils is quite limited as compared to systems established on fertile soils. Though, agroforestry systems can play an important role in reducing nutrient losses on both. Litter production and quantities of nutrients recycled in litter are greater on fertile than on infertile soils, however, management techniques for hastening nutrient fluxes through pruning appear to hold promise for increasing plant productivity on the latter soil. Litter production, decomposition, and soil organic matter dynamics are key processes affecting soil fertility and the sustainability of agroforestry systems based on number or limited use of chemical fertilizers.

Nair (1993) inferred that the atmospheric biological nitrogen fixation has nutrient cycling potential in agroforestry systems and plays significant role in resolving these problems. In case of legume, most of the nitrogen fixing tree species are from Mimosoideae and Caesalpinioideae. Within these sub-families, 98, 60 and 30 per cent of the tested mimosoids, papilionoids and caesalpiniods, respectively showed potential to fix atmospheric nitrogen. The non-legume families, such as Betulaceae, Casuarinaceae, Chrysobalanaceae, Coriariaceae, Eleagnaceae, Myricaceae, Rosaceae and Ulmaceae also showed N_2 fixing capabilities. There are more than 650 tree species known to fix nitrogen. Biological nitrogen fixation takes place through symbiotic and non-symbiotic means. Symbiotic fixation occurs through the association of plant roots with nitrogen-fixing microorganisms. Many legumes form an association with the bacteria Rhizobium while the symbionts of a few non-leguminous species belong to a genus *Frankia*. Non-symbiotic fixation is affected by free-living soil organisms, and can be a significant factor in natural ecosystems, which have relatively modest nitrogen requirements from outside systems. Also, nutrients released from the fine root biomass are another important pathway of the improving soil nutrient health. Trees allocate a large portion of gross primary production to Below-ground for the production and maintenance of roots and mycorrhizae (Nair *et al.*, 2009).

Alegre and Cassel (1996) investigated a shift from slash-and-burn to constantly planted agricultural systems, that is underway in humid tropics with the purpose to characterise the dynamics of soil physical properties under slash-and-burn and other systems in Yurimaguas, Peru. Different land-clearing methods and post-clearing management systems were investigated for their influence on soil physical attributes. Bulk density was found to be lower in the agroforestry systems with trees or cover crops (multistrata, peach palm production, shifting agriculture low input and high input continuous cropping), where the bulk density of bedded and flat planted soil was 1.14 and 1.29 g cm^{-3}, respectively. Similarly, porosity was also affected with infiltration rate decreasing from 420 mm h^{-1} to 35 mm h^{-1} after cutting. Hence, they advocated well-managed alternatives against slash-and-burn to can prevent soil deterioration, maintain soil fertility, and increase long-term productivity.

Nayak (1996) studied soil chemical properties under 9-year-old plantations of *Eucalyptus tereticornis*, *Leucaena leucocephala* and *Melia azederach* and reported that pH was reduced and nutrient values increase under tree planted area compared to unplanted area. Also, pH reduction was relatively higher in the top layer as compared to the deeper layers. The order of efficiency of the species was: *Eucalyptus tereticornis* > *Leucaena leucocephala* > *Melia azederach*.

Mathew *et al.* (1997) collected soil and litter samples from plantation of multipurpose tree species and observed lower pH under *Phyllanthus emblica* (amla), higher available P and K under *Casuarina equisetifolia* and higher organic Carbon and total nitrogen under *Paraserianthes falcataraia* and *Acacia auriculiformis*. They further reported that plantations significantly influence the chemical properties and moisture status of the soil.

Mongia *et al.* (1998) worked on improving effects of forest trees on acidic soils in Haryana. It was found that growing *Acacia nilotica* for 3 years, the organic matter, Fe and Mn content increased while pH, electrical conductivity and $CaCO_3$ content of soil lowered.

Saha *et al.* (1999) investigated quantitative multivariate sense, accessible soil moisture, soil physical qualities, and nutrient availability, different silvipastoral systems of pure Eucalyptus, Bhabbar (*Eulaliopsis binata*), Eucalyptus + Bhabbar grass and Eucalyptus + Vetiver. in the rainfed foothill region of north India. The organic carbon content was higher (2.5 g Kg^{-1}) in the silvipastoral systems than in the cropped land, while the pH and soil texture were nearly identical in all systems (1.5 g Kg^{-1}). In comparison to other plots, the pure Bhabbar plot (14 Kg ha^{-1}) had a significant increase in phosphorus (7.5 Kg ha^{-1}). Potassium availability ranged from 78 to 113 Kg ha^{-1}. Cumulative infiltration, absorptivity and moisture content (90-120 cm depth) of the soil, as well as soil chemical characteristics such accessible phosphorus and organic carbon were stated to be key discriminators.

Jobaggy and Jackson (2001) tested three well established predictions: the most limiting nutrients for plants would have the shallowest average distributions across habitats; along a gradient of soil types with increasing weathering-leaching intensity, the limiting nutrients would be proportionally more abundant due to preferred cycling by plants and the vertical distribution of a limiting nutrient would be shallower as the nutrient grew more scarce. Plant-cycled nutrients like N, P and K were more concentrated in the topsoil (upper 20 cm) than nutrients like Na and Cl, which are normally less limiting for plants. Shallowest to deepest ranking of vertical distributions among nutrients on a global scale was: P > K > Ca > Mg > Na= Cl= SO_4.

Aggarwal *et al.* (2005) studied litchi (*Litchi chinensis* Sonn) and mango (*Mangifera indica)* plantation based systems for soil properties. Soil samples were taken up to 90 cm depths around trees at various distances (i.e., 1,2,3,4, and 5 m) from the tree trunk. DTPA iron (Fe), manganese (Mn), and zinc (Zn) concentrations were substantially higher in soils under both the systems, although DTPA copper concentrations were significantly lower in soils under mango trees (Cu).

Jha and Gupta (2005) analysed top 1 foot of soil under six land use systems, agriculture, agroforestry, barren land, forests, pastures and plantations for comparing their carbon storage in soil. Highest carbon storage potential was shown by forests 120.0 t ha^{-1}, 83.6 t ha^{-1} by agroforestry followed closely by plantations 80.5 t ha^{-1}, agriculture 66.0 t ha^{-1} pastures 40.0 t ha^{-1} and barren land 20 t ha^{-1}. They implicated tall size of vegetation to be the reason for higher carbon sequestration.

Amusan *et al.* (2006) investigated five soil parameters bulk density, gravel content, soil pH, organic matter content, and accessible phosphorus under six land use systems *viz.*

Cacao plantation, legume-planted fallow, bush fallow with mostly herbaceous weed species, cassava-cowpea intercropped plot, continuous maize-soybean cropping plot, and secondary woodlands. The tree crop plot has a gravel concentration of 65.52 per cent, bulk density was slightly greater in continuous cropping plots, such as cassava/cowpea plot 1.54 g cm^{-3} and minimum was recorded in tree crop at 1.54 g cm^{-3}. The usage of heavy machinery and lower organic matter addition on the plot may explain the somewhat higher bulk density in continuous cultivation plots compared to other land use types.

Augustine *et al.* (2006) evaluated the success of agroforestry treatment in improving the sustainability of mountainous agricultural systems in terms of soil nutrient status and erosion control using alley cropped Maize (*Zea mayes*) and pastures with nitrogen fixing *Gliricida sepium* trees. Significantly high SOM (soil organic matter) was reported compared to plots with no alley-cropping and higher total nitrogen (0.16 per cent) in comparison to only 12 per cent non-agroforestry plots. However, significant differences in available soil P were not observed.

Saha *et al.* (2007) studied five multipurpose tree species (*Alnus nepalensis, Gmelina arborea*, *Michelia oblonga*, *Parkia roxburghii* and *Pinus kesiya*) maintained under normal recommended practices at ICAR complex, Umiam, Meghalaya, to select tree species having capabilities to bio-ameliorate and provide higher economic returns in highly degraded soils of the north-eastern hill regions of India. It was concluded that *Alnus nepalensis*, *Michelia oblonga* and *Pinus kesiya* were best suited for the purpose. With greater surface cover, constant leaf litter fall and extensive root systems increased the soil organic carbon by 96.2 per cent, improved aggregate stability by 24.0 per cent, available soil moisture by 33.2 per cent, and in turn reduced soil erosion by 39.5 per cent.

Singh *et al.* (2007) experimented on a five-year-old poplar plantation with two row directions and three spacings, to study litter fall addition and nutrient returns. The concentrations of several macro and micronutrients varied dramatically across months, but there was no discernible pattern. During November and December, the return of several nutrients was much higher than in other months. In the different spacings, the total return of Fe were reported to be highest (6,854-7,767 g ha^{-1}) while the total return of Cu were the lowest (103.1-115.6 g ha^{-1}).

Das and Chaturvedi (2008) studied five agroforestry tree species *viz.*, *Acacia auriculiformis*, *Azadirachta indica*, *Bauhinia variegta*, *Bombax ceiba* and *Wendlandiaex serta* at a research farm in Rajendra Agricultural University, Pusa, Bihar and concluded that although all these species had improved soil fertility status, but, *Acacia auriculiformis* outperformed all others.

Yimer *et al.* (2008) scrutinised various soil chemical properties, such as soil pH, exchangeable base concentrations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}), CEC, and percentage base saturation (PBS) in three nearby land-use types: agriculture, grazing land, and natural forest in agriculture, grazing, and forest soils in Ethiopia's Bale Mountains. The soil nutrients Ca^{2+} and Mg^{2+} levels changed greatly depending on land use and soil depth, while Ca^{2+} and Mg^{2+} levels varied with soil depth. The conversion of a native forest habitat to agriculture raised soil pH and PBS while lowering Na^{+} and K^{+} levels. When compared to the natural forest, the CEC in agriculture was reduced by 37.7% (2.6 percent each year), which was attributed to lower organic matter concentrations.

Rawat *et al.* (2009) stated that litter production in agroforestry systems mainly depends upon the nature of tree-crop species and factors *viz.*, climatic, edaphic, topographic and biotic as they affect plant growth and phenology. The chemical properties of the litter include Nitrogen content, C: N ratio, phosphorus content, C: P ratio, phenolics, phenolics to N or P ratio, lignin content and lignin to N ratio. Litter nutrients release depends upon not only litter composition but also soil type, microbial communities and soil properties. The high values of C:N ratio, C:P ratio, phenolics, phenolics to N or P ratio, lignin content and lignin to N ratio lower down the decomposition rate, whereas, high nitrogen and phosphorus content accelerate decomposition rate.

Illany *et al.* (2010) studied the effect of monoculture of *Ilex paraguariensis* and its intercropping with *Araucaria angustifolia* in two different age classes of 30 and 50 years old for soil fertility status. Various chemical properties of soil were analysed to evaluate Al, C, Ca, Mg, N, P, K, CEC and pH in two topsoil layers (0-5 cm and 5-10 cm). In younger plantations, the agroforestry sites had lower nutrient value than the pure stands of *Ilex paraguariensis*. However, the pure stands were also more prone to soil nutrient degradation with time as compared to the agroforestry sites particularly in C, Ca, CEC and N for both soil layers.

Singh *et al.* (2010) compared soil nutrient status of Poplar based agroforestry systems at PAU, Ludhiana with pure stands of 13-year-old *Acacia catechu*, *Albizia lebbeck*, *Dalbergia sissoo*, *Eucalyptus tereticornis*, *Azadirachta indica*, *Leucaena leucocephala* and *Melia azederach* and their adjoining open areas (Control) at PAU regional station, Bathinda. Soil was studied depth wise for soil organic carbon (SOC) and available N, P and K. Results showed slightly higher SOC and available nutrients in surface layers (0-15 cm) vis à vis deeper layers irrespective of the tree species. Also, the soil nutrients under tree species were far higher compared to the open field (Control). S increased by 7.25 g Kg^{-1} under *Albizia lebbeck*, 7.03 g Kg^{-1} in *Acacia arabica*, 6.94 g Kg^{-1} in *Dalbergia sissoo* and 6.88 g Kg^{-1} in *Leucaena leucocephala* compared to 3.81 g Kg^{-1} in control. Available N, P and K were also higher under these tree species.

Kumar (2011) inferred that the floral diversity of agroforestry systems creates suitable conditions for soil microbes, which play a major role in litter decomposition and release of nutrients. In N_2 fixing tree species, litter decomposes faster as compared to non N_2 fixing tree and crop species. Any dip in litter N concentration, increase lignin content and elevated atmospheric CO_2 concentration marked decrease in rate of litter decomposition and timing of nutrient release but the largest change is caused by environmental factors, such as temperature, moisture and evapotranspiration, etc.

Chisanga (2012) studied the carbon storage and soil properties of different land use systems in dry temperate North West Himalayas. He stated that all of the agroforestry systems had greater nitrogen levels, which was most likely owing to the yearly leaf litter production, fertilizer application, cattle grazing, and other anthropological factors.

Munishamappa *et al.* (2012) concluded that crop species contribute least as compared to perennial woody tree species in total litter production in agroforestry systems. Deciduous species contribute more in litter fall as compared to the evergreen species due to litter fall occurred throughout the year. The summer and spring season recorded higher litter fall and contributed 25% each, whereas, autumn season recorded least. Generally, wind velocity increases in summer and spring season which promote the leaves abscission.

Bhardwaj *et al.* (2013) investigated different soil properties in seven land uses, including agrihorticulture (AH), silvipasture (SP), agrisilviculture (AS), horticulture (H), forest (F), agriculture (A), and grassland (G), over three elevational gradients of 1500-1800 m, 1800-2100 m, and 2100-2400 amsl, and found that the maximum bulk density under horticultural land use system (1.207 g cm^{-3}), and lowest in forest and silvipasture (0.983 g cm^{-3}) and because of the concurrent reduction in bulk density with increasing altitude, the total soil organic carbon pool also decreased as the altitudinal range increased.

Yitbarek *et al.* (2013) studied the impact of land cover on the physicochemical parameters of soils in three land use types, namely forest, grazing and arable lands. The concentrations of soil OM, total N, CEC, exchangeable Mg and accessible micronutrients (Mn, Zn, and Cu) were lower in farmed land than in nearby forest area, respectively. The gazing area had considerably lower PBS and accessible micronutrients (Fe, Mn, Zn, and Cu) than the nearby forest land. However, no significant variations in soil OM, total N, CEC or accessible P were found between forests and grazing pastures. According to the findings of this study, soil quality and health were relatively maintained under the tree cover, whereas the influence on most parameters was negative on the soils of cultivated land, indicating the need for integrated soil fertility management to optimise and maintain favourable soil physico-chemical properties in the long run, which may be achievable under agroforestry based cultivations.

Sarvade *et al.* (2014) reported that trees on the field are the important component of the sustainable land use systems (agroforestry), which improves soil nutrient status by various processes, such as litter addition, decomposition, nutrient release, atmospheric N_2 fixation, nutrient pumping, etc. The nutrient loss through soil erosion is also controlled by tree species. The improved soil through agroforestry systems helps to meet increased food requirement and serve as an evergreen revolution.

Gardini *et al.* (2015) carried out investigation on changes in soil physical and chemical properties in Cacao based agroforestry systems for extended period of time in Peruvian Amazon. The physical properties such as bulk density, porosity, field capacity and wilting point have considerable effects on productivity of the systems. In general, bulk density was lower in surface soil layers and increased as soil depth increased (1.39 g cm^{-3} and 1.42 g cm^{-3}, respectively). They concluded that the management strategies and kind of vegetative cover can modify the soil physical qualities over time as, the lower the bulk density, the better it is for root development, especially in tree plantations, since with increase in soil bulk density, soil strength also rises and soil aeration declines, resulting in unfavourable impacts on root growth.

Negasa *et al.* (2017) investigated variation in soil properties under different land use types managed by small holder farmers in southern Ethiopia, finding that soil properties such as sand, clay, soil bulk density, electrical conductivity (EC), soil organic carbon (SOC per cent) and total nitrogen. All these soil parameters exhibited greater value in agroforestry land than that in cropland, indicating a considerable variance among land use types.

Pardon *et al.* (2017) studied spatial variability of soil organic carbon, acidity and nutrient status (N, P, K, Ca, Mg and Na) of the plough layers were analyzed on a set of 17 arable agroforestry fields comprising 6 young (<5 years) alley cropping fields and 11 fields bordered by a row of trees of moderate to older age (15–47 years) in Belgium. Significantly higher soil organic carbon and soil nutrient concentrations of N, P, K, Mg and Na were observed in the vicinity of trees in field boundaries, most likely resulting from the input of tree litter and nutrient-enriched throughfall water (for K and Na). Observed increases were strongly related to the distance from the tree row, resulting in a gradual change in soil conditions up to at least 30 m into the field. These results highlight the potential of middle-aged to mature tree rows to increase soil organic carbon stocks and nutrient availability for the agricultural crop in AFS.

Reddy *et al.* (2017) compared soil nutrient status of Teak (*Tectona grandis*) and bamboo (*Dendrocalamus strictus*) plantations at a agroforestry research farm in Nagpur to pure agriculture land. Soil samples were studied in two layers: 0-15 cm and 15-30 cm of teak (8-9 years old), bamboo (14-19 years old) plantations and farm lands. Soil was analysed for available N, P, K, exchangeable Ca and Mg, inorganic Carbon, organic Carbon and PH. The pH was quite high in cultivable land and lower in teak followed by bamboo. Bamboo had higher organic and inorganic Carbon, Sulphur and exchangeable Calcium and Magnesium compared to teak plantations and farmland. Available N and P was highest in teak followed by bamboo and farmland.

Costa *et al.* (2018) studied soil organic matter and CO_2 fluxes in small tropical watersheds, under forest and cocoa agroforestry. In the two agroforestry systems, managed Cacao based agroforestry system (MC) and unmanaged Cacao based agroforestry system (UC), Ca+ and Mg+ ions concentrations were likewise higher at depths of 0–20 metres, the values were higher as compared to PF, and there was no pattern in the concentration distribution. They also stated that reserved forests had lower Fe and H^+ + Al concentrations by several orders as compared to the MC and UC, with concentrations sometimes tending to grow with depth, though no discernible pattern was observed and similarly in total of exchangeable bases values.

Jiang *et al.* (2019) evaluated the hydrological process in soils which are critical for carrying and distributing water in rubber-based agroforestry systems. A correlation between water flow behaviours, soil physical qualities, infiltration patterns of soil showing distinct soil layers and variation patterns in water flow behaviour was observed. The soil physical qualities of forestry patches under *Hevea brasiliensis* (HB) and *Citrus reticulata* (CR) were shown to be superior to those of areas with no vegetation (NV) and the field capacity of the soil strata at depths of 20 cm to 60 cm rose by 26% in the CR plot and 8% in the HB plot. The field capacity, saturated water-holding capacity, and saturated hydraulic conductivity were all strongly affected by the soil bulk density, non-capillary porosity, and capillary porosity.

Matos *et al.* (2020) studied soil properties and litter quality under agroforestry systems of south-eastern Brazil. In case of soil physical qualities, the forest had the best aggregate stability and the lowest bulk density, implying that these soils may support higher water infiltration rates and better erosion management. The pasture, on the other hand, had the highest bulk density, indicating possible compaction problems may be due to poor grazing and soil fertility management. The bulk densities of the agroforestry system plots were all close to that of forest soil, implying that compaction difficulties had been mitigated or avoided since eight years when the agroforestry systems were established on degraded pastures.

Gusli *et al.* (2020) conducted a study in mountainous landscape of Sulawesi (Indonesia), and measured organic carbon concentration and soil physical attributes of different land cover types: secondary forest, multistrata cocoa–based agroforestry, and multistrata (mixed fruit and wood) agroforests in chronosequence. They measured five pools of C-stock, according to IPCC recommendations: soil bulk density (BD), macro porosity (MP), hydraulic conductivity (Ks) and accessible water capacity of the soil (AWC). Following forest conversion, soil compaction increased BD while decreasing MP, Ks, and AWC. In older agroforestry, AWC per meter of rooted soil profile increased by 5.7 mm per unit (g Kg^{-1}) increase in organic carbon. The repaired AWC can support evapotranspiration, which helps in climate change adaptation.

Kaur *et al.* (2020) studied and observed a poplar (*Populus deltoides* Bartr.) based agroforestry system (AFS) for 10, 20, and 30 years in order to assess the fractions of cationic micronutrients (Fe, Mn, Zn, and Cu). They reported that trees in major agricultural systems may help to alleviate micronutrient deficits by increasing the mobilization of micronutrients in the soil. At different depths, the residual fraction of all micronutrients was higher than the other fractions. The use of a poplar-based AFS resulted in the accumulation of total micronutrients and their different pools in the soil. Hence; the use of a poplar-based AFS resulted in the accumulation of total micronutrients and their different pools in the soil.

Sarkar *et al.* (2020) worked on three agroforestry systems: Kadamb (*Anthocephalus cadamba* Miq.) based agrisilvicultural system, Simarouba (*Simarouba glauca* DC) based agrisilvicultural system, Litchi (*Litchi chinensis* Sonn.) based agrihorticultural system and one open agroforestry system (without trees) to study the effects of agroforestry systems on soil micronutrient status up to 30 cm soil depth. DTPA extraction solution was used to assess available micronutrient cations (Copper, Zinc, Iron, and Manganese). According to the findings, all agroforestry systems had the ability to boost micronutrient levels. Over the control plot, the contents of both Simarouba had the highest micronutrient revival capability. In all plots, the presence of all micronutrients was far higher in the surface soil as compared to the lower soil.

Narender *et al.* (2021) carried out a study in the semi-arid region of Haryana, in Gillan Khera in the district Fatehabad. pH, electrical conductivity (EC), organic carbon, soil moisture, and accessible nitrogen, phosphorus, and potassium were all measured in soil samples. Under trees, the soil pH and EC declined more than under control (single wheat crop), dropping from 8.09 to 7.89 and 0.46 to 0.44 dSm^{-1}, respectively. At both soil depths, intercropped situations had greater levels of N, P, K, organic carbon (131.38,16.00, 301.10 (Kg ha^{-1}) and 0.46 percent, respectively) and soil moisture content. The increased amount of nutrients is justified by the extra moisture under shady conditions, which resulted in faster litter decomposition, mineralization, and nitrogen uptake as compared to full sunlight situations. Under the influence of trees, organic carbon and other beneficial changes occurred in the soil. Under the influence of trees, organic carbon and other beneficial changes occurred in the soil.

2.2.2 Soil microbiological properties

Arunachalam *et al.* (1999) explored the effect of soil characteristics on microbial populations, activity, and biomass in humid subtropical mountainous habitats of India. These parameters were monitored in slightly acid organic soils of major mountainous humid subtropical terrestrial ecosystems along a soil fertility gradient to examine the impact of soil properties on microbial populations, activity, biomass and perhaps to better understand the dynamics of microbial biomass. Soil respiration was lowest in the 7-year-old regrowth and natural grassland, despite the fact that fungus abundance was highest in the undisturbed forest. The MBC (microbial biomass carbon) was mostly determined by the soil's organic C condition and values in mature forest were generally greater than in natural grassland, 1-year-old jhum fallow, and 4-year-old alder plantation. They deduced that several soil parameters, particularly nutrient levels, had a significant effect on enzyme activity, soil respiration, bacterial and fungal populations, and microbial biomass.

Kaur *et al.* (2000) analyzed the role of agroforestry systems in enhancing soil organic matter status, microbial activity, and nitrogen availability in moderately alkaline soils at Karnal, Haryana. A rice–berseem crop cycle was used with agrisilvicultural systems of Acacia, Eucalyptus, and Populus, as well as rice–berseem and single species tree plantings. In tree-based systems, microbial biomass was 42 per cent higher (microbial C) and 13 per cent higher (microbial N) than in monocropping. In tree-based systems, microbial biomass immobilised 2.32–2.57 per cent of soil carbon and 4.08–4.48 per cent of soil nitrogen. The integration of trees with crops over 6–7 years enhanced soil carbon by 11–52 per cent. In comparison to monocropping, soil inorganic N levels were 8–74 per cent higher in tree-based systems, and nitrogen mineralization was 12–37 per cent greater. Agrisilvicultural systems have been found to be ecologically sustainable land-use systems for employing moderately alkaline soils due to enhanced soil organic matter content, expanded soil microbial biomass pool, and improved soil N availability.

Tangjang *et al.* (2009) studied three arecanut-based traditional agroforestry systems practised by two ethnic communities, the Kalitas and Nyishis, for investigating seasonal and depth-wise variation in bacterial and fungal populations. With an increase in soil organic C, total N, and accessible P, the soil organic C, total N, and available P dropped. Bacterial population was highest during spring and that of fungi during autumn. Nonetheless, the highest microbial counts were recorded in the topsoil (0-10 cm) layer except during the rainy season when the population was greater in the subsurface (10-20 cm) layer. Altogether, 29 soil micro-fungal forms were recorded from three sites. The microbial colony forming units were related to the concentrations of organic C and total N in the soil. Plant residues, additional organic matter, vegetation, plant species composition, and soil mineral nutrients were found to change the microbial population and species composition in a classic agroforestry system. Plant residues, additional organic matter, vegetation, plant species composition, and soil mineral nutrients were found to change the microbial population and species composition in a classic agroforestry system.

Abbasi *et al.* (2010) looked at changes in soil characteristics and microbiological indices across several management sites in Jammu and Kashmir's mountain settings. The forest had 22.3 x 10^5 bacteria, 8.2 x 10^5 actinomycetes, and fungus 2.5 x 10^3 fungus, whereas it was 8.2 x 110^5 in arable land. Both season (temperature) and soil depth (15-30 cm subsurface layer) had a significant influence on microbial development, since both activity and nutrient content decreased significantly in the winter. They discovered that the organic matter content of soils collected from the forest, grassland, and arable land was 3.4, 2.0, and 1.5 per cent, respectively, and that the growth and population microbes showed a significant correlation with SOM (r^2 = 0.87, 0.82, and 0.67, respectively), implying that natural vegetation appears to be a major contributor to soil quality.

Yu *et al.* (2012) in a subtropical mountainous location of southern China, investigated soils from a representative land-use sequence in a subtropical region of China, including four natural forests, two plantations, and a citrus orchard to determine the response of soil microbial diversity to land-use conversion of natural forests to plantations as soil microbial community diversity, soil organic matter, and nutrient cycling can all be affected by land-use conversion. Phospholipid fatty acid (PLFA) analysis, denaturing gradient gel electrophoresis (DGGE) and real-time quantitative polymerase chain reaction (PCR) were used to explore soil microbial diversity. The amount of PLFA and the number of bacterial 16 S rRNA gene copies were considerably reduced when natural woods were converted to plantations. In the CUL plantation and the citrus orchard, the average quantity of PLFA was lower by 31 per cent and 57 per cent, respectively, than in natural forests. Changes in the amount of litter and the state of soil nutrients caused by land use conversion promote these indirect changes. At the same time, the average copy number of the bacterial 16 S rRNA gene reduced considerably from 8.1 x 10^{10} g $^{-1}$ dry weight (DW) in wild forest to 4.9 x 10^{10} g $^{-1}$ DW in *Cinninghamia lanceolata* (CUL) plantation. They inferred that these indirect changes were affected by changes in litter fall and soil nutrient status as a result of land-use modification and deliberate management has a negative impact on soil microorganisms, which does not favour the sustainability of the ecosystem.

Lingappa *et al.* (2013) performed a long-term fertilizer experiment studying effects of N, P and K fertilizer application on the soil microbes. The study revealed that a balanced N, P and K treatment boosted microbial population and biomass growth and improved community composition, whereas an unbalanced fertilization decreased microbial N levels while increasing the C: N ratio of microbial biomass.

Bagyaraj *et al.* (2015) compared soil micro organisms *viz.*, bacteria, fungi, actinomycetes and arbuscular mycorrhizal (AM) fungi present in different typologies of coffee production systems. Two types of coffee plants were grown under different agroforestry management such as coffee under one specialized shade species, multi-storey coffee systems with 2 shade tree species, and evergreen ecological conditions. Under evergreen conditions, Arabica coffee had the maximum amount of infective propagules of AM fungus. Bacteria, fungus, and actinomycetes populations were higher in an evergreen habitat than in a deciduous one. When compared to a deciduous habitat, the abundance of nitrogen-fixing bacteria was more than doubled in evergreen settings. Evergreen ecosystems had more lignin degrading bacteria than deciduous ecosystems, whereas deciduous ecosystems had more starch hydrolyzing bacteria and pectin-utilizing bacteria. It can be concluded that evergreen coffee system supports higher population of microorganisms. Coffee cultivated beneath two shade tree types supported the highest population of all microbes of the three typologies.

Radhakrishnan *et al.* (2016) measured soil physico-chemical parameters and the quantity of microorganisms while working on the status of microbial diversity in agroforestry systems in Tamil Nadu. In different samples analysed, the bacterial population was found to be the most prevalent (64 per cent), followed by actinomycetes (23 per cent) and fungi (13 per cent). The total bacterial count was linked to soil organic carbon (C), moisture content, pH, nitrogen (N), and micronutrients like iron (Fe), copper (Cu), and zinc (Zn). Similarly, bulk density, moisture content, pH, C, N, phosphorus (P), potassium (K), calcium (Ca), copper (Cu), magnesium (Mg), manganese (Mn), and zinc (Zn) all had positive associations with total actinomycetes count. Similarly, bulk density, moisture content, pH, C, N, phosphorus (P), potassium (K), calcium (Ca), copper (Cu), magnesium (Mg), manganese (Mn), and zinc (Zn) all had positive associations with total actinomycetes count. The microbial population in agroforestry systems was also affected by soil organic matter, vegetation, and soil nutrients.

Chapter-3

MATERIALS AND METHODS

The present study entitled **“Evaluation of established Agroforestry systems for their Carbon sequestration and Soil enrichment potential in mid-hills of Himachal Pradesh”** was conducted in the mid hill zone of Himachal Pradesh during 2020-2021. The description of study, techniques and methodology put into use in the present study is given as below.

3.1 SITE DESCRIPTION

3.1.1 Site and Location

The present study was carried out at the Silviculture and Agroforestry Research Farm, Majhgaon, Department of Silviculture and Agroforestry, Dr. Y. S. Parmar university of Horticulture and Forestry, Nauni, Solan (H.P.) and adjoining areas during the year 2020-21. The experimental area is located in the mid-hill zone of Himachal Pradesh, 13 km away from Solan town. The latitude and longitude coordinates of the site are 30˚50’30’’ to 30˚52’00’’ N and 77˚08’30’’to 77˚11’30’’ E, respectively, having an average elevation of about 1,250 m above mean sea level.

3.1.2 Climatic and Edaphic factors

The area falls under sub-humid mid-hill zone of Himachal Pradesh, India and is considered to be a transitional zone between sub-tropical and sub-temperate zone. According to the data available with Department of Environmental Sciences, YSPUHF, Nauni, the study site experiences hot summers and cold winters with average minimum and maximum temperature varying from 3˚C during winters (January) to 32˚C during summers (June). The average annual temperature however, is 19˚C and, the annual rainfall varies from 1,000-1,400 mm with an average of 64 rainy days. Most of the rains are confined mainly to the monsoon season (July to September) with few pre monsoon showers, along with limited winter rains, received in January and February. The soil represents the ‘Inceptisol’ group and is dominantly clayey loam.

3.2. METHODOLOGY

3.2.1 Experimental Details

Experiment I To quantify the biomass production and carbon sequestration potential (CSP) of different artificially designed as well as natural agroforestry systems of sub humid mid-hill zone of Himachal Pradesh.

The treatment detail of the experiment is as below:

A. Agroforestry Systems

T_1 - Sole Cropping
T_2 - Agri-silvi-horticulture system
T_3 - Agri-silviculture system
T_4 - Fruit tree based agroforestry system
T_5 - Fodder tree based agroforestry system
T_6 - Bamboo based agroforestry system
T_7 - Melia based agroforestry system
T_8 - Poplar based agroforestry system
T_9 - Silvipasture system

Design	:	One-way ANOVA
Treatments	:	9 (Agroforestry systems)
Replications	:	3
Sample plot size	:	50 × 20 sq. m. (for trees)
		1 × 1 sq. m. (for crops and herbage)

Experiment II To study soil physical, chemical and biological properties of agroforestry systems of sub-humid mid hill zone of Himachal Pradesh.

The treatment detail of the experiment is as below:

A. Agroforestry Systems

T_1 - Sole Cropping
T_2 - Agri-silvi-horticulture system
T_3 - Agri-silviculture system
T_4 - Fruit tree based agroforestry system
T_5 - Fodder tree based agroforestry system

T_6 - Bamboo based agroforestry system

T_7 - Melia based agroforestry system

T_8 - Poplar based agroforestry system

T_9 - Silvipasture system

B. Soil Depths

S_1 - 0-20 cm

S_2 - 21-40 cm

S_3 - 41-60 cm

Design	:	Two-way ANOVA
No. of Treatment combinations	:	27 {9 (agroforestry systems) × 3 (soil depths)}
Replications	:	3

3.2.2 Observations recorded

3.2.2.1 Tree parameters:

1. Height (m)

Height of all the trees in the sample plot was measured individually, using Ravi multimeter. Later, used in the estimation of stem biomass.

2. Diameter (m)

Diameter of each tree was taken at breast height with the help of tree caliper. The girth of the fodder trees was taken at breast height whereas, in fruit trees, basal girth (5-10cm above-ground level) was measured. In bamboos, diameters of individual culms were measured and, total diameter was determined by adding diameters of all the culms.

B) Biomass Characters:

Tree component

i) Stem biomass

To estimate biomass, all the trees falling in sample plot were enumerated. The diameter at breast height (d.b.h) and height of each tree was measured. Later, stem biomass was calculated using volume equations developed for particular species present in the agroforestry system.

ii) Branch biomass

Total number of branches irrespective of size were counted in each of the sample tree and then categorized on the basis of basal diameter into three groups, *viz.*, <6 cm, 6-10 cm and >10 cm. Fresh and dry weight of three sampled branches from each group was recorded separately. The following formula (Chidumaya, 1990) was used to determine the dry weight of branches.

$Bdwi = Btwi/1 + Mcbdi$

Where,

Bdwi - oven dry weight of branch
Btwi - Fresh/green weight of branches
Mcbdi – Moisture content of branch on dry weight basis

Total branch biomass (Fresh/dry) per sample tree was determined as given by:

$Bbt = n1bw1 + n2bw2 + n3bw3 -\sum nibwi$

Where,

Bbt - Branch biomass (fresh/dry) per tree
ni – number of branches in the i^{th} branch group
bwi – average weight of branch of i^{th} group
i – 1, 2, 3, --------

iii) Leaf biomass

For leaf biomass also, branches were taken and categorized on the basis of basal diameter into three groups, *viz.*, <6 cm, 6-10 cm and >10 cm. Leaves from three sample branches from each group were removed, weighed and oven dried separately to a constant weight at 80 ± 5˚C (Chidumaya, 1990) for dry biomass estimation. An estimate was made of biomass present in each of the sample branch which was used later to estimate the total biomass of all the leaves in the trees, individually.

iv) Tree biomass

The total tree biomass was the sum of stem biomass, branch biomass and leaf biomass. The tree biomass was converted into carbon fraction by factor of 0.5 (IPCC default value).

B. Crop component

The following tree-crop combinations (Table 1) were evaluated for biomass production, carbon sequestration and soil enrichment potential of different agroforestry systems.

i) Crop & herbage biomass

Crop biomass was estimated using 1 × 1 sq. m. quadrates, with three samples drawn from each sampling plot. All the crops and herbage occurring within the borders of the quadrate were cut at ground level and weighed. Later, these samples were sub - sampled and oven dried at 65 ± 5°C to a constant weight. The crop biomass was converted into carbon by multiplying it with a factor of 0.45 (Woomer, 1993).

ii) Grass biomass

Grass biomass was estimated using 1m × 1m quadrates, with three samples drawn from each sampling plot. The total grass biomass occurring within the borders of the quadrate were cut at ground level and collected samples were weighted, sub sampled and oven dried at 65 ± 5°C to a constant weight. The crop biomass was converted into carbon by multiplying with a factor of 0.45 (Woomer, 1993).

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

AFS	Code	Tree-crop combinations	Plot size (ha)	Area under tree (ha^{-1})	Area under crop/grass (ha^{-1})
Sole Cropping System	**T_1**	Red chilies - Wheat/Pea	0.1	-	0.1
		Cabbage - Garlic			
		Cauliflower - Onion			
Agri-silvi-horticulture System	**T_2**	Apricot + Celtis + Tomato - Wheat	0.1	0.02	0.8
		Grewia + Pear + Maize - Wheat			
		Grewia + Plum + Maize - Garlic			

Agri-silviculture system	$\mathbf{T_3}$	Grewia + Toona + Soybean - Mustard	0.1	0.02	0.08
		Grewia + Celtis + Okra - Wheat			
		Grewia + Bauhinia + Soybean - Pea			
Fruit tree based AFS	$\mathbf{T_4}$	Apricot + Peach + Okra - Wheat	0.1	0.04	0.06
		Plum + Pear + Cabbage - Potato			
		Plum + Pear + Soybean - Linseed			
Fodder tree based AFS	$\mathbf{T_5}$	Grewia + Capsicum - Potato	0.1	0.03	0.07
		Morus + Maize - Chickpea			
		Grewia + Soybean - Linseed			
Bamboo based AFS	$\mathbf{T_6}$	Bamboo + Soybean - Ginger	0.1	0.04	0.06
		Bamboo + Capsicum - Mustard			
		Bamboo + Turmeric - Mustard			
Melia based AFS	$\mathbf{T_7}$	Melia + Cauliflower - Radish	0.1	0.04	0.06
		Melia + Cabbage - Garlic			
		Melia + Soybean - Mustard			
Poplar based AFS	$\mathbf{T_8}$	Poplar + Turmeric - Wheat/Pea	0.1	0.04	0.06
		Poplar + Capsicum - Mustard			
		Poplar + Turmeric – Wheat			
Silvipasture System	$\mathbf{T_9}$	Leucaena + Grewia + Grasses	0.1	0.08	0.02
		Grewia + Morus + Grasses			
		Bauhinia + Grewia + Grasses			

C. Surface leaf litter

To quantify surface litter inside any agroforestry system, litter was randomly collected at five sample sub-plots, using a 1 × 1 sq. m. quadrate size. All the floor litter inside the quadrate was collected and oven dried at 60°C and weighed. To convert litter biomass to carbon, biomass was multiplied by a default value of 0.370 (Smith and Heath, 2001).

3.3 ABOVE-GROUND BIOMASS

3.3.1 Above-ground tree biomass

3.3.1.1 Volume estimation

The trees falling in the plot of 50 × 20 sq. m. were enumerated. The diameter at breast height (d.b.h.) was measured with the help of tree caliper and the height was measured with Ravi's multimeter. Volumetric equations developed for specific tree species and regions were used for calculating the volume of the trees of the sample plot. The volume equations as put forth by FSI (FSI, 1996; 2009; 2011; 2015) are given ahead:

Plate 1. Agri-silvi-horticulture system

Plate 2. Agri-silviculture system

Plate 3. Fruit trees based AFS

Plate 4. Fodder trees based AFS

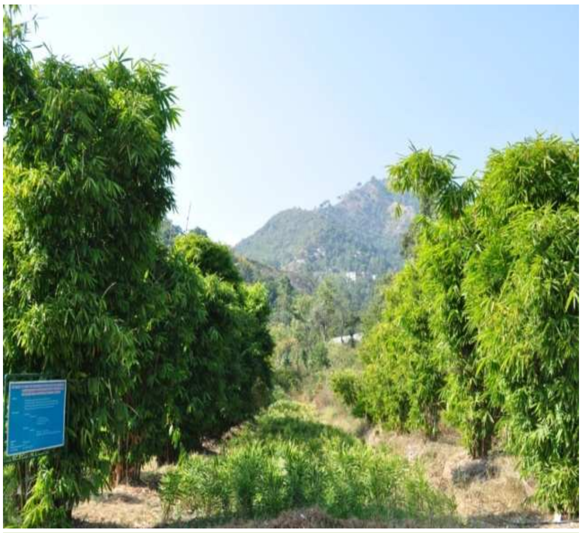

Plate 5. Bamboo based AFS

Plate 6. Melia based AFS

Plate 7. Poplar based AFS

Plate 8. Silvi-pasture System (Protein bank)

Table 2: Volume equations used for volume estimation of different woody tree species

Sr. No.	Tree species	Volume equations
1	*Bauhinia variegata*	$V/D^2 = 0.007602/D - 0.033037/D + 1.868567 + 4.483454 \times D$
2	*Celtis australis*	$V/D^2 = 0.007602/D^2 - 0.033037/D + 1.868567 + 4.483454 \times D$
3	*Grewia optiva*	$V/D^2 = 0.007602/D^2 - 0.033037/D + 1.868567 + 4.483454 \times D$
4	*Melia composita*	$V = 0.00045 + (0.000026 \times D^2 \times H)$
5	*Morus alba*	$V = 0.167174-1.735312 \times D + 12.039017 \times D^2$
6	*Populus deltoides*	$V = 0.193297 - 2.2667002 \times D + 10.679492 \times D^2$
7	*Prunus armeniaca*	$V = 0.193297 - 2.267002 \times D + 10.679492 \times D2$
8	*Prunus domestica*	$V = 0.193297 - 2.267002 D + 10.679492 \times D^2$
9	*Prunus persica*	$V = 0.193297 - 2.267002 D + 10.679492 \times D^2$
10	*Pyrus communis*	$V/D^2 = 0.775 - 7.787 \times D + 22.748 \times D^2$
11	*Toona ciliata*	$V/D^2 = 0.007602/ D^2 - 0.033037/D + 1.868567 + 4.483454 \times D$

(Where, D = Tree diameter; H = Tree Height; V = Volume)

3.3.1.2 Biomass stock estimation (Mg ha^{-1})

The estimation of Above-ground biomass of the trees was done by using specific gravity and expansion factors, developed for the non-destructive estimation of above-ground biomass of trees.

Stem biomass (Mg ha^{-1}) = VOB × WD

Above-ground biomass density (Mg ha^{-1}) = Stem biomass × BEF

Where,

VOB = Volume over bark

WD = Volume weighed wood density

BEF = Biomass expansion factor

3.3.1.3 Wood density (g cm^{-3})

The wood density of the different tree species present in the experimental plots has been given as below.

Table 3: Wood density of different woody tree species

S. No.	Name of species	Wood density	Source
1.	*Bauhinia variegata*	**0.67**	IPCC (2006)
2.	*Celtis australis*	**0.71**	Sheikh *et. al.* (2011)
3.	*Grewia optiva*	**0.71**	Sheikh *et. al.* (2011)
4.	*Leucaena leucocephala*	**0.74**	Sheikh *et. al.* (2011)
5.	*Melia composita*	**0.70**	Sheikh *et. al.* (2011)
6.	*Morus alba*	**0.74**	Sheikh *et. al.* (2011)
7.	*Populus deltoides*	**0.40**	Wiemann M C (1990)
8.	*Prunus armeniaca*	**0.63**	AF Tree Database, ICRAF
9.	*Prunus domestica*	**0.63**	AF Tree Database, ICRAF
10.	*Prunus persica,*	**0.63**	AF Tree Database, ICRAF
11.	*Pyrus communis*	**0.54**	AF Tree Database, ICRAF
12.	*Toona ciliata*	**0.55**	Sheikh *et. al.* (2011)

3.3.1.4 Biomass expansion factor (BEF)

It is the ratio of the total above ground oven-dry biomass density of trees (minimum d.b.h. = 10 cm or more) to the oven dry biomass density of inventoried volume. Some of the expansion factors developed for different tree species are given in table ahead.

Table 4: Biomass expansion factor of different woody tree species present at the study site

.S.No.	Name of species	Expansion factor	Source
1.	*Bauhinia variegata*	**1.40**	IPCC (2003)
2.	*Celtis australis*	**1.32**	Kishwan *et al*. (2010)
3.	*Grewia optiva*	**2.01**	Kishwan *et al*. (2010)
4.	*Morus alba*	**1.30**	IPCC (2003)
5.	*Populus deltoides*	**1.58**	Rawat *et al.* (2015)
6.	*Prunus armeniaca*	**1.43**	Hidayat and Simpson (1994)
7.	*Prunus domestica*	**1.43**	Hidayat and Simpson (1994)
8.	*Prunus persica*	**1.43**	Hidayat and Simpson (1994)
9.	*Toona ciliata*	**1.40**	IPCC (2003)
10.	For remaining trees	**1.50**	Brown and Lugo (1984)

3.3.2 Above-ground Biomass of Crops

Five quadrates of 1 m × 1 m were used for estimating the crop biomass in a sample plot. The total biomass was estimated by uprooting all the crops from the quadrates at harvesting stage and then isolated root and above ground parts were weighed separately to decide the fresh weight. All the crop samples were collected, weighed, sub-sampled and oven dried at 65 ± 5°C until a constant weight, and then converted into carbon by multiplying with a factor of 0.5 (IPCC default value).

3.4 BELOW-GROUND BIOMASS

3.4.1 Below-ground tree biomass

Below-ground biomass of trees was calculated by multiplying Above-ground biomass with a factor of root: shoot ratio of particular tree as per the guidelines of IPCC (1996), Cairns *et al.* (1997), Mokany *et al.* (2006) and others. The root-shoot ratio of different tree species are given below in the table:

Table 5: Root-Shoot ratio of different woody tree species present in the study site

S.No.	Name of tree species	Root-Shoot ratio	Source
1.	*Bauhinia variegata*	**0.27**	IPCC (2003)
2.	*Celtis australis*	**0.21**	Hidayat and Simpson (1994)
3.	*Grewia optiva*	**0.32**	Rana *et. al.* (1989)
4.	*Morus alba*	**0.26**	Rajput *et. al.* (1985)
5.	*Populus deltoides*	**0.19**	Kumar (1998)
6.	*Prunus armeniaca*	**0.27**	IPCC (2003)
7.	*Toona ciliata*	**0.27**	Rajput *et. al.* (1985)
8.	*For remaining soft wood trees*	**0.21**	IPCC (2006)
9.	*For remaining hard wood trees*	**0.25**	IPCC (2006)

Table 6: Root-Shoot ratio of different agriculture crops concerned

S. No.	Name of crop species	Root-Shoot ratio	Source
1.	*Brassica campestris*	**0.20**	Kumar *et al.* (2008)
2.	*Capsicum annum*	**0.41**	A’fifah *et al.* (2015)
3.	*Cicer arietinum*	**0.22**	Gan *et al.* (2009)
4.	*Glycine max* (L.) Merill	**0.25**	Kushwah *et al.* (2014)
5.	*Solanum lycopersium*	**0.36**	Ghanem *et al.* (2011)
6.	*Phaseolus vulgaris* L.	**0.26**	Boutraa (2009)
7.	*Pisum sativum* L.	**0.11**	Gan *et al.* (2009)
8.	*Solanum melongena*	**0.35**	Kuchay and Zarger (2016)
9.	*Triticum aestivum* L.	**0.20**	Gan *et al.* (2009)
10.	*Zea mays* L.	**0.20**	Kushwah *et al.* (2014)
11.	Others	**-**	Determined in Laboratory

The data pertaining to root: shoot ratio of trees was estimated by:

Below-ground biomass = Above-ground biomass × root: shoot ratio

3.4.2 Below-ground biomass of crops and herbs

Below-ground biomass of crops and grasses was calculated by multiplying above-ground biomass of crops/grasses with a factor of root: shoot ratio of particular crop/grass.The root: shoot ratio of different crop species are given in Table 6. Below-ground biomass of some grasses and crops, whose root: shoot ratios were unavailable, were estimated by direct measurements in the laboratory.

3.5 CARBON STOCK

3.5.1 Vegetation Carbon Stock (Mg ha^{-1})

The above ground and below ground carbon stock of vegetation was estimated by vegetation biomass multiplied with default value 0.5 (IPCC, 1996). Total carbon stock in vegetation was determined by adding Above-ground and Below-ground carbon.

Carbon stock = Biomass × 0.5 (IPCC default value)

3.5.2 Soil Carbon Stock (Mg ha^{-1})

The soil organic carbon stock was expressed in Megagrams per hectare for a particular depth was estimated using the formulae of Carlos *et al*. (2001). The carbon concentration data and the bulk density of soil was used to estimate the amount of Carbon per unit area of each agroforestry system, as follows:

C (Mg ha^{-1}) = Bulk density of soil (g cm^{-3}) × Soil depth (cm) × Carbon (%)

3.6 CARBON AND CO_2 ESTIMATION

3.6.1 Carbon (Mg ha^{-1})

Above and below-ground carbon stock in vegetation was determined by multiplying vegetation biomass with 0.5 (IPCC default value, 1996).

Carbon = Biomass × 0.5

3.6.2 Vegetation carbon density (Mg ha^{-1})

Vegetation Carbon density = tree biomass carbon + herb biomass

3.6.3 Carbon sequestration rate (Mg ha^{-1} yr^{-1})

Carbon sequestration was estimated by subtracting the carbon stock outside the agroforestry systems (sole cropping in the adjoining area) from that inside the system and dividing it by the average age of the trees present in the system.

$$\text{Carbon sequestration rate} = \frac{\text{Carbon stock of study area} - \text{Carbon stock of adjoining land}}{\text{Age of the trees}}$$

Here, study area = area under agroforestry system;

adjoining land = area just outside the agroforestry system

S.No.	Agroforestry Systems	Year of establishment	Average age of trees
1.	T_4 (Fruit tree based AFS)	2006	14
2.	T_5 (Fodder tree based AFS)	2006	14
3.	T_6 (Bamboo based AFS)	2006	14
4.	T_7 (Melia based AFS)	2006	14
5.	T_8 (Poplar based AFS)	2003	17
6.	T_9 (Silvipasture system)	2001	20

3.6.4 CO_2 mitigation rate (Mg ha^{-1} yr^{-1})

Carbon mitigated = Carbon sequestered × 3.67

3.7 SOIL ANALYSIS

Collection and preparation of Soil samples

At least three soil samples were drawn from three different depths from each agroforestry system using pickaxe, spade and power earth auger. Composite samples of each depth were then prepared. Soil samples were shade dried, grinded in pestle and mortar, sieved through 2 mm sieve and then stored in cloth bags for laboratory analysis, later. Various physical and chemical properties of soil were determined using standard methods as given below:

3.7.1 Soil physical properties

S.No.	Physical Property	Method employed
1.	Bulk density	Core method (Blake,1965)
2.	Particle density	Pycnometer method
3.	Soil Porosity	Bulk density method
4.	Soil texture	Hydrometer method

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

Bulk density (BD) of soil samples was determined in the laboratory after using core-tube method in the field. It was calculated using the formula:

$$\rho_b = \frac{Wsc}{Vc}$$

Where,

ρb = bulk density of soil

Wsc = weight of oven dry soil in the core (g)

Vc = Volume of the core/soil (cm^3)

3.7.1.2 Particle density (g cm^{-3})

Particle density (PD) of soil samples was determined in the laboratory by standard pycnometer method and was calculated using the formula:

$$\rho_s = \frac{Ws}{Wpw + \mathrm{Ws} + Wpsw}$$

Where,

ρ_s = particle density of soil

Ws = weight of soil

Wpw = weight of water filled pycnometer (g)

Wpsw = weight of pycnometer + water + soil (g)

3.7.1.3 Porosity (per cent)

The porosity of collected soil samples was determined by taking into consideration the values of bulk density and particle density with the help of following formula:

$$Porosity\ (\%) = \frac{1-\rho b}{\rho s} \times 100$$

Where,

P_b = Bulk density (g cm^{-3})

ρ_s = Particle density (g cm^{-3})

3.7.1.4 Soil texture

Hydrometer method was used to measure the particle sizes of soil samples based on Stoke's law. Later, using soil particle size, the textural class of the soil is determined with the help of textural triangle as per the amount of sand, silt and clay particles present in the soil sample.

3.7.2 Soil chemical Properties

Sr. No.	Chemical property	Method employed
1.	pH	1:2 Soil:Water suspension, measured with digital pH meter (Jackson,1973)
2.	EC	1:2 Soil:Water suspension, measured with digital EC meter (Jackson,1973)
3.	Organic Carbon	Walkley and Black wet digestion method (Walkley and Black, 1934)
4.	Available N	Alkaline $KMnO_4$ method (Subbiah and Asija, 1956)
5.	Available P	Olsen method (Olsen *et al.*, 1954)
6.	Available K	Ammonium acetate method (Merwin and Peech, 1951)
7.	Available Ca	Ammonium acetate method (Merwin and Peech, 1951)
8.	Available S	0.15% $CaCl_2$ method (Bardsley and Lancaster, 1960)
9.	Available micronutrients	Diethyl triamine penta acetic acid (DPTA) method
10.	Microbial count	Pore plate method (Subba Rao, 1999)

3.7.3 Soil biological Properties

Microbial population analysis was done of fresh samples sealed in containers and estimated within 24 hrs of sampling. The samples were serially diluted with distilled water up to 10^6 dilutions and 100 µl of aliquot was poured on plates having special growing media (Nutrient Agar for bacteria; Potato Dextrose Agar for fungi; Ken Knights and Munaier's Agar for actinomycetes). The Petri-plates were incubated at optimum temperature (28 ± 1°C for bacteria; 30 ± 1°C for fungi and actinomycetes) in triplicate. On appearance of microbial colonies their counting was done (3 days for bacteria; 5 days for fungi; 7 days for actinomycetes) after incubation and expressed as total culturable colony forming units per gram of dry weight (cfu g^{-1}) of soil sample. For actinomycetes, streptomycin and cycloheximide were added to inhibit the growth of bacteria and fungi at a final concentration following Yang and Yang (2001).

3.7.3 Soil Quality Index

The soil quality index was developed by taking into consideration, all the soil physico-chemical characteristics investigated. These were used as a set of quantitative properties (indicators) to monitor soil quality (Dalal and Moloney, 2000) and variations in these markers can be used to measure overall soil quality. The weighted mean values of the parameters were transformed using linear scoring method as suggested by Andrews *et al*. (2002). To do so, the weighted mean values of soil characteristics were sorted in ascending order, with the 'more is better' method applied if a larger magnitude of the parameter is preferable for enhancing soil quality. On the other hand, those parameters whose reduction is deemed a positive quality were grouped in decreasing order and the 'less is better' strategy was applied. Each 'more is better' observation was divided by the highest observed value, with the highest observed value earning the highest possible score of 1. For 'less is better' parameters, the lowest observed value was divided by each observation, giving the lowest recorded value a maximum score of 1. Further the factors were ranked from 1 to 10 based on their relevance and reactivity to soil aggradation or degradation, as outlined by Dalal and Moloney (2000) and followed by Sharma *et al.* (2005). The resulting product was totaled and divided by the sum of the scores. As a result, the Soil Quality Index was named after the single value acquired for each land use system. The effect on soil quality was compared using the single value indices produced for each land use system.

$$\text{SQI} = \frac{\Sigma \text{ Linear score} \times \text{Score value of respective parameter}}{\text{Sum total of scores}}$$

Table 7: Scoring chart for indicators of soil quality index

S. No.	Selection criteria	pH	E.C.	Organic matter	Available nutrients	Total nutrients
1.	Responsiveness	7	5	7	8	6
2.	Ease of capture	8	6	7	6	4
3.	Interpretation	7	9	8	8	6
4.	Measurement error	7	6	8	7	5
5.	Stable to measure	9	9	10	7	5
6.	Frequency	8	8	8	6	3
7.	Cost	8	7	6	5	4
8.	Aggregation	6	8	9	5	4
9.	Mappable	9	8	9	5	4
10.	Acceptance	9	8	10	9	5
	Total Score	79	74	82	66	51
	Average Score*	7.9	7.4	8.2	6.6	5.1

Plate 9. Bacteria on NA, Actinomycetes on K&M and Fungi on PDA media

Plate 10. Fungal growth on PDA media

* Average score used to multiply with deviations were: pH 7.9, EC 7.4, organic carbon 8.2, exchangeable Ca, Mg, Na, and K each 6.6, and for total nutrients *viz*., N, P, K, Ca, Mg, Mn, Zn, Fe, each 5.1.

3.8 STATISTICAL ANALYSIS

The data obtained was subjected to statistical analysis as per the procedure suggested by Gomez and Gomez (1984). In case of exhibition of significance of 5 per cent level of probability critical difference (CD) was calculated. Analysis of variance was carried out on computer using SPSSS software.

Chapter-4

RESULTS AND DISCUSSION

The carbon sequestration and soil enrichment potentials of various established agroforestry systems were estimated by conducting field studies in University campus and adjoining areas of Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Nauni during the year 2020-21. In addition to it, soil samples collected from different agroforestry systems were subjected to physico-chemical analysis at the laboratory facility available at Department of Silviculture and Agroforestry, Dr Yashwant Singh Parmar University of Horticulture and Forestry, Nauni. Different agroforestry systems selected under the present study were 3-natural (agri-silvi-horticulture system and agri-silviculture system) as well as, 6-experimental agroforestry systems (fruit tree based agroforestry system, fodder trees-based agroforestry system, bamboo based agroforestry system, melia based agroforestry system, poplar based agroforestry system and silvipasture system). Each system has a wide range of biomass turnout, carbon storage, carbon sequestration and CO_2 mitigation potential because of the differences in their origins, structure, function, tree species, density and management. The data obtained for various biomass and soil characteristics, were subjected to analysis of variance for determining the comparison on average basis, and have been presented and discussed under the following heads and subheads.

4.1 Biomass and biomass carbon density
4.2 Carbon stock in different component (vegetation, litter and soil pools)
4.3 Carbon Density and carbon sequestration potential
  4.4.2 Carbon density inside and outside agroforestry systems
  4.4.2 Carbon Sequestration and CO_2 mitigation potential
4.4 Soil physico-chemical and microbial properties

4.1 BIOMASS AND BIOMASS CARBON DENSITY

The biomass output of vegetation is an indicator of its constituent species' production capacity in a given environment, density, climatic and edaphic variables, quantity and intensity of management, all have a role in determining the carbon density and biomass in a specific agroforestry system (Swamy and Puri 2005; Nair *et al*., 2009; Niu and Duiker 2006; Jana *et al*., 2009; Dash and Behera, 2013; Liu *et al*., 2015; Yadav *et al*., 2016). To improve total carbon estimates, the above-ground tree biomass, below-ground biomass, shrub, and herb/grass biomass must all be calculated (Hamberg, 2000). The biomass output is categorized as tree above-ground biomass, below-ground biomass, total tree biomass, and herb/grass biomass.

Globally, vegetation biomass is largest storehouse for carbon as compared to the atmosphere and acts as a major terrestrial carbon sink (Devi, 2011). Thus, the biomass stored in vegetation can affect the climate at local, regional and even global level. Among different kind of land-use systems, agroforestry is quite well-known and has been identified as having the best potential for C sequestration among all land uses studied in the LULUCF assessment (IPCC, 2000). Biomass estimation and evaluation is imperative for the quantification of carbon sequestration potential of the different systems, as the underlying concept of carbon sequestration capacity of land-use systems including agroforestry systems, is simply related to the basic physiological processes *viz*., photosynthesis and respiration in plants (Dixon *et al*., 1994).

4.1.1 Tree biomass

4.1.1.1 Tree Above-ground biomass

The tree Above-ground biomass is divided into biomass present in different components *viz*., stem, branch and leaf biomass. Table 8 showcases the same.

Table 8: Biomass in different components of the agroforestry systems in the sub-humid mid-hill conditions of Himachal Pradesh

Agroforestry systems	Tree stem biomass (Mg ha^{-1})	Tree branch biomass (Mg ha^{-1})	Tree leaf biomass (Mg ha^{-1})	Total tree above-ground biomass
T_1 (Sole Cropping system)	-	-	-	-
T_2 (Agri-silvi-horticulture system)	22.21^{d}	4.33^{c}	2.31^{bc}	28.84^{e}
T_3 (Agri-silviculture system)	18.81^{d}	4.51^{c}	1.75^{c}	25.08^{ef}
T_4 (Fruit tree based AFS)	15.68^{d}	1.71^{c}	0.79^{c}	18.18^{f}
T_5 (Fodder tree based AFS)	42.91^{c}	3.81^{c}	1.13^{c}	47.85^{d}
T_6 (Bamboo based AFS)	16.10^{d}	3.54^{c}	1.37^{c}	21.01^{ef}
T_7 (Melia based AFS)	66.11^{b}	10.18^{b}	2.86^{bc}	79.14^{b}
T_8 (Poplar based AFS)	73.44^{a}	18.76^{a}	7.36^{a}	99.55^{a}
T_9 (Silvipasture system)	49.58^{c}	12.23^{b}	3.38^{b}	65.19^{c}
Mean	38.15	7.38	2.62	48.11
$SE_{(M)}$	2.255	1.604	0.493	2.687
$CD_{0.05}$	6.840	4.866	1.497	8.150

4.1.1.1.1 Tree Stem biomass

The data on tree stem biomass is depicted in Table 8. It reveals that the tree biomass varied significantly amongst different agroforestry systems. Maximum stem biomass was accumulated by the poplar based agroforestry system, which was closely followed by melia based agroforestry system, only. The tree stem biomass production in fodder based system and silvipasture systems remained statistically at par. Similarly, the stem biomass production in the agroforestry systems, like agri-silvi-horticulture, agri-silviculture, fruit tree based and bamboo based agroforestry systems also remained statistically identical.

Higher stem biomass of the poplar and melia trees can be attributed to the genetic makeup of the trees and their unrestricted growth. Whereas, stem biomass in silvipasture and fodder tree based agroforestry system was also comparatively higher due to higher plantation density, despite having smaller sized trees. The d.b.h. and height of the stem have an influence on volume and biomass estimation because of tree stem biomass being a function of volume of stem density (Rizvi *et al.*, 2011). This can also be applied in context of agri-silvi-horticulture and agri-silviculture systems, which showed lesser biomass due to decreased tree densities, as they were naturally present on bunds or planted as boundary plantations. Further, the trees were regularly pruned and lopped. Lesser stem biomass was recorded in fruit tree and bamboo based systems due to smaller tree size for easy canopy management and hollow stems, respectively.

4.1.1.1.2 Tree Branch biomass

It is crystal clear from the Table 8 that the branch biomass varied markedly among different agroforestry systems in a significant manner. Maximum tree biomass (18.76 Mg ha^{-1}) was recorded in poplar based agroforestry system, which was closely followed by silvipasture and melia based agroforestry systems. The tree branch biomass production in all other agroforestry systems remained significantly lower and statistically alike.

Higher branch biomass allocated to tree branches in poplar and melia trees, is mainly due to their untended canopies, whereas in case of silvipasture system it is due to higher tree density per hectare in protein banks, along with regular seasonal lopping being practiced. Agri-silviculture and agri-silvi-horticulture systems also showed lesser branch biomass due to their comparatively lesser plant density. Lowest branch biomass was observed in fruit trees based agroforestry systems because these trees are regularly trained/ pruned for fruit production.

4.1.1.1.3 Tree Leaf biomass

It is evident from the data presented in Table 8 that the leaf biomass production of the trees under different agroforestry systems varied significantly. Maximum leaf biomass accumulation (7.36 Mg ha^{-1}) was observed in poplar based system, which was found to be significantly higher than all other agroforestry systems. The tree leaf biomass under different agroforestry systems *viz*., agri-silvi-horticulture, melia based and silvipasture system remained statistically identical to each other. Most of the agroforestry systems, except for polar based and silvipasture systems, showed statistical similarity. Minimum leaf biomass production (0.79 Mg ha^{-1}) was exhibited by fruit tree based agroforestry system, followed by bamboo based and fodder tree based agroforestry systems.

Leaf biomass is directly proportional to branch biomass and therefore higher amount of leaf biomass in poplar and melia can be due to large and untended canopies. Likewise, higher leaf biomass in silvipasture system was due to larger tree density along with seasonal lopping leading to continuous flushing of new leaves after each cut. Agri-silvi-horticulture and agri-silviculture systems also had greater leaf biomass due to large size of trees in natural agro-ecosystems along the fields and hence, larger leaf yields. Minimum leaf biomass was observed in fruit tree based agroforestry system owing to harsh canopy management practices of fruit trees in form of training and pruning, in winters.

4.1.1.1.4 Total tree above-ground biomass

A perusal of the data presented in table 8 reveals the biomass in the Above-ground varying significantly and was observed to be ranging from 18.16 Mg ha^{-1} to 99.55 Mg ha^{-1}. The maximum tree above-ground biomass was accumulated by poplar based agroforestry system, which was found to be significantly higher than all other agroforestry systems under investigation. The trend followed by different agroforestry systems was: poplar based agroforestry system (99.55 Mg ha^{-1}) > melia based agroforestry system (79.14 Mg ha^{-1}) > silvipasture (65.19 Mg ha^{-1}) > fodder tree (47.85 Mg ha^{-1}) > agri-silvi-horticulture (28.88 Mg ha^{-1}) > agri-silviculture (25.08 Mg ha^{-1}) > bamboo based agroforestry system (21.01 Mg ha^{-1}) > fruit based system (18.16 Mg ha^{-1}). Agri-silvi-horticulture was statistically at par with agri-silviculture and bamboo based agroforestry system, whereas fruit based system was statistically at par with agri-silviculture and bamboo based agroforestry system.

The amounts of biomass production in the present study is more or less similar to values reported by Minj (2008) and Toppo (2012) in Himachal Pradesh. Tree above-ground biomass depends upon the number of plants per unit area, size of the tree stem, number and volume of branches, etc. Arora *et al*. (2014) calculated the above-ground biomass of a poplar plantation in Tarai region of Central Indian Himalayas, and reported the values from 0.5 Mg ha^{-1} in 1 year old plantation to 90.1 Mg ha^{-1} in 11 years old plantation. They documented a total biomass of 202.59 Mg ha^{-1}, with 78.68 per cent attributed to above-ground biomass, alone. The interaction between tree species diversity and genetic diversity within dominant tree species determines variations in Above-ground biomass output (Crawford and Rudgers 2012). The above-ground biomass recorded in fruit tree based agroforestry system is lower (about 2/3rd) to that reported by Rajput (2010) in Kullu valley. He reported the above-ground biomass in agri-horticulture system to be 37.82 Mg ha^{-1}, against 24.14 Mg ha^{-1} in the present study. Kaonga and Smith (2011) also studied the effects of five *Leucaena spp* on soil and plant C stock in Zambia. In seven-year-old woodlots, the measured stem and total above-ground tree C stocks ranged from 17.1 to 29.2 and 24.5 to 55.9 Mg ha^{-1}, respectively, which is partly in agreement with findings in the present study.

4.1.1.2 Tree below-ground biomass

Data regarding tree below-ground biomass is presented in Table 9. The analysis of data shows that tree below-ground biomass varied significantly among different agroforestry systems under investigation. Similar to above-ground biomass, the below-ground biomass in trees was found to be significantly maximum (24.89 Mg ha^{-1}) under poplar based agroforestry system, which was followed closely by melia based agroforestry system (21.37 Mg ha^{-1}) and silvipasture system (18.42 Mg ha^{-1}), which however, remained statistically identical to one another. The minimum below-ground system was recorded in fruit tree based agroforestry system (4.54 Mg ha^{-1}), which was found to be significantly at par with agri-silvi-horticulture system and agri-silviculture system. Similarly, agri-silvi-horticulture, agri-silviculture and bamboo based agroforestry system also remained statistically identical to one another.

The root shoot ratio is the ratio of below-ground biomass to the above-ground biomass, major approach used worldwide to measure the Below-ground biomass and carbon stock (Mokany *et al*., 2006). The below-ground biomass of tree component of the agroforestry systems is dependent on the tree species and the above-ground biomass of the same. Highest below-ground biomass was observed in poplar and melia based agroforestry systems. Bamboo based system also showed exceptionally higher below-ground biomass in comparison to above-ground biomass owing to wide rhizome network. In the Terai area of the Central Himalayas, Singh and Lodhiyal (2009) credited 40.83 Mg ha^{-1} (21.32 per cent), of the total 202.59 Mg ha^{-1}, to below-ground biomass, in an eight-year-old *Populus deltoides* based agroforestry system.

4.1.1.3 Total tree biomass

A perusal of data in Table 9 depicts that total tree biomass varied significantly with the different agroforestry systems. The maximum total tree biomass (124.44 Mg ha^{-1}) was amassed by poplar based agroforestry system, which was found to be significantly higher than all other agroforestry systems (natural as well as experimental agroforestry systems). The biomass accumulation in different agroforestry systems followed the trend: T_8 (124.44 Mg ha^{-1}) > T_7 system (100.50 Mg ha^{-1}) > T_9 (83.62 Mg ha^{-1}) > T_5 (61.73 Mg ha^{-1}) > T_2 (36.05 Mg ha^{-1}) > T_6 (32.49 Mg ha^{-1}) > T_2 (31.35 Mg ha^{-1}) > T_4 (22.72 Mg ha^{-1}). The minimum total tree biomass was documented in fruit based agroforestry system, albeit, it remained statistically at par with agri-silviculture and bamboo based agroforestry system.

Total tree biomass was estimated by aggregating the above-ground and the below-ground biomass of the trees of particular agroforestry system. The average total biomass of all the systems stood at 61.34 Mg ha^{-1}, of which, 48.11 Mg ha^{-1} (79 per cent) was contributed by above-ground and 13.23 Mg ha^{-1} (21 per cent) by below-ground biomass. The results are entirely synchronous with those of Chhabra *et al*. (2002), who calculated standing biomass of forest trees in India and reported exactly the same contributions of 79 and 21 per cent, in above-ground and below-ground biomass, respectively. Similarly, in the Terai region of the Central Himalayas, Singh and Lodhiyal (2009) examined eight-year-old *Populus deltoides* agroforestry plantations. They found a total biomass of 202.59 Mg ha^{-1}, with 21.32 per cent (63.45 Mg ha^{-1}) below-ground biomass. Individual tree size may be accounted for biomass estimate, which is typically measured by variations in tree diameter at breast height (d.b.h.) and height (Ali and Mattsson, 2017). Hence, highest tree biomass was recorded in poplar based and melia based systems due to their comparatively incredible size, leading to higher above-ground biomass. These are followed by silvipasture system and fodder tree based system because of their relatively higher below-ground biomass as discussed above, earlier.

Similarly, Schmitt-Harsh *et al.* (2012), also revealed that the biomass in Guatemalan coffee agroforests ranged from 74.0 and 259.0 Mg ha^{-1}, with a mean of 127.6 Mg ha^{-1}, attributing 73.18 Mg ha^{-1} and 54.45 Mg ha^{-1} to above-ground and below-ground biomass, respectively. Ram *et al.* (2016) also reported standing biomass in the tree component from 0.58 to 113.12 Mg ha^{-1}, in various tree based farming systems.

4.1.2 Crop biomass

4.1.2.1 Above-ground crop biomass

The data presented in Table 9, regarding crop above-ground biomass, reveals the total tree biomass varied significantly among agroforestry systems, from a minimum of 3.15 Mg ha^{-1} to a maximum of 6.07 Mg ha^{-1}. It is evident from the data in Table 9 that the maximum above-ground crop biomass was accumulated by sole cropping system (6.07 Mg ha^{-1}), which however, remained statistically at par with fruit tree based agroforestry system (5.96 Mg ha^{-1}) and agri-silvi-horticulture system (5.84 Mg ha^{-1}). The agri-silviculture system (4.87 Mg ha^{-1}), fruit tree based system (5.96 Mg ha^{-1}), agri-silvi-horticulture system (5.84 Mg ha^{-1}), poplar based system (5.07 Mg ha^{-1}), melia based system (4.29 Mg ha^{-1}), bamboo based system (4.25 Mg ha^{-1}), all remained statistically at par to each other with respect to crop above-ground biomass. However, minimum value (3.15 Mg ha^{-1}) was recorded in silvipasture system, which was statistically identical to fodder tree based agroforestry system (3.37 Mg ha^{-1}).

Maximum above-ground biomass in agriculture crops was observed in sole cropping system, which may be an outcome of no interference of tree canopies on sunlight reaching the ground, along with no adverse impact of tree-crop interaction and hence, an increase in vegetative biomass yield of the crops in monoculture (Reynolds *et al*., 2007).

Further, some other negative interactions such as, allelopathy can also take a toll up to some extent on the crop biomass and productivity under tree canopies. Dutt and Gupta (2005) too attribute the drop in herbage biomass to a fall in LAI of herbage beneath trees. Similar conditions under fruit tree based system, agri-silvi-horticulture and agri-silviculture systems due to relatively sparse canopy or wider spacing may have caused them to follow closely. Also, Bahar (2003) stated that climate conditions, edaphic features, phenology, and floristic diversity govern the production of every ecological system, including agroforestry systems.

Table 9: Tree and crop biomass (Mg ha^{-1}) under different AFS in sub-humid mid-hill conditions of Himachal Pradesh

Agroforestry systems	Tree Biomass (Mg ha^{-1})			Crop Biomass (Mg ha^{-1})			Total Vegetation Biomass (Mg ha^{-1})
	Above-ground biomass	Below-ground biomass	Total tree biomass	Above-ground biomass	Below-ground biomass	Total crop biomass	
T_1 (Sole Cropping system)	-	-	-	6.07^{a}	1.82^{a}	7.89^{a}	7.89^{g}
T_2 (Agri-silvi-horticulture system)	28.84^{e}	7.21^{de}	36.05^{e}	5.84^{ab}	1.75^{a}	7.60^{a}	43.65^{e}
T_3 (Agri-silviculture system)	25.08^{ef}	6.27^{de}	31.35^{ef}	4.87^{b}	1.02^{c}	5.89^{b}	37.24^{ef}
T_4 (Fruit tree based AFS)	18.18^{f}	4.54^{e}	22.72^{f}	5.96^{ab}	1.78^{a}	7.75^{a}	30.48^{f}
T_5 (Fodder tree based AFS)	47.85^{d}	13.88^{c}	61.73^{d}	3.37^{c}	1.01^{c}	4.38^{c}	66.11^{d}
T_6 (Bamboo based AFS)	21.01^{ef}	9.23^{d}	30.30^{ef}	4.25^{bc}	1.27^{bc}	5.53^{bc}	35.83^{ef}
T_7 (Melia basedAFS)	79.14^{b}	21.37^{b}	100.51^{b}	4.29^{b}	1.29^{b}	5.58^{b}	106.09^{b}
T_8 (Poplar based AFS)	99.55^{a}	24.89^{a}	124.44^{a}	5.07^{b}	1.36^{b}	6.43^{b}	130.87^{a}
T_9 (Silvipasture system)	65.19^{c}	18.42^{b}	83.62^{c}	3.15^{c}	0.94^{c}	4.10^{c}	87.72^{c}
Mean	48.11	13.23	61.34	4.60	1.31	5.91	67.24
$SE_{(M)}$	2.687	1.016	3.610	0.304	0.089	0.393	3.381
$CD_{0.05}$	8.15	3.080	10.82	0.913	0.266	1.178	10.05

These findings are partly in agreement with those of Kumar *et al*. (2021) who recorded above-ground crop biomass of wheat under different agroforestry systems prevalent in the Himalayan foothills to be ranging from 8.62 ± 0.12 Mg Cha^{-1} under *A. procera* based agroforestry system to 9.81 ± 0.17 Mg Cha^{-1} under *P. deltoides* based agroforestry system.

4.1.2.2 Below-ground crop biomass

Data pertaining to below-ground biomass of crops among agroforestry systems as depicted in Table 9 reveals it to be ranging from 0.94 Mg ha^{-1} to 1.82 Mg ha^{-1}. The maximum below-ground biomass was registered by sole cropping (1.82 Mg ha^{-1}), which was statistically at par with fruit tree based agroforestry system (1.78 Mg ha^{-1}) and agri-silvi-horticulture system (1.75 Mg ha^{-1}). These were followed by poplar based agroforestry system (1.36 Mg ha^{-1}), milea based agroforestry system (1.29 Mg ha^{-1}), bamboo based agroforestry system (1.27 Mg ha^{-1}), agri-silviculture system (1.02 Mg ha^{-1}), statistically at par with the fodder based agroforestry system (1.01 Mg ha^{-1}), which remained statistically at par to one another. The minimum below-ground crop biomass was recorded in silvipasture system (0.94 Mg ha^{-1}), which showed statistical similarity to fodder tree based, bamboo based and agri-silviculture systems.

Crop below-ground biomass in the present study expectedly followed the same trends as that of the above-ground biomass, reason being, its derivation from the above-ground biomass using the root-shoot ratio (Mokany *et al*., 2006). Kumar *et al*., 2021, reported below-ground biomass of wheat crop along with the above-ground biomass under different agroforestry systems prevalent in the Himalayan foothills to be ranging from 1.22 ± 0.02 Mg ha^{-1} in melia based agroforestry system to 2.04 ± 0.5 Mg ha^{-1} in *P. deltoides* based system.

4.1.2.3 Total crop biomass

A perusal of data presented in Table 9 reveals that the total (above-ground + below-ground) crop biomass varied from 4.10 to 7.89 Mg ha^{-1}. The highest value was exhibited by sole cropping system (7.89 Mg ha^{-1}), which was statistically identical to fruit tree based agroforestry system (7.75 Mg ha^{-1}). These were further followed by agri-silvi-horticulture system (7.60 Mg ha^{-1}), poplar based agroforestry system (6.43 Mg ha^{-1}), agri-silviculture system (5.89 Mg ha^{-1}), melia based agroforestry system (5.58 Mg ha^{-1}), bamboo based agroforestry system (5.53 Mg ha^{-1}), and fodder tree based agroforestry system (4.38 Mg ha^{-1}), respectively, in descending order. The lowest values of total crop biomass was exhibited by silvipasture system (4.10 Mg ha^{-1}), which, however remained statistically identical to bamboo based and fodder tree based agroforestry systems.

The maximum total crop biomass was found in sole cropping system which can be as described earlier, to the absence of over head trees, unhampered sunlight reaching the crops, unlike other agroforestry systems. These findings are in consonance with those of Zahoor *et al*. (2021), who reported higher crop biomass in monocropping systems as compared to the agri-horticulture based farming systems. Also, higher light and temperature conditions in sole cropping system may have led to higher photosynthetic rate and hence, more biomass production as also reported by number of workers (Grelen and Whrey, 1978; Singh and Singh, 1980; Hazra and Patil, 1986, and, Heinrichs and Schmidt, 2010). Further, intercropping of crops and trees leads to competition for available light, water and soil nutrients *etc*. (Nair *et al*., 2009). Sole cropping is followed by the fruit trees based and agri-silvi-horticulture system, which also share higher light and temperature conditions due to smaller, sparser canopies and large spacing between the trees, respectively. The overall biomass of herbage found in present study (4.10 to 7.89 Mg ha^{-1}) is partly in agreement with that of Gupta *et al*. (2015), who also found that the total biomass of herbaceous vegetation ranging from 3.02 to 4.72 Mg ha^{-1} under various tree-based systems. Biomass under agroforestry was comparatively lower than in sole cropping system, which might be owing to the fact that monocrop had a greater plant population than that in tree based systems, as well as inter and intraspecific competition for different growth factors (Gupta and Gupta, 2017). Gaur (2012) compared carbon storage in poplar based agroforestry system at different sites, and concluded that wheat crop yield ranged from 7.06-7.40 Mg ha^{-1} in Salimpur, Bihar to 7.32-7.68 Mg ha^{-1} in Kalesar, Haryana.

4.1.3 Total Vegetation Biomass

The total vegetation biomass is depicted Table 9. It showcases the total biomass of different agroforestry systems varied markedly in the present study with poplar based agroforestry system demonstrating the highest total biomass (130.87 Mg ha^{-1}), which significantly exceeded than all other agroforestry systems in the present investigation. After poplar based agroforestry system, the trend followed by the agroforestry systems was: melia based system (106.09 Mg ha^{-1}) > silvipasture system (87.72 Mg ha^{-1}) > fodder based agroforestry system (66.11 Mg ha^{-1}) > agri-silvi-horticulture system (43.65 Mg ha^{-1}) > agri-silviculture system (37.24 Mg ha^{-1}) > bamboo based agroforestry system (35.83 Mg ha^{-1}) >

fruit tree based agroforestry system (30.48 Mg ha^{-1}). The lowest vegetation biomass was observed in the sole cropping system (7.89 Mg ha^{-1}).

The total biomass documented in agri-silvi-horticulture system (43.65 Mg ha^{-1}), agri-silviculture system (37.24 Mg ha^{-1}) and fruit tree based agroforestry system (30.48 Mg ha^{-1}), in the present study are somewhat comparable to those reported by Rajput (2017) as 48.07 Mg ha^{-1}, 41.04 Mg ha^{-1} and 37.83 Mg ha^{-1} for agri-silvi-horticulture, agri-silviculture and agri-horticulture systems, respectively, in the mid-hill zone of Himachal Pradesh. Wood density, total tree height and tree diameter are key predictive factors for estimating forest biomass and these properties vary among species, ages and soil fertility (Muller-Landau 2004; Chave *et al.*, 2006; Ter *et al.*, 2006; Swenson and Enquist, 2007 and Nogueira *et al.*, 2008). Furthermore, the biomass is clearly being observed to be affected by the size and density of trees. This statement is supported by the findings of De Jong *et al*. (1995), who manifested that conversion of maize fields to farm forestry systems in Mexico resulted in an estimated increase in carbon density from 46.7 Mg ha^{-1} to 236.7 Mg ha^{-1}. The poplar and melia based systems lead the table of total vegetal biomass along with the tree biomass, whereas, fruit tree based, bamboo based, agri-silviculture as well as silvipasture systems lag for the same reason. These are in consonance with the proposals of Albrecht and Kandji (2003), Luedeling *et al*. (2011) and Esslin *et al.* (2015), who manifested that biomass in agriculture emphasized agroforestry systems is primarily dependent on the species and number of woody plants. The total biomass under silvipasture system according to Rajput (2010) in Kullu valley is 102.10 Mg ha^{-1} vis-à-vis 87.72 Mg ha^{-1}, in the present study. The total biomass observed in present investigation is almost similar to the values (37.8 Mg ha^{-1} in the pear + wheat and 10.8 Mg ha^{-1} in wheat mono cropping) reported by Yadav *et al*. (2015) for fruit tree based land use systems in Indian Himalayas. Variability in agroforestry system production, as shown, is also consistent with observations of Albrecht and Kandji (2003). Crop biomass has little contribution to the total vegetal biomass except for the sole cropping, which lacks the tree component. Ram *et al*. (2016), reported total biomass (tree + crop) in agroforestry systems to be ranging from 4.96 to 123.58 Mg ha^{-1}. Gupta *et al*. (2017), studied biomass storage across various agroforestry systems and reported total (above-ground + below-ground) biomass in the systems to be 84.46 (67.14 + 17.33) Mg ha^{-1} in silvipasture system, which is comparable to 83.62 (65.19 + 18.42) Mg ha^{-1} recorded for the silvipasture system in present study.

4.2 CARBON STOCK IN DIFFERENT COMPONENT (VEGETATION, LITTER AND SOIL)

The carbon stock under different components (vegetation, leaf litter and soil) as well as total carbon density has been described under Table 10.

Table 10: Carbon pool in different components (vegetation, litter and soil) of the system as influenced by average effect of the agroforestry system

Type of Agroforestry system	Vegetation carbon density (Mg ha^{-1})	Leaf litter carbon density (Mg ha^{-1})	Soil carbon density (Mg ha^{-1})	Total carbon density (Mg ha^{-1})
T_1 (Sole Cropping system)	3.95^{g}	0.08^{f}	84.74^{e}	88.76^{e}
T_2 (Agri-silvi-horticulture system)	21.82^{e}	0.49^{c}	107.28^{b}	129.59^{c}
T_3 (Agri-silviculture system)	18.62^{ef}	0.25^{e}	94.76^{d}	113.62^{d}
T_4 (Fruit tree based AFS)	15.24^{f}	0.33^{d}	100.29^{c}	115.86^{d}
T_5 (Fodder tree based AFS)	33.06^{d}	0.27^{e}	95.24^{d}	128.56^{c}
T_6 (Bamboo based AFS)	17.91^{ef}	0.47^{c}	114.69^{a}	133.08^{c}
T_7 (Melia based AFS)	53.04^{b}	0.60^{b}	104.01^{bc}	157.66^{b}
T_8 (Poplar based AFS)	65.44^{a}	0.66^{a}	107.81^{b}	173.91^{a}
T_9 (Silvipasture system)	43.86^{c}	0.30^{de}	113.71^{a}	157.86^{b}
Mean	30.33	0.38	102.50	133.21
$SE_{(M)}$	1.719	0.012	1.554	2.256
$CD_{0.05}$	5.153	0.035	4.659	6.764

4.2.1 Vegetation carbon density

A cursory look at the table reveals that vegetation carbon density varied appreciably amongst different agroforestry systems. Significantly highest vegetation carbon density was registered in poplar based agroforestry system. It was followed by other systems in the following trend: melia based agroforestry system (53.04 Mg ha^{-1}) > silvipasture system (43.86 Mg ha^{-1}) > fodder tree based agroforestry system (33.06 Mg ha^{-1}) > agri-silvi-horticulture system (21.82 Mg ha^{-1}) > agri-silviculture system (18.62 Mg ha^{-1}) > bamboo based agroforestry system (17.91 Mg ha^{-1}) > fruit tree based agroforestry system (15.24 Mg ha^{-1}) > sole cropping system (3.95 Mg ha^{-1}), respectively, in the decreasing order. However, fruit tree based agroforestry system and agri-silvi-horticulture systems were statistically at par with agri-silviculture system and bamboo based agroforestry system. Significantly minimum vegetation carbon density was recorded in sole cropping system.

Vegetation carbon density is the amount of carbon stored by the plants as biomass, expressed in Mega grams per hectare (Mg ha^{-1}). Carbon storage is directly proportional to the amount of biomass in particular component of agroforestry system. However, tree species' growth, biomass output, and carbon stock are all influenced by environmental factors, anthropogenic activities, and genotypic response (Horvath, 2016). According to Pandey (2002), carbon sequestration in Indian agroforestry ranges from 19.56 Mg ha^{-1} in Uttar Pradesh to 23.46–47.36 Mg ha^{-1} in tree-bearing dry agro-ecosystems of Rajasthan. Arora *et al.*, 2014, also investigated the vegetation carbon stock in 11 year old poplar plantation in Tarai region of Central Indian Himalayas, to be 90.1 Mg ha^{-1}. Chauhan *et al.* (2010) also documented higher net carbon sequestration in agroforestry based farming systems (34.61 Mg ha^{-1}) as compared to wheat monocropping systems (18.74 Mg ha^{-1}). Moreover, the frequency of pruning and other management activities affect the carbon storage potential of the systems (Montagnini and Nair, 2004). The carbon stock was lowest in sole cropping system due to the absence of tree component in the system. According to Ciampitti *et al.* (2011), trees absorb more carbon in agroforestry systems, crops also fix and store significant amounts of carbon and enhance soil organic matter, which is an important component of the terrestrial carbon sink.

4.2.2 Leaf litter carbon density

Data presented in Table 10 reveals that the carbon stored in the leaf litter to be varying significantly under different agroforestry systems, extending from 0.08 Mg ha^{-1} to 0.66 Mg ha^{-1}. The highest leaf litter carbon stock was documented in poplar based agroforestry system (0.66 Mg ha^{-1}), which was found to be significantly higher than all other agroforestry systems. It further followed the trend: melia based agroforestry system (0.60 Mg ha^{-1}) > agri-silvi-horticulture system (0.49 Mg ha^{-1}) > bamboo based system (0.47 Mg ha^{-1}) > fruit tree based agroforestry system (0.33 Mg ha^{-1}) > silvipasture system (0.30 Mg ha^{-1}) > fodder tree based agroforestry system (0.27 Mg ha^{-1}) > agri-silviculture system (0.25 Mg ha^{-1}). However, agri-silvi-horticulture system and bamboo based agroforestry systems remained statistical identical. Silvipasture system also remained statistically at par with the fodder tree based agroforestry system. The lowest leaf litter carbon stock was observed in the sole cropping system (0.08 Mg ha^{-1}), which was found to be significantly lower than all other agroforestry systems.

Litter has the capability of storing carbon which can be retained for a long time before biological breakdown releases it back into the atmosphere. Litter also offer a plethora of ecological benefits in addition to carbon storage, such as providing a local micro habitat for soil organisms, reducing runoff surface water, and aiding the process of water absorption into the soil as well as becoming a nutrient source for the plants. Litter formation is a crucial aspect of the organic matter transfer from vegetation to the soil. Lodhiyal *et al*. (2017), stated that the nutrients released by litter decomposition in the soil are critical for keeping up the soil fertility and productivity of particular agroforestry system and also, for carbon storage for extended period of time. Carbon stock present in surface litter is totally dependent on quantity and quality of litter production. The winter season corresponds with a considerable spike in litter fall for all the tree species (November to February). Litter was positively related to the size of the tree and spacing adopted along with the canopy management which is discernible by the fact that litter was far higher in poplar, melia and bamboo based systems as compared to fruit tree and fodder tree based agroforestry systems, beside natural agroforestry systems (agri-silvi-horticulture and agri-silviculture system) studied. Sole cropping exhibited lowest litter carbon density due to absence of full size tree in vicinity and received small amount of litter only from agriculture crop, herbage, waste, etc. The values of leaf litter in current study are similar to those of Muhdi *et al*., 2021, who reported the average total litter carbon produced in rubber agroforestry system to be 0.56 Mg ha^{-1}, in Indonesia. Also, Matos *et al.* (2020), having conducted a study in Brazil, reported that leaf litter biomass in rubber based agroforestry systems ranged from 1.18 Mg ha^{-1} to 1.32 Mg ha^{-1}, which is equivalent to 0.59 Mg ha^{-1} and 0.66 Mg ha^{-1} of litter carbon stock.

4.2.3 Soil carbon density

Similar to vegetation and leaf litter carbon density, soil carbon density also varied appreciably amongst different agroforestry systems. Maximum soil carbon density (114.69 Mg ha^{-1}) was recorded in bamboo based agroforestry system, which however, remained statistical on par with the silvipasture system (113.71 Mg ha^{-1}), only. The soil carbon density recorded under poplar based agroforestry system remained statistically identical to melia based agroforestry system and agri-silvi-horticulture systems. Minimum soil carbon density (84.74 Mg ha^{-1}) was recorded under sole cropping system. The soil carbon density of different agroforestry systems under different layers *viz*., 0-20 cm, 20-40 cm and 40-100 cm has been tabulated in Table 11. The table reveals that the soil carbon density varied significantly at each layer.

The soil carbon density (SCD) is the largest depository of carbon stock in all the terrestrial ecosystems, and, is a portrayal of miscellany of various factors affecting it *viz*. bulk density, organic carbon, and, especially depth. Data regarding soil carbon density is inscribed in Table 11, which depicts the effect of increasing soil depths on the amount of SOC stored in different layers of the soil.

Table 11: Soil carbon density (Mg ha^{-1}) at different soil layers under AFS in sub-humid mid-hill conditions of Himachal Pradesh

Agroforestry systems	**Soil carbon density**			
	D_1	**D_2**	**D_3**	**Total**
T_1 (Sole Cropping system)	24.81^{d}	17.60^{f}	42.33^{d}	84.74^{e}
T_2 (Agri-silvi-horticulture system)	28.90^{a}	24.46^{bc}	53.91^{bc}	107.28^{b}
T_3 (Agri-silviculture system)	26.44^{c}	21.53^{d}	46.79^{cd}	94.76^{d}
T_4 (Fruit tree based AFS)	28.04^{b}	22.72^{cd}	49.54^{c}	100.29^{c}
T_5 (Fodder tree based AFS)	26.28^{c}	20.19^{e}	48.76^{c}	95.24^{d}
T_6 (Bamboo based AFS)	26.59^{c}	25.36^{a}	62.74^{a}	114.69^{a}
T_7 (Melia based AFS)	27.03^{c}	23.92^{c}	53.06^{bc}	104.01^{bc}
T_8 (Poplar based AFS)	26.66^{c}	24.32^{bc}	56.84^{b}	107.81^{b}
T_9 (Silvipasture system)	28.20^{ab}	26.95^{a}	58.56^{ab}	113.71^{a}
Mean	27.00	23.01	52.50	102.50
$SE_{(M)}$	0.271	0.414	1.586	1.554
$CD_{0.05}$	0.81	1.24	4.76	4.66

4.2.3.1 0-20 cm soil depth

In 0-20 cm soil layer, soil carbon density though significant, showed a slight variation in under different agroforestry systems. Maximum soil carbon density (28.90 Mg ha^{-1}) has been recorded in natural (agri-silvi-horticulture) system, which however, remained statistically identical to the silvipasture system. The soil carbon density under different agroforestry systems *viz*., agri-silviculture system, fodder based, bamboo based, melia based and poplar based agroforestry systems remained statistically at par with one another. Similarly, soil carbon density under fruit tree based agroforestry system and silvipasture system remained statistically identical. Minimum soil carbon density (24.81 Mg ha^{-1}) was recorded in sole cropping system..

Highest soil organic carbon stock in agri-silvi-horticulture system may be due to large canopies causing higher litter fall and larger root systems of native species in natural conditions. Variation in carbon stocks in the top layer of the soil among different ecosystems represents the contrast in leaf litter quantity and quality, amount of carbon present in litter and also, it`s disintegration and degradation (Mo *et al*., 2002). Higher carbon density in the top layer of the soil can be associated with greater root biomass of trees in the top layer together with the crops and herbage besides higher effects of the nutrient cycling causing pumping of nutrients from the sub soil and returning it to the surface layer in the form of organic matter, exorbitant in organic carbon which builds up in the soil with time. Schmitt-Harsh *et al.* (2012) discovered the soil carbon pool to be in 38.84 Mg Cha^{-1} to 45.09 Mg Cha^{-1} range, in a study of coffee based agroforestry system. Moreover, Gaur and Gupta (2012) investigated the top layer of soil for estimating carbon storage in soil plant systems in response to site circumstances in *Populus deltoides* based agroforestry system. The soil organic carbon (SOC) pool ranged from, 22.31-20.28 Mg Cha^{-1} at Kalesar in Haryana, compared to 19.63-30.11 Mg Cha^{-1} at Salimpur, Bihar.

4.2.3.2 20-40 cm soil depth

In the second soil layer (20-40 cm), maximum soil carbon density (26.95 Mg Cha^{-1}) was observed in silvipasture system which was found to be statistically at par with bamboo based agroforestry system (25.36 Mg Cha^{-1}), only. It was closely followed by agri-silvi-horticulture system, poplar based agroforestry system, melia based agroforestry system, fruit tree based agroforestry system, agri-silviculture system and fodder tree based agroforestry system, respectively in the descending order. The minimum soil carbon density (17.60 Mg Cha^{-1}) was recorded in sole cropping system.

In case of the aggregated results of top two soil layer of the present study are considered, the outcomes become comparable to those of Ciais *et al*. (2011), who reported the mean soil organic carbon reserves for the top layer (0–40 cm), to be 30 to 140 Mg Cha^{-1} in the African savannah and woodland ranges. Likewise, Zhuang *et al*. (2015) estimated the total soil carbon storage in Moso bamboo (*Phyllostachys pubescens*) stands in the forests to be 90.6 Mg Cha^{-1} up to 60 cm soil depth, which is expectedly higher than the present findings of approximately 60 Mg Cha^{-1}, up to same soil depth in bamboo based agroforestry systems. Also, the soil carbon density decreases in the sub soil due to the fact that the root biomass is also decreasing with increasing depth, along with lesser percolation and accumulation of organic carbon. Moreover, the lower layers are also relatively devoid of anthropological disturbances and biological processes (Shreshtha *et al*., 2004). Findings of Sanneh (2007) about the soil organic carbon storage potential of various land use systems: 105.46 Mg Cha^{-1} in agri-horticulture, agri-silviculture (40.40 Mg Cha^{-1}) and silvi-pastoral systems (33.54 Mg Cha^{-1}) up to 40 cm soil depth, as compared to 50.76, 47.97 and 55.15 Mg Cha^{-1}, respectively, for the same systems, in the present study. Rajput *et al*. (2017) too reported highest soil organic carbon pool in forestry based land use system (98.08 Mg Cha^{-1}) the 0–40 cm layer, followed by agroforestry systems *viz*., agri-horticulture (41.05 Mg Cha^{-1}), horticulture (39.16 Mg ha^{-1}), silvi-pasture (35.79 Mg ha^{-1}), and agriculture systems (33.88 Mg Cha^{-1} ha^{-1}).

4.2.3.3 40-100 cm soil depth

The deepest soil layer (40-100 cm) showed decrease in soil carbon density, bearing in mind its 60 cm extent as compared to 20 cm in previous two layers. The maximum soil carbon density (62.47 Mg Cha^{-1}) was observed in bamboo based agroforestry system, which however, showed statistical similarity to silvipasture system (58.86 Mg Cha^{-1}). The soil carbon density under poplar based system, agri-silvi-horticulture system and melia based systems remained statistically identical to each other. Similarly, fruit tree based system, fodder tree based system and agri-silviculture system also showed statistical similarity. Significantly minimum soil carbon density was recorded under sole cropping system (42.33 Mg Cha^{-1}). The growth and physiology of the plants are dependent on the plant nutrients present in the soil whereas the soil carbon stock is dependent on the accruals from the vegetation growing above, which can be in the form of surface litter addition or in the form of fine roots present below-ground, as advocated by Bloomfield *et al*. (1996), as well as, decomposition of roots after the tree dies. Therefore, an inter-relationship among the two is clearly visible. With depths up to one meter, the nutrient availability reduces drastically and hence, the organic carbon also reduces along, due to decreased root biomass.

4.2.3.4 Total soil carbon density (SOC)

Table 12 also depicts the total soil carbon density which ranges from 84.74 Mg Cha^{-1} (sole cropping system) up to 114.69 Mg Cha^{-1} (bamboo based agroforestry system). Total soil carbon density represents combined carbon storage of individual layers. The total SOC stock was observed in the following trend: bamboo based agroforestry system (114.69 Mg Cha^{-1}), statistically at par with silvipasture system (113.71 Mg Cha^{-1}), further followed by poplar based system (107.81 Mg Cha^{-1}), agri-silvi-horticulture system (107.28 Mg ha^{-1}), melia based system (104.01 Mg Cha^{-1}), fruit tree based system (100.29 Mg Cha^{-1}), fodder tree based agroforestry system (95.24 Mg Cha^{-1}), statistically at par with agri-silviculture system (94.76 Mg Cha^{-1}) and lowest in sole cropping system (84.74 Mg Cha^{-1}).

The resulting SOC stock is in line with the findings of Bustamante *et al*. (2006) who studied the soils in tropical and temperate savannas concluding the soils of Cerrado region having SOC stock of 117 Mg Cha^{-1} (ranging from 100-174 Mg Cha^{-1}) despite having lower Above-ground biomass. The outcomes of the present study are also synchronous with those of Dhillon and Van Rees (2017), as they published SOC stock for the top 50 cm soil under shelterbelts in Saskatchewan averaged to be 119.1 Mg Cha^{-1}, higher by 18.6 Mg Cha^{-1} than those of adjacent fields. Gupta *et al*. (2009) discovered that in *P. deltoides* (poplar) based agroforestry soils, average soil organic carbon increased as the age of the trees increased and agroforestry soils had 2.9-4.8 Mg Cha^{-1} more soil organic carbon than monocropping system soils. Furthermore, as discussed earlier under the tree above-ground biomass, Kaonga and Smith (2011) have also reported along with the above-ground C stock, the SOC stocks in Leucaena stands ranged from 106.9 (*L. diversifolia*) to 186.0 Mg Cha^{-1} (*L. leucocephala*), when measured at 0–200 cm depth. Moreover, in n the present study, the total carbon density of fruit tree based agroforestry system is on the higher side (115.86 Mg Cha^{-1}) compared to that suggested by Rajput (2010) under agri-horticulture system in the Kullu valley (90.88 Mg Cha^{-1}). Also, Nair *et al*. (2010) have classified various land-use systems in the following order for the SOC content: forests > agroforests > tree plantations > arable crops.

Soil organic carbon concentration kept decreasing significantly with increasing depth but there was not much dissimilarity in the top layer across all the systems, which is in line with the findings of Cardinael *et al*. (2016). The carbon proportion in the system is also improved by tree roots acting as a control on soil erodibility. The top layer is protected because it contains a higher proportion of organic matter (Gupta *et al*., 2006). Fact being, more than half of the sequestered carbon is transferred below-ground via root development and turnover, root exudates (of organic compounds), and litter deposition, soils hold the majority of the carbon in any ecosystem (Montagnini and Nair, 2004). Though, carbon stock measurement is not accurate, factor being the sampling and measurement problems (Koskela *et al*., 2000). Guo *et al*., 2020, converted the fields from croplands to poplar and poplar + metsequoia systems over 10 years, and, the SOC stocks of the poplar plantation and poplar and metasequoia system reached 90.35 Mg Cha^{-1} and 98.12 Mg Cha^{-1}, respectively. SOC stocks always decline once croplands are converted to forestlands, but they progressively grow after plantations are established (Laganiere *et al*., 2010; Mao *et al*., 2010; Nave *et al*., 2013). The SOC diminishes with depth regardless of vegetation type and soil texture (Trujilo *et al*., 1997).

4.2.4 Total carbon density (vegetation + litter + soil)

Data pertaining to total carbon density is inscribed in Table10. It is evident from the data that maximum total carbon density was recorded under poplar based agroforestry system (173.91 Mg ha^{-1}), which was found to be significantly higher than all other agroforestry systems. Melia based and silvipasture systems displayed statistically similar values. Similarly, bamboo based agroforestry system, agri-silvi-horticulture system and fodder tree based agroforestry system remained statistically identical to one another, whereas, fruit tree based agroforestry system and natural agroforestry system displayed statistically similar values. Minimum total carbon density (88.76 Mg ha^{-1}) was recorded in sole cropping system, which was found to be significantly lower than all other agroforestry systems. The carbon densities under different agroforestry systems followed the trend: poplar based agroforestry system (173.91 Mg ha^{-1}) > silvipasture system (157.86 Mg ha^{-1}) > melia based system (157.66 Mg ha^{-1}) > bamboo based system (133.08 Mg ha^{-1}) > agri-silvi-horticulture system (129.59 Mg ha^{-1}) > fodder tree based system (128.56 Mg ha^{-1}) > fruit tree based system (115.86 Mg ha^{-1}) > agri-silviculture system (113.62 Mg ha^{-1}) > sole cropping system (88.76 Mg ha^{-1}).

The system supporting highest vegetal biomass also excelled in SOC stock. Poplar and melia based agroforestry systems held highest carbon stock because of their large amount of biomass due to their comparatively larger size, and higher plant densities. Chauhan *et al*. (2015), compared carbon density in poplar block plantations with boundary plantations in various conditions and, found the total carbon stock to be 20.27 Mg ha^{-1} in block plantation against 6.20 Mg ha^{-1} in boundary plantations. Bamboo based and silvipasture system also claimed comparable carbon density because of the fact that they housed the highest SOC stock. Sole cropping stood the least because of lowest vegetal as well as SOC stock. Arora *et al*. (2014) found an increase in the total carbon density (vegetation + soil) of a poplar stand from 64.4 Mg ha^{-1} to 173.9 Mg ha^{-1}, over a period of eleven years. Further, the carbon storage inside agroforestry systems has been estimated by Nair *et al*. (2010) to be ranging from 0.29 to 15.21 Mg ha^{-1} in aboveground and 30 to 300 Mg ha^{-1}, for the top 1 m soil depth.

4.3 CARBON DENSITY AND CARBON SEQUESTRATION POTENTIAL

The carbon sequestration potential and CO_2 mitigation potential were only calculated for the experimental agroforestry systems because of the fact that age of trees in the systems is required for its calculation. The rate of carbon sequestration and CO_2 mitigation was calculated by comparing the carbon density under the agroforestry systems with carbon density outside the respective systems. The Table 12 juxtaposes the carbon stock present under the agroforestry systems vis-à-vis outside agroforestry systems.

Table 12: Carbon density (Mg ha^{-1}) inside and outside different AFS in sub-humid mid-hill conditions of Himachal Pradesh

Agroforestry systems	Carbon density under AFS			Carbon density outside AFS		
	Soil	Vegetation	Total	Soil	Vegetation	Total
T_4 (Fruit tree based AFS)	100.29^c	15.24^f	115.53^d	77.57^b	3.04^b	80.61^b
T_5 (Fodder tree based AFS)	95.24^d	33.06^d	128.30^c	68.89^b	1.41^f	76.45^b
T_6 (Bamboo based AFS)	114.69^a	17.91^{ef}	132.60^c	89.33^a	1.89^d	91.24^a
T_7 (Melia based AFS)	104.01^{bc}	53.04^b	157.05^b	80.08^{ab}	3.35^a	83.44^{ab}
T_8 (Poplar based AFS)	107.81^b	65.44^a	173.25^a	83.50^{ab}	2.12^c	85.62^{ab}
T_9 (Silvipasture system)	113.71^a	43.86^c	157.57^b	86.76^{ab}	1.71^e	88.47^{ab}
Mean	105.96	38.09	144.05	81.02	2.25	84.30
$SE_{(M)}$	1.64	1.93	2.36	3.05	0.05	3.03
$CD_{0.05}$	5.16	6.07	7.45	9.62	0.14	9.53

4.3.1 Carbon density inside and outside agroforestry systems

The carbon density under experimental agroforestry systems (where the age is known) has been depicted in Table 12. The table shows that carbon density in the soil sphere is significantly influenced due to the effect of different agroforestry systems. It was found to be maximum in bamboo based agroforestry system (114.69 Mg ha^{-1}) followed by silvipasture system (113.71 Mg ha^{-1}), poplar based agroforestry system (107.81 Mg ha^{-1}), melia based agroforestry system (104.01 Mg ha^{-1}), fruit tree based agroforestry system (100.29 Mg ha^{-1}) and fodder tree based agroforestry system (95.24 Mg ha^{-1}). The soil carbon density under bamboo based and silvipasture system remained statistically identical to one another.

Similarly, soil carbon density under poplar and melia based agroforestry systems also showed statistical similarity.

It is also evident from the Table 12 that vegetation carbon density varies significantly among various agroforestry systems. It was found to be highest in poplar based agroforestry system (65.44 Mg ha^{-1}) and followed the trend: melia based agroforestry system (53.04 Mg ha^{-1}) > silvipasture system (43.86 Mg ha^{-1}) > fodder tree based agroforestry system (33.06 Mg ha^{-1}) > bamboo based agroforestry system (17.91 Mg ha^{-1}) > fruit tree based agroforestry system (15.24 Mg ha^{-1}).

The total carbon density (soil + vegetation) also varied significantly among different agroforestry systems. The maximum carbon density was observed in poplar based agroforestry systems (173.25 Mg ha^{-1}), which was found to be significantly higher than all other agroforestry systems and followed the order: silvipasture system (157.57 Mg ha^{-1}) > melia based agroforestry system (157.05 Mg ha^{-1}) > bamboo based agroforestry system (132.60 Mg ha^{-1}) > fodder tree based agroforestry system (128.30 Mg ha^{-1}) > fruit tree based agroforestry system (115.53 Mg ha^{-1}). Carbon density immediately outside the agroforestry systems in soil and vegetation as well as total carbon density (soil + vegetation) show the slide what significant variation.

4.3.2 Carbon Sequestration and CO_2 mitigation potential

Carbon sequestration is the net removal of CO_2 from the atmosphere and its accumulation in terrestrial ecosystem (Sedjo *et al.*, 2003). It occurs in nature during the photosynthesis process, when trees and plants utilize carbon dioxide and store it (CO_2) throughout the process of development. Increasing vegetation cover is imperative to avert global warming because it absorbs carbon dioxide that would otherwise be released and trap heat in the atmosphere. The difference between the carbon stocks of the adjacent sole cropping ecosystems was then divided by the respective average age of the planted trees inside the agroforestry systems to calculate the carbon sequestration rate on per year basis.

The rate of carbon sequestration with respect to experimental agroforestry systems in soil and vegetation and total (soil + vegetation) has been depicted in table 13. The table shows that agroforestry systems significantly influenced the rate of carbon sequestration potential in soil mass. It was found to be maximum in bamboo based agroforestry system (1.81 Mg ha^{-1}yr^{-1}) followed by melia based system (1.71 Mg ha^{-1}yr^{-1}), fruit tree based system

(1.62 Mg ha^{-1}yr^{-1}), fodder tree based system (1.55 Mg ha^{-1}yr^{-1}), poplar based system (1.43 Mg ha^{-1}yr^{-1}) and silvipasture system (1.35 Mg ha^{-1}yr^{-1}), respectively.

Table 13: Rate of carbon sequestration (Mg ha^{-1}yr^{-1}) and CO_2 mitigation (Mg ha^{-1}yr^{-1}) potential of different agroforestry systems in sub-humid mid- hill conditions of Himachal Pradesh

Agroforestry systems	Rate of Carbon sequestration (Mg ha^{-1} yr^{-1})			Rate of CO_2 mitigation (Mg ha^{-1} yr^{-1})		
	Soil	Vegetation	Total	Soil	Vegetation	Total
T_4 (Fruit tree based AFS)	1.62^{c}	0.87^{c}	2.49^{c}	5.95^{c}	3.20^{c}	9.15^{c}
T_5 (Fodder tree based AFS)	1.55^{c}	1.86^{b}	3.41^{bc}	5.70^{c}	6.83^{b}	11.19^{bc}
T_6 (Bamboo based AFS)	1.81^{a}	1.14^{c}	2.95^{c}	6.65^{a}	4.20^{c}	10.85^{c}
T_7 (Melia based AFS)	1.71^{b}	3.55^{a}	5.26^{a}	6.27^{b}	13.03^{a}	19.30^{a}
T_8 (Poplar based AFS)	1.43^{d}	3.72^{a}	5.15^{a}	5.25^{d}	13.67^{a}	18.91^{a}
T_9 (Silvipasture system)	1.35^{d}	2.11^{b}	3.46^{b}	4.95^{d}	7.73^{b}	12.68^{b}
Mean	1.58	2.21	3.79	5.79	8.11	13.68
$SE_{(M)}$	0.022	0.11	0.16	0.81	0.40	0.55
$CD_{0.05}$	0.070	0.35	0.50	2.56	1.27	1.72

These findings are synchronous with those of Dhyani *et al.* (2016) according to whom; the carbon sequestration potential of soil in agroforestry systems in India is estimated to be between 0.003 to 3.98 Mg ha^{-1}yr^{-1}. Several studies around the globe comparing different land-use strategies and studies on carbon sequestration in soils indicated a general trend of comparative increase in the soil carbon sequestration (SCS) in agroforestry. Gupta *et al.* (2009), worked on soil organic carbon under poplar based agroforestry systems in relation to tree age , revealing that during the first year of plantation, the poplar trees were able to store more soil organic carbon in the 0-30 cm profile (6.07 Mg ha^{-1}yr^{-1}), than in following years (1.95-2.63 Mg ha^{-1}yr^{-1}). The carbon sequestered by sandy clay soil was higher (2.85 Mg ha^{-1}yr^{-1}) than in loamy sand soil (2.32 Mg ha^{-1}yr^{-1}).

Similarly in vegetation, the vegetation carbon density was also found to be significantly influenced due to the effect of agroforestry systems. The maximum rate of carbon sequestration in vegetation was found in poplar based agroforestry system (3.72 Mg ha^{-1}yr^{-1}), which however, remained statistically identical to melia based agroforestry system (3.55 Mg ha^{-1}yr^{-1}), only. Similarly, silvipasture system (2.11 Mg ha^{-1}yr^{-1}) and fodder tree based agroforestry system (1.86 Mg ha^{-1}yr^{-1}) remained statistically at par. Minimum vegetation carbon density (0.87 Mg $ha^{-1}yr^{-1}$) was recorded under fruit tree based agroforestry system.

Total carbon sequestration (soil + vegetation) was also found to be significantly influenced due to the impact of different agroforestry systems. Maximum carbon sequestration rate (5.26 Mg $ha^{-1}yr^{-1}$) was observed in melia based agroforestry system, which however, remained statistically identical to poplar based agroforestry system (5.15 Mg $ha^{-1}yr^{-1}$). The rate of total carbon sequestration followed the order: melia based system (5.26 Mg ha^{-1} yr^{-1}) > poplar based (5.15 Mg $ha^{-1}yr^{-1}$) > silvipasture system (3.46 Mg $ha^{-1}yr^{-1}$) > fodder tree based system (3.41 Mg $ha^{-1}yr^{-1}$) > bamboo based system (2.95 Mg $ha^{-1}yr^{-1}$) > fruit tree based agroforestry system (2.49 Mg $ha^{-1}yr^{-1}$).

The rate of carbon dioxide mitigation potential was calculated by multiplying the rate of carbon sequestration with 3.67. The rate of carbon dioxide mitigation potential in soil vegetation and total (soil + vegetation) was found to be significantly dissimilar due to the effect of agroforestry systems, and follows the same trend as that of rate of carbon sequestration potential.

Carbon sequestration was evaluated by subtracting carbon density outside agroforestry systems from that, inside. Feliciano *et al.* (2018), while working on various land use systems, found that improved fallows (11.29 Mg $ha^{-1}yr^{-1}$) have more soil and above-ground carbon sequestration than silvo-pastoral agroforestry systems (4.38 Mg $ha^{-1}yr^{-1}$). Goswami *et al*. (2013) also reported the carbon sequestration in mid Himalayas under agri-silvi-horticulture and agri-horti-silviculture systems to be 14.78 Mg ha^{-1} and 14.45 Mg ha^{-1}, respectively. Similarly, according to Pandey (2002), carbon sequestration in Indian agro-forests ranges from 19.56 Mg Cha^{-1} yr^{-1} in Uttar Pradesh, north India, to 23.46 to 47.36 Mg Cha^{-1} yr^{-1} in Rajasthan's tree-bearing desert agro-ecosystems.

Agroforestry systems in India are supposed to have carbon sequestration capabilities as high as 10 Mg C $ha^{-1}yr^{-1}$ (Chavan *et al*., 2015), with a 25 Mg Cha^{-1} sequestration potential, as proposed by Singh and Pandey, 2011. The total C sequestered in each component varies substantially, depending on the geography, species, system, site quality, and historical land use (Ram *et al*., 2016). These factors, as well as the agro-ecological conditions (altitude, climate, wind) and soil characteristics (structure, texture, fertility, and physical, chemical, and biological conditions) in which the various agroforestry systems are used, have an impact on soil and above ground carbon sequestration (Baah-Acheamfour *et al*., 2017; Marone *et al*., 2017). van Noordwijk *et al.* (2002), also reported that the conversion of sun-coffee systems to shade coffee systems in Sumatra was expected to raise average landscape level carbon stocks by 10 Mg ha^{-1} over a 20-year period, or 0.5 Mg C ha^{-1}yr^{-1}. The conclusive rates of carbon sequestration in the present study are partly analogous with those of Montagnini and Nair (2004), who have published the potential C sequestration rates for smallholder agroforestry systems in the tropics to be ranging from 1.5 Mg ha^{-1}yr^{-1} to 3.5 Mg ha^{-1}yr^{-1}. Similarly, under poplar block and poplar boundary plants, Gera *et al*. (2006, 2011), reported 66 and 37 Mg ha^{-1} carbon sequestration capacity (2.20 and 1.37 Mg ha^{-1}yr^{-1}, respectively).

4.4 SOIL PHYSICO-CHEMICAL AND MICROBIAL PROPERTIES

Soil physico-chemical and biological properties, *viz*., pH, EC (dS m^{-1}), organic carbon (per cent), available N, P, K, Ca and S (kg ha^{-1}), micronutrients Cu, Fe, Mn and Zn (mg kg^{-1}), bulk density (g cm^{-3}), particle density (g cm^{-3}), porosity (per cent), soil texture and microbial count (cfu g^{-1}) were observed in three soil layers ranging from 0-20, 20-40 and 40-100 cm soil layer under different agroforestry tree species and have been delineated in tables discussed below, individually.

4.4.1 Physical properties of soil

The physical properties of the soil were studied for four parameters *viz*., bulk density, particle density, soil porosity and soil texture.

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

The data displayed in Table 14 shows that the bulk density of different soil layers, *i.e*. 0-20, 20-40, 40-100 cm layer is significantly influenced due to agroforestry systems and soil depths. The mean bulk density ranged from 1.09 g cm^{-3} to 1.28 g cm^{-3} amongst different agroforestry systems investigated. The highest mean bulk density was recorded in the sole cropping system (1.28 g cm^{-3}) which was however, statistically at par with the agri-silviculture system (1.28 g cm^{-3}), which was followed by, agri-silvi-horticulture system, fruit tree based system, silvipasture system, fodder tree based system, melia based system, poplar based system and bamboo based agroforestry system (1.09 g cm^{-3}), respectively in the descending order. Further, irrespective of the agroforestry systems, soil depths also significantly influenced the bulk density. It is observed to be constantly increasing with increasing soil depth. Also, it is evident from the interaction effect, that in all the agroforestry systems, soil bulk density enhanced from D_1 (1.15 g cm^{-3}) to D_2 (1.20 g cm^{-3}) and D_2 to D_3 (1.28 g cm^{-3}). But, the enhancement is less sharp in silvipasture systems, than other agroforestry systems. The interaction between soil depth and agroforestry systems, also markedly affected the soil bulk density. The minimum bulk density was recorded in bamboo based agroforestry system at 0-20 cm soil depth (1.01 g cm^{-3}) and maximum in sole cropping system at 40-100 cm soil depth (1.37 g cm^{-3}).

Table 14: Effect of agroforestry systems, soil depths and interaction between them on bulk density (g cm^{-3})

Agroforestry systems	Soil Depths			Mean
	D_1	**D_2**	**D_3**	
T_1 (Sole Cropping system)	1.21	1.26	1.37	1.28^{a}
T_2 (Agri-silvi-horticulture system)	1.20	1.23	1.26	1.23^{b}
T_3 (Agri-silviculture system)	1.23	1.26	1.36	1.28^{a}
T_4 (Fruit tree based AFS)	1.19	1.22	1.27	1.22^{bc}
T_5 (Fodder tree based AFS)	1.18	1.20	1.26	1.21^{c}
T_6 (Bamboo based AFS)	1.01	1.07	1.18	1.09^{f}
T_7 (Melia based AFS)	1.11	1.18	1.28	1.19^{d}
T_8 (Poplar based AFS)	1.04	1.14	1.23	1.14^{e}
T_9 (Silvipasture system)	1.15	1.22	1.29	1.22^{bc}
Mean	1.15^{c}	1.20^{b}	1.28^{a}	
Factors	**$SE_{(M)}$**	**$CD_{0.05}$**		
Soil depth	0.002	0.007		
AFS	0.004	0.011		
Interaction	0.007	0.020		

The bulk density results show some relativity with the organic carbon content of the soil which further, is associated with lesser number of trees or leaf fall inside particular agroforestry system soils. Matos *et al*. (2020) also found the bulk densities of soils under eight year old agroforestry systems to be lower than adjacent pastures and similar to those of forests. Higher soil bulk density leads to soil strength increment due to which soil aeration reduces, detrimentally affecting the root growth. Berhe *et al*. (2013) found the bulk densities outside the tree canopies to be higher than the bulk densities under the tree canopies, owing to litter addition into the soil, higher concentration of tree roots near the tree base, and exposure of soil outside the tree canopy to direct sunlight. Moreover, the reduced bulk densities can have a positive effect on root development, especially in tree plantations. The bulk densities under experimental agroforestry systems were lower as compared to control (sole cropping) and traditional agroforestry systems in both, surface as well as sub surface layers. These outcomes are totally in line with similar work carried out by Gardini *et al*. (2015) under Cacao based agroforestry systems in Peru, who concluded that increased vegetation cover increases fresh organic matter and reduces the bulk density of soils because of the decomposing organic matter components being less dense than mineral components.

The surface soil layer shows a lot of variance in bulk density, but the variance tends to decrease in all the agroforestry systems in the deeper soil layers. Bulk density showed an increasing trend with increasing depth in all the systems due to lower organic matter content and continuous compaction of soil layers. These results are synchronous with those of Bargali and Bargali (2020), who reported the bulk densities of surface and sub-surface layers to be ranging from 0.62 to 1.16 g cm^{-3} and 0.79 to 1.22 g cm^{-3}, respectively.

4.4.1.2 Particle density (g cm^{-3})

A scrutiny of data in Table 15 shows that particle density is significantly influenced due to the effect of agroforestry systems, soil depths and interaction between them. Irrespective of soil depths, maximum particle density (2.29 g cm^{-3}) was recorded in sole cropping and agri-silviculture systems, which however, remained statistically similar to fruit tree based agroforestry system. The particle density under agri-silviculture system, bamboo based and melia based agroforestry systems remained statistically identical to one another. Similarly, particle density under fodder based, bamboo based, melia based, poplar based, agri-silvi-horticulture and silvipasture systems also remained statistically at par. In the average effect of soil depths, the particle density enhanced significantly from D_1 (2.19 g cm^{-3}) to D_2 (2.24 g cm^{-3}) and, further to D_3 (2.32 g cm^{-3}). In the interaction effect between agroforestry systems and soil depths, it was observed that in all the agroforestry systems, the particle density declined all the way from D_1 to D_3. But, significant decline from D_1 to D_2 could be observed only in agri-silvi-horticulture, fruit based, bamboo based, melia based, poplar based and silvipasture systems. Whereas, from D_2 to D_3, significant decline was observed in sole cropping system, agri-silviculture, fruit based, bamboo based, poplar based and silvipasture systems.

Maximum particle density was observed in T_1D_3 system (2.38 g cm^{-3}) and T_3D_3 (2.37 g cm^{-3}) at 40-100 cm depth, whereas, minimum particle density was recorded in T_8D_1 (2.12 g cm^{-3}), which was found to be significantly lower than all other treatment combinations.

Minimum particle density at D_3 soil depth was recorded in T_5D_3 (2.25 g cm^{-3}), which however, remained statistically at par with T_9D_3 (2.28 g cm^{-3}) treatment combination.

Table 15: Effect of agroforestry systems, soil depths and interaction between them on particle density (g cm^{-3})

Agroforestry systems	Soil Depths			Mean
	D_1	D_2	D_3	
T_1 (Sole Cropping system)	2.23	2.25	2.38	2.29^a
T_2 (Agri-silvi-horticulture system)	2.22	2.26	2.28	2.25^b
T_3 (Agri-silviculture system)	2.24	2.27	2.37	2.29^a
T_4 (Fruit tree based AFS)	2.24	2.28	2.32	2.28^a
T_5 (Fodder tree based AFS)	2.20	2.22	2.25	2.22^c
T_6 (Bamboo based AFS)	2.16	2.23	2.33	2.24^{bc}
T_7 (Melia based AFS)	2.15	2.22	2.35	2.24^{bc}
T_8 (Poplar based AFS)	2.12	2.23	2.31	2.22^c
T_9 (Silvipasture system)	2.17	2.24	2.28	2.23^b
Mean	2.19^c	2.24^b	2.32^a	
Factors	**$SE_{(M)}$**	**$CD_{0.05}$**		
Soil depth	0.004	0.013		
AFS	0.007	0.019		
Interaction	0.012	0.033		

Particle density of the different systems varied significantly depth wise as compared various agroforestry systems due to the fact that soil depth had greater effect on soil particle density because of compaction of soils and hence; dense packing of the soil particles. Also, particle density results showed reciprocated values to that of organic carbon, similar to that with bulk density as discussed above earlier. Thereby, lowest particle density is evident in poplar based and silvipasture system may be due to the fact that they had comparatively highest litter fall and closer spacing adopted in silvipasture systems, respectively. Singh and Sharma (2007) reported addition of organic matter and its subsequent decomposition in the presence of soil and microbial fauna to improve the soil physical qualities, such as bulk density and particle density. Rawat *et al*. (2018) compared *Populus deltoides, Anthocephalus cadamba* and *Madhuca indica* based agroforestry systems, and found lowest soil particle density (2.62 g cm^{-3}) under *Populus deltoides based system* at 0-15 cm soil depth, increasing with increasing depth.

4.4.1.3 Porosity (per cent)

The data on porosity is demonstrated in Table 16. It is evident from the table that porosity is significantly influenced due to the average effect of agroforestry systems, soil depths and interaction between them. The soil porosity showed a slide what significant variation among the different agroforestry systems investigated. Maximum porosity was measured in bamboo based agroforestry systems (51.63 %), followed closely by poplar based (48.81 %) and melia based agroforestry systems (46.88 %), respectively. Minimum soil porosity was recorded under agri-silviculture system (44.11 %), which however, remained statistically identical to sole cropping system (44.18 %). Irrespective of agroforestry systems, the soil porosity declined appreciably from D_1 (47.85 %) to D_2 (46.63 %) and further to D_3 (44.90 %). In the interaction between agroforestry systems and soil depths, it was observed that all the combinations of bamboo based agroforestry systems *i.e.* T_6D_1, T_6D_2, and T_6D_3, displayed significantly higher soil porosity than all other treatment combinations, at their respective soil depths. In general, bamboo based, melia based, poplar based and silvipasture systems displayed significantly higher porosity than sole cropping, agri-silvi-horticulture, agri-silviculture, fruit based and fodder based agroforestry systems, at their respective soil depths.

Table 16: Effect of agroforestry systems, soil depths and interaction between them on soil porosity (per cent)

Agroforestry systems	**Soil Depths**			**Mean**
	D_1	**D_2**	**D_3**	
T_1 (Sole Cropping system)	45.85	44.16	42.53	44.18^f
T_2 (Agri-silvi-horticulture system)	46.04	45.43	44.79	45.42^e
T_3 (Agri-silviculture system)	45.26	44.56	42.50	44.11^f
T_4 (Fruit tree based AFS)	46.95	46.56	45.37	46.29^{cde}
T_5 (Fodder tree based AFS)	46.51	45.67	44.23	45.47^d
T_6 (Bamboo based AFS)	53.54	52.23	49.14	51.63^a
T_7 (Melia based AFS)	48.41	46.73	45.51	46.88^c
T_8 (Poplar based AFS)	50.84	48.98	46.61	48.81^b
T_9 (Silvipasture system)	47.24	45.31	43.42	45.32^{de}
Mean	47.85^a	46.63^b	44.90^c	
Factors	**$SE_{(M)}$**	**$CD_{0.05}$**		
Soil depth	0.115	0.371		
AFS	0.199	0.567		
Interaction	0.345	0.983		

Higher soil porosity in systems comprising of huge trees and larger foliage such as poplar, melia and bamboo is conspicuous, whereas the fodder tree based and silvipasture agroforestry systems showed lower soil porosity, reason being, regular lopping and collection of fodder leading to less retention of leaf litter and organic matter within the system. Porosity showed somewhat direct proportionality with bulk density, which is similar to the findings of Gusli *et al*. (2020), who put forth that increased bulk density causing some of the macropores to vanish (when >60 µm), reducing the soil's capacity to transport water and affecting soil water availability. Lowest soil porosity was recorded in sole cropping and agri-silviculture system due to meager organic matter addition to the soils which results in compaction with time. Thus, it can be discerned that greater prospect of litter fall and the accumulation of plant litter created by diverse trees provides for higher rainwater infiltration, limiting soil moisture loss and boosting water holding capacity of soil, demonstrating that the types of crops and management strategies affect soil porosity. An inverse relationship between bulk density and soil porosity is evident in the present study results, which are consistent with previous research work done by Amusan *et al*. (2006), who also reported inverse associations between soil bulk density and porosity under various farming methods. Odewumi *et al*. (2013) also found bulk density and pore spaces having an inverse relationship, with lower bulk density and higher porosity in soil under teak canopy than in soil outside teak canopy. Furthermore, soil porosity decreased with increasing depth under all agroforestry systems. This reduction in soil porosity might be attributed to root activity and decrease in soil organic matter with depth, slowing soil water infiltration (Franzluebbers, 2002; Pierret *et al.*, 2016).

4.4.1.4 Soil texture

The data with respect to soil texture of different agroforestry systems as recorded in top soil layer is depicted in Table 17. USDA triangular soil classification chart (Anderson and Ingram, 1998) was used for working out the soil texture according to size of the soil particles. The table reveals that sole cropping and fruit tree based agroforestry systems showed loam type soil texture, whereas, fodder based, agri-silvi-horticulture and silvipasture systems showed sandy clay loam type of texture. Agri-silviculture, bamboo based, melia based and poplar based agroforestry systems displayed clay loam texture. Maximum sand percentage varied appreciably among agroforestry systems, ranging between 40.16 per cent and 51.34 per cent. Bamboo based, melia based and poplar based agroforestry systems displayed highest values of silt content, as compared to other agroforestry systems. Whereas, clay content was found to be higher under agri-silviculture system, closely followed by bamboo based and melia based agroforestry systems.

Table 17: Effect of agroforestry systems, soil depths and interaction between them on soil texture

Agroforestry systems	Sand (%)	Silt (%)	Clay (%)	Texture
T_1 (Sole Cropping system)	49.77	25.79	24.43	Loam
T_2 (Agri-silvi-horticulture system)	47.21	27.86	24.93	Sandy Clay Loam
T_3 (Agri-silviculture system)	44.7	25.84	29.45	Clay Loam
T_4 (Fruit tree based AFS)	46.87	28.71	24.42	Loam
T_5 (Fodder tree based AFS)	46.87	27.71	25.42	Sandy Clay Loam
T_6 (Bamboo based AFS)	40.16	31.42	28.42	Clay Loam
T_7 (Melia based AFS)	41.25	30.33	28.42	Clay Loam
T_8 (Poplar based AFS)	40.4	31.92	27.68	Clay Loam
T_9 (Silvipasture system)	51.34	27.24	21.42	Sandy Clay Loam

Although the amounts of sand, silt and clay varied, there were fewer variations in percentage silt content between the different agroforestry systems, which is similar to the results proposed by Evans *et al*. (2014), while working on various soil physical properties under different land use systems in Ghana. Kumar *et al*. (2018) also found that forest land uses had greater silt content than barren, agricultural, and orchard land uses. The soils on all locations were dominantly loam and, categorised as loam, clay loam and sandy clayey loam. The fact that the soils have comparable textural compositions implies that they were produced from similar parent materials under similar environmental circumstances and management techniques (Evans *et al*., 2014). Slight variation in the texture class can be owed to the type of plant material and root system of the plants, which plays a vital role in the breakdown of the parent material.

4.4.2 Chemical properties of soil

4.4.2.1 pH

Table 18 demonstrates that the soil pH was significantly influenced due to the effect of agroforestry systems, soil depths and interaction among them. Irrespective of the soil depths, maximum soil pH was recorded under sole cropping system (7.11), which was found to be appreciably higher than soil pH values under all other agroforestry systems. However, it was closely followed by silvipasture system, fruit tree based and agri-silviculture systems.

Other agroforestry systems *viz.*, agri-silviculture and fodder tree based agroforestry systems displayed statistically identical values. Significantly lowest pH value (6.75) was recorded under bamboo based agroforestry system. However, as an average effect of soil depths, the soil pH enhanced noticeably from D_1 (6.82) to D_2 (6.92) and D_2 to D_3 (7.03). But, the rate of enhancement is quite marked under sole cropping and silvipasture systems. Maximum (7.01) and minimum (6.64) pH values in D_1 layer were recorded in sole cropping system and bamboo based agroforestry systems, respectively. Moreover, bamboo based agroforestry system exhibited significantly lower values of soil pH (6.75) than other agroforestry systems, at their respective soil depths.

Table 18: Effect of agroforestry systems, soil depths and interaction between them on soil pH

Agroforestry systems	Soil Depths			Mean
	D_1	**D_2**	**D_3**	
T_1 (Sole Cropping system)	7.01	7.11	7.20	7.11^{a}
T_2 (Agri-silvi-horticulture system)	6.79	6.87	6.92	6.86^{e}
T_3 (Agri-silviculture system)	6.94	6.97	7.00	6.97^{cd}
T_4 (Fruit tree based AFS)	6.85	7.02	7.09	6.98^{c}
T_5 (Fodder tree based AFS)	6.88	6.91	7.03	6.94^{d}
T_6 (Bamboo based AFS)	6.64	6.75	6.86	6.75^{g}
T_7 (Melia based AFS)	6.74	6.85	6.94	6.84^{ef}
T_8 (Poplar based AFS)	6.70	6.78	7.00	6.82^{f}
T_9 (Silvipasture system)	6.82	7.00	7.24	7.02^{b}
Mean	6.82^{c}	6.92^{b}	7.03^{a}	
Factors	**$SE_{(M)}$**	**$CD_{0.05}$**		
Soil depth	0.006	0.018		
AFS	0.010	0.028		
Interaction	0.017	0.048		

The lower pH under agroforestry is attributed to increased accumulation of above-ground biomass, associated cation uptake and production of organic acids by the tree component of agroforestry systems all have a significant impact on soil pH (Gupta and Sharma, 2009; Sarvade *et al*., 2014). Similar findings were reported by Nayak (1996) who reported the pH to be reduced, and, nutrient values increased under 9-year-old agroforestry species *viz*. *Eucalyptus tereticornis*, *Leucaena leucocephala* and *Melia azederach* plantations as compared to unplanted areas. Mongia *et al*. (1998) investigated the ameliorative impact of forest trees on acidic soils in Haryana and discovered that after three years of cultivating *Acacia nilotica*, soil pH and EC, both decreased. In a fruit-based agri-horticultural paradigm (mango + cowpea - toria), Rathore *et al*. (2013) documented a fall in soil pH (12.12–15.62 %) compared to the original value measured in 1995 before the orchard was set up. Dalal *et al*. (2000) concluded agri-silvi-horticulture system to be exhibiting lower pH than monocropping. Soil pH outside tree canopies is higher than soil pH under tree canopy, with soil pH increasing with increasing distance from the tree stem. This was linked to a number of processes that release H^+ ions, including soil base cation absorption, organic matter breakdown to organic acids and CO, root respiration, and nitrification (Berhe *et al*., 2013). An increasing trend of pH with increasing soil depths was also observed in the present study. This may be attributed to the fading away of effects of plant composition on soil nutrients and water in deeper layers and as soil pH is influenced by the content and movement of soil water, it increased marginally as soil depth increased (Wu *et al*., 2020).

4.4.2.2 Electrical Conductivity (dS m^{-1})

A perusal of data regarding soil EC of soils under different agroforestry systems has been displayed in Table 19 which shows that the soil EC was significantly influenced due the effect of agroforestry systems, soil depths and interaction between them. Irrespective of the soil depths, maximum soil EC (0.49 dS m^{-1}) was recorded under bamboo based agroforestry systems, which was significantly higher than soil EC of all other agroforestry systems, and was closely followed by poplar based and melia based agroforestry systems. Other agroforestry systems *viz*., agri-silvi-horticulture, agri-silviculture, fruit tree based and silvipasture systems exhibited statistical similarity. Significantly lowest soil EC (0.27 dS m^{-1}) was recorded under sole cropping system. Irrespective of agroforestry systems, the soil EC values diminished significantly from D_1 (0.43 dS m^{-1}) to D_2 (0.37 dS m^{-1}) and further to D_3 (0.30 dS m^{-1}). But, the rate of decline is quite marked under sole cropping and fodder tree based agroforestry systems. Moreover, bamboo based agroforestry system exhibited significantly higher values of soil EC than other agroforestry systems, at their respective soil depths.

EC is affected by various factors, and higher EC in soils under all agroforestry systems can be linked with higher nutrient pumping (Gowda and Kumar, 2008) and deposition on the soil surface by addition of more organic matter via litter production leading to higher minerals present in the top layer to form salts and act as electrolytes when exposed to water.

Table 19: Effect of agroforestry systems, soil depths and interaction between them on soil E.C. (dS m^{-1})

Agroforestry systems	Soil Depths			Mean
	D_1	D_2	D_3	
T_1 (Sole Cropping system)	0.37	0.26	0.19	0.27^f
T_2 (Agri-silvi-horticulture system)	0.41	0.36	0.29	0.35^{cd}
T_3 (Agri-silviculture system)	0.38	0.35	0.26	0.33^d
T_4 (Fruit tree based AFS)	0.42	0.39	0.31	0.37^c
T_5 (Fodder tree based AFS)	0.39	0.29	0.22	0.30^e
T_6 (Bamboo based AFS)	0.53	0.50	0.43	0.49^a
T_7 (Melia based AFS)	0.46	0.40	0.35	0.41^b
T_8 (Poplar based AFS)	0.48	0.44	0.37	0.43^b
T_9 (Silvipasture system)	0.45	0.33	0.25	0.35^{cd}
Mean	0.43^a	0.37^b	0.30^c	
Factors	**$SE_{(M)}$**	**$CD_{0.05}$**		
Soil depth	0.004	0.012		
AFS	0.007	0.019		
Interaction	0.011	0.032		

Less evaporative requirement of plants and less canopy interception of rainfall causes higher leaching in open fields than those under tree cover (Reynolds *et al*., 1988; Naidu *et al*., 1996; Abbasi *et al*., 2010). Therefore, lower soil EC reported in sole cropping in the current systems suggests active ion leaching owing to sparse plant cover. These results are in consonance with those of Bhat (2015), who found that soil EC in agroforestry systems is higher than in, open conditions. Bamboo, poplar and melia based agroforestry systems demonstrate highest soil EC, reason being larger canopies, larger crown spread and hence, higher addition of minerals to the top layer of the soil by means of litter, increasing salt content within the system. Sharma and Gupta (1989), Chakraborthy and Chakraborthy (1989), and Abbasi *et al*. (2010), all found that tree-based systems have higher electrical conductivity than arable land. These results correspond with the proposals of Berhe *et al*. (2013), who observed EC to be higher under trees with a larger crown spread than it was under trees with a lower crown spread which may be due to increased above-ground biomass accumulation. According to Gowda and Kumar (2008) also, the rooting depth of trees impact their ability to collect nutrients from the subsoil and make them available in the topsoil, due to which minerals start diminishing with increasing depths. This leads to diminished salt concentrations and therefore, reduced EC in the lower layers of the soil.

4.4.2.3 Organic Carbon (g kg^{-1})

Data regarding soil organic carbon content in Table 20 evinces that organic carbon is significantly influenced due to agroforestry systems, soil depths and interaction between them. Irrespective of soil depths, soil organic carbon varied markedly among different agroforestry systems. Maximum OC (11.3 g kg^{-1}) was recorded in bamboo based agroforestry systems which was significantly higher than soil OC of all other agroforestry systems. The OC under different agroforestry systems followed the trend: bamboo based agroforestry system (11.3 g kg^{-1}) > poplar based system (10.4 g kg^{-1}) > silvipasture system (10.3 per cent) > melia based system (9.8 g kg^{-1}) > agri-silvi-horticulture system (9.7 g kg^{-1}) > fruit tree based system (9.2 g kg^{-1}) > agri-silviculture system (8.4 g kg^{-1}), fodder tree based system (8.3 g kg^{-1}) > sole cropping system (7.8 g kg^{-1}). However, in the average effect of soil depth, OC content declined from D_1 (11.9 g kg^{-1}) to D_2 (9.7 g kg^{-1}) and further to D_3 (6.8 g kg^{-1}) in a significant manner. In the interaction effect, bamboo based agroforestry system displayed higher OC values than all other agroforestry systems, at their respective depths. Maximum OC was observed in treatment combination T_6D_1 (13.2 g kg^{-1}) and minimum in T_1D_3 (5.2 g kg^{-1}).

Table 20: Effect of agroforestry systems, soil depths and interaction between them on Organic Carbon (g kg^{-1})

Agroforestry systems	Soil Depths			Mean
	D_1	D_2	D_3	
T_1 (Sole Cropping system)	10.7	7.6	5.2	7.8^f
T_2 (Agri-silvi-horticulture system)	12.0	9.9	7.1	9.7^c
T_3 (Agri-silviculture system)	10.8	8.6	5.7	8.4^e
T_4 (Fruit tree based AFS)	11.8	9.3	6.5	9.2^d
T_5 (Fodder tree based AFS)	11.1	8.4	5.4	8.3^e
T_6 (Bamboo based AFS)	13.2	11.9	8.8	11.3^a
T_7 (Melia based AFS)	12.2	10.1	7.0	9.8^c
T_8 (Poplar based AFS)	12.8	10.7	7.7	10.4^b
T_9 (Silvipasture system)	12.3	11.0	7.6	10.3^b
Mean	11.9^a	9.7^b	6.8^c	
Factors	**$SE_{(M)}$**	**$CD_{0.05}$**		
Soil depth	0.005	0.017		
AFS	0.009	0.026		
Interaction	0.016	0.045		

Organic carbon is observed to be directly related to tree species' plantation density and larger tree canopy leading to higher litter fall. Lower soil organic carbon under agriculture land use can be attributed to reduced amounts of organic material returned to the soil and a high rate of oxidation of soil organic matter as a result of continuous cultivation without fallowing. Further, loss of organic matter due to water erosion, and removal of green materials may all contribute to lower soil organic carbon under agriculture land use (Yimer *et. al*., 2007; Girmay *et al*., 2008). These results are in consonance with those of Kaushal *et al*. (2016) who found that in comparison to a fallow plot, grewia-based agroforestry system has 13-46 per cent higher organic carbon. Similarly, Kumar *et al*. (2017), when compared agroforestry with a field without tree planting, reported a rise in organic carbon from 0.12 per cent to 0.27 per cent under tree component. Palsaniya *et al*. (2009), also discovered that when shisham and subabul were planted with agriculture crops, organic carbon content rose substantially, compared to pure crop and lone trees. Similarly, Momin *et al*. (2016) found that the gamhar + mango + pigeon pea agri-silvi-horticulture system had the largest increase (33 per cent increase in O.C.) in organic carbon content compared to the sole mango based agroforestry model (7.1 per cent increase) and solo gamhar based agroforestry model (3.5 per cent increase). Organic carbon was higher under larger trees than beneath smaller ones which might be related to an increase in organic matter buildup (Sharma *et al*., 2017). Moges and Holden (2008) also discovered agricultural land having considerably less soil organic carbon than grazing and tree-based systems. According to Devi *et al*. (2020), the diminishing trend of organic carbon with increasing depth could be seen as a result of more accumulation and mineralization besides reduction in the root biomass in the deeper soil layers and pumping of carbon by trees from deeper layers on to the surface. The present finding are analogous to the findings of Devi *et al*. (2020), who have reported surface soil depth, 0-15 cm, had the highest average organic carbon concentration (0.53 percent), while deepest, 60-90 cm depth had the lowest (0.13 percent).

4.4.2.4 Available Nitrogen (kg ha^{-1})

The data depicted in Table 21 reveals that available nitrogen contents in the soil is significantly influenced by the agroforestry systems, soil depths and interaction between them. In the average effect of agroforestry systems, maximum available nitrogen (301.47 kg ha^{-1}) nitrogen was recorded under bamboo based agroforestry system, which was closely followed by poplar based (293.64 kg ha^{-1}) and melia based (292.11 kg ha^{-1}) agroforestry systems. Both poplar and melia based agroforestry systems remained statistically identical to one another. Similarly agri-silvi-horticulture and silvipasture systems remained statistically at par with each other. Minimum available nitrogen was recorded under fruit tree based agroforestry system (255.24 kg ha^{-1}), which however, remained statistically identical to sole cropping system (258.80 kg ha^{-1}). Irrespective of agroforestry systems, the available nitrogen content declined significantly from D_1 (297.87 kg ha^{-1}) to D_2 (277.91 kg ha^{-1}) and D_2 to D_3 (250.64 kg ha^{-1}). Moreover, in the interaction effect, maximum value was recorded in T_8D_1 (317.52 kg ha^{-1}), while minimum in T_4D_3 (226.34 kg ha^{-1}). The available nitrogen declined significantly from D_1 to D_2, but, the decline is more marked in agri-silviculture, fruit tree based and fodder tree based, poplar based and silvipasture systems, as compared to bamboo and melia based agroforestry systems.

Table 21: Effect of agroforestry systems, soil depths and interaction between them on available Nitrogen (kg ha^{-1})

Agroforestry systems	Soil Depths			Mean
	D_1	**D_2**	**D_3**	
T_1 (Sole Cropping system)	278.92	266.82	230.65	258.80^{ef}
T_2 (Agri-silvi-horticulture system)	297.93	283.46	251.10	277.50^{c}
T_3 (Agri-silviculture system)	294.26	274.78	236.31	268.45^{d}
T_4 (Fruit tree based AFS)	287.26	252.12	226.34	255.24^{f}
T_5 (Fodder tree based AFS)	279.15	264.23	227.58	256.99^{ef}
T_6 (Bamboo based AFS)	313.89	298.07	292.46	301.47^{a}
T_7 (Melia based AFS)	303.42	292.91	280.01	292.11^{b}
T_8 (Poplar based AFS)	317.52	292.46	270.95	293.64^{b}
T_9 (Silvipasture system)	308.49	276.33	240.33	275.05^{c}
Mean	297.87^{a}	277.91^{b}	250.64^{c}	
Factors	**$SE_{(M)}$**	**$CD_{0.05}$**		
Soil depth	0.853	2.753		
AFS	1.477	4.205		
Interaction	2.558	7.283		

Singh and Sharma (2007), proposed that due to differences in litter fall addition, nutrient return to soil varies substantially depending on tree species, spacing, plantation age, intercrops, and management approaches. A correspondence between organic matter and nitrogen was conspicuous which is similar to results proposed by Meysner *et al*. (2006), who claimed that the amount of nitrogen in the soil (> 90 percent) to be closely linked to the amount of organic matter. Lodhiyal *et al*. (2017) also reported that the N to be continuously increasing over one year after leaf litter, which increased by 1.96 to 2.06 times, the initial concentration. The steady decrease in the N values with increasing soil depths is in accordance with the findings of Jobaggy and Jackson (2001) who also worked on distribution of soil nutrients with depth. They suggested that the most limiting of the plant soil nutrients shall have the shallowest distributions and the scarcer the nutrients, the shallower their distribution. This might also be attributed to significant leaf litter accumulation in the top soil layer (Mathew *et al*., 1997). Pardon *et al*., 2017, also propose carbon and nutrient intake into the top soil layer via tree litter, particularly tree leaves, and to a lesser amount by nutrient-rich throughfall water to be a major cause of much higher N in top layer of soil as compared to the deeper layers.

4.4.2.5 Available Phosphorus (kg ha^{-1})

Data regarding Phosphorus content of soils under different agroforestry systems is presented in Table 22. Phosphorus in the soils varied significantly due to the average effect of different agroforestry systems, soil depths and interaction between them. In the average effect of agroforestry systems, maximum available phosphorus (40.64 kg ha^{-1}) was recorded in fruit tree based agroforestry system, which however, remained statistically identical to bamboo based agroforestry system. P content in different agroforestry systems followed the trend: fruit tree based agroforestry system (40.64 kg ha^{-1}) > bamboo based system (40.27 kg ha^{-1}) > agri-silviculture system (35.67 kg ha^{-1}) > melia based system (34.20 kg ha^{-1}) > poplar based system (32.99 kg ha^{-1}) > agri-silvi-horticulture system (32.57 kg ha^{-1}) > silvipasture system (31.92 kg ha^{-1}) > fodder tree based system (28.22 kg ha^{-1}) > sole cropping system (24.92 kg ha^{-1}). Irrespective of agroforestry systems, the available P declined slightly with increase in soil depth from D_1 (42.45 kg ha^{-1}) to D_2 (33.54 kg ha^{-1}) and D_2 to D_3 (24.48 kg ha^{-1}). In the interaction effect of both, maximum available P was recorded in T_4D_1 *i.e.* fruit tree based agroforestry system at D_1 depth, (49.57 kg ha^{-1}), which, however remained statistically identical to T_6D_1 (47.19 kg ha^{-1}) treatment combination, only. Phosphorus content declined slightly from D_1 to D_2 and D_2 to D_3, under all the agroforestry systems in the present study. Minimum Phosphorus was recorded in treatment combination of T_7D_3 (16.94 kg ha^{-1}), which however, remained statistically identical to T_8D_3 (18.01 kg ha^{-1}) treatment combination.

The available phosphorus present in different soil layers (0-20, 20-40 and 40-100 cm) under wide range of agroforestry systems was found to be significantly varying despite being optimum in all the systems. Phosphorus was significantly higher in all the tree based systems as compared to the sole cropping systems, which is analogous to the findings of Singh *et al*.

(2018), who examined available P in agroforestry systems such agri-silvi-horticulture, agrihorticulture, agri-silviculture, silvipastoral vis-à-vis pure agriculture.

Table 22: Effect of agroforestry systems, soil depths and interaction between them on Phosphorus (kg ha^{-1})

Agroforestry systems	Soil Depths			Mean
	D_1	D_2	D_3	
T_1 (Sole Cropping system)	29.78	24.04	20.96	24.92^{e}
T_2 (Agri-silvi-horticulture system)	41.78	31.01	24.91	32.57^{c}
T_3 (Agri-silviculture system)	43.50	35.87	27.65	35.67^{b}
T_4 (Fruit tree based AFS)	49.57	39.64	32.71	40.64^{a}
T_5 (Fodder tree based AFS)	38.31	24.70	21.64	28.22^{d}
T_6 (Bamboo based AFS)	47.19	41.73	31.88	40.27^{a}
T_7 (Melia based AFS)	44.67	40.97	16.94	34.20^{bc}
T_8 (Poplar based AFS)	46.14	34.82	18.01	32.99^{c}
T_9 (Silvipasture system)	41.08	29.08	25.60	31.92^{c}
Mean	42.45^{a}	33.54^{b}	24.48^{c}	
Factors	**$SE_{(M)}$**	**$CD_{0.05}$**		
Soil depth	0.331	1.069		
AFS	0.574	1.634		
Interaction	0.994	2.829		

They found significantly greater levels of P in agroforestry systems than in mono agriculture land use systems. Phosphorus was recorded to be medium (22-44 kg ha^{-1}), in almost all the systems which can be affiliated with the parent material of the local mountain range being limestone and dolomite. Lodhiyal *et al.* (2017) also concluded that the P level of persistent litter to be increasing during the breakdown cycle of one year and, the phosphorus content was 1.6-2.1 times higher than it was at the beginning. Saha *et al.* (1999). attributed higher P to finer root density, increased microbial activity in favorable conditions, mycorrhizal relationships and the impact of plant roots on Phosphorus solubility. Highest P in fruit tree based system can also be linked to the frequent external application of phosphatic fertilizers, which are commonly applied to fruit crops during the winter season for growth, development and reproduction (Kumar *et al.*, 2017). Matos *et al.* (2020), also advocated that the agroforestry systems had higher amounts of accessible P than pastures, adding to the agroforestry plots' overall higher soil fertility. Tree roots' organic anion exudation and acid phosphatase activity have been demonstrated to increase P mobilization in the rhizosphere, which might explain the considerable influence of tree-based systems and soil depth on soil accessible phosphorus (Cardwell, 2005). Further, low phosphorus availability was observed in the lower layers of the soil as compared to the top layer among all agroforestry systems.

Surface soil has a higher P concentration than deeper soil layers (Kaushik *et al.*, 2017). This can also be ascribed to better nutrient cycling and surface enrichment in tree-based agroforestry systems as a result of high litter formation and faster decomposition rates (Starr *et al.*, 2005).

4.4.2.6 Available Potassium (kg ha^{-1})

The data depicted in Table 23 reveals that potassium contents in the soil is significantly affected by the average effect of agroforestry systems, soil depths and interaction between them. In the average effect of agroforestry systems, maximum available potassium (245.69 kg ha^{-1}) was documented in the soils under bamboo based agroforestry system, closely followed by poplar based agroforestry systems (226.30 kg ha^{-1}). All the agroforestry systems displayed significantly higher values than sole cropping system. Though, potassium varied widely among different agroforestry systems, in some systems *viz*., agri-silvi-horticulture and fruit tree based agroforestry systems remained statistically identical. Similarly, fodder tree based and agri-silviculture systems also showed statistical similarity. Minimum available potassium was documented in sole cropping system (173.47 kg ha^{-1}), which was significantly lower than all other agroforestry systems.

Table 23: Effect of agroforestry systems, soil depths and interaction between them on Potassium (kg ha^{-1})

Agroforestry systems	**Soil Depths**			**Mean**
	D_1	**D_2**	**D_3**	
T_1 (Sole Cropping system)	145.66	178.44	196.30	173.47^g
T_2 (Agri-silvi-horticulture system)	174.59	190.32	217.94	194.28^e
T_3 (Agri-silviculture system)	163.77	184.22	210.26	186.08^f
T_4 (Fruit tree based AFS)	171.41	195.07	224.07	196.85^e
T_5 (Fodder tree based AFS)	165.22	177.24	207.78	183.41^f
T_6 (Bamboo based AFS)	220.32	242.06	274.70	245.69^a
T_7 (Melia based AFS)	192.03	200.46	224.62	205.70^d
T_8 (Poplar based AFS)	213.13	222.13	243.63	226.30^b
T_9 (Silvipasture system)	203.75	215.83	233.29	217.62^c
Mean	183.32^c	200.64^b	225.84^a	
Factors	**$SE_{(M)}$**	**$CD_{0.05}$**		
Soil depth	1.232	3.976		
AFS	2.134	6.073		
Interaction	3.695	10.520		

Irrespective of agroforestry systems, the potassium content increased significantly from D_1 (183.32 kg ha^{-1}) to D_2 (200.64 kg ha^{-1}) and then from D_2 to D_3 (225.84 kg ha^{-1}). Further, as an interaction effect, maximum value was recorded in T_6D_3 (274.70 kg ha^{-1}), while minimum was recorded in T_1D_1 (145.66 kg ha^{-1}). The potassium content enhanced significantly from D_1 to D_2, but the increase is much sharp in sole cropping, agri-silvi-horticulture and fruit tree based agroforestry systems, as compared to fodder tree based, bamboo based, melia based, poplar based and silvipasture systems.

Optimum accessible potassium in all agroforestry systems could be due to nutrient-rich tree litter, which could have contributed to more potassium being returned to the soil in the form of litter (Rao *et al*., 2000 and Moges *et al*., 2013). Available K within the canopy was more than available K just outside of the tree canopy, and that K declined as distance from the tree stem increased (Tanga *et al*., 2014). In comparison to fields without planting, Kumar *et al*. (2017) found an increase in available K (336 to 393 kg ha^{-1}) under tree species. Matos *et al*. (2020) studied soil properties and litter quality in agroforestry systems of Brazil and revealed that the soil chemical characteristics of the forest, pasture, and agroforestry systems to be markedly different. The agroforestry system had inferior fertility (in terms of SOC and accessible K) than the forest but, better than pasture plots. Sileshi (2016) also found that under the tree canopy, K levels were higher than outside the tree canopy. With the increasing depth, the K content is seen to be increasing which can be attributed to leaching of potassium in form of soluble salts with water and accumulation in deeper layers. Havlin *et al*. (2005) proposed sluggish transfer of K from primary minerals to the soil-water solution, and K released from mineralization of SOM, a reason behind drop in soil K concentration.

4.4.2.7 Exchangeable Calcium (mg kg^{-1})

Data in table 24 shows that calcium content in the soil is significantly influenced only due to agroforestry systems and soil depths. Irrespective of the soil depths, maximum calcium content was noticed in bamboo based agroforestry system (1496.53 mg kg^{-1}), which was found to be closely followed by poplar based agroforestry system (1327.59 mg kg^{-1}), only. All the agroforestry systems displayed appreciably higher values of calcium content as compared to the sole cropping system, and followed the trend: bamboo based agroforestry system (1496.53 mg kg^{-1}) > poplar based agroforestry system (1327.59 mg kg^{-1}) > silvipasture system (1052.89 mg kg^{-1}) > fruit based system (940.26 mg kg^{-1}) > agri-silvi-horticulture system (908.50 mg kg^{-1}) > melia based system (890.77 mg kg^{-1}) > fodder tree based system (826.86 mg kg^{-1}) > agri-silviculture system (767.32 mg kg^{-1}) > sole cropping system (701.40 mg kg^{-1}). In the average effect of soil depth, the soil calcium content declined markedly from D_1 (1108.09 mg kg^{-1}) to D_2 (1007.55 mg kg^{-1}) and D_2 to D_3 (855.07 mg kg^{-1}).

Table 24: Effect of agroforestry systems, soil depths and interaction between them on exchangeable Calcium (mg kg^{-1})

Agroforestry systems	Soil Depths			Mean
	D_1	D_2	D_3	
T_1 (Sole Cropping system)	835.83	754.86	513.53	701.41^f
T_2 (Agri-silvi-horticulture system)	1023.83	953.96	747.72	908.50^d
T_3 (Agri-silviculture system)	919.17	761.51	621.27	767.32^e
T_4 (Fruit tree based AFS)	1031.31	977.12	812.34	940.26^d
T_5 (Fodder tree based AFS)	933.33	850.00	697.25	826.86^e
T_6 (Bamboo based AFS)	1650.10	1490.67	1348.83	1496.53^a
T_7 (Melia based AFS)	1013.31	900.33	758.67	890.77^{de}
T_8 (Poplar based AFS)	1425.27	1345.83	1211.67	1327.59^b
T_9 (Silvipasture system)	1140.67	1033.67	984.33	1052.89^c
Mean	1108.09^a	1007.55^b	855.07^c	
Factors	**$SE_{(M)}$**	**$CD_{0.05}$**		
Soil depth	14.446	46.630		
AFS	25.022	71.229		
Interaction	43.339	NS		

A sort of relationship could be perceived between litter fall in various agroforestry systems and calcium content in soils. These can be an outcome of high litter fall and better nutrient cycling of the exchangeable base contents under the tree based agroforestry systems (Yitbarek *et al*., 2013). High Ca concentrations found in poplar leaf litter in general, is also reported by Pardon *et al*., 2017. Singh *et al*. (2007) analyzed litter fall and nutrient dynamics in poplar plantations in Ludhiana and concluded that amongst the macronutrients, the maximum increase in the concentration of calcium was found, post litter fall. Additionally, nutrient pumping from the subsoil by the deep rooted trees and returning them on to the topsoil was discernible, similar to the findings of Yimer *et al*. (2008) and Gowda and Kumar (2008). The trend of diminishing nutrient concentration with increasing soil depth was also observed by Kar *et al*., 2019. They too, ascribed it to nutrient pumping by trees from deeper layers and deposition on the surface layers.

4.4.2.8 Sulphur (kg ha^{-1})

A perusal of the data in Table 25 reveals that sulphur content in soil varied significantly due to the average effect of agroforestry systems, soil depths and interaction effect of agroforestry systems and soil depth. Irrespective of soil depth, sulphur content showed significantly different values among all the agroforestry systems. The maximum sulphur content (34.07 kg ha^{-1}) was noticed in bamboo based agroforestry system which was closely followed by agri-silvi-horticulture (32.25 kg ha^{-1}) and agri-silviculture systems (31.36 kg ha^{-1}). Minimum sulphur content (15.77 kg ha^{-1}) was recorded in silvipasture system. In the average effect of soil depths, sulphur content declined significantly with increase in soil depth in all the agroforestry systems. But, the rate of decline is more marked under all agroforestry systems as compared to the sole cropping. The maximum and minimum values of sulphur were recorded in treatment combination T_6D_1 (48.62 kg ha^{-1}) and T_7D_3 (10.47 kg ha^{-1}), respectively.

Table 25: Effect of agroforestry systems, soil depths and interaction between them on Sulphur (kg ha^{-1})

Agroforestry systems	**Soil Depths**			**Mean**
	D_1	**D_2**	**D_3**	
T_1 (Sole Cropping system)	29.39	27.21	15.89	24.16^g
T_2 (Agri-silvi-horticulture system)	41.80	31.83	23.11	32.25^b
T_3 (Agri-silviculture system)	39.03	31.05	24.00	31.36^c
T_4 (Fruit tree based AFS)	36.54	27.28	17.80	27.21^d
T_5 (Fodder tree based AFS)	33.51	23.02	19.11	25.21^f
T_6 (Bamboo based AFS)	48.62	35.82	17.79	34.07^a
T_7 (Melia basedAFS)	28.86	16.83	10.47	18.72^h
T_8 (Poplar based AFS)	32.58	29.71	17.48	26.59^e
T_9 (Silvipasture system)	21.11	14.32	11.89	15.77^i
Mean	34.61^a	26.34^b	17.50^c	
Factors	**$SE_{(M)}$**	**$CD_{0.05}$**		
Soil depth	0.489	1.57		
AFS	0.848	2.40		
Interaction	1.468	4.17		

Mineralization of organic sulphur owing to decomposition of organic matter and increased availability of sulphate sulphur in soil was proposed by Waienwright *et al*. (1986), under agroforestry systems. Further, soil sulphur was found optimum in surface layers of all the systems and decreased with increasing soil depths.

4.4.2.9 Micronutrients

Soil micronutrients are important elements for plant growth despite being required in small quantities for day to day physiological processes. Micronutrients have been increasingly used in recent years in order to achieve higher yields and meet our agricultural demands as excess fertilizer application can harm our soil and make it impossible to function as a long-term supply source (Young, 1989). Individual tables ahead, display the concentrations of the four major micronutrients under different agroforestry systems.

4.4.2.9.1 Copper (mg kg^{-1})

It is evident from the data presented in table 26 that copper (Cu) content varied significantly due to the average effect of agroforestry systems, soil depths and interaction among them. Irrespective of the soil depth, maximum Cu content (3.05 mg kg^{-1}) was recorded under fruit tree based agroforestry system which was found to be significantly higher than all other agroforestry systems. Agroforestry systems *viz.*, agri-silvi-horticulture, agri-silviculture, poplar based and silvipasture systems displayed significantly lower values than sole cropping system. Minimum Cu content (0.61 mg kg^{-1}) was recorded in silvipasture systems. The concentration of copper decreased slightly with increase in soil depth, from D_1 (2.33 mg kg^{-1}) to D_2 (1.94 mg kg^{-1}) and D_2 to D_3 (1.66 mg kg^{-1}). In the interaction effect, fruit tree based agroforestry system displayed significantly higher values of copper content at all the soil depths, than all other agroforestry systems, at their respective soil depths. Maximum copper content was recorded in treatment combination T_4D_1 (3.64 mg kg^{-1}), and minimum in T_9D_3 (0.56 mg kg^{-1}).

Table 26: Effect of agroforestry systems, soil depths and interaction between them on Copper (mg kg^{-1})

Agroforestry systems	**Soil Depths**			**Mean**
	D_1	**D_2**	**D_3**	
T_1 (Sole Cropping system)	2.10	1.92	1.88	1.97^e
T_2 (Agri-silvi-horticulture system)	2.92	2.49	2.01	2.47^c
T_3 (Agri-silviculture system)	1.95	1.53	1.27	1.58^g
T_4 (Fruit tree based AFS)	3.64	3.10	2.43	3.05^a
T_5 (Fodder tree based AFS)	2.17	1.89	1.58	1.88^f
T_6 (Bamboo based AFS)	3.23	2.31	2.05	2.53^b
T_7 (Melia based AFS)	2.60	1.97	1.89	2.15^d
T_8 (Poplar based AFS)	1.68	1.63	1.33	1.55^g
T_9 (Silvipasture system)	0.65	0.61	0.56	0.61^h
Mean	2.33^a	1.94^b	1.66^c	
Factors	**$SE_{(M)}$**	**$CD_{0.05}$**		
Soil depth	0.007	0.022		
AFS	0.012	0.033		
Interaction	0.02	0.057		

Overall the copper content of the soils remained far higher across all the agroforestry systems, as normal range of copper occurs from 0.2 to 0.4 mg kg^{-1}. Campanha *et al.* (2007)

also reported Cu levels to be higher in coffee based agroforestry systems than in monoculture systems. The lowest concentration of copper visible in poplar based systems may be elucidated to difference in addition of various nutrients to the soil by litter fall, as a function of concentration of those very nutrients in litter, according to Singh *et al.* (2007). Similar to present study, Singh *et al.* (2007) reported increase in Cu concentration of the soil to be lowest among all the micronutrients, in poplar based plantations. A decrease in the copper concentrations with increasing depth was observed. This may be due to slow mineralization under low temperature conditions (Dar *et al.*, 2012), which is common in deeper soil layers. Breakdown of leaf litter and dead roots increases mineralization, which adds nutrients, thus soil's micronutrient content rises (He *et al.*, 2016). Further, similar to present study, in Haryana, kinnow + eucalyptus + wheat system had the most accessible Cu in the surface, 0-15 cm (0.64 mg kg^{-1}) of the total (1.9 mg kg^{-1}) in 0-90 cm soil profile, which was considerably greater than the pure agriculture (Devi *et al.*, 2020).

4.4.2.9.2 Iron (mg kg^{-1})

Table 27 shows that iron (Fe) content varied significantly due to the average effect of agroforestry systems, soil depths and interaction amongst them. Irrespective of the soil depths, highest Fe content (31.10 mg kg^{-1}) was documented in the soils under fruit tree based agroforestry system which was found to be significantly higher than all other agroforestry systems.

Table 27: Effect of agroforestry systems, soil depths and interaction between them on Iron (mg kg^{-1})

Agroforestry systems	Soil Depths			Mean
	D_1	**D_2**	**D_3**	
T_1 (Sole Cropping system)	15.10	11.16	10.42	12.23^{d}
T_2 (Agri-silvi-horticulture system)	34.34	24.80	14.31	24.49^{b}
T_3 (Agri-silviculture system)	30.40	20.58	13.30	21.43^{c}
T_4 (Fruit tree based AFS)	45.41	28.31	19.59	31.10^{a}
T_5 (Fodder tree based AFS)	26.49	24.23	17.26	22.66^{bc}
T_6 (Bamboo based AFS)	18.31	13.54	8.76	13.54^{d}
T_7 (Melia based AFS)	26.20	21.78	20.78	22.92^{bc}
T_8 (Poplar based AFS)	23.09	20.34	15.95	19.80^{c}
T_9 (Silvipasture system)	6.40	3.75	3.17	4.44^{e}
Mean	25.08^{a}	18.72^{b}	13.73^{c}	
Factors	**$SE_{(M)}$**	**$CD_{0.05}$**		
Soil depth	0.511	1.648		
AFS	0.884	2.517		
Interaction	1.532	4.360		

Some agroforestry systems *viz*., agri-silvi-horticulture, fodder tree based and melia based systems displayed statistical similarity. Similarly, agri-silviculture, fodder tree based, melia based and poplar based agroforestry systems also remained statistically identical to one another. Minimum Fe content (4.44 mg kg^{-1}) was recorded in the silvipasture system. The concentration of iron decreased notably with increase in soil depth, from D_1 (25.08 mg kg^{-1}) to D_2 (18.72 mg kg^{-1}) and D_2 to D_3 (13.73 mg kg^{-1}). Furthermore, in the interaction effect, fruit tree based agroforestry system displayed significantly higher values of iron, than all other agroforestry systems, at their respective soil depths. Maximum copper content was recorded in treatment combination T_4D_1 (45.41 mg kg^{-1}), and minimum in T_9D_3 (3.17 kg^{-1}).

Costa *et al*. (2018) also found more Fe concentration in cacao based agroforestry field when compared to a control field. The decreasing concentration of available Fe with increasing depth in present study can be attributed to lower mineralization under low temperature conditions common in deeper soil layers. Devi *et al*. (2020) also declared the Fe content of the surface soil layer (0-15 cm) to be ranging from 27.7 per cent to 29.7 per cent of the total Fe content of the soil profile examined (0-90 cm), in eucalyptus and kinnow based agroforestry systems in Haryana. Also, Khanmirzaei *et al*. (2011) concluded a significant increase in soil micronutrients, especially Fe in the top layer of the soil (0-20 cm), with values rising from 1.85 to 3.6 mg kg^{-1}.

4.4.2.9.3 Manganese (mg kg^{-1})

Data pertaining to the manganese (Mn) content of soils under various agroforestry systems is displayed in Table 28. It is evident from the data that the Mn content varied significantly due to the average effect of agroforestry systems, soil depths and interaction between them. Irrespective of the soil depth, maximum Mn content (17.31 mg kg^{-1}) was recorded under fruit tree based agroforestry system which is significantly higher than all other agroforestry systems. It was followed by agri-silvi-horticulture (13.69 mg kg^{-1}) and melia based (12.90 mg kg^{-1}) agroforestry systems, which were found to be statistically identical. Agroforestry systems *viz*., agri-silviculture, sole cropping system and fodder tree based agroforestry systems, were also statistically at par with each other. Some other agroforestry systems *viz*., fodder tree based, bamboo based, poplar based and silvipasture systems displayed significantly lower values than sole cropping system. Minimum Mn content (3.86 mg kg^{-1}) was recorded in silvipasture systems. But, in the average effect of soil depths, the concentration of manganese decreased moderately with increasing soil depth, from D_1 (13.95 mg kg^{-1}) to D_2 (10.67 mg kg^{-1}) and D_2 to D_3 (8.13 mg kg^{-1}). Further, due to the interaction effect, fruit tree based agroforestry system displayed markedly higher values of Mn content at all the soil depths, than all other agroforestry systems, at their respective soil depths. Maximum and minimum Mn values were recorded in treatment combination T_4D_1 (22.84 mg kg^{-1}) and T_9D_3 (2.95 mg kg^{-1}), respectively.

Table 28: Effect of agroforestry systems, soil depths and interaction between them on Manganese (mg kg^{-1})

Agroforestry systems	Soil Depths			Mean
	D_1	D_2	D_3	
T_1 (Sole Cropping system)	14.70	12.56	7.20	11.49^c
T_2 (Agri-silvi-horticulture system)	18.36	13.31	9.39	13.69^b
T_3 (Agri-silviculture system)	14.47	11.61	6.36	10.81^{cd}
T_4 (Fruit tree based AFS)	22.84	15.51	13.58	17.31^a
T_5 (Fodder tree based AFS)	12.87	9.76	9.13	10.59^d
T_6 (Bamboo based AFS)	11.88	7.91	7.40	9.06^e
T_7 (Melia based AFS)	15.26	13.73	9.71	12.90^b
T_8 (Poplar based AFS)	10.46	7.68	7.48	8.54^e
T_9 (Silvipasture system)	4.69	3.93	2.95	3.86^f
Mean	13.95^a	10.67^b	8.13^c	
Factors	**$SE_{(M)}$**	**$CD_{0.05}$**		
Soil depth	0.180	0.581		
AFS	0.312	0.888		
Interaction	0.540	1.537		

Similarly, Mongia *et al*. (1998) also investigated the ameliorative impact of forest trees on acidic soils in Haryana and discovered that after three years of cultivating *Acacia nilotica*, the organic matter and Mn content in the soil, increased. Oballa *et al*. (2010), also documented an increase in Mn concentrations of the soil under short rotation Eucalyptus spp. plantations in Kenya. The decrease in Mn concentrations with increasing soil depths was conspicuous in the present study. Likewise, Jiang *et al*. (2009) discovered that when soil depth was increased, the DTPA extractable Mn dropped considerably. Decreasing trend of Manganese with increasing soil depth is also analogous to the findings of Dar *et al*. (2012).

Moreover, Khanmirzaei *et al*. (2011) also found a substantial increase in soil accessible micronutrients, particularly Mn in top layer of soil (0-20 cm), as Mn rose from 2.10 to 11.3 mg kg^{-1}. The breakdown of leaf litter and dead roots enhances mineralization, which provides nutrients to the soil, and the micronutrient content of the soil increases (He *et al*., 2016). According to Devi *et al*. (2020), with in kinnow and eucalyptus based agroforestry systems, the accessible Mn content, in the surface soil layer ranged from 8.8 mg kg^{-1} in the wheat monocropping to 12.1 mg kg^{-1} in the kinnow + eucalyptus + wheat system.

4.4.2.9.4 Zinc (mg kg^{-1})

Table 29 regarding the zinc (Zn) content evinces that zinc content in the soil varied significantly due to the average effect of agroforestry systems, soil depths and interaction between them. Irrespective of the soil depth, maximum Zn content (2.38 mg kg^{-1}) was observed under bamboo based agroforestry system which was found to be significantly higher than all other agroforestry systems in the present investigation. Sole cropping and agri-silvi-horticulture systems remained statistically at par with each other. Minimum Zn content (0.99 mg kg^{-1}) was recorded in poplar based agroforestry systems. The concentration of zinc decreased faintly with increase in the soil depth, from D_1 (2.66 mg kg^{-1}) to D_2 (1.38 mg kg^{-1}) and D_2 to D_3 (0.96 mg kg^{-1}). In the interaction effect, bamboo based agroforestry system displayed significantly higher values of Zn content than all other agroforestry systems, at their respective soil depths. Maximum copper content was recorded in treatment combination T_6D_1 (3.76 mg kg^{-1}), and minimum in T_8D_3 (0.43 mg kg^{-1}).

Table 29: Effect of agroforestry systems, soil depths and interaction between them on Zinc (mg kg^{-1})

Agroforestry systems	Soil Depths			Mean
	D_1	D_2	D_3	
T_1 (Sole Cropping system)	2.49	1.25	0.77	1.50^{e}
T_2 (Agri-silvi-horticulture system)	2.35	1.37	1.01	1.57^{e}
T_3 (Agri-silviculture system)	2.05	1.01	0.55	1.20^{f}
T_4 (Fruit tree based AFS)	2.82	1.62	1.10	1.85^{d}
T_5 (Fodder tree based AFS)	2.15	1.01	0.51	1.22^{f}
T_6 (Bamboo based AFS)	3.76	1.77	1.62	2.38^{a}
T_7 (Melia basedAFS)	3.02	1.91	1.29	2.07^{c}
T_8 (Poplar based AFS)	1.88	0.67	0.43	0.99^{g}
T_9 (Silvipasture system)	3.44	1.79	1.34	2.19^{b}
Mean	2.66^{a}	1.38^{b}	0.96^{c}	
Factors	**$SE_{(M)}$**	**$CD_{0.05}$**		
Soil depth	0.019	0.060		
AFS	0.032	0.092		
Interaction	0.056	0.159		

Devi *et al*. (2020) worked in Haryana on kinnow and eucalyptus based agroforestry systems, also reported that among various systems, available Zn in the surface layer was highest in kinnow + eucalyptus + wheat (2.06 mg kg^{-1}) and, almost half in control (1.12 mg kg^{-1}). Some plant micronutrients have a higher likelihood of leaching down and being recycled by trees with deep root systems (Jobbagy and Jackson, 2001). Also, that along a leaching gradient, the limiting nutrients are comparatively less depleted due to greater uptake and retention by plants. Devi *et al.* (2020) also reported that the upper two soil depths had 77.5 per cent and 76.9 percent of the Zn content in kinnow + eucalyptus + wheat and kinnow + wheat system, respectively. Further, bearing in mind the natural deficiency of micronutrients in Indian soil, the findings are also in line with the results of Kaur *et al.* (2020) who worked on the cationic micronutrients under poplar based agroforestry systems in India and opined that with increasing time period, the cationic soil micronutrients *viz.* copper, iron, manganese and zinc also increased. He *et al.* (2016) have also reported that the soil micronutrients to be higher under plants due to larger litter fall and decomposition.

The results pertaining to the soil micronutrients indicate that all the agroforestry systems are rich in soil micronutrients, and, agroforestry development increased the availability of concerned four micronutrients in all soil depths. All treatments increased micronutrient levels on the surface soil. Under the AFSs, the concentration of Fe, Mn, Zn, and Cu was greater by 15, 31, 101, and 86 per cent, respectively, than that in the fields without trees (Kumar *et al.,* 2017). These outcomes are analogous with the findings of Sarkar *et al.* (2020), who worked on the soil micronutrients status of soils under various agroforestry systems in north Bihar region of India and concluded that the soils under all the agroforestry systems to be richer in micronutrients, when compared with control and also, the decrease in the micronutrients availability with increasing soil depth. In comparison to conventional agriculture, agroforestry recycles plant micronutrients more effectively perhaps due to deep root system and substantial litter fall. The return of several micronutrients, such as Fe and Cu is much higher in winter months (Singh *et al*., 2007). Hence, crop production could be replaced by agroforestry system development as a stable and revitalizing choice for soil sustainability.

4.4.3 Microbial count (× 10^5 cfu g^{-1})

Data pertaining to the microbial count of agroforestry systems, along soil depths has been displayed in Table 30. The highest microbial count among all the agroforestry systems is observed in poplar based agroforestry system (35.32 x 10^5 cfu g^{-1}) and the minimum in sole cropping system (16.41 x 10^5 cfu g^{-1}). The microbial count among different agroforestry systems followed the trend: poplar based agroforestry system (35.32 x 10^5 cfu g^{-1}) > bamboo based system (30.43 x 10^5 cfu g^{-1}) > melia based system (26.73 x 10^5 cfu g^{-1}) > agri-silvi-horticulture system (25.01 x 10^5 cfu g^{-1}) > fruit tree based system (23.68 x 10^5 cfu g^{-1}) > silvipasture system (21.64 x 10^5 cfu g^{-1}) > agri-silviculture system (20.47 x 10^5 cfu g^{-1}) > fodder tree based system (19.21 x 10^5 cfu g^{-1}) and sole cropping system (16.41 x 10^5 cfu g^{-1}). However, melia based agroforestry system remained statistically identical to agri-silvi-horticulture system. Soil depths also significantly affected the microbial population of the soil. Maximum microbial population was noticed in D_1 (38.67 x 10^5 cfu g^{-1}), followed by D_2 (21.50 x 10^5 cfu g^{-1}) and D_3 (11.85 x 10^5 cfu g^{-1}), respectively. The interaction of agroforestry system and soil depths also appreciably affect the microbial populations with maximum microbial colonies being recorded in treatment combination T_8D_1 (53.25 x 10^5 cfu g^{-1}) whereas, minimum was in, T_1D_3 (7.62 x 10^5 cfu g^{-1}). Microbial count declined considerably under all the agroforestry systems with increase in soil depth.

Table 30: Effect of agroforestry systems, soil depths and interaction between them on total microbial count (× 10^5 cfu g^{-1})

Agroforestry systems	**Soil Depths**			**Mean**
	D_1	**D_2**	**D_3**	
T_1 (Sole Cropping system)	25.14	16.49	7.62	16.41^{g}
T_2 (Agri-silvi-horticulture system)	42.01	21.53	11.48	25.01^{cd}
T_3 (Agri-silviculture system)	32.93	17.80	10.68	20.47^{ef}
T_4 (Fruit tree based AFS)	38.48	20.40	12.15	23.68^{d}
T_5 (Fodder tree based AFS)	29.57	18.50	9.57	19.21^{f}
T_6 (Bamboo based AFS)	48.88	27.99	14.43	30.43^{b}
T_7 (Melia based AFS)	43.87	23.22	13.11	26.73^{c}
T_8 (Poplar based AFS)	53.25	28.53	15.77	32.52^{a}
T_9 (Silvipasture system)	33.92	19.05	11.96	21.64^{e}
Mean	38.67^{a}	21.50^{b}	11.86^{c}	
Factors	**$SE_{(M)}$**	**$CD_{0.05}$**		
Soil depth	0.381	1.23		
AFS	0.66	1.88		
Interaction	1.143	3.25		

The microbial community's richness, abundance, and activity are influenced by plant type, *i.e.*, substrate quantity and quality, as well as environmental factors such as temperature, moisture, pH, soil type, and soil depth (Jha *et al.*, 1992 and Zhang *et al.*, 2013). Further, microbial development and structure are determined by the available organic material and its quality, (Myers *et al.*, 2001; Bezemer *et al.*, 2006; Ravindran and Yang, 2015). Fresh organic matter is a suitable substrate for microbial activity, which functions as an agent for increasing aggregate stability. The present results are synchronous with the findings of Radhakrishnan *et al.* (2016), according to whom, microbial population was favorably associated to the physico-chemical parameters of soil.

Table 31: Weighted means of chemical soil quality parameters used for computing soil quality index (SQI)

AFS	**Soil characteristics**																
	pH	**EC**	**N**	**P**	**K**	**Ca**	**S**	**Cu**	**Fe**	**Mn**	**Zn**	**OC**	**Bulk Density**	**Particle Density**	**Poro-sity**	**Microbial Count**	**SQI**
T_1	7.11	0.27	258.80	24.92	173.47	701.41	24.16	1.97	12.23	11.49	1.50	7.8	1.28	2.29	44.18	16.41	**0.72**
T_2	6.86	0.35	277.50	32.57	194.28	908.50	32.25	2.47	24.49	13.69	1.57	9.7	1.23	2.25	45.42	25.01	**0.83**
T_3	6.97	0.33	268.45	35.67	186.08	767.32	31.36	1.58	21.43	10.81	1.20	8.4	1.28	2.29	44.11	20.47	**0.75**
T_4	6.98	0.37	255.24	40.64	196.85	940.26	27.21	3.05	31.10	17.31	1.85	9.2	1.22	2.28	46.29	23.68	**0.87**
T_5	6.94	0.30	256.99	28.22	183.41	826.86	25.21	1.88	22.66	10.59	1.22	8.3	1.21	2.22	45.47	19.21	**0.76**
T_6	6.75	0.49	301.47	40.27	245.69	1496.53	34.07	2.53	13.54	9.06	2.38	11.3	1.09	2.24	51.63	30.43	**0.89**
T_7	6.84	0.41	292.11	34.20	205.70	890.77	18.72	2.15	22.92	12.90	2.07	9.8	1.19	2.24	46.88	26.73	**0.81**
T_8	6.82	0.43	293.64	32.99	226.30	1327.59	26.59	1.55	19.80	8.54	0.99	10.4	1.14	2.22	48.81	32.52	**0.79**
T_9	7.02	0.35	275.05	31.92	217.62	1052.89	15.77	0.61	4.44	3.86	2.19	10.3	1.22	2.23	45.32	21.64	**0.70**

In Eastern Uttar Pradesh, India, Maurya *et al.* (2012) found that agroforestry had greater *Azospirillum* and *Azotobacter* populations than vegetables and grassland-based crop rotations. Likewise, Hombegowda *et al*. (2015) stated that microbial populations are determined by soil pH and organic carbon. Neutral soil pH and high soil organic carbon boost microbial population in agroforestry systems, which is influenced by increased soil toxicity and high pH fluctuations. Bhutia (2017) discovered that soil microbial populations are significantly connected to physio-chemical characteristics, organic carbon and moisture content being positively correlated, and soil pH, EC and bulk density was being negatively correlated. Several other researchers have also set forth the strong correlation between soil organic C in tree based systems and agriculture land with the soil microbial populations (Arunachalam *et al.*, 1999; Yu *et al*., 2012 and Yadav, 2017).

In the present study, microbial population was observed to be diminishing significantly with soil depth, which can be owed to lack of substrate (available N and P) in the deeper layers. This decreasing trend of microbial populations with increasing soil depth was in consonance with work of Tangjang *et al.* (2009), who reported microbial colony forming units (cfu) to be higher in top soil as compared to the sub soil except for in rainy season. The colony forming units according to them were related to the organic carbon and nitrogen content in the top soil which is similar to current findings of diminishing microbial count with increasing soil depth.

4.4.4 Soil Quality Index

Soil quality refers to a certain type of soil's ability to function within natural or controlled ecosystem boundaries in order to sustain plant and animal productivity, maintain or improve water and air quality, and support human health and habitation (Karlen *et al*., 1997). A set of quantitative properties known as ‘indicators’ can be used to monitor soil quality which are further classified as physical, chemical and biological (Dalal and Moloney, 2000) and variations in these markers can be used to measure overall soil quality. Soil organic matter is a vital component of soil fertility because it is a repository of necessary plant nutrients.

The soil quality index developed by taking into consideration, all the soil physico-chemical characteristics investigated is presented in Table 31. The data shows that the soil quality index is influenced by the type of agroforestry systems put in place. The soil quality index followed the order: bamboo based agroforestry system (0.89) > fruit tree based agroforestry system (0.87) > agri-silvi-horticulture system (0.83) > melia based agroforestry system (0.81) > poplar based agroforestry system (0.79) > fodder tree based agroforestry system (0.76) > agri-silviculture system (0.75) > sole cropping system (0.72) > silvipasture system (0.70).

It was found that soil quality index under all the agroforestry systems, was better than the sole cropping system, except in the silvipasture system, which means that the continuous export of nutrients through fodder leaf removal has impacted the soil quality index adversely. Therefore, from the present investigation, it can be made out that the tree-based agriculture is critical not only for raising system productivity, but also for preventing further deterioration of the soil and improving soil physico-chemical quality across all the soil layers.

Chapter-5

SUMMARY AND CONCLUSION

The present investigations entitled **“Evaluation of established Agroforestry systems for their Carbon sequestration and Soil enrichment potential in mid-hills of Himachal Pradesh”** was carried out at experimental farm of Department of Silviculture and Agroforestry, Dr. Y S Parmar university of Horticulture and Forestry, Nauni, Solan (H.P.) and adjoining areas during the year 2020-21. The experimental area is located in the sub humid, mid hill zone of Himachal Pradesh. The latitude and longitude coordinates of the site are 30˚50’30’’ to 30˚52’00’’ N and 77˚08’30’’to 77˚11’30’’ E, respectively, having an average elevation of about 1,250 m above mean sea level. The study was aimed at evaluating various natural and experimental agroforestry systems in and around the University campus for their carbon sequestration and soil enrichment potential in the sub humid and mid-hill zone of Himachal Pradesh.

5.1 TREE CHARACTERISTICS OF TREES UNDER DIFFERENT AGROFORESTRY SYSTEMS

Basic tree characteristics were recorded inside sample plots using standard methods and equipments. Parameters recorded were, tree height, crown height, crown length, diameter and crown spread.

- Tree height was observed to be maximum (24.37 m) in poplar based agroforestry system and minimum (3.62 m) in fruit tree based agroforestry system, while, the crown height was observed to be maximum (4.39 m) in melia based agroforestry system and minimum (0.40 m) in fodder tree based agroforestry system. Further, the maximum crown length (20.40 m) was exhibited by poplar based agroforestry system and minimum (2.47 m) by agrisilvihorticulture system.
- The tree diameter was recorded to be maximum (0.27 m) in poplar based agroforestry system, while, minimum diameter (0.11 m) was recorded both, in fruit tree based agroforestry system and fodder tree based agroforestry system, each displaying identical values. However, the largest crown spread (8.35 m) was recorded in melia based agroforestry system, whereas, minimum (4.11 m) was recorded in silvipasture system.

5.2 BIOMASS QUANTIFICATION IN DIFFERENT AGROFORESTRY SYSTEMS

Biomass and carbon density was evaluated for each agroforestry system by enumerating and calculating biomass for each tree individually. Further, biomass from each part of the trees was computed differently to finally sum it up as total above ground tree biomass.

- Above-ground tree biomass production was found to be maximum in poplar based agroforestry system (99.55 Mg ha^{-1}) followed by melia based agroforestry system and silvipasture system. Similar trend was followed by the below-ground tree biomass production. Hence, maximum total tree biomass (124.44 Mg ha^{-1}) was evident in poplar based agroforestry system followed by melia based agroforestry system and silvipasture system, whereas, minimum (22.72 Mg ha^{-1}) in fruit tree based system. The total tree biomass in poplar based agroforestry system was more than five times that of fruit tree based system.
- Crop biomass among different agroforestry systems also varied considerably with sole cropping displaying higher values of crop biomass in all other agroforestry systems. The maximum above-ground crop biomass (6.07 Mg ha^{-1}) was observed in sole cropping system followed by fruit tree based and agri-silvi-horticulture system. The below-ground crop biomass followed the same trend. Hence, the total crop biomass varied from a maximum of 7.89 Mg ha^{-1} under sole cropping system to a minimum of 4.10 Mg ha^{-1} under silvipasture system.
- Maximum total (tree + crop) biomass was observed in followed the trend: poplar based agroforestry system (130.87 Mg ha^{-1}) > melia based system (106.09 Mg ha^{-1}) > silvipasture system (87.72 Mg ha^{-1}) > fodder based agroforestry system (66.11 Mg ha^{-1}) > agri-silvi-horticulture system (43.65 Mg ha^{-1}) > agri-silviculture system (37.24 Mg ha^{-1}) > bamboo based agroforestry system (35.83 Mg ha^{-1}) > fruit tree based agroforestry system (30.48 Mg ha^{-1}). The lowest vegetation biomass was observed in the sole cropping system (7.89 Mg ha^{-1}). Total biomass production in poplar based agroforestry system was sixteen times that of control i.e. sole cropping.

5.3 CARBON STOCK IN DIFFERENT CARBON POOLS

Terrestrial carbon sinks can be sub-classified as carbon storage in vegetation and soils. The carbon stock in present study was categorized into three carbon pools: vegetation, litter and soil, respectively.

- Highest vegetation carbon density (65.44 Mg ha^{-1}) was displayed by poplar based agroforestry system, followed by melia based and silvipasture system. Minimum vegetation carbon was exhibited by sole cropping system (3.95 Mg ha^{-1}). Leaf litter carbon density followed the same trend.
- Maximum soil carbon density (114.69 Mg ha^{-1}) was recorded in bamboo based agroforestry system, which however, remained statistical on par with the silvipasture system (113.71 Mg ha^{-1}), while, minimum soil carbon density (84.74 Mg ha^{-1}) was recorded under sole cropping system.
- Overall, the total carbon density (soil + vegetation + litter fall) under different agroforestry systems followed the trend: poplar based agroforestry system (173.91 Mg ha^{-1}) > silvipasture system (157.86 Mg ha^{-1}) > melia based system (157.66 Mg ha^{-1}) > bamboo based system (133.08 Mg ha^{-1}) > agri-silvi-horticulture system (129.59 Mg ha^{-1}) > fodder tree based system (128.56 Mg ha^{-1}) > fruit tree based system (115.86 Mg ha^{-1}) > agri-silviculture system (113.62 Mg ha^{-1}) > sole cropping system (88.76 Mg ha^{-1}).

5.4 CARBON SEQUESTRATION

The carbon sequestration and CO_2 mitigation potential was evaluated only for the six experimental agroforestry systems, where the age of the systems was known.

- Rate of carbon sequestration in the soil sphere was found to be maximum in bamboo based agroforestry system (1.81 Mg ha^{-1}yr^{-1}) followed by melia based, fruit tree based system, fodder tree based, poplar based and silvipasture system.
- Whereas, the maximum rate of carbon sequestration in vegetation was documented in poplar based agroforestry system (3.72 Mg ha^{-1}yr^{-1}), which however, remained statistically identical to melia based agroforestry system (3.55 Mg ha^{-1}yr^{-1}). These were followed by silvipasture, fodder tree based, bamboo based and fruit tree based agroforestry systems.

- The rate of total carbon sequestration followed the order: melia based system (5.26 Mg $ha^{-1}yr^{-1}$) > poplar based (5.15 Mg $ha^{-1}yr^{-1}$) > silvipasture system (3.46 Mg $ha^{-1}yr^{-1}$) > fodder tree based system (3.41 Mg $ha^{-1}yr^{-1}$) > bamboo based system (2.95 Mg $ha^{-1}yr^{-1}$) > fruit tree based agroforestry system (2.49 Mg $ha^{-1}yr^{-1}$).

Furthermore, as we know, CO_2 mitigation potential is just a function of carbon sequestration potential, order followed by both is the same. Hence, maximum CO_2 mitigation potential (19.30 Mg $ha^{-1}yr^{-1}$) was again, documented in melia based agroforestry system, whereas, minimum (9.15 Mg $ha^{-1}yr^{-1}$), in fruit tree based agroforestry system. And, the trend followed was same as rate of carbon sequestration.

5.5 SOIL PROPERTIES

5.5.1 Soil physical properties

- Agroforestry systems affect the bulk density of the soils up to some extent over an extended period of time. In the present study, maximum bulk density (1.28 g cm^{-3}) was exhibited sole cropping system and agrisilviculture system, each displaying identical values, whereas, minimum (1.09 g cm^{-3}), was exhibited by T_6 (bamboo based agroforestry system). But, with respect to soil depth, soil bulk density enhanced from D_1 to D_2 (1.15-1.20 g cm^{-3}) and D_2 to D_3 (1.20-1.28 g cm^{-3}).
- Maximum particle density (2.29 g cm^{-3}), was observed in sole cropping system and agrisilviculture system, each displaying identical values, whereas, minimum (2.22 g cm^{-3}) was observed in poplar based agroforestry system. Further, in the average effect of soil depths, soil particle density enhanced from D_1 to D_2 (2.19 -2.24 g cm^{-3}) and D_2 to D_3 (2.24-2.32 g cm^{-3}).
- Soil porosity is a function of pore spaces present in the soil which can be estimated by the bulk density and particle density of soil samples. Hence, maximum porosity was measured in bamboo based agroforestry systems (51.63 %), followed closely by poplar based (48.81 %), melia based (46.88 %), respectively. Minimum soil porosity was recorded under agri-silviculture system (44.11 %) which, however remained statistically identical to sole cropping system (44.18 %). Irrespective of agroforestry systems, the soil porosity declined appreciably from D_1 (47.85 %) to D_2 (46.63 %) and further to D_3 (44.90 %).

- Soil texture was recorded to be of loam class in all the agroforestry systems. The soils under sole cropping and fruit tree based agroforestry systems showed loam type soil texture. Agri-silviculture, bamboo based, melia based and poplar based agroforestry systems displayed clay loam texture, whereas, fodder based, agri-silvi-horticulture and silvipasture systems showed sandy clay loam type of texture. The major part of all the soils was made by sand, ranging between 40.16 per cent and 51.34 per cent.

5.5.2 Soil chemical properties

All the available macro and micronutrients were found to be in their normal range and even surplus, indicating the lucrative prospects of agroforestry systems in terms of soil enrichment potential. All the agroforestry systems especially, experimental systems displayed ascendancy over sole cropping and natural agroforestry systems, prevalent in the mid-hills of the Himalayas.

- Soil pH varied substantially among different agroforestry systems, with highest soil pH (7.11) observed under sole cropping system followed by silvipasture system and fruit tree based agroforestry system. pH was minimum (6.75) under bamboo based agroforestry system. As an average effect of soil depths, the soil pH enhanced noticeably from D_1 to D_2 (6.82-6.92) and D_2 to D_3 (6.92-7.03).
- Soil EC remained well below the critical levels, with highest mean soil EC (0.49 dS m^{-1}) being exhibited by T_6 (bamboo based agroforestry system), followed by poplar based and melia based agroforestry systems. Whereas, minimum soil EC (0.27 dS m^{-1}) was exhibited by sole cropping system. Soil EC decreased considerably with increasing soil depths, from D_1 (0.43 dS m^{-1}) to D_2 (0.37 dS m^{-1}) and further to D_3 (0.30 dS m^{-1}).
- The soil OC under different agroforestry systems followed the trend: bamboo based agroforestry system (11.3 mg kg^{-1}) > poplar based system (10.4 mg kg^{-1}) > silvipasture system (10.3 per cent) > melia based system (9.8 mg kg^{-1}) > agri-silvi-horticulture system (9.mg kg^{-1}) > fruit tree based system (9.2 mg kg^{-1}) > agri-silviculture system (8.4 mg kg^{-1}), fodder tree based system (8.3 mg kg^{-1}) > sole cropping system (7.8 mg kg^{-1}). But, in the average effect of soil depths, the OC declined from D_1 (11.3 mg kg^{-1}) to D_2 (9.7 mg kg^{-1}) and D_2 to D_3 (6.8 mg kg^{-1}).
- The highest available nitrogen (301.47 kg ha^{-1}) was recorded under bamboo based agroforestry system, closely followed by poplar based (293.64 kg ha^{-1}) and melia

based (292.11 kg ha^{-1}) agroforestry systems, respectively. Minimum available nitrogen was recorded under fruit tree based agroforestry system (255.24 kg ha^{-1}), which however, remained statistical identical to sole cropping system (258.80 kg ha^{-1}). But with increasing soil depth, the available nitrogen content declined significantly from D_1 to D_2 (297.87 kg ha^{-1}) (277.91 kg ha^{-1}) and D_2 to D_3 (250.64 kg ha^{-1}).

- The maximum available phosphorus (40.64 kg ha^{-1}) was recorded in fruit tree based agroforestry system, which, however remained statistically identical to bamboo based agroforestry system (40.27 kg ha^{-1}), and minimum (24.92 kg ha^{-1}) in sole cropping system. Irrespective of agroforestry systems, the available P declined slightly with increase in soil depth from D_1 to D_2 (42.45-33.54 kg ha^{-1}) and further to D_3 (24.48 kg ha^{-1}).
- The highest available potassium (245.69 kg ha^{-1}) was documented in the soils under bamboo based agroforestry system, closely followed by poplar based agroforestry systems (226.30 kg ha^{-1}) and minimum (173.47 kg ha^{-1}) in sole cropping system. But, with respect to soil depth, potassium content increased from D_1 to D_2 (183.32-200.64 kg ha^{-1}) and then from D_2 to D_3 (200.64-225.84 kg ha^{-1}).
- Amongst all the agroforestry systems, highest available calcium (1496.53 mg kg^{-1}) was recorded under T_6 (bamboo based agroforestry system) followed by poplar based agroforestry system and silvipasture system. The lowest calcium content (701.40 mg kg^{-1}) was recorded under sole cropping system. Whereas, irrespective of agroforestry systems, the soil calcium content declined markedly with increasing soil depth.
- Th**e** highest sulphur content (34.07 kg ha^{-1}) was noticed in bamboo based agroforestry system, which was closely followed by agri-silvi-horticulture and agri-silviculture systems, whereas, minimum sulphur content (15.77 kg ha^{-1}) was recorded in silvipasture system. But, with respect to soil depths, the soil calcium content declined markedly.
- The result regarding soil micronutrients shows that all agroforestry systems have optimum to high concentration of soil micronutrients. Soils of all agroforestry systems were found to be richer in micronutrients than control plots, with a sharp decline in micronutrient availability as soil depth rose. All four micronutrients were found to be comparatively higher at all soil depths as a result of agroforestry practices. On the surface soil, all systems improved the micronutrient levels**.**

- Highest copper concentration (3.05 mg kg^{-1}) was recorded in soils of fruit tree based system, and minimum (0.61 mg kg^{-1}) in the soils under silvipasture system. Whereas, in the average effect of soil depth, concentration of copper decreased slightly with increase in soil depth, from D_1 to D_2 (2.33-1.94 mg kg^{-1}) and D_2 to D_3 (1.94-1.66 mg kg^{-1}).
- The highest iron concentration (31.10 mg kg^{-1}) was exhibited by soils in fruit tree based system, and, minimum (3.86 mg kg^{-1}) under silvipasture system, irrespective of the soil depth. But, the concentration of iron decreased notably with increase in soil depth, from D_1 to D_2 (25.08-18.72 mg kg^{-1}) and D_2 to D_3 (18.72-13.73 mg kg^{-1}).
- Among the various agroforestry systems, highest manganese concentration (17.31 mg kg^{-1}) was evident in soils under fruit tree based system and, minimum (4.44 mg kg^{-1}) in soils under silvipasture system. But, with respect to soil depth, the manganese concentration decreased moderately with increase in soil depth, from D_1 to D_2 (13.95-10.67 mg kg^{-1}) and to D_2 to D_3 (10.67-8.13 mg kg^{-1}).
- The highest zinc concentration (2.38 mg kg^{-1}) was documented in the soils of bamboo based agroforestry system, and minimum (0.99 mg kg^{-1}) in soils under poplar based agroforestry system. But, in the average effect of soil depths, the concentration of zinc decreased with increasing soil depth, from D_1 (2.66 mg kg^{-1}) to D_2 (1.38 mg kg^{-1}) and further to D_3 (0.96 mg kg^{-1}).

All the agroforestry systems, had notably higher pH, EC, OC, N, P, K, Ca, Mg, and S values as compared to pure agrarian land use system owing to continuous addition of organic matter, rich in all types of soil nutrients required by plants.

5.5.6 Soil biological properties

The highest microbial population (35.32 x 10^5 cfu g^{-1}) was observed in soils under poplar based agroforestry system followed closely by bamboo based agroforestry system (35.32 x 10^5 cfu g^{-1}) and, minimum (16.41 x 10^5 cfu g^{-1}) in soils under sole cropping system. But, with respect to increasing soil depth, the microbial populations decreased from D_1 to D_2, (38.67-21.50 x 10^5 cfu g^{-1}) and D_2 to D_3 (21.50-11.85 x 10^5 cfu g^{-1}).

5.6 SOIL QUALITY INDEX

Soil quality index under all the agroforestry systems was better than the sole cropping system, except in the silvipasture system, which means that the continuous export of nutrients through fodder leaf removal has impacted the soil quality index adversely. The soil quality index followed the order: bamboo based agroforestry system (0.89) > fruit tree based (0.87) > agri-silvi-horticulture (0.83) > melia based (0.81) > poplar based (0.79) > fodder tree based (0.76) > agri-silviculture system (0.75) > sole cropping system (0.72) > silvipasture system (0.70).

CONCLUSIONS

- Vegetation biomass production (Mg ha^{-1}) varied significantly amongst different AFS and followed the following order: poplar based system > melia based system > silvipasture system > fodder tree based system > agrisilvihorticulture system > agrisilviculture system > bamboo based system > fruit tree based agroforestry system > sole cropping system.
- The total biomass was higher among all the agroforestry systems as compared to control systems and maximum biomass was evident in poplar based agroforestry system, which was more than sixteen times that of pure agriculture.
- Furthermore, all the agroforestry systems – natural as well as experimental AFs displayed significantly higher soil carbon storage at all soil depths.
- Highest carbon sequestration potential was documented in melia based agroforestry system followed closely by poplar based agroforestry system. Also, carbon sequestration was much higher in vegetation as compared to soil pool.
- Soil properties were found to be favourably affected by all the agroforestry systems, for physical, chemical as well as biological properties. All the physico-chemical properties, total microbial count and soil quality index improved under the Agroforestry systems vis-à-vis sole cropping systems. The bamboo based and fruit tree based agroforestry system demonstrated best results as far as all the aspects of soil enrichment potential were concerned.

From the present study, it can be concluded that experimental as well as natural agroforestry systems are better than sole cropping systems for carbon sequestration and soil enrichment point of view. Among all the agroforestry systems, bamboo, melia and poplar based agroforestry systems performed better than other agroforestry systems.

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APPENDIX – I

ANOVA of Table 8

Biomass in different components of the agroforestry systems - tree stem biomass

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	12.01	2.00	6.00	0.39	0.68
Systems	11399.92	7.00	1628.56	106.77	0.00
Error	213.55	14.00	15.25		
Total	46472.50	24.00			

Biomass in different components of the agroforestry systems - tree branch biomass

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	20.72	2.00	10.36	1.34	0.29
Systems	714.10	7.00	102.01	13.21	0.00
Error	108.11	14.00	7.72		
Total	2150.96	24.00			

Biomass in different components of the agroforestry systems - tree leaf biomass

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	2.33	2.00	1.17	1.60	0.24
Systems	93.12	7.00	13.30	18.21	0.00
Error	10.23	14.00	0.73		
Total	270.37	24.00			

Biomass in different components of the agroforestry systems - Total tree above-ground biomass

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	25.014	2.000	12.507	1.715	0.216
Systems	18953.347	7.000	2707.621	371.274	0.000
Error	102.099	14.000	7.293		
Total	75254.478	24.000			

ANOVA of Table 9

Tree above-ground biomass under different AFS

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	25.01	2.00	12.51	1.71	0.22
Systems	18953.35	7.00	2707.62	371.27	0.00
Error	102.10	14.00	7.29		
Total	75254.48	24.00			

Tree below-ground biomass under different AFS

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	4.27	2.00	2.14	0.69	0.61
Systems	1215.35	7.00	173.62	56.12	0.00
Error	43.31	14.00	3.09		
Total	5465.84	24.00			

Total tree biomass under different AFS

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	36.30	2.00	18.15	1.09	0.36
Systems	29618.96	7.00	4231.28	253.09	0.00
Error	234.06	14.00	16.72		
Total	120996.96	24.00			

Crop above-ground biomass under different AFS

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	2.51	2.00	1.25	4.51	0.03
Systems	28.29	8.00	3.54	12.72	0.00
Error	4.45	16.00	0.28		
Total	648.53	27.00			

Crop below-ground biomass under different AFS

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	0.20	2.00	0.10	4.23	0.03
Systems	2.92	8.00	0.36	15.38	0.00
Error	0.38	16.00	0.02		
Total	53.68	27.00			

Total crop biomass under different AFS

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	4.13	2.00	2.06	4.46	0.03
Systems	47.62	8.00	5.95	12.86	0.00
Error	7.41	16.00	0.46		
Total	1073.48	27.00			

Total vegetation biomass under different AFS

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	17.31	2.00	8.65	0.52	0.60
Systems	38401.08	8.00	4800.14	290.00	0.00
Error	264.84	16.00	16.55		
Total	138806.48	27.00			

ANOVA of Table 10

Total vegetation carbon density under different AFS

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	4.35	2.00	2.18	0.53	0.60
Systems	9599.80	8.00	1199.98	289.98	0.00
Error	66.21	16.00	4.14		
Total	34703.01	27.00			

Total litter carbon density under different AFS

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	0.00083	2	0.000415	1.041	0.38
Systems	0.839452	8	0.104931	263.55	0.00
Error	0.00637	16	0.000398		
Total	4.8295	27			

Total soil carbon density under different AFS

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	1.973607	2	0.986804	0.14	0.87
Systems	2281.915	8	285.2394	39.37	0.00
Error	115.9123	16	7.244516		
Total	286085	27			

Total carbon (vegetation + litter + soil) density under different AFS

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	23.55	2.00	11.77	0.61	0.56
Systems	16669.75	8.00	2083.72	107.11	0.00
Error	311.28	16.00	19.45		
Total	496140.95	27.00			

ANOVA of Table 11

Soil carbon density in 0-20 cm soil layer under AFS

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	0.486007	2	0.243004	1.11	0.36
Systems	36.20234	8	4.525293	20.58	0.00
Error	3.517726	16	0.219858		
Total	19716.19	27			

Soil carbon density in 20-40 cm soil layer under AFS

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	0.516956	2	0.258478	0.50	0.61
Systems	195.3611	8	24.42013	47.55	0.00
Error	8.216378	16	0.513524		
Total	14495.38	27			

Soil carbon density in 41-100 cm soil layer under AFS

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	0.421007	2	0.210504	0.03	0.97
Systems	964.4352	8	120.5544	15.97	0.00
Error	120.7482	16	7.546762		
Total	75509.6	27			

Total Soil carbon density at different soil layers under AFS

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	1.973607	2	0.986804	0.14	0.87
Systems	2281.915	8	285.2394	39.37	0.00
Error	115.9123	16	7.244516		
Total	286085	27			

ANOVA of Table 12

Carbon density in soils under agroforestry systems

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	3.15	2.00	1.57	0.20	0.83
System	871.78	5.00	174.36	21.71	0.00
Error	80.31	10.00	8.03		
Total	203046.39	17.00			

Carbon density in soils under agroforestry systems

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	14.42	2.00	7.21	0.65	0.54
System	5878.73	5.00	1175.75	105.48	0.00
Error	111.46	10.00	11.15		
Total	32120.64	17.00			

Total carbon density in (soil + vegetation) under agroforestry systems

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	30.45	2.00	15.23	0.91	0.43
System	7190.48	5.00	1438.10	85.86	0.00
Error	167.49	10.00	16.75		
Total	380895.67	17.00			

Carbon density in soils outside the agroforestry systems

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	150.37	2.00	75.18	2.69	0.12
System	804.74	5.00	160.95	5.76	0.01
Error	279.51	10.00	27.95		
Total	119399.04	17.00			

Carbon density in vegetation outside the agroforestry systems

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	0.01	2.00	0.01	0.98	0.41
System	8.98	5.00	1.80	290.45	0.00
Error	0.06	10.00	0.01		
Total	100.41	17.00			

Total carbon density in (soil + vegetation) outside the agroforestry systems

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	66.58	2.00	33.29	1.21	0.34
System	429.85	5.00	85.97	3.13	0.06
Error	274.61	10.00	27.46		
Total	128697.98	17.00			

ANOVA of Table 13

Carbon sequestration rate of the soils under agroforestry systems

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	0.53	2.00	0.26	1.78	0.22
System	0.44	5.00	0.09	0.60	0.70
Error	1.48	10.00	0.15		
Total	47.29	17.00			

Carbon sequestration rate of the vegetation under agroforestry systems

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	0.05	2.00	0.03	0.71	0.52
System	21.43	5.00	4.29	116.26	0.00
Error	0.37	10.00	0.04		
Total	109.72	17.00			

Total carbon sequestration rates (soils + vegetations) of agroforestry systems

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	0.45	2.00	0.22	3.00	0.10
Systems	19.93	5.00	3.99	53.63	0.00
Error	0.74	10.00	0.07		
Total	279.37	17.00			

Carbon dioxide mitigation rate of the soils under agroforestry systems

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	7.11	2.00	3.56	1.79	0.22
Systems	6.04	5.00	1.21	0.61	0.70
Error	19.87	10.00	1.99		
Total	637.04	17.00			

Carbon dioxide mitigation rate of the vegetation under agroforestry systems

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	0.72	2.00	0.36	0.74	0.50
System	288.86	5.00	57.77	118.01	0.00
Error	4.90	10.00	0.49		
Total	1478.38	17.00			

Total carbon dioxide mitigation rate (soils + vegetation) under agroforestry systems

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	8.01	2.00	4.01	4.46	0.04
Systems	284.02	5.00	56.80	63.24	0.00
Error	8.98	10.00	0.90		
Total	3670.13	17.00			

ANOVA of Table 14

Effect of agroforestry systems, soil depths and interaction between them on bulk density

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	0.00	2.00	0.00	0.42	0.66
Depth	0.24	2.00	0.12	815.49	0.00
Systems	0.28	8.00	0.04	244.97	0.00
Depth * Systems	0.03	16.00	0.00	13.84	0.00
Error	0.01	52.00	0.00		
Total	118.60	81.00			

ANOVA of Table 15

Effect of agroforestry systems, soil depths and interaction between them on particle density

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	0.00	2.00	0.00	0.89	0.42
Depth	0.21	2.00	0.10	253.81	0.00
Systems	0.06	8.00	0.01	16.79	0.00
Depth * Systems	0.05	16.00	0.00	7.04	0.00
Error	0.02	52.00	0.00		
Total	410.89	81.00			

ANOVA of Table 16

Effect of agroforestry systems, soil depths and interaction between them on soil porosity

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	0.21	2.00	0.10	0.29	0.75
Depth	118.51	2.00	59.25	165.71	0.00
Systems	419.54	8.00	52.44	146.66	0.00
Depth * Systems	16.96	16.00	1.06	2.97	0.00
Error	18.59	52.00	0.36		
Total	175393.51	81.00			

ANOVA of Table 18

Effect of agroforestry systems, soil depths and interaction between them on pH

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	0.01	2.00	0.00	3.38	0.04
Depth	0.61	2.00	0.31	361.36	0.00
Systems	0.89	8.00	0.11	132.17	0.00
Depth * Systems	0.15	16.00	0.01	11.14	0.00
Error	0.04	52.00	0.00		
Total	3882.86	81.00			

ANOVA of Table 19

Effect of agroforestry systems, soil depths and interaction between them on soil EC

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	0.00	2.00	0.00	1.19	0.31
Depth	0.24	2.00	0.12	309.28	0.00
Systems	0.31	8.00	0.04	101.70	0.00
Depth * Systems	0.02	16.00	0.00	3.32	0.00
Error	0.02	52.00	0.00		
Total	11.45	81.00			

ANOVA of Table 20

Effect of agroforestry systems, soil depths and interaction between them on soil organic carbon

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	0.00	2.00	0.00	0.52	0.60
Depth	3.30	2.00	1.65	2305.02	0.00
Systems	0.98	8.00	0.12	172.14	0.00
Depth * Systems	0.06	16.00	0.00	5.38	0.00
Error	0.04	52.00	0.00		
Total	76.95	81.00			

ANOVA of Table 21

Effect of agroforestry systems, soil depths and interaction between them on soil nitrogen

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	275.89	2.00	137.95	7.03	0.00
Depth	30358.10	2.00	15179.05	773.08	0.00
Systems	21292.90	8.00	2661.61	135.56	0.00
Depth * Systems	3729.44	16.00	233.09	11.87	0.00
Error	1020.99	52.00	19.63		
Total	6203380.15	81.00			

ANOVA of Table 22

Effect of agroforestry systems, soil depths and interaction between them on soil phosphorus

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	11.76	2.00	5.88	1.98	0.15
Depth	4359.00	2.00	2179.50	735.40	0.00
Systems	1862.92	8.00	232.87	78.57	0.00
Depth * Systems	798.66	16.00	49.92	16.84	0.00
Error	154.11	52.00	2.96		
Total	98026.39	81.00			

ANOVA of Table 23

Effect of agroforestry systems, soil depths and interaction between them on soil potassium

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	75.09	2.00	37.54	0.92	0.41
Depth	24692.07	2.00	12346.03	301.36	0.00
Systems	38176.16	8.00	4772.02	116.48	0.00
Depth * Systems	1485.38	16.00	92.84	2.27	0.01
Error	2130.32	52.00	40.97		
Total	3413295.90	81.00			

ANOVA of Table 24

Effect of agroforestry systems, soil depths and interaction between them on soil calcium

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	42837.29	2.00	21418.65	3.80	0.03
Depth	876413.94	2.00	438206.97	77.77	0.00
Systems	4976537.45	8.00	622067.18	110.40	0.00
Depth * Systems	55453.76	16.00	3465.86	0.62	0.86
Error	293012.20	52.00	5634.85		
Total	85670236.56	81.00			

ANOVA of Table 25

Effect of agroforestry systems, soil depths and interaction between them on soil sulphur

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	0.00	2.00	0.00	0.06	0.18
Depth	3.52	2.00	1.76	2308.34	0.00
Systems	0.94	8.00	0.12	153.33	0.00
Depth * Systems	0.05	16.00	0.00	3.94	0.00
Error	0.04	52.00	0.00		
Total	77.10	81.00			

ANOVA of Table 26

Effect of agroforestry systems, soil depths and interaction between them on copper content in soil

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	0.00	2.00	0.00	2.01	0.14
Depth	5.97	2.00	2.99	2485.86	0.00
Systems	35.75	8.00	4.47	3721.42	0.00
Depth * Systems	2.27	16.00	0.14	117.99	0.00
Error	0.06	52.00	0.00		
Total	360.66	81.00			

ANOVA of Table 27

Effect of agroforestry systems, soil depths and interaction between them on iron content in soil

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	0.19	2.00	0.09	0.01	0.99
Depth	1748.96	2.00	874.48	124.25	0.00
Systems	4493.82	8.00	561.73	79.81	0.00
Depth * Systems	788.77	16.00	49.30	7.00	0.00
Error	365.99	52.00	7.04		
Total	37185.03	81.00			

ANOVA of Table 28

Effect of agroforestry systems, soil depths and interaction between them on manganese content in soil

Source of variation	Sum of Squares	df	Mean Square	$F_{calculated}$	Sig
Replications	2.06	2.00	1.03	1.18	0.32
Depth	459.70	2.00	229.85	262.74	0.00
Systems	1006.77	8.00	125.85	143.85	0.00
Depth * Systems	127.35	16.00	7.96	9.10	0.00
Error	45.49	52.00	0.87		
Total	11292.91	81.00			

ANOVA of Table 29

Effect of agroforestry systems, soil depths and interaction between them on zinc content in soil

Source of variation	**Sum of Squares**	**df**	**Mean Square**	**$F_{calculated}$**	**Sig**
Replications	0.03	2.00	0.02	1.82	0.17
Depth	42.67	2.00	21.33	2291.85	0.00
Systems	17.01	8.00	2.13	228.49	0.00
Depth * Systems	1.62	16.00	0.10	10.85	0.00
Error	0.48	52.00	0.01		
Total	286.42	81.00			

ANOVA of Table 30

Effect of agroforestry systems, soil depths and interaction between them on microbial population of soil

Source of variation	**Sum of Squares**	**df**	**Mean Square**	**$F_{calculated}$**	**Sig**
Replications	12.11	2.00	6.06	1.55	0.22
Depth	9958.30	2.00	4979.15	1270.74	0.00
Systems	1988.83	8.00	248.60	63.45	0.00
Depth * Systems	634.37	16.00	39.65	10.12	0.00
Error	203.75	52.00	3.92		
Total	59498.97	81.00			

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Title of Thesis	**:**	**“Evaluation of established Agroforestry systems for their Carbon sequestration and Soil enrichment potential in mid-hills of Himachal Pradesh”**
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ABSTRACT

The present investigation entitled **“Evaluation of established Agroforestry systems for their Carbon sequestration and Soil enrichment potential in mid-hills of Himachal Pradesh”** was carried out during 2020-21 to analyze biomass production, carbon stock, and physico-chemical characteristics of soils under various agroforestry systems, as well as to find optimal land use systems with significant carbon storage and soil enrichment potential. Six experimental agroforestry systems viz., fruit tree based, fodder tree based, bamboo based, melia based, poplar based, and silvipasture systems were compared with the conventional systems prevalent in the mid-hills, such as agriculture, agrisilvihorticulture, and agrisilviculture systems. Tree biomass of all the systems was calculated using a 1,000 sq. m. plot, whereas crop, grass, and litter biomass, using 1 sq. m. plot. By a ratio of 0.5 (IPCC default value), the tree biomass was transformed into carbon stock. Soil physical properties (bulk density, particle density, porosity, and soil texture), chemical properties (pH, EC, organic carbon, available NPK, exchangeable calcium, and available sulphur), and microbiological properties (soil microbial count) were also investigated. Maximum above ground biomass (104.62 Mg ha^{-1}), below ground biomass (26.25 Mg ha^{-1}) and total biomass (130.87 Mg ha^{-1}) was recorded in poplar based agroforestry system. Total biomass production of different land use systems followed the order: poplar based AFS > melia based AFS > silvipasture system > fodder tree based AFS > agri-silvi-horticulture system > agri-silviculture system > bamboo based AFS > fruit tree based AFS > sole cropping system. The trend for carbon density (Mg ha^{-1}) remained the same. Rate of carbon sequestration was evaluated only for the experimental systems, as their age was known. The rate of carbon sequestration followed the order: melia based AFS (5.26 Mg ha^{-1} yr^{-1}) > poplar based AFS (5.15 Mg ha^{-1}yr^{-1}) > silvipasture system (3.46 Mg ha^{-1}yr^{-1}) > fodder tree based AFS (3.41 Mg ha^{-1}yr^{-1}) > bamboo based AFS (2.95 Mg ha^{-1}yr^{-1}) > fruit tree based AFS (2.49 Mg ha^{-1}yr^{-1}). Soil physico-chemical and microbial analysis revealed that maximum bulk density (1.28 g cm^{-3}) and particle densities (2.29 g cm^{-3}) were maximum in the sole cropping system, whereas, the bamboo based AFS exhibited maximum amount of pore space (51.63 %). Soil texture was dominantly clay loam and it can be inferred that tree based systems increased silt content, over a period of time. Soil pH decreased under all the agroforestry systems, whereas, electrical conductivity and organic carbon increased. Soil pH was minimum (6.75) and EC (0.53 dS m^{-1}), as well as organic carbon (11.3 mg kg^{-1}) were maximum under bamboo based AFS. Highest available nitrogen (301.47 kg ha^{-1}), potassium (245.69 kg ha^{-1}), exchangeable calcium (1496.53 mg kg^{-1}) and sulphur (34.07 kg ha^{-1}) were observed under bamboo based systems. However, fruit tree based AFS markedly dominated other AFS in terms of all major micronutrients (Cu, Fe, Mn and Zn). Silvipasture system showed the poorest soil enrichment potential, lagging behind sole cropping system. In soil microbial analysis, maximum microbial population (35.32 x 10^5 cfu g^{-1}) in poplar based AFS. However, in the average effect of depths, all soil physico-chemical properties were found to decrease appreciably with the increase in soil depths, except for bulk density, particle density, soil pH, available potassium. According to the findings of the present study, melia based AFS and poplar based AFS, play an important role in biomass accumulation and carbon sequestration. In terms of soil enrichment potential, bamboo based AFS and fruit tree based AFS excelled significantly among all other agroforestry systems in sub-humid mid hill zone of Himachal Pradesh.

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