CARBON SEQUESTRATION POTENTIAL OF TREE BASED AGROFORESTRY SYSTEMS IN THE ARID REGION OF INDIA

काशी हिन्दू विश्वविद्यालय BANARAS HINDU UNIVERSITY BHU capital of knowledge

Thesis submitted in partial fulfilment of the requirements for the award to the degree of

Master of Science (Agriculture)
in
Soil Science and Agricultural Chemistry

Supervisor
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ID. No. 18412SAC025 **2020** **Enrolment No. 406182**

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Certificate

To,
The Registrar
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Sir,

This is certified that the thesis entitled **"Carbon sequestration potential of tree based agroforestry systems in the arid region of India"** submitted in partial fulfilment of the requirements for the award of the degree of **Master of Science (Agriculture) in Soil Science and Agricultural Chemistry**, Department of Soil Science & Agricultural Chemistry, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi is a record of bonafide research carried out by **Mr. Rajendra Gadhwal, I.D. No. 18412SAC025.**

I certified that the entire work presented in thesis was planned and carried out by the candidate under my guidance. To the best of my knowledge and belief, the data presented in the thesis are genuine and original. No part of the work has been submitted for any degree or distinction.

Thanking you.

Yours faithfully,

(A. K. Ghosh)
Chairman of Advisory Committee

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BY

Rajendra Gadhwal

THESIS SUBMITTED IN THE PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF DEGREE OF

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Date:

Place: Varanasi (Rajendra Gadhwal)

Contents

List of Symbols and Abbreviations

%	Percent
/	Per
AF	Agroforestry
C.D.	Critical Difference
Ca	Calcium
cm	Centimetre
d.f.	Degree of freedom
dSm^{-1}	Deci siemen per meter
EC	Electrical Conductivity
et al.	And others
Fig.	Figure
g	Gram
ha	Hectare
HWC	Hot Water Soluble Carbon
HWCh	Hot Water Soluble Carbohydrate
i.e.	Id est (that is)
K	Potassium
kg	Kilogram
MBC	Microbial Biomass Carbon
M	Meter
mg	Milligram
mha	Million hectare
mL	Milliliter
MT	million tons
N	Nitrogen
No.	Number
^{o}C	Degree centigrade
OC	Organic Carbon
pH	Puissance de Hydrogen
P	Phosphorus
ppm	Parts per million
Q	Quintal
RBD	Randomized Block Design
S	Sulphur
TOC	Total Organic Carbon
Viz.	namely

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Chapter I

Introduction

The arid zone of India covers about 12% of the country's total geographical area (TGA). A total of 32 million ha is hot arid and is spread over parts of Rajasthan (61%), Gujarat (20%), Andhra Pradesh and Karnataka (10%), and Punjab and Haryana (9%). The additional 7 million ha is cold and arid, situated in the Ladakh area of Jammu and Kashmir and the Lahul Spiti area of Himachal Pradesh. The area under desert in India is about 3.5 times the combined area of Punjab and Haryana. Nearly 20 million people live in the Indian desert which is about twice the total population of Haryana. Besides the human population, the cattle population is also quite large i.e. 23 million (Sharma *et al.,* 2013).

The Thar Desert (Great Indian Desert) is a large arid region in the north-western part of the Indian subcontinent that covers an area of 200,000 km^2 (20 million ha) and forms a natural boundary between India and Pakistan. About 85% of the Thar Desert is located within India and remaining 15% in Pakistan (Sinha *et al.,* 1996). The problem of desert control becomes extremely complex and challenging because the technology evolved has to be introduced and implemented effectively in such a manner that it not only sustains but also improves large human and cattle population. Moreover apart from its social and economic importance, the desert has direct and indirect influences on the entire country. An assessment has revealed that Rajasthan is the only state among nine falling within the major arid regions of the country where the degraded land area has registered a decrease over the years.

The hot arid region is characterized mainly by scarce natural resources with an inhospitable climate. Rainfall varies from less than 100 mm to 400 mm, and is highly erratic and unpredictable. The region experiences extremes of temperature (−2 to 48ºC), long day sunshine, high wind speed (35–40 km/h) and thus very high evaporation. Nearly 41–85% of ground water is saline (8–60 ppt). Pearl millet, cluster bean, moth bean, mung bean, gingelly (sesame), and mustard are major crops grown under rain-fed conditions or with limited irrigation. Rain-water is the critical input in determining productivity in all these areas, but the inability to manage erratic and deficit rain-water through proper harvesting methods has always been a constraint in upgrading productivity. Soils are highly deficient in major and a few minor/micro nutrients. The erosion of top soil by wind is a wide spread problem. Livestock is the major source of survival of the people because cropping is not a secure and definite proposal (Behera *et al.*, 2016).

Agroforestry (AF) is the growing of multipurpose trees along with agricultural crops or trees and pastures within the same field. It is one of the key paths towards the prosperity of poor people suffering from hunger, malnutrition, extreme poverty and deterioration of the environment in the areas that have been bypassed by the Green revolution. The United Nations Framework Convention on Climate Change (UNFCCC) defined 'carbon sequestration' as 'the process of removing C from the atmosphere and depositing it in a reservoir'. It indicates the transfer of atmospheric CO_2, and its storage in long-lived pools (Nair, 2011). From the agroforestry point of view, C sequestration basically involves the fixation of atmospheric CO2 during photosynthesis and the transfer of the fixed C into vegetation and soil pools for "long-term" (i.e. secure) storage (Nair *et al*. 2010). Agroforestry (AF) is believed to increase the soil organic carbon (SOC) through litter fall, check soil erosion, increase land productivity and diverse the farm income. However, these systems have not yet been fully considered in the approach to C accounting developed by the Intergovernmental Panel on Climate Change, largely due to the high diversity of agroforestry systems and scarcity of relevant data (Nair, 2011).

Presence of trees within a landscape affects its hydrological characteristics, just as deforestation increases the run-off. Agroforestry is thus the most feasible option to tackle land degradation and to bring about eco-restoration and also to sustain soil resources (Gupta *et al.*, 2009). To gain maximum benefit from agroforestry system, it is essential to minimize the negative concerns linked to it viz. competition of trees with crops for resources, allelopathic effects of trees on crops, rapid growth of some tree species within agricultural fields occupying the space of crops, entry of invasive species in the agricultural land, and trees serving as habitat for harmful pests and diseases. The positive results can, however, be obtained if positive interactions of agroforestry outweigh the negative interactions (Gupta *et al.*, 2009).

Trees generally have their roots well below the crop zone, use water from the lower soil layers, and thus do not affect crop. Rather, tree roots act as safety nets and capture the nutrients that are lost because of leaching. Incorporation of trees in the croplands can help in maintaining the nutrient pool and enhance soil fertility both under sequential and simultaneous agroforestry (Noordwijk *et al*. 2015). Tree litter and prunings improve soil fertility not only through the release of nutrients in the soil by mineralization but also by adding soil organic matter. However, it depends upon the quality and quantity of tree litter or prunings, soil type and climatic conditions of the area and increasing activity of microorganisms in the root zone (Gupta *et al.*, 2009).

Agroforestry system has a great scope in sequestering the above-ground biomassand below-ground soil carbon and helps in mitigating the greenhouse effect by reducing carbon emissions (Nair *et al.*, 2009). Carbon can be sequestered in the mineral soil after the conversion of intensively cropped agricultural fields to more extensive land uses such as afforested ecosystems. Understanding the agroforestry systems that involve greater diversity and complexity has become a research interest worldwide posing fundamental questions like carbon sequestration (Nair et al., 2009). Swamy and Puri (2005) observed 3.5 Mg ha-1 more C under *Gmelinaarborea* than agri-silviculture system after 5 years of study. Forest plantation may sequester SOC especially in cases of establishment on cultivated lands where SOC has been depleted (Ram *et al.*, 2016).

Carbon sequestration occurs in two major segments of the AFS: aboveground biomass and belowground biomass. Each of them can be grouped into sub-segments: the aboveground into specific plant parts (i.e. stem, leaves, etc., of herbaceous and tree components), and the belowground into living biomass such as roots and other plant parts, soil organisms, and C stored in various soil layers (horizons). The total amount of carbon sequestered in each segment differs greatly depending on a number of factors, including the ecoregion, site quality, type of system (and the nature of components and age of perennials such as trees), and previous land use. On an average, the aboveground parts and the soil components (including roots and other living biomass) are estimated to hold roughly one-thirds and two-thirds, respectively, of the total amount of C stored in tree-based land use systems. Based on the belief that tree incorporation in croplands and pastures would result in a greater net C storage both above- and belowground, AFSs are believed to have a higher potential to sequester C than field crops or pastures growing under alike ecological conditions (Nair et al., 2010).

Besides the advantages of agroforestry mentioned above, there are some disadvantages also with using agroforestry viz. allelopathic effects of trees on crops, shading effect on crops, trees harbour birds, pests and diseases, and pose hindrance in mechanical operations. But the advantages outweigh the disadvantages and, therefore, the present study was intended to work on agroforestry systems, to study carbon sequestration and to help improve the livelihood of people living in these arid zones. Hence the thesis entitled **Carbon sequestration potential of tree based agroforestry systems in the arid region of India** was undertaken with the following objectives:

1. To evaluate the carbon sequestration potential of a long term tree based agroforestry systems
2. To evaluate changes in carbon pools and enzyme activities
3. To evaluate change in available nutrients
4. To evaluate the effect of agroforestry system on yield of intercrops.

Chapter II

Review of Literature

2.1 Introduction

It has been a practice to cultivate agricultural crops and tree species in intimate association throughout the world. **King (1968)** found that in the Europe, it was the general trend to clear-cut forest, burn the slash followed by cultivating food crops for different periods of time on the cleared lands, and to plant trees before, along, or after sowing of the agricultural crops. **Wilken (1977)** found that in America, many of the societies have conventionally simulated forest conditions on their farms to obtain the advantageous effects of forest structures. **Conklin (1953)** saw the Hanunoo of Philippines, in Asia practised a complex but somewhat sophisticated form of shifting cultivation. While clearing the forests for agricultural use, they knowingly left some selected trees which would provide a partial canopy-cover of fresh foliage by the end of growing season to avert excessive exposure to the sun at the time when moisture is of greater importance than that of sunlight for maturing grain.

These examples show the wide geographical coverage of the system, and its early origins. Tree cultivation was an integral part of the farming system. The ultimate aim was not the tree production instead it was food production.

An attempt has been made in this chapter to compile the information available on ***'Carbon sequestration potential of tree based agroforestry systems in the arid region of India'.*** The literature has been viewed under the following heads.

2.2 Agroforestry Systems

As per **Cardinael *et al.* (2020)** agroforestry systems include trees and crops, or trees and pastures in the same area. They cover around 1 billion hectares of land globally and significantly contribute to the livelihoods of over 900 million people. Agroforestry systems have the capability of sequestrating large quantities of carbon in both soil and biomass (plants). These systems, however, have not yet been fully considered in the C accounting approach developed by the IPCC, largely due to the greater diversity of agroforestry systems and scarcity of appropriate data.

Ramachandran Nair *et al.* (2009) explored that agroforestry has been recognised worldwide, over the last three decades, as an integrated approach for sustainable land-use because of its environmental benefits and economic production. It has recently been recognised as GHG (greenhouse gas) mitigation strategy under Kyoto Protocol hence earned attention as a stratagem for biological C sequestration. The principal behind is that greater efficiency of integrated system in utilization of limited resources (water, nutrients and sunlight) than the single species system will result in greater C sequestration.

Lal, 2004 investigated that global dry-land soils occupy a vast area with a wide range of land uses and habitats and ecosystems. There is a severe issue of desertification or dry-land destruction possibly caused by land waste, soil mismanagement and harsh climate. Historical depletion of SOC due to desertification and deterioration for a total pool of 241 Pg (1 Pg = 10^{15} gram) is estimated at 20 to 30 Pg. Of the historical depletion, 12–20 Pg (approximately two-thirds) can be re-sequestered by restoring desertified soils and habitats. The mean sequestration potential for SOC is about 1 Pg C / year, through afforestation with Mesquite, Acacia, Neem etc., and the adoption of RMPs (recommended management practices) on cropland and grazing land.

Gupta *et al.* (2019) reported that agroforestry is one of the most promising options for mitigating climate change through carbon sequestration. Carbon sequestered in agroforestry systems, however, depends on various factors, such as type of tree species, tree density, and age of the system, soil, and climate. Tree density is one of the most important factors for increasing the carbon sequestration per unit land area. *Hardwickia binata* has been reported as an appropriate species of agroforestry tree with multiple advantages in arid and semi-arid regions, but the role and impact of tree density in carbon sequestration is poorly reported.

As per **FSI 2017** a large number of agroforestry systems of various types and forms exist in India, just as great diversity in climate. Since the exact assessment of area under various agroforestry systems is quite difficult. However, the area under agroforestry in India, as reported by **Dhyani *et al.*, 2013; Dagar *et al.*, 2014 and CAFRI 2015**, is estimated as 25.31 m ha (million hectares) or 8.2% of TGA of country. Among the states, Maharashtra, Gujarat and Rajasthan are leading states regarding total agroforestry area.

Agroforestry opportunities in India: Indian agroforestry systems include traditional as well as modern land use systems and provides employment to rural and urban populace

through production, and processing and value addition. As per an estimation, 1 hectare of plantation in wood - based industries can create nearly 450 man days employment, hence a 30 million hectares plantation has the potential to create nearly 15000 million man days employment (**Singh and Dhyani, 2014**).

As per FSI-2017 (**Forest Survey of India-2017**), the current area under forest and tree cover in India is 79.42 m ha (million hectares) which is nearly 24.39% of TGA but as per National Forest Policy - 1988 at least 33 percent of country's area should be under forest and tree cover. To fill up this gap of 9.00 %, large scale afforestation and reforestation are urgently needed but at the same time it seems to be tough task for developing countries, say India. However, agroforestry is the viable option to achieve the target i.e. 33 percent area of country under forest and tree cover.

As per **CAFRI (2015)**, there is scope of increasing area under agroforestry by 2050 by another 28 million hectares, hence a total of 53.23 million hectares (17.5% of reported area of country) under agroforestry. Looking at the current scenario, land holding's size of farmers is decreasing at a very fast rate and agroforestry seems to be only trustworthy option to augment farm productivity (**National Forest Policy - 2014**). Gross productivity in agroforestry is higher in comparison to mono-cropping which gives higher financial returns to farmers.

A comprehensive study conducted by **Chavan *et al.* (2015)** reveals economic viability of agroforestry with a B:C ratio ranging from 1.01 to 4.17 and internal rate of return between 25 to 68 for 24 AF systems from various agro-climatic regions of the country. Agroforestry activities can thus be an effective tool for achieving sustainable growth of 4 per cent in agriculture (**National Agroforestry Policy, 2014**).

It is noteworthy that, as stated by the IPCC, agroforestry is one of the essential tools for combating climate change and building farmers' resilience to climate change threats and natural calamities because agroforestry provides services such as moderating microclimate, conserving biodiversity, carbon sequestration, protection of water resources, soil erosion and soil pollution (**Chavon *et al.* 2015**).

Future of Agroforestry in India: Agroforestry is likely to play a major role in the future, not only because of its significance in food and livelihood security but also because of its role in addressing environmental challenges, because the land area of the country cannot be expanded. As per **CAFRI**`s estimate (**2015**), fodder requirement will increase by 1.5 times;

food grain and fuel wood requirement will double; and timber requirement will triple by 2050 as shown in table-2.1.

Table-2.1: Total domestic demand for various commodities and agroforestry contribution in 2050 (CAFRI-2015).

Items	2010-11	Projected for 2050	Contribution from agroforestry in 2050
Food grains (million t)	218.20	457.10	41.14*
Fruits (million t)	71.20	305.30	47.74*
Fodder (million t)	1061.00	1545.00	154.50
Fule wood (million t)	308.00	629.00	308.00
Timber (million t)	120.00	347.00	295.00
Biodiesel required (million t) for 20 blending of diesel	12.94	37.92	30.34
Area (million hectares) required for TBOS	12.32	21.67	17.34
Agroforestry (million hectares)	25.32	53.32	

* Food grains/fruits production from systematic agroforestry systems viz. agri-silviculture or agri-horticulture only considered.

Courtesy: Sharma, Prashant *et al.* (2017)

Nair *et al.* (2009) believed that agroforestry systems which integrate tree production with crop and animal production systems have higher potential for sequester C than pastures or field crops. This presumption is based on the notion that higher net C sequestration above ground as well as underground would benefit from tree integration into croplands and pastures. Since some estimates of the agroforestry systems' so-called "C-sequestration potential" are available, these are mostly stock estimates of C and, overall, the data are not rigorous. Methodological difficulties in estimating C stock of biomass and the level of soil C storage under various conditions and the lack of accurate estimations of area under agroforestry systems are significant constraints in exploiting these low-cost environmental benefits of agroforestry. Globally, C trade is expanding rapidly, and the CDM under Kyoto Protocol provides an attractive economic incentive for subsistence farmers in developing countries, the main agroforestry practitioners, to sell the C sequestered to developed countries through agroforestry activities. It would also be an economic advantage for the global community at large. The political environment is also advantageous for improving smallholder participation in GHG mitigation projects. Success in implementing these projects would depend on the enthusiasm of the farmers to take part in the project.

Pandey, D. (2002) explored that Asia, South America and Africa provide incentives for carbon sequestration by agroforestry and forest management activities at the local level. The next obvious move is specific global policies and programs to maintain existing agroforestry carbon pool, expansion and productivity enhancement of existing pool, development of new pool, and long-term carbon lock-up in wood products. Local forest management activities need to be promoted through the implementation of effective policies, accompanied by comprehensive country-wide scientific studies aimed at better understanding agroforestry's potential for climate change mitigation and human welfare.

In Patagonia in Chile, **Jose & Bardhan (2012**) investigated the carbon (C) sequestration capacity of three predominant ecosystems: pine plantations (PPP), *Pinus ponderosa*-based silvo-pastoral systems (SPS) and natural pasture (PST). Silvo-pastoral systems are highly efficient in increasing productivity for both plants and animals because in a properly managed silvo-pastoral system, mutually optimal conditions for growth and development are established. Plants benefit from introducing manure in the system and partial shade from the canopy by nutrient cycling, while animals enjoy optimal temperature and humidity under the canopy of the tree. They observed that silvo-pastoral system have higher aboveground and belowground C (in trees), and soil organic C stock in comparison to the other systems.

A similar study was performed by **Ermson *et al.*** from 2006 to 2010 in the south-eastern United States where they observed the impact of grazing and forage enhancement on total soil Carbon (TSC), soil N, and P dynamics in goat (*Capra hircus*) - loblolly pine (*Pinus taeda* L.) silvo-pastural system in Alabama. However, silvo-pasture plots were characterized in this study by low initial pH, low TSC, and N and P deficiencies in the soils. In June 2010, four (4) years after tree thinning and three (3) years of grazing, the silvo-pasture treatment still exhibited low soil pH (<6) and TSC levels below 20 g / kg. The authors hypothesized that in the long run, grazing without additional soil management practices could still increase soil fertility by recycling nutrients and sequestration of Carbon and thus make the goat-loblolly silvo-pasture system sustainable both environmentally and economically. (**Jose & Bardhan, 2012**).

Agroforestry provides a cost-effective mitigation option available in developing countries such as India and China, which have great potential for carbon sequestering and providing people with products and services. The estimated mitigation cost through

agroforestry varies from US$ 1.6 per tonne of carbon in India to US$ 16.3 per tonne of carbon in China. It should be noted that such estimates do not include land`s opportunity costs, costs of management of a complex system, rising wage rates tropical region, etc. Taking all these factors into consideration, the private cost of carbon sequestration could be as high as US$ 100 per tonne of C. However, compared to energy alternative (renewable energy, energy saving and efficiency, and fuel switch) tree-growing is still a cost-effective option because of the secondary social and environmental benefits. Costs vary for different regions within the forestry sector- the most expensive in developed countries, and the least expensive in developing countries (**Pandey, D., 2002**).

Agroforestry as a better GHG mitigation option than oceanic, and other terrestrial options: If the oceans were fertilized by adding large quantities of iron, huge amounts of CO_2 could be removed from the atmosphere by the consequent increase in phytoplankton bloom. Efforts in that direction, however, might not be viable either through iron fertilization programs (**Chisholm *et al.*, 2001**), or through CO_2 injection into the deep sea as it may affect the marine biota in ways that science is not currently knowing about. Studies on how such a deep-sea disposal of CO2 can affect organisms living in these environments warns that even small disturbances in CO_2 or pH can have significant consequences for deep-sea ecosystems and global biogeochemical cycles (**Seibel and Walsh, 2001**). It would be extremely difficult to validate iron fertilization and would significantly alter oceanic food webs and biogeochemical cycles (**Chisholm *et al.*, 2001**).

The agroforestry emerges as an important mitigation option pending detailed studies on this aspect. The benefits of carbon sequestration can be further maximized by linking the bioenergy options to CDM (**Hall *et al.*, 1991; Schlamadinger *et al.*, 2001**). An important component of the Kyoto Protocol shall be activities which reduce dependence on fossil fuels by means of product substitution (**Pandey, D., 2002**).

2.3 Intercrops in Agroforestry System

India launched its National Agroforestry Policy on 10th of February 2014, with the promise to dramatically reduce rural India's poverty and repair the wood-based sector, in addition to combining food production with environmental services. This strategy is critical not only to India's ambitious target of achieving 33% forest and tree cover, but also to reduce agricultural GHG emissions.

A study conducted by **Ajit *et al.* (2016)** wherein they used dynamic CO2FIXv3.1 model for estimation of carbon sequestration potential of their existing agroforestry systems for a simulation period of 30 years in 26 districts from 10 selected states of India. The number of trees found in these districts on the farmers' fields ranged from 1.81 to 204 per hectare with an average value of 19.44 trees per hectare. The tree component biomass ranged from 0.58 to 48.50 Mg DM (dry matter) ha^{-1}, while the total biomass (tree and crop) ranged from 4.96 to 58.96 Mg DM ha^{-1}. The organic carbon in the soil varied from 4.28 to 24.13 Mg C ha^{-1}. The AFS's approximate average carbon sequestration capacity, reflecting differing edapho-climatic conditions, was 0.21 Mg C $ha^{-1}yr^{-1}$ on farmers' field at country level. At national level, current AFS is expected to decrease CO_2 emissions by 109.34 million tonnes $year^{-1}$, which will cover one-third (33 %) of total agricultural GHG emissions. An approximate average value of 0.21 Mg $ha^{-1}yr^{-1}$ carbon sequestration capacity of the agroforestry systems (AFS) was reported at country level equal to 0.77 Mg $ha^{-1}yr^{-1}$ CO_2 mitigation. Considering the reported GHG emissions from the agricultural sector as 334.41 million tonnes of CO_2 equivalent in India (**Indian Network for Climate Change Assessment Report - 2010, Govt. of India**), the AFS on farmers' fields is estimated to offset one-third (33%) of total agricultural GHG emissions annually and more than 6% of total country-level GHG emissions. Estimation of the potential for GHG reduction from established cropland trees (excluding the recorded forest cover) by agroforestry systems at Indian country level was not available yet.

2.4 Changes in soil properties as a Result of Agroforestry

2.4.1 Carbon Sequestration

Soil plays a major role in sequestration of C, being able to contain 1.5 to 3.0 times more carbon than in vegetation itself. The amount of C sequestered in the soil depends on a large range of factors, including area, site quality, current land-use, earlier land-use, and soil profile portion in the event of land-use changes **(Nair *et al.*, 2010)**. Soil is typically 60% of the total C contained in tree-based land-use structures **(Lal 2004d; Lorenz and Lal 2005; Lal 2007; Nair *et al.* 2010)**. Soil C sequestration takes place in two ways: (1) direct fixation of atmospheric CO_2, which converts CO_2 into soil-inorganic C (SIC) compounds, (2) and indirect fixation of atmospheric CO_2, in which atmospheric CO_2 is absorbed into the plant tissue via the photosynthetic processes, and consequently, part of plant biomass is indirectly sequestered as SOC through decomposition processes **(Burras *et al.*, 2001)**. Globally, the overall soil C

pool was measured at 2157 to 2296 Pg, of which 1462 - 1548 Pg is organic soil C (SOC), and 659 - 748 Pg is inorganic soil C (SIC) **(Batjes 1996)**. The overall soil C pool is nearly three times the average atmospheric C pool, and 3.8 times the vegetation C pool **(Lal 2004b; Nair *et al.* 2010)**; hence any change in the soil carbon pool will have a substantial effect on the global C budget. Among land use, agriculture and degraded soil have a promising potential for sequestration of C. These soils have been drained from a large portion of their initial organic C reservoir and the introduction of new management strategies, such as trees and permanent vegetation, may dramatically improve their potential for carbon sequestration **(De Stefano *et al.*, 2017).**

Labile fractions of soil organic C are considered essential soil quality measures as these can react rapidly to changes in land use and farm management. **Benbi *et al.* (2012)** conducted an experiment comparing three land use systems say 1. rice-wheat, 2. maize-wheat, and 3. agroforestry. The maize-wheat and agroforestry systems had SOC stocks 65 - 88 per cent higher than the rice-wheat system and predominantly labile C was characterized. Approximately 56 - 60 percent of total organic C existed as labile and very labile C in maize-wheat and agroforestry systems, compared to 37 percent in rice-wheat system. In contrary to this, the bulk of organic C (63 %) in rice-wheat soils in less labile and recalcitrant forms is stabilized. For maize-wheat and agroforestry systems the HWC and MBC were both higher relative to the rice-wheat system **(Benbi *et al.*, 2012)**.

In another study, **Maia *et al.* (2007)** also compared different systems of land use or different treatments. The treatments used were as follows: traditional agroforestry (TRAG), agrosilvopasture (AGP), silvopasture (SILV), intensive cropping (IC) and native forest (NF). Their study found that there was a significant deterioration in soil quality under those treatments that encouraged more intense soil disruption, such as AGP, TRAG, and IC, which was primarily shown by reductions in the labile C pools. Soil mobilization also encouraged improvements in the humic compounds in the AGP and IC therapies, implying a deterioration of the HUM portion, suggesting a strong degradation of the soil surroundings. Thus the silvopasture method (SILV) has preserved and in some cases strengthened the position of the organic carbon pools among all the treatments assessed.

As per estimation of **Lorenz and Lal (2014)**, in agroforestry systems, up to 2.2 Pg C (1 Pg=10^{15} g) can be sequestered above and below ground over 50 years, but estimates of global land area occupied by agroforestry systems are particularly uncertain. Areas at global level

under tree intercropping, silvopasture, protective systems, multistrata systems, and tree woodlots were estimated at 700, 450, 300, 100 and 50 Mha, respectively. Storage of SOCs in agroforestry systems is still unknown and may be as high as 300 Mg C ha^{-1} to a 1.00 m depth.

Global anthropogenic carbon dioxide (CO_2) emissions to the atmosphere rose to around 9.7 Pg carbon (C) (1Pg=10^{15} g) in 2012 primarily due to increased burning of fossil fuels (**Peters *et al.*, 2013**). Not all released CO_2 accumulates in the atmosphere, though, as land-based sinks suck up large volumes, i.e. about 28% of anthropogenic CO_2 emissions were taken up on average between 2002 and 2011 **(Peters *et al.*, 2012)**.

More effective control of the flows of carbon (C) in agricultural environments will reduce anthropogenic CO_2 emissions in particular (**Smith *et al.*, 2008**). Reducing the C footprint of agriculture is therefore key to curbing climate change (**Vermeulen *et al.*, 2012**). In particular, certain agroforestry systems have received increased attention due to their capacity to trap atmospheric CO_2 and store C in plants and soil (**Nair, 2012a**) regarding their net C sequestration effect (**Lorenz and Lal, 2014**).

Effects of trees on soil organic carbon: The trees have large root systems that can deeply expand into the mineral soil. The root-derived C supplies are vital sources to deeper soil horizons for the SOC pool (**Kell, 2012**). In fact, root-derived C is more likely to be preserved in soil by physicochemical interactions with soil particles compared to shoot-derived C (**Rasse *et al.*, 2005**). For eg, European beech's (*Fagus sylvatica* L.) relative root contribution to SOC was 1.55 times that of shoots (**Scheu and Schauermann, 1994**).

Similarly, overall root-derived C added to SOC from 1.5 times and more than 3 times more than shoot-derived C in croplands (**Johnson *et al.*, 2006**). Therefore, agroforestry systems store more C in deeper layers of soil around trees than they do away from trees (**Nair *et al.*, 2010**). Quantitative knowledge about inputs in agroforestry structures below ground C is, however, scanty. Other explanation for encouraging SOC sequestration in agroforestry systems apart from deep soil C inputs is that tree roots have the ability to recover nutrients from below the crop rooting zone. The resulting enhanced growth of the tree and crop plants by subsequent nutritional increase in nitrogen (N) may contribute to an increase in sequestration of SOCs (**van Noordwijketal, 1996**). Similar mixed plantings with Nitrogen fixing trees may result in higher production of biomass and, therefore, SOC sequestration and pools, particularly in deeper soil horizons as N may promote humification rather than decay, but the interactions between SOC and N are not fully understood (**Gärdenäs *et al.*, 2011; Nair *et al.*, 2009a**). Changes in

population composition of microbial decomposers under N-fixing trees may also contribute to greater preservation of fairly stable SOCs (**Resh *et al.*, 2002**). Due to partitioning of niches, N-fixing trees in mixtures with non-fixing trees that grow deeper root profiles (**da Silva *et al.* 2009**). The old agroforestry method of achieving optimum agronomic benefits by greater resource productivity, i.e., nutrients, light and water capture and reuse, has recently gained increased exposure due to the potential contribution of SOC sequestration to climate change mitigation. The addition of trees, i.e. N-fixing, may directly increase the conservation of SOCs in agroforestry systems. In addition to the advantages of environment, agroforestry will also provide advantages for rural growth. However, observed SOC sequestration rates are particularly highly variable and only a very limited number of field experiments have been specifically designed to rigorously test the effects of agroforestry practices on SOC. Not before SOC sequestration processes in soil profiles are not understood well earlier can land use and soil management practices be recommended for site - specific SOC sequestration in agroforestry systems. (**Lorenz and Lal, 2014**).

The study of **Gupta *et al.*, (2019)** found that tree density had a significant effect on carbon sequestration in the agroforestry system. In an individual tree, a system with high tree density had less C-accumulation compared to a low density system; but, in a high density tree system, overall carbon sequestered per hectare area was slightly higher. Tree spacing was also reported to affect intercrop yield as well as tree yield due to competition and shade effect which increases with system age. Therefore, to get optimal benefits in terms of carbon sequestration, intercrop and tree yield, determination of optimum tree density is important. In this study, developed old agroforestry systems with varying tree densities provide a good platform for determining carbon sequestration capacity along with identifying better tree density for mitigating and adapting climate change. *Hardwickia binata* Roxb. based high-density agroforestry system (666 tree ha^{-1}) was found to be suitable in this study to improve carbon sequestration per hectare over low-density system and single cropland. This system has a capacity to sequester about 116.1 ± 46.2 Mg CO_2 ha^{-1} in biomass with a survival rate of 58 % in 30 years.

In a similar experiment, by **Gupta *et al.* (2009)**, poplar-based agroforestry system found to increase soil accumulation of C in the form of leaf biomass by way of large volumes of organic matter. The age of the poplar trees and the type of soil influenced the degree of the change. The average soil organic carbon rose in agroforestry soils to 0.66 % from 0.36 percent in sole crop. In loamy sand, the rise was larger than in sandy clay. With an increase in tree age

the soil organic carbon also increased. Under agroforestry, the soils had 2.9 - 4.8 Mg ha^{-1} higher organic soil carbon than in single crops. During the first year of their planting (6.07 Mg ha^{-1} $year^{-1}$) the poplar trees could sequester higher soil organic carbon in 0–30 cm of profile than the following years (1.95 - 2.63 Mg ha^{-1} $year^{-1}$). The sandy clay may be higher carbon sequester (2.85 Mg ha^{-1} $year^{-1}$) than in loamy sand (2.32 Mg ha^{-1} $year^{-1}$) (**Gupta *et al.*, 2009**). Fig. 2.1 represents various carbon sinks and sources in a field windbreak.

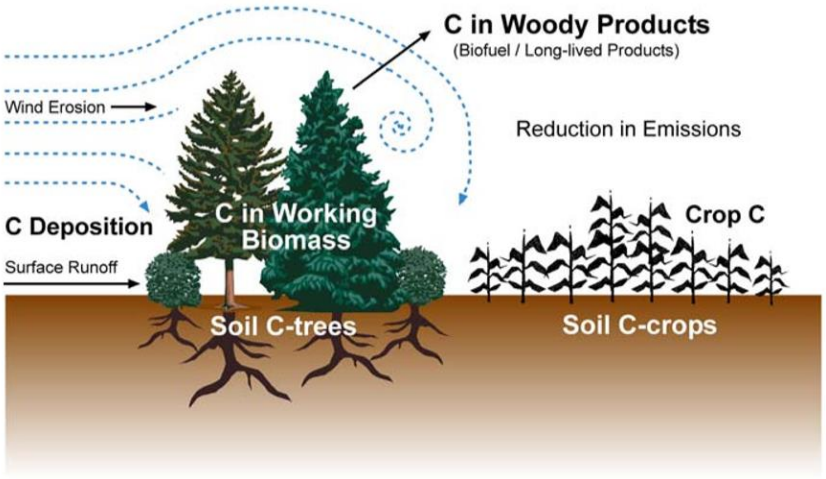


Fig-2.1: Various carbon sinks and sources in a field windbreak.

Courtesy: Schoeneberger, M. (2009)

Chiemela *et al.* (2018) observed that a change from degraded and intensively cultivated land to smallholder AF (agroforestry) systems resulted in major increase in C stock. Various forms of LULC identified in the study area were bushland (BL), shrubland (SL), intensively cultivated soil (C1), moderately cultivated soil (C2), sparsely cultivated soil (C3), bare soil and rock-out crops (BarL / RoC) and waterway / body (WC/B). The stock of C in different C reservoirs has the ability to decrease the amount of atmospheric CO_2 enrichment. They found that the C3 had the highest vegetation carbon, and C1 had the lowest volume of vegetation and soil carbon. In BL, the highest soil C has been observed. Nevertheless, the overall volume of C sequestered relied primarily on the height of the LU, type of tree, and composition of the vegetation. They concluded that the LULCC to the AF systems considerably improved the study area's vegetation and soil C. Positive changes in LULC type demonstrated the potential of agroforestry systems to offer C-sequestration and C-trading environmental services. The

reflectance of the sampled parcels showed to rely on the greenness of an area regardless of the composition of the vegetation. Although NDVI (Normalised Difference Vegetation Index) and SAVI (Soil Adjusted Vegetation Index) could not explain nicely the vegetation C, whereas soil C and total C showed a relatively higher linear relationship with vegetation indices. This result offers valuable and practical knowledge in the application of remote sensing data to accounting for C for further study.

Jose and Bardhan (2012) studied three papers that include new insights on sequestration of soil C and its interrelation with decomposition of organic matter and regeneration of nutrients. First paper by Kim explored how an intercropping system with a nitrogen (N)-fixing tree (*Gliricidia*) and maize could help alleviate climate change by increased sequestration of soil C in sub-Saharan Africa while resolving soil GHG emissions. Using data from **Makumba *et al.* (2007)**, the author calculated that, within the first seven years of intercropping, 67.4 percent of sequestered soil C (76 Mg C / ha at 0 to 2 m soil depth) was lost as CO_2 from system. Sequestered and lost soil C has reported an annual net gain of 3.5 Mg C / ha / year. **Jose and Bardhan (2012)** also found that if N_2O emissions were also decreased, the total mitigation gain achieved from the intercropping program will be larger. These findings indicate that measurements and simulations of CO_2, N_2O and CH_4 emissions should be taken into account when calculating C sequestration in agroforestry systems. In Benin, West Africa, Gaiser *et al.* tested *Leucaena* (*Leucaena leucocephala*) (L), *Senna siamea* (S), and maize (M) residue addition for aggregation of soil organic matter under sub - humid tropical conditions. A cumulative volume of 30 Mg / ha of dry matter was added within 18 months on *Imperata cylindrica* (I) dominated grass fallow. Changes were found in the light and heavy soil organic C fraction [LF (light fraction) and HF (heavy fraction)] and the overall soil organic C volume (LF + HF) in the topsoil. Both organic products greatly improved the proportion of the LF fraction in the soil. The increase in HF, depending on the source of organic content, was 39 - 51 % of the rise in overall organic C. The ability of the organic materials tested to increase overall organic C content of soil (including all organic C fractions of soil) was in the order L > S > M > I, while the order of the HF fraction was L = S > I > M. The transformation efficiency ranking of applied plant residues into the fraction of the heavy organic soil C was I > L = S > M. The amount of transformation of residues could not be explained by lignin or lignin to N ratio, but rather explained by extractable polyphenols. The findings demonstrate that deposition of the heavy fraction in tropical soils is feasible by adding large amounts of plant residues, but is highly dependent on the nature of the added organic matter. Zaia *et al.* evaluated the effect

of plant litter accumulation on soil C, N, P and microbial biomass in cacao agroforestry systems in Bahia, Brazil. They researched five agroforestry systems under two different soils (Oxisol and Inceptisol) of different ages for cacao. Overall, the average stocks of organic C, total N and total organic P were 89072, 8838 and 790 kg / ha, respectively, for 0–50 cm soil depth. At this depth of soil the average labile organic P stock was 55.5 kg / ha. Microbial biomass, with a mean of 286 kg / ha of microbial biomass C, 168 kg / ha of microbial biomass N and 79 kg / ha of mineralizable N, was mainly dominated in the 0–10 cm soil range. In comparison to the N dynamics, the dynamics of organic P in these cacao agroforestry systems have not been directly related with organic C dynamics in soils (**Jose and Bardhan, 2012**).

After the Kyoto Protocol, agroforestry has been attracting more interest from both developed and developing nations as a tool to sequester C. The available estimates of C stored in agroforestry range from 0.29 to 15.21 Mg C ha^{-1} $year^{-1}$ above ground, and from 30–300 Mg C ha^{-1} up to 1 m deep in soil (**Nair *et al.* 2010**). Since the industrial revolution, atmospheric CO_2 has increased by more than 40 percent , from 280 ppm in 1,750 to about 392 ppm in 2012 and at the current rate it is expected to surpass 400 ppm by 2015 (**Hutchinson *et al.* 2007; Tans 2012**). From 2010 to 2012, CO_2 emissions rose in the three years at an alarming rate of 2 ppm per year, or 4.4 Pg C $year^{-1}$. While agroforestry has been recognised as having the greatest capacity for C sequestration (Fig-2.2) of all land uses examined in the IPCC's Land-Use, Land-Use Transition and Forestry Survey (2000), our interpretation of C sequestration in particular agroforestry activities from around the world is at best limited (**Jose and Bardhan, 2012**). Fig-2.2 is representing carbon sequestration potential of different land use systems by 2040 (**adapted from IPCC-2000**).

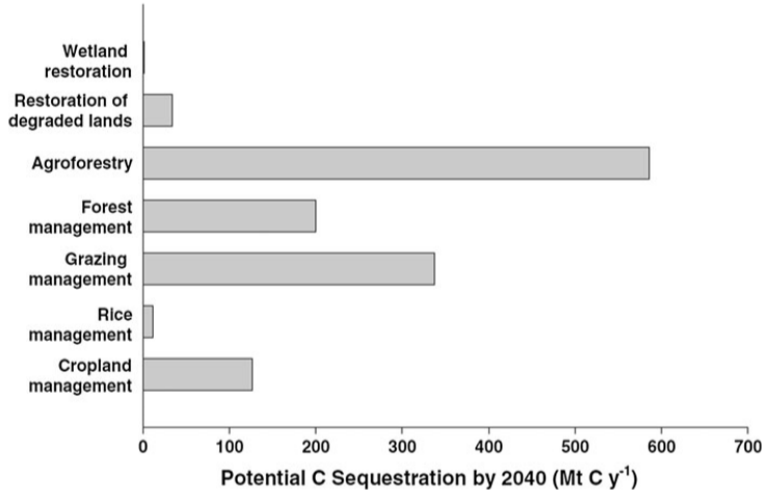


Fig-2.2: Carbon sequestration potential of different land use systems by 2040 (adapted from IPCC-2000)

For developing carbon sequestration equations, the ways must also be considered through which the biomass of managed plots is used. If used for wood, over an additional period of five years or more than that, approximately 25 per cent of the carbon from the system can be considered sequestered. With the concept of "carbon credits" that is being paid by fossil fuel emitters to projects that can sequester or reduce carbon output becoming more common as many nations and organizations are seeking to find inventive ways to sequester carbon. The clearing of primary forest releases more carbon than natural growth or fast-growing plantations could recover in 25 or more years. Protection of primary forest should, therefore, be important when looking at ways to reduce tropical carbon emissions. The most important role that agroforestry and plantations can play is in offsetting primary forest destruction by supplying the requisite wood products from the already cleared land. Total carbon accumulation in semiarid, sub-tropical, tropical, and temperate regions was measured at 9, 21, 50, and 63 Mg C per ha by agroforestry activities. Potential Carbon sequestration levels for smallholder agroforestry systems in the tropics vary from 1.5 to 3.5 Mg C ha^{-1} yr^{-1}. In addition to that, agroforestry may have an indirect influence on C sequestration as it helps to minimize the pressure on natural forests, which are the largest sink of terrestrial C. Agroforestry systems with seasonal crops can be essential sinks of carbon whereas intensively controlled agroforestry systems with annual crops are more close to traditional farming. To harness this massively unrealized capacity of sequestration of C by agroforestry in both subsistence and commercial enterprises in the tropics and temperate zone, revolutionary policies must be placed in motion, based on robust research findings (**Montagnini and Nair, 2004**).

Using bio-economic optimization models of two regions of Western Australia farming systems, **Flugge & Abadi (2006)** saw that higher sequestration levels made carbon farming more competitive in the Great Southern region of medium rainfall than in the Eastern Wheat-belt region of low rainfall. Thus, carbon farming in the Great Southern farm became an ideal land use choice at lower carbon prices than was the case with the Eastern Wheat-belt. This was attributed to higher productivity of agricultural activities, despite land in the former having higher opportunity costs associated with that. In both cases, however, carbon farming was by a large amount less competitive than current agricultural undertakings. The relatively low sequestration levels and the lack of saleable timber components meant that the carbon price

would have to be \$45/t CO_2-e in the Great Southern region and \$66/t CO_2-e in the Eastern Wheat Belt area to compete with current land use.

Soil Organic Matter in Rice Soils of India: Rice is an important crop in our country. Out of the total area under cereal cultivation (99.5 M ha), 42.3 M ha or 42.5 percent is under rice cultivation (**FAO, 2001**). Out of this rice area, 10 M ha are cultivated in the Indo-Gangetic plains as a rice-wheat cropping system (**Ladha *et al.*, 2000**). Rice comprises 122 million Mg or 56 per cent of total production out of a total cereal production of 219 million Mg. The planting of rice is separate from that of the upland crops. It is grown under flooded conditions, and the seedbed is prepared by puddling or ploughing under saturated soil conditions to remove aggregates and reduce the water penetration rate. Thus created anaerobic conditions result in the emission of methane (CH_4) and probably nitrous oxide (N_2O) by inefficient use of fertilizers (**Bronson and Singh, 1994**). Out of the world's total CH_4 emissions of 25.4 to 54 Tg from all sources, nearly 16 to 34 Tg is only from rice cultivation, and that from rice paddies in India are estimated at 2.4 to 6 Tg (Sass, 1994). The average methane (CH_4) flux for rice paddies varies from 9 - 46 g / m^2 for a period of 120 - 150 day growing season (**Prashar *et al.*, 1994**). Owing to a favourable water regime over the rice season, the amount of SOC in rice soils is more than in upland soils. Rice straw, however, is removed for fodder and other uses similar to those of other crops, and it reduces C input into the system.

Swarup (1998) stated that integrated nutrient management increased the rice soil SOC concentration from < 5 g / kg in 1973 to about 8 g / kg in 1994. Work is ongoing to find ways to grow rice without puddling so that greenhouse gas emissions can be decreased and fossil fuel usage reduced (**Duxbury *et al.*, 2003**). Rapid adoption of conservation tillage in the Indo-Gangetic plains (**Hobbs and Gupta, 2003; Malik *et al.*, 2003**) may increase concentration of SOCs in those soils. It will further reduce the use of fossil fuel for plowing and puddling **(Lal, R., 2004**).

Plant production in agro-ecosystems such as agroforestry, ethnoforests and trees outside forests will reduce emissions of greenhouse gases (GHGs). Agroforestry systems are a better choice to combat climate change than oceanic ones and other terrestrial alternatives because of the secondary environmental benefits such as helping to achieve food security and stable land tenure in developed countries, conserving soil, maintaining watershed hydrology, increasing farm production, preserving and sustaining biodiversity above and below ground, pathways between protected forests such as CH_4 sinks. Agricultural forestry or agroforestry

also mitigates timber demand and reduces the burden on natural forests. Promoting the woodcarving industry promotes long-term carbon lock-up in carved wood and new sequestration by intensifying tree growth. It can be assisted by making use of local knowledge, resources, quality of living, trade and industry. Suitable policies need to be developed with support from robust country-wide scientific studies aimed at better understanding the potential of agroforestry and ethnoforestry for mitigating climate change and human well-being (**Pandey, D., 2002**).

2.4.3 Physical Properties

Gupta *et al*. (2009) conducted an experiment in central Punjab wherein they found that the mean soil aggregate weight diameter (MWD) rose by 3.2, 7.3 and 13.3 times in soils with planting for 1, 3 and 6 years, respectively, from that in single crops. The rise in agroforestry MWD was higher in loamy sand compared with sandy clay soil. Water stable aggregates (WSA > 0.25 mm) rose by 14.4, 32.6 and 56.9 times, respectively, in soils of 1, 3 and 6-year plantations from those of single crop. The WSA >0.25 mm was 6.02 times higher in loamy sand and 2.2 times higher in sandy clay than in sole cultivated soils.

2.4.4 Chemical Properties

Another long-term con ducted by **Arévalo-Gardini *et al*. (2015)** wherein they compared various treatments and observed that improved natural agroforestry system-INAS and improved traditional agroforestry systems-ITAS of adapted cacao genotypes management systems have important effects on the physical and chemical properties of soil in the Peruvian Amazon region. In the systems, soil physical and chemical properties tend to reach equilibrium following 6 years of management. In both management systems the characteristics of soil physical indicators have improved substantially relative to secondary natural forest (SF) and original estimates. Years of assessment and soil depth have significant effects on physical properties of soil such as bulk length, porosity, field capacity, and wilting point, but cacao genotypes had minimal effects on the physical properties of soil on overall basis. In both management systems the SOM content increased with years at different soil depths, but the rise in SOM, extractable P, K, and Mg, and exchangeable K and Cu in the surface soil layer (0-20 cm) was very significant. Overall INAS had a significant influence on soil pH, CEC, exchangeable Mg and (H + Al) gain relative to ITAS. Longer time is required to better understand the effect of cacao management on soil properties of natural or conventional agroforestry systems. The perennial crop management agroforestry system play a significant role in increasing soil fertility by preserving large quantities of organic carbon in the soil, while maintaining considerable nutrient content. Future Work is expected to explore the effect on soil degradation, biodiversity of plants, soil bacteria, birds, animals and socioeconomic resources of long-term agroforestry management of perennial crops.

2.4.5 Biological Properties

Soil microbial biomass constitutes about 1-5 percent of total soil organic carbon. It acts as a source and sink for plant nutrients to play a crucial role in the dynamics of nutrient cycling and soil organic matter. It is the main agent involved in the decomposition of plant residues, in soil resource recovery and cycling cycles (**Singh *et al.* 1989; Smith and Paul 1990**). Consequently, the microbial biomass was used as an indicator of soil fertility, which depends on nutrient fluxes (**Hassink *et al.*, 1991**). A rise in the size of soil microbial biomass is deemed necessary for soil fertility development. Plant covering affects microbial biomass by its effect on the quantity and nature of organic matter inputs (**Wardle, 1992**). The biomass itself is the organic component of the earth, which supported the most complex reservoir (**Jenkinson, 1988**).

Studies also indicate that enzyme activities are more widespread in cropping practices in agroforestry alleys due to variations in litter quantity and consistency, and root exudates (**Mungai *et al.*, 2005**).

The organic matter in the soils that is subjected to microbial decay comes from various sources. The fast-growing woody perennials in agroforestry have an almost permanent litter cover; the newly dropped material replenishes the decomposing organic matter in the form of litter. The study conducted by **Yadav *et al.* (2010)** revealed major differences in C-mic, N-mic, and P-mic attributable to multipurpose trees (MPTs). C-mic ranged from 262 to 320 ug g^{-1} soil through MPTs dependent agroforestry systems, N-mic from 32.1 to 42.4 ug g^{-1} soil, and P-mic from 11.6 to 15.6 ug g^{-1} soil. Under agroforestry systems, the soil microbial nutrients were slightly higher ($P < 0.01$) compared with sole cropping systems. Microbial nutrients did not differ significantly ($P<0.01$) under *D. sissoo, A. nilotica* and *A. leucophloea* based agroforestry system, except P-mic which was significant under *D. sissoo* and *A. leucophloea* based system. The rise in soil C-mic, N-mic and P-mic attributed to the incorporation of trees with crops relative to sole crop was in the range of 38.1 to 85.7 %, the highest being in *P. cineraria* based system. Under various MPTs based systems, the measured quantities of C, N, and P flux is 1.38 to 1.85 times higher relative to single cropping. Statistics revealed that the fluxes of C, N and P in specific land uses for agroforestry is significantly higher than those of cropping. In agroforestry systems the annual flux of C, N and P followed the order: *P. cineraria* > *D. sissoo* > *A. leucophlocloea* > *A. nilotica*.

Owing to various agroforestry systems based on MPTs, the dehydrogenase activity increased significantly ($P<0.01$) relative to single cropping. There was a 1,60 - 1,87-fold rise

in dehydrogenase activity due to various land use systems based on MPTs as opposed to sole cropping, with maximal production under the agroforestry method based on *P. cineraria*. Dehydrogenase production under the agroforestry method based on *P. cineraria* was considerably higher than with other systems based on MPTs. The use of MPTs in arable cropping systems has also resulted in a substantial rise in soil production of alkaline phosphatase. The rise in alkaline phosphatase production in soil due to different cropping systems dependent on MPTs ranged from 88.3 - 163 per cent compared to cropping. The substantially highest activity of alkaline phosphatase was found under the cropping system of *P. cineraria* followed by *D. sissoo* Cropping (**Yadav *et al.*, 2010**).

As compared to the rice-wheat system, the HWC and MBC were both higher in maize-wheat and agroforestry systems as described by **Benbi *et al.*, (2012)**.

Materials and Methods

3.1 Study area description

The study site was located in the campus of Agriculture Research Station, Fatehpur, SKN Agriculture University, Jobner, in village Harsava of Fatehpur tehsil in Sikar district of Rajasthan with coordinates of 27°56'11.2"N latitude and 74°58'50.0"E longitude with nearly flat topography (https://maps.google.com). The site lies in IIA agro-climatic zone of Rajasthan, named as 'Transitional Plain of Inland Drainage' with an average annual rainfall of 300-500 mm. The temperature of the zone is very fluctuating going below freezing point (up to – 2.5^{o} C) during winter and up to 52^{o} C during summer months. Pearl millet, Cluster bean, and pulses are major crops during *kharif* season and mustard and gram during *Rabi* season grown in the region. Khejri (*Prosopis cineraria*) and Babul/Babool (*Acacia nilotica*) are important tree species (Sharma, P., 2013) of the region.

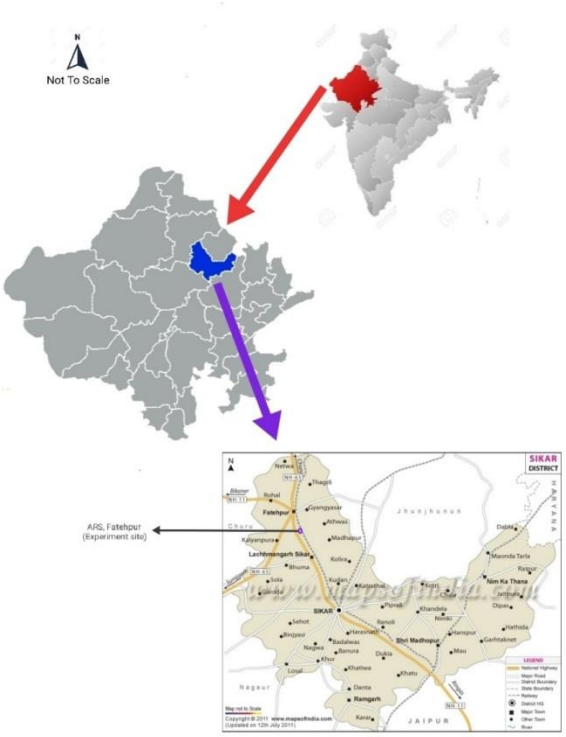


Fig-3.1. Location map of the experiment site (ARS, Fatehpur)

Fig-3.1. Google earth image of the experiment site (ARS, Fatehpur)

3.2 Experimentation and treatment details

A long term agri-silvicultural system was established in 2004 at ARS Fatehpur, which falls under agro-climatic zone -2A (Internal drainage dry zone), with two tree species and five different types of crops in a two factor Factorial Randomised Block Design replicated three times. Tree species was considered as the first factor and crops as the second factor. There were three levels of the first factor viz,

1. Sole cropping (no tree species),
2. Anjan (*Hardwickia binata*), and
3. Khejri (*Prosopis cineraria*)] and

The second factor was 'crop species' which were at 5 levels viz.,

1. Cluster bean (*Cymopsis tetragonoloba* L.),
2. Cowpea (*Vigna unguiculata* L.),
3. Mung bean (*Vigna radiata* L.),
4. Moth bean (*Vigna aconitifolia*), and
5. Pearl millet (*Pennisetum glaucum* L.)

Hence, there were 15 treatment combinations (3 tree species X 5 crop species) which were replicated thrice. The trees were planted at a spacing of 5 X 5 meters and the crops were sown in between the tree rows in plots measuring 5 X 5 meter.

The crops were usually sown from mid-June to third week of July each year. After 2-3 ploughings, the field was finely prepared. The crops were sown in line with a fixed row to row and plant to plant spacing.

Further, there was no additional nutrient management for trees, but N, P, K were applied at 100% of RDF to crops. RDF for the zone for different crops was as follows.

Vigna unguiculata L.	10 kg N ha^{-1}	30 kg P_2O_5 ha^{-1}	0 kg K_2O ha^{-1}
Cymopsis tetragonoloba L.	10 kg N ha^{-1}	40 kg P_2O_5 ha^{-1}	0 kg K_2O ha^{-1}
Vigna radiata L.	10 kg N ha^{-1}	30 kg P_2O_5 ha^{-1}	0 kg K_2O ha^{-1}
Vigna aconitifolia	10 kg N ha^{-1}	30 kg P_2O_5 ha^{-1}	0 kg K_2O ha^{-1}
Pennisetum glaucum L.	40 kg N ha^{-1}	20-30 kg P_2O_5 ha^{-1}	0 kg K_2O ha^{-1}

3.3 Yield of crops

Crops were harvested at maturity, usually in the month of September each year. Harvesting was done from each plot with a sickle and crops were removed from the field without leaving any residue behind. The harvested total biomass was dried in the shade and the total biological weight was recorded. The crops were threshed and the grain/seed yield was also recorded.

3.4 Estimation of root biomass

In our study, root shoot ratio of crop plants was determined by harvesting sample plants at flowering stage as the ratio is expected to be highest at this stage. Plants were harvested using a spade by digging an extra volume of soil and removed gently along with soil. Soon after removing plants, the roots were washed gently in a bucket full of water. Plants were left on a plastic sheet a while for air drying of roots. They were cut at root shoot junction with sharp knife and put into paper bags separately. After air and oven drying of roots and shoots, their weights were taken.

3.5 Carbon stock assessment methodology

The whole procedure to assess carbon stock has been categorised into different steps for convenient understanding.

3.5.1 Above-ground tree biomass (C_{AG}) assessment

The tree Above-ground biomass was estimated using the equation developed by Kuyah et al., 2012 (for *P. cineraria*) and by Singh and Singh, (2015) (for *H. binata*). Diameter of trunk at breast height (DBH) was measured (1.3 meters above the ground) and was used in calculating the above ground biomass of respective trees. Five trees from each system were selected to measure DBH and to average out the biomass per tree which was further multiplied with the number of trees to assess the biomass unit area basis.

3.5.2 Below-ground tree biomass (C_{BG}) assessment

No tree was harvested to assess below ground biomass instead, it was estimated from above ground biomass by multiplying with a certain factor say "0.24" for *H. binata* (Singh and Singh, 2015) and "0.27" for *P. cineraria* (Kuyah et al., 2012).

3.5.3 Crop biomass (C_{CB}) assessment

Crop biomass data was derived from the yield data. Root biomass was calculated from crop yield data using root: shoot ratio and root biomass combined with shoot biomass gives total crop biomass.

3.5.4 Determination of root shoot ratio of crops

Root shoot ratio is an important indication of growth characteristic of a crop as it is directly related with nutrient acquisition efficiency of the plants. As the length and volume of roots increases, plants are able to derive more and more nutrients and water from soil system. In water stress or drought conditions root length increases resulting in uptake of water from deeper layers, hence mitigating the drought period. Monocots have fibrous root system deriving nutrients and water from shallower layers while dicots have tap roots deriving nutrients and water from that of deeper layers.

The weight of roots was divided by weight of respective shoots to get root:shoot ratio.

$$\text{Root : Shoot} = \frac{\text{Weight of root (g)}}{\text{Weight of shoot (g)}}$$

3.5.5 Soil sampling

The samples were collected twice, first in mid-season (at flowering stage) and second after harvesting of the crops. Depth of first sampling was 0-15 cm (furrow slice) while after harvest samples were collected from four depths (1. 0-5 cm, 2. 5-15 cm, 3. 15-45 cm, and 4. 45-90cm) and stored in freezer for further chemical and biological analysis.

3.5.6 Analysis of soil samples

The soil samples further used for analysis of physical, chemical, and biological properties.

3.5.6.1 Physical properties

i. ***Bulk density***

Bulk density of soil was determined by core sampling. Soil collected with core sampler was dried in hot air oven at 105° C for 24 hours and bulk density was calculated as follows.

$$\text{Bulk density of soil (g/cm}^3\text{)} = \frac{\text{Weight of dry soil (g)}}{\text{Volume of the core (cubic cm)}}$$

Core size	Core diameter	4.8 cm
	Core length	5.4 cm
	Core volume	97.755 cm^3

3.5.6.2 Chemical properties

i. ***Soil pH***

Soil pH was measured after preparing a soil-water suspension in the ratio of 1:2.5 (10 g soil with 25 mL of distilled water) with the help of pH meter. (Sparks *et al.* 1996)

ii. ***Electrical conductivity***

The previously prepared soil-water suspension for determination of pH was used to determine the EC of the soil. Soil suspension was allowed to settle till supernatant become clear and electrical conductivity was measured with the help of EC meter and expressed as dSm^{-1} (Sparks *et al.* 1996).

iii. ***Organic carbon***

Organic Carbon in the soil was determined using Walkley and Black method (Walkley and Black, 1934). For this, 0.5 gram of soil was taken in a 500 mL of conical flask and 10 mL of neutral normal (1 N) $K_2Cr_2O_7$ solution was added and mixed. After addition of 20 mL of concentrated H_2SO_4, the flask was swirled 2-3 times and allowed to stand for 30 minutes (in dark). Then the suspension was diluted with 200 mL of distilled water. A pinch of sodium fluoride (NaF) was added along with 10-15 drops of diphenylamine indicator and titrated against the solution of 0.5 N Ferrous Ammonium Sulphate till colour changed from violet to bright green. Blank titration was also carried out the same manner without soil.

Calculation

$$\% \text{ Organic Carbon in soil} = \frac{10(B-T) \times 0.003 \times 100}{B \times \text{wt. of soil (g)}}$$

Where, B = Volume of 0.5 N FAS solution used for blank titration

T = Volume of 0.5 N FAS solution used for sample titration

is the volume of $K_2Cr_2O_7$ used

iv. ***Available nitrogen***

Available Nitrogen content in soil was determined using KELPLUS **DISTYL-EM** by alkaline Potassium permanganate method (Subbiah and Asija, 1956). The method has been widely adopted due to its rapidity and reproducibility and gives a reliable index of Nitrogen availability in soil. For this, 5.0 gram of soil was weighed and transferred in a distillation tube. 25 mL of 0.32% $KMnO_4$ was added to it and the distillation tube was set to the instrument. 20 mL of 2 % boric acid mixed indicator was taken in a 150 mL conical flask and receiver tube was dipped into it. About 25 mL of 2.5% NaOH was sucked automatically and added to the distillation tube. Then instrument was put on distillation for 9 min. During this process the N released from organic matter in the form of ammonia is trapped in boric acid, which develops green colour. The flask containing the distillate was removed and titrated against 0.02 N H_2SO_4 until pink colour developed.

Calculation

$$\text{Mineralisable N kg ha}^{-1} = \frac{(S-B) \times 0.00028 \times \times 10^6 \times 2.24}{5}$$

Where,

S = Sample titration reading

B = Blank titration reading

The factor 0.00028 is arrived at by considering the following simple equation:

$2NH_4OH + H_2SO_4 = (NH_4)_2SO_4 + 2H_2O$

98 g of H_2SO_4 or 1L of 2N H2SO4 = 28g N

Or

1mL of 0.02 N H_2SO_4 = 0.00028g N

v. Available Phosphorous

Available phosphorous in soil was determined by Olsen`s method (Olsen et. al., 1954). For this, 2.5 grams of soil was extracted with 50 ml of 0.5M $NaHCO_3$ (pH 8.5) in the presence of activated charcoal. Phosphorous in extract forms heteropoly complexes reacting with ammonium molybdate which gives faint yellow colour. Heteropoly complexes gives blue colour on reaction with ascorbic acid which is proportional to the concentration of P. Intensity of the colour was measured at 660 nm wavelength. After shaking the contents (soil + Olsen`s reagent) for half an hour, they were filtered through Whatman No. 1 filter paper and 5 ml of it was taken in a 25 ml volumetric flask, 0.6 ml of 5 N H_2SO_4 was added and shaken till effervescences stop. An amount of 4 ml of ascorbic acid was added and volume made up with distilled water. The intensity of colour developed after half an hour was read at 660 nm.

Calculation

Total dilution = 100 times

Concentration of sample = S ppm

Concentration of blank = B ppm

Actual concentration of P in sample = S-B ppm

Available P concentration in soil = (S-B) * 100 ppm

Available P in soil (kg/ha) = (S-B) * 100 * 2.24

Available P_2O_5 in soil (kg/ha) = (S-B) * 100 * 2.24 * 2.29

vi. Available potassium

Available potassium content of soil was determined by Flame Photometer using 1 N ammonium acetate as extractant (Hanway and Heidal, 1952). Exactly 5 gram soil was taken in a 150 mL conical flask, 25 mL of 1 N ammonium acetate solution was added to it and was shaken for 5 minutes. Thereafter, the suspension was filtered through Whatman No. 1 filter paper and concentration of potassium was measured using flame photometer. Firstly, standard reading was taken followed by sample readings.

Calculation

Dilution factor = 25 / 5 = 5 times

Available K (kg ha^{-1}) = R x 5 x 2.24

Where, R = Reading of the flame photometer for the test sample

Available K_2O (kg ha^{-1}) = Available K (kg ha^{-1}) x 1.2

vii. Hot Water Soluble Carbon (HWC)

The term water soluble organic carbon (WSOC) is described as the total pool of water soluble organic carbon which is either sorbed on soil/sediment particles or dissolved in interstitial pore water. The carbon bonded in organic matter is dissolved by hot water and further determined by oxidising it with potassium dichromate. Firstly, 5 g of soil was weighted and dissolved in 50 ml of distilled water. After shaking for 10 minutes on mechanical shaker, it was kept at 80^o celsius for 16 hours. It was then filtered firstly through Whatman No. 1 filter paper followed by membrane filters (Cellulose nitrate 0.45 microns). Exactly 10 ml of filtrate was taken in a 250 ml conical flask and 2 ml of potassium dichromate (0.4 N), 10 ml of

concentrated sulphuric acid and 5 ml of concentrated orthophosphoric acid were added subsequently followed by heating at 120^{o} C for half an hour. The contents were diluted by 150 ml of distilled water and titrated against 0.087 N ferrous ammonium sulphate in the presence of ferroin indicator.

Calculation

Weight of soil taken = 5 g

Volume of water added = 50 ml

Dilution = 50/5= 10 times

Volume of aliquot of extract used for C determination = 10 ml

Volume of FAS used in blank titration = B ml

Volume of FAS used in sample titration = S ml

$$\text{C (ug/ml of extract)} = \frac{\text{(B-S) * Strength of FAS * 3 * 1000}}{\text{Volume of aliquot of extract used for C determination}}$$

C (ug/g of soil or ppm) = C (ug/ml) * dilution factor

viii. Hot Water Soluble Carbohydrate (HWCh)

The filtrate obtained from soil samples in the procedure of hot water extractable carbon (HWC) were used for further determination of hot water soluble carbohydrate. One ml of filtrate was taken in test tube and 1 ml of phenol (5%) was added to it. Further, 5 ml concentrated sulphuric acid was added followed by mixing well with the help of vortex mixture. Test tubes were then allowed to stand for 1 hour at room temperature. Absorbance of the solution was then read at 485 nm in spectrophotometer.

Calculation

The hot water soluble carbohydrate was calculated from standard curve of glucose and multiplied with dilution factor (which is 10 times), and was further expressed in micrograms of carbohydrate per gram of soil (ug/g).

ix. Fractionation of soil organic carbon

Soil organic carbon is the fundamental source of food for almost all kinds of soil microbes. But all the parts of that carbon is not equally available to micro-organisms instead some part of it they (micro-organisms) can utilize very easily while some can't be utilise at all or used at very slow rate. Therefore, soil organic carbon is divided into different fractions based on its liability or susceptibility to oxidation to chromic acid. In essence the procedure is a modification of the Walklery and Black method using 5, 10 and 20 ml of concentrated sulphuric acid which corresponds to 12, 18 and 24 N H2SO4 (Datta *et al.*, 2015).

1. Fraction-1 (C_{VL}-Very labile carbon): Organic carbon oxidised by 5 ml of concentrated sulphuric acid.
2. Fraction-2 (C_L – Labile carbon): Difference in organic carbon oxidised by 5 ml concentrated H_2SO_4 and 10 ml concentrated H_2SO_4.
3. Fraction-3 (C_{LL} -Less labile carbon): Difference in organic carbon oxidised by 10 ml concentrated H_2SO_4 and 20 ml concentrated H_2SO_4.
4. Fraction-4 (C_{NL} – Non labile carbon): Difference in organic carbon oxidised by 20 ml concentrated H_2SO_4 and TOC of soil.

In our experiment, 1 gram of soil was used to determine organic carbon (Walkley and black, 1934) with the different amounts of concentrated sulphuric acid (as stated above), other steps remaining same. But for the determination of TOC, 1 g soil was heated on hot plate at a temperature of 150°C for half an hour along with 10 ml potassium dichromate and 20 ml concentrated H_2SO_4 and next steps remaining same as the OC determination.

3.4.6.2.10 Active and passive Carbon pools

The above fractions were grouped into active carbon pool (C_{AP}) {$\sum$ (C_{VL} + C_L)} and passive carbon pool (C_{PP}) {$\sum$ (C_{LL} + C_{NL})}.

3.4.6.2.11 Labiality Index (LI) of Soil Organic Carbon

Further lability index (LI) was calculate using the following equation ((Datta *et al.,* 2015)

$$LI=3\frac{C_{VL}}{SOC}+2\frac{C_L}{SOC}+\frac{C_{LL}}{SOC}$$

3.4.6.2.12 Recalcitrance Index (RI) of Soil Organic Carbon

Non-lability index or Recalcitrance Index (RI) was calculated using two equations (Datta *et al,* 2017).

$$RI_1=\frac{C_{LL}+C_{NL}}{C_{VL}+C_L}$$

$$RI_2=\frac{C_{NL}}{SOC}$$

Calculation

Same as 'organic carbon'- section **3.4.5.2** ***(iii)***

3.5.6.3 Biological Properties

i. Dehydrogenase Activity (DHA)

Dehydrogenase activity is the relative index of microbial activity in soil as the enzyme dehydrogenase is involved in carbon metabolism in microbes. It oxidises soil organic matter by transferring protons (P^+) and electrons (e^-) from substrates to acceptors.

Dehydrogenase activity in the soil samples was estimated using spectrophotometric method (Casida *et al.,* 1964). In this methodology, 2,3,5- triphenyltetrazolium chloride (TTC) acts as terminal electron acceptor in the absence of oxygen (anaerobic condition), which on accepting electron gets converted into triphenylformazon (TPF). TTC is water soluble but TPF is water insoluble, therefore, methanol is used to dissolve TPF.

At first 1 g of soil was taken in a test tube and 0.2 mL of 3% 2,3,5- triphenyltetrazolium chloride (TTC) solution was added in the test tube as electron acceptor followed by 0.5 mL of 1% glucose solution as substrate for microorganisms. The bottom of the tube was gently tapped, to drive out all trapped O_2, till no air bubble was coming out and a water seal was formed above the soil. The test tube was put for incubation at 37^0C temperature for 24 hours. After incubation, 10 ml of methanol was added it the tube and shaken vigorously to mix well the contents. After 6 hours, clear pink colour supernatant liquid was taken out for estimation concentration of triphenyl formazan (TPF) in spectrophotometer at 485 nm (blue film).

Calculation

A standard series was prepared by taking 0.1, 0.25, 0.5, 0.75, 1.0, 1.5 and 2.5 mL of 1000 µg mL^{-1} triphenyl tetrazolium formazan (TPF) solution in 50 mL volumetric flasks and volume was made up with methanol. Reading was taken at 485 nm wavelength on spectrophotometer. The concentration of TPF thus obtained from the standard curve is multiplied with dilution factor '10.7' (0.2 ml TTC + 0.5 ml glucose + 10 ml methanol) and expressed in ug g^{-1} hr^{-1}.

ii. ***Microbial Biomass Carbon (MBC)***

Soil microbial biomass is the living portion of soil organic matter which is smaller than 5 x 10^{-3} um (5 nm) in size and constitute about 1-5 % of it. It serves both as source and sink of plant nutrients present in soil organic matter (viz. C, N, P and S) and is also the centre of soil biological activity.

For convenience, the procedure for determination of microbial biomass carbon has been categorised in three steps...

1. Killing the microbes
2. Extracting the cell constituents
3. Determining the Carbon

1. Killing the microbes

The standard method for killing microbes is by using Chloroform as fumigant (Chloroform Fumigation), but at the same time it is time consuming and risky also. An alternative method for the same is use of microwave irradiation for a predetermined time. It is less laborious and faster method than that of chloroform fumigation.

For irradiation of soil by microwave, 20 gram of soil was taken in a Petri dish at 80 percent of water holding capacity then exposed to microwave radiation in the microwave oven for 30 seconds (30 seconds each sample). The sample was further used for extraction of the cell constituents.

2. Extracting the cell constituents

The fumigated soil was transferred to a conical flask with a total of 80 ml 0.5 N K_2SO_4 then shaken on a mechanical shaker for half an hour. The sample was then filtered through Whatman No. 1 filter paper. That filtrate was further used for determination of Carbon. Another 20 gram fresh sample (without irradiation in microwave) was taken in a separate conical flask keeping other treatments same as irradiated sample.

3. Determination of Carbon

For determination of Carbon in the sample 10 ml of filtrate was taken in a 500 ml conical flask (irradiated and without irradiation separately). 2 ml of $K_2Cr_2O_7$ (0.04 N), 10 ml of concentrated sulphuric acid and 5 ml of concentrated Phosphoric acid were added to it. Thereafter it was put on hot plate at 120^oC for half an hour along with 2 blanks - 'hot blank'. Another 2 blanks were also put along the samples (not on hot plate - 'cold blank'). The cold blanks were, further, used for determination of actual strength of ferrous ammonium sulphate

(FAS). After heating, flasks were removed and about 200 ml of distilled water was added to it followed by 2-3 drops of DPA indicator. It was finally titrated against FAS.

Calculation

$$\text{Actual strength of FAS} = \frac{\text{Strength of } K_2Cr_2O_7 * \text{Volume of } K_2Cr_2O_7 \text{ used}}{\text{Volume of FAS consumed}}$$

$$\text{C (ug/ml)} = \frac{(\text{Hot blank} - \text{sample reading in ml}) * \text{Strength of FAS} * 3 * 1000}{\text{Aliquot of extract used for carbon determination}}$$

$$\text{C (ug/g soil)} = \frac{\text{C (ug/ml)} * \text{volume of extractant used}}{\text{Dry weight of sample + water content}}$$

Soil Microbial Biomass Carbon (ug/g soil) = 2.64 * (C in sample with irradiation – C in sample without irradiation)

{Here 2.64 is efficiency factor, assuming that extraction efficiency is 38 % only. (100/38=2.64)}

3.5.7 Assessment of soil carbon stock (C_S) in

Percent total organic carbon in soil was converted to total organic carbon (TOC) stock (t C/ha) using the following formula...

TOC (tonne per ha) - soil = % TOC x p x D x 100

Where, p = Bulk density of soil (Mg m^{-3}), and D = depth of soil (m)

3.5.8 Total Organic Carbon (TOC) Stock of the System

Total carbon stock is the sum of all sorts of carbon estimated above...

TOC (tonne per ha) - system = $C_{AG} + C_{BG} + C_{CB} + C_S$

Where, C_{AG} - Above-ground tree biomass (tonne per ha)

C_{BG} - Below-ground tree biomass (tonne per ha)

C_{CB} - Crop biomass (tonne per ha)

C_S - Soil carbon stock (tonne per ha)

3.6 Estimation of carbon sequestration potential

Carbon sequestration potential of system was calculated by multiplying the TOC stock by a factor of 3.67 (Chiemela et al., 2018).

3.7 Estimation of carbon trade potential

Carbon trading is, basically, the process of buying and selling credits and permits to emit carbon dioxide (CO_2). It has been a central effort of the European Union (EU) to slow down climate change. European Union Emissions Trading System (EU-ETS) is the world's biggest and leading carbon trading system. It is still full of corruption and problems, nevertheless countries such as China and Brazil continue to pursue carbon trading, as a way to tackle growing emissions. The potential of using carbon credits from agroforestry (AF) projects for farmers in the developing areas has become more common in Clean Development Mechanism and also in voluntary carbon markets (https://www.fern.org). In this way C trading potential of an agroforestry system can be estimated as follows…

Carbon trading potential USD ($) = TOC in system (tons) x Price per ton of Carbon

As of now India has not fixed a price; but many companies are using different price of carbon for their internal purposes. Here, we are using the price used by Google i.e. USD 14 per metric ton (or tonne) of carbon which is further converted to Indian Rupee.

1 United States Dollar = 74.89 Indian Rupee (As on 30 Jul, 2020; 3:53 pm UTC).

3.8 Statistical analysis

Data from crop yield and from the parameters analysed in the laboratory were statistically analysed using the statistical design “Factorial Randomised Block Design”. ANOVA (Analysis of variance) and DMRT (Duncan’s multiple range test) for comparison of means were used (using software SPSS). The statistical significance was determined @ $P < 0.05$. Effects of treatment combinations and soil depth on different soil parameters were analysed using a two-way ANOVA.

Chapter IV

Results and Discussion

In the present day situation of rising global average temperature and over exploitation of ground water, water has become a limiting factor for irrigation and drinking purposes especially in dry regions. These areas cannot support multiple cropping until and unless a regular source of water becomes available. Higher temperatures and very low soil moisture status cannot support vegetation except those of xerophytic nature, also the organic matter of soil gets oxidised faster. Under such circumstances, it becomes important to sequester atmospheric carbon to soil and plant material. Trees present in agroforestry systems moderate sudden changes in temperature, and, therefore, slows down this oxidation process. Hence, the present investigation entitled "**Carbon Sequestration Potential of Tree Based Agroforestry System in Arid Regions of India**" was carried out: (1) To evaluate the above and below ground carbon sequestration potential of a long term tree based agroforestry system, (2) To evaluate changes in carbon pools and enzyme activities, (3) To evaluate change in available nutrients and, (4) To evaluate the effect of agroforestry systems on yield of intercrops.

4.1 Influence of tree based agroforestry systems on physical properties of soil

4.1.1 Bulk Density of Soil

Bulk density of soil was determined at four depths viz. 0-5 cm, 5-15 cm, 15-45 cm, and 45-90 cm. Table-4.1 shows long term influence of different tree species on bulk density of soil (g cm^{-3}). Bulk density was not found to be significant at any particular depth but on an average it showed an increasing trend with depth ranging from 1.43 Mg m^{-1} at 0-5 cm to 1.55 Mg m^{-1} at 45-90 cm.

4.2 Influence of tree based agroforestry systems on chemical properties of soil

In the present study, several soil chemical properties were determined in the laboratory viz. pH, EC, oxidisable organic carbon, available N, available P and available K, hot water

extractable carbon, hot water soluble carbohydrate, and fractions of organic carbon. These are described hereunder.

4.2.1 Soil pH

pH of the soil was measured in soil samples obtained at 0-15 cm depth and it was found that the trees did not differ significantly with regard to soil pH, but crops did. The data pertaining to soil pH is presented in table-4.2. Soil pH was neutral to slightly alkaline, varying from 7.12 to 7.71 with an average of 7.44. Here, *Vigna unguiculata* (cowpea) and *Vigna radiata* (mung bean) had significantly lower soil pH over *Vigna aconitifolia* (moth bean) and *Pennisetum glaucum* L. (pearl millet) but not over *Cymopsis tetragonoloba* L. (cluster bean). Also, cluster bean had significantly lowers soil pH over moth bean but not over pearl millet. As pulses are thought to release more H^+ ions in compensation to uptake of more divalent and polyvalent cations, they lower the soil pH. Jose and Bardhan (2012) compared three different ecosystems in Chile and investigated C sequestration potential of *Pinus ponderosa* based silvopastoral system, pine plantation, and natural pasture. They observed that silvopastoral system exhibited lower soil pH (pH < 6.0) as compared to other systems.

4.2.2 Electrical conductivity of Soil

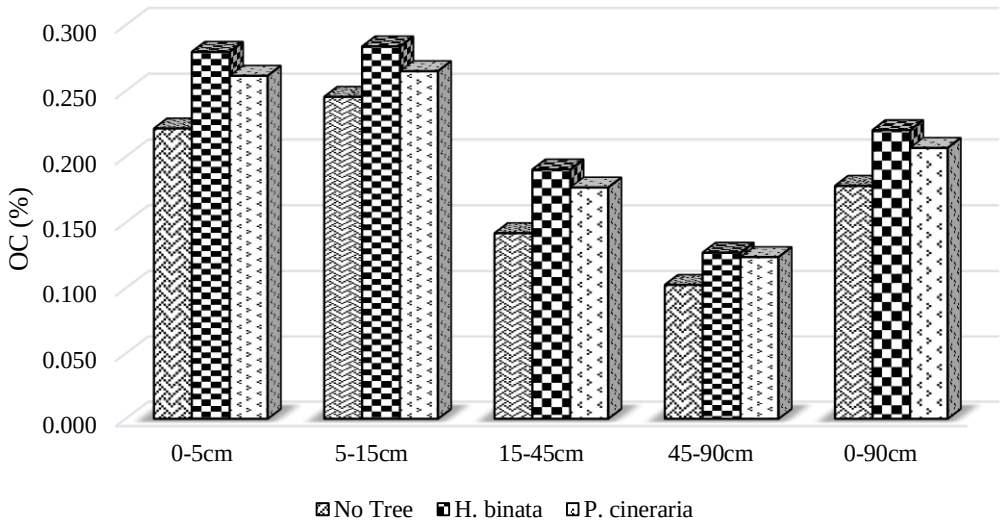
EC was measured in supernatant of 1:2.5 soil:water suspension and expressed in dSm^{-1}. The electrical conductivity (EC) of soil was found to be lower and soils were non-saline. Among the crops, all the pulses showed slightly lower values of EC as compared to the cereal (Pearl millet). In case of trees, *P. cineraria* showed slightly higher conductivity than the rest two systems. EC of the analysed soil samples is represented in the following table-4.3.

4.2.3 Soil organic carbon

SOC represents the food material available for activity of microbial population of soil. SOC was determined using Walkley and Black (wet digestion) method at all four depths (0-5 cm, 5-15 cm, 15-45 cm, and 45-90 cm). Fig.-4.1 and table-4.4 shows long term influence of different tree species on SOC. Both crops and trees differed significantly with regard to SOC (%) at 0-5 cm and 5-15 cm. But at 15-45 cm and 45-90 cm, only trees were found to be significant but crops did not. Averaged over all depths, *H. binata* system was highest in SOC status followed by *P. cineraria* system and 'No tree' system had the lowest SOC. SOC was

found to be higher under legumes and slightly lower under cereal (pearl millet). *H. binata* increased SOC status over *P. cineraria* and all the legumes increased SOC status over pearl millet, because of their (of *H. binata* and of legumes) dense foliage. In the furrow slice (0-15 cm), lowest value of SOC i.e. 0.187% was found in pearl millet under 'No tree' system and highest value i.e. 0.300% was found in cluster bean under *'H. binata'*, cowpea under *'H. binata'*, and cluster bean under *'P. cineraria'* system. The least value of SOC (0.092% only) was found in pearl millet under 'No tree' system at 45-90 cm depth. When averaged over all depths (0-90 cm average), Anjan tree system was highest (0.217 %) in OC followed by Khejri tree system (0.194%) and sole cropping (no tree) system was found to be the lowest (0.166%). Gupta *et al.* (2019) found *Hardwickia binata* to significant increase SOC over control *C. setigerus* field. Biomass per tree was higher in sparsely planted system, but biomass per hectare was higher in densely planted system. Same results were obtained by Benbi *et al.* (2012) in Rupnagar district of Punjab wherein they compared rice-wheat, maize-wheat and poplar based agroforestry system and found that agroforestry system significantly increased soil organic carbon status over rice-wheat system cropping system. They suggested that the higher SOC under agroforestry may be due to input of C through litter fall which occurs at the beginning of winter season and also to greater root biomass in comparison to sole annual crops. In another study, Maia *et al.* (2007) found silvo-pastoral system (SILV) and agroforestry (AGP) system to increase SOC status over intensive cropping system. This result may due to the quantity of plant residues that were produced by partial deforestation of native vegetation and then left on the soil in the SILV and AGP treatment when the experiments were started, and also other new sources of organic matter (pruning, manure and weeding).

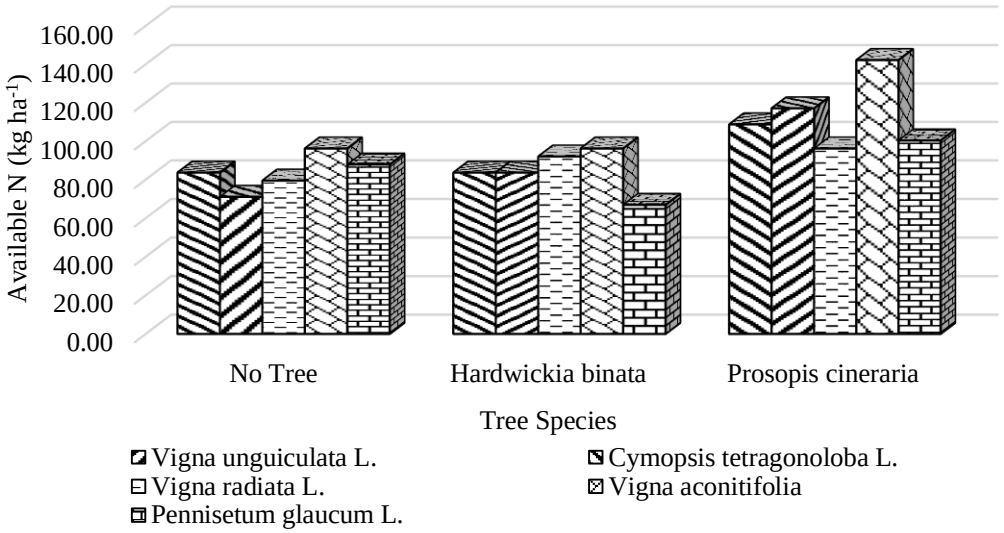
Fig.-4.1: Long term influence of different agroforestry systems on oxidisable organic carbon (%)



4.2.4 Available nitrogen

The trend in available nitrogen content was similar to organic carbon content, but *Prosopis cineraria* agroforestry system had significantly higher N content over both sole cropping system and *Hardwickia binata* (Anjan) based agroforestry system as can be seen in Fig.-4.2 and table-4.5. As *P. cineraria* (Khejri) is a legume plant, it fixes atmospheric nitrogen (N_2) and hence also enriches the soil with nitrogen. Among the crops, *Vigna aconitifolia* (moth bean) had higher available N content over all other crops. The interaction of trees with crops was found non-significant. The nitrogen content ranged from 66.90 kg ha^{-1} in pearl millet (*Pennisetum glaucum* L.) under 'Anjan tree (*H. binata*)' system to 142.17 kg ha^{-1} in moth bean under Khejri plantation. Paulo *et al.* (2015) conducted an experiment wherein they compared native forest (NT), annual crop (AC), perennial crop (PC), and pasture (PT). They found native forest (NT) and pasture (PT) to be higher in available N as compared to annual crop (AC) and perennial crop (PC) systems. They suggested that this increase can be explained by more intensive soil ploughing in cropping systems (AC and PC) historically and consequently higher C loss due to oxidation and erosion.

Fig.-4.2: Long term influence of different agroforestry systems on soil available N (kg ha^{-1})



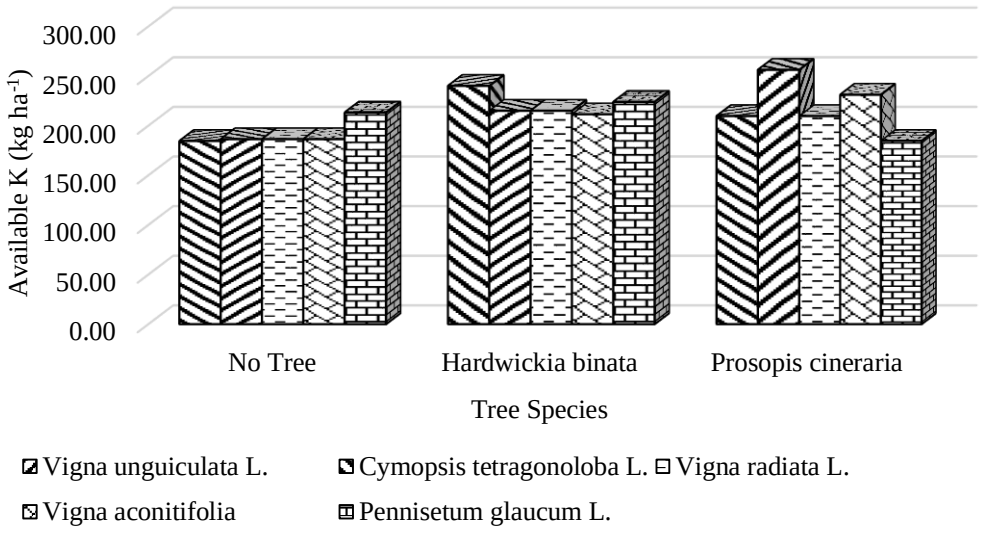
4.2.5 Available phosphorous

Table-4.6 are representing data pertaining to available P (kg/ha) in soil. None of the factors (trees, crops, and interaction of these two) was found to be significantly affect soil phosphorous in the present study. However, among the observed cases mung bean (*Vigna radiata* L.) and pearl millet (*Pennisetum glaucum* L.) under 'no tree' system were lowest in available P content (5.61 kg P ha^{-1}) and mung bean under Khejri plantation was highest in available P content (15.68 kg P ha^{-1}).

4.2.6 Available potassium

Tree species differ significantly with reference to potassium content but the crops do not. Fig.-4.3 and table-4.7 represent the available K (kg ha^{-1}) in soil. Here, two tree species {*Hardwickia binata* (Anjan) and *Prosopis cineraria* (Khejri)} were found to have significantly higher available K over sole cropping system (no tree), which may be due to addition of organic matter by trees as residues, which are thought to be high in potassium content. Lowest value of available K was observed in cowpea (*Vigna unguiculata* L.) under 'no tree' system and pearl millet under Khejri plantation i.e. 184.58 kg K ha^{-1} and highest in cluster-bean under Khejri plantation (256.26 kg K ha^{-1}).

Fig.-4.3: Long term influence of different agroforestry systems on soil available K (kg ha^{-1})



4.2.7 Hot Water Soluble Carbon (HWC)

Hot water soluble carbon (HWC) represents a fraction of carbon that easily gets dissolved in water upon heating. Trend of variation of HWC is nearly similar to that of oxidisable organic carbon (OC). In our study, both trees and crops differ significantly regarding HWC at 5-15 cm, but on two depths i.e. 0-5 cm and 45-90 cm, only trees were found to be significant, and none at 15-45 cm. As can be seen in table-4.8, the HWC goes on decreasing with depth in all cases. In furrow slice (average of 0-15 cm), pearl millet in sole cropping (no tree system) showed lowest value of HWC i.e. 204.45 ug C g^{-1} soil and highest value i.e. 432.02 ug C g^{-1} soil was shown by moth bean under Anjan trees and cluster bean under Khejri trees. On an average, all the legumes are relatively higher in HWC as compared to pearl millet (cereal). Benbi *et al.* (2012) observed that agroforestry system is higher in HWC status than that of rice-wheat and maize wheat cropping systems. They found HWC to be related with very labile and labile fractions of C, which may be related to the root exudation pattern of plant species. Lower values of HWC, in present study, in sole cropping system suggest that the organic matter (OM) is more stable under this systems than in the other two agroforestry systems (i.e. Anjan based and Khejri based systems). Therefore, the total organic carbon (TOC) under Anjan based and Khejri based systems though slightly higher than the 'no tree' system, could be easily lost by decomposition if the existing management is obsolete. Schulz (2004) suggested that hot water soluble carbon indicates easily degradable fraction of soil organic carbon (SOC) and it has suggested as a stability indicator of soil organic matter.

4.2.8 Hot Water Soluble Carbohydrate (HWCh)

Hot water soluble carbohydrate (HWCh) followed a very similar trend of change to that of HWC. table-4.9 represent the observed data of HWCh. At 0-5 cm and 5-15 cm, both trees and crops are significant, only trees were significant at 45-90 cm, but at 15-45 cm none was significant. In none of the cases the interaction of these two was significant. At first two depths i.e. 0-5 cm and 5-15 cm the observations are nearly same but on later two depths it goes on decreasing. At all depths Anjan tree based agroforestry system is higher followed by Khejri planted system and sole cropping system to the least. The lowest value of HWCh in furrow slice (25.85 ug C g^{-1}) was observed in pearl millet in sole cropping and highest (41.35 ug C g^{-1}) in cluster bean under Anjan tree plantation. Ghani *et al.* (2003) observed that the carbohydrates content is higher in pasture systems compared to the intensive cropping systems. They found hot water soluble carbohydrates to be strongly related with that of HWC. Both HWC and HWCh decreased not only with intensity of cropping but also with intensity of grazing as these leads to faster oxidation of labile fractions of organic matter.

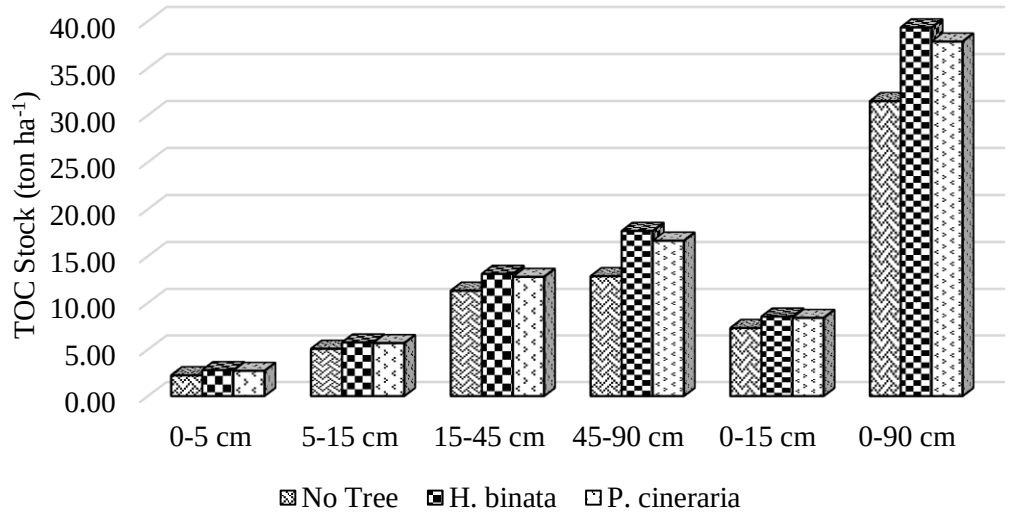
4.2.9 Total Organic Carbon % (TOC %) and TOC Stock (t ha^{-1}) in soil

Table-4.10 represents crops under different agroforestry systems on percent total organic carbon (TOC) in soil and table-4.11 on TOC stock (t ha^{-1}) in soil. At 0-5 cm soil, *H. binata* tree plantation showed highest TOC percent i.e. 0.389% followed by *P. cineraria* plantation system (0.378 %) and 'No tree' system showed lowest value of TOC (0.313 %). Not only at 0-5 cm, but at all depths TOC % was in the sequence of *H. binata* system > *P. cineraria* system > 'No tree' system. On an average (0-90 cm) Anjan tree (*H. binata*) system had 0.335%, Khejri tree (*P. cineraria*) system had 0.325% and sole cropping (no tree) system had 0.276% of TOC in soil. When averaged over all depths, pulse crops increased TOC percent over cereal crop (pearl millet).

TOC stock (t ha^{-1}) in soil was calculated by multiplying % TOC with bulk density and depth of soil. Fig.4.4 is representing TOC stock (t ha^{-1}) of the soil. At 0-5 cm and 5-15 cm soil depths Anjan tree plantation (2.78 t ha^{-1} and 5.75 t ha^{-1} respectively) was higher in TOC stock than that of Khejri tree plantation (2.70 t ha^{-1} and 5.68 t ha^{-1} respectively). Both of them were much higher than TOC stock in sole cropping system (2.23 t ha^{-1} and 5.08 t ha^{-1}). At 15-45 cm and 45-90 cm, Anjan tree plantation system was higher (13.12 t ha^{-1} and 17.68 t ha^{-1} respectively) that of Khejri tree plantation system (12.80 t ha^{-1} and 16.64 t ha^{-1} respectively). At these depths also, both of these systems were higher than sole cropping system (11.31 t ha^{-}

[1] and 12.87 t ha^{-1} respectively). When summed over all the depths, Anjan tree system was found to be slightly higher (39.33 t ha^{-1}) than Khejri tree system (37.82 t ha^{-1}) and much higher than sole cropping system (31.49 t ha^{-1}). Pulse crops increased TOC stock in furrow slice (0-15 cm) over cereal crop (pearl millet). Mangalassery *et al.* (2014) reported that total soil organic carbon stock (TOC-soil) in a 15 years old silvi-pastoral system (*Azadirachta* or *Acacia tortilis* + *Cenchrus setigerus* /*C. ciliaris*) in arid region of Gujarat was observed to be improved by 27.1–70.8 % in comparison to the sole 'pasture' system (*Cenchrus setigerus* and *Cenchrus ciliaris*) up to a depth of 100 cm soil. Saha *et al.* (2009) observed in Thrissur (Kerala) that home gardens (HG) with greater number of plant species and tree density have observed higher total soil organic carbon (TOC), especially upto top 50 cm of soil (61.5 to 73 Mg C ha^{-1}). Sharma *et al.* (2009), Shreenivas *et al.* (2010), and Paul *et al.* (2002) suggested that this improvement in soil organic carbon (SOC) stock under agroforestry system might be due to addition of leaf litter from trees, reduced soil erosion and modification in microclimatic conditions. Climatic effects such as modification in soil microclimate due to addition of leaves, effect of trees may also influence sequestration and decomposition of soil organic carbon (SOC). Paul *et al.* (2002) suggested that due to shading and high transpiration, surface soils are generally drier and cooler under plantations than under pasture. This factor might contribute to slower decomposition rates following tree plantation. Further, accumulation of soil carbon was reported to be the greatest, when deciduous hard woods or N_2-fixing species were established on uncropped land in tropical or subtropical regions (Paul et al., 2002).

Fig.-4.4: Long term influence of different agroforestry systems on TOC (t ha^{-1})



4.2.9 Carbon fractionation

The organic carbon in soil was categorised into different fractions viz. very labile C (fraction-1), labile C (fraction-2), less labile C (fraction-3) and non-labile C (fraction-4). Table-4.12, Table-4.13, Table-4.14, Table-4.15 and Table-4.16 are representing long term influence of crops under different agroforestry systems on various fractions of organic carbon as percentage of TOC in 0-5 cm soil, 5-15 cm soil, 15-45 cm soil, 45-90 cm soil and 0-90 cm soil. Appendix-I, Appendix-II, Appendix-II, Appendix-IV, and Appendix-V are representing long term influence of crops under different agroforestry systems on various fractions of organic carbon in 0-5 cm soil, 5-15 cm soil, 15-45 cm soil, 45-90 cm soil and 0-90 cm soil. In 0-5 cm soil layer trees and crops differ significantly regarding very labile C (fraction-1), labile C (fraction-2) and less labile C (fraction-4). Very labile carbon was highest in Anjan planted system (0.179%) which was significant over sole cropping. Labile carbon was highest in Khejri planted system (0.063%) and less labile carbon was highest in sole cropping (0.0446%). At this depth, crops were also differed significantly regarding very labile carbon and its highest amount was found in mung bean (0.179%). Neither the tree nor the crop was significantly different regarding non-labile carbon fraction.

As can be seen in appendix-II, trees differed significantly for very labile and labile C fraction at 5-15 cm depth, but not for less labile and non-labile carbon. Crops were found significant for any fraction at this depth. At this depth, highest value of very labile C was in Anjan tree plantation (0.071) followed by Khejri based system (0.056) and sole cropping system at the last (0.045).

At 15-45 cm depth, trees differed regarding very labile C only, and crops differed regarding non labile C only. Highest value of the previous was reported in Khejri plantation (0.089) followed by Anjan plantation (0.088) and sole cropping system was least (0.048). Non labile C was highest in mung bean at 15-45 cm depth (appendix-III). Trees were significantly different for very labile and non-labile carbon at 45-90 cm depth. In both the cases Anjan tree plantation was dominant regarding C content.

However, when averaged over all the depths (0-90 cm) very labile C (fraction-1) was significantly higher in *H. binata* (0.109 %) and *P. cineraria* (0.104 %) plantation but non-labile C (fraction-3) was higher in Khejri plantation (0.118 %) followed by Anjan plantation (0.115 %). In between two tree species *H. binata* comprises little higher percentage of very labile, and labile C. The reason may thought to be that higher annual addition of litter to the soil in tree plantations increases very labile and labile C fractions but in no tree system, in the absence of higher addition of organic material to soil, easily oxidisable portion of OM gets oxidised due

to high temperatures (because of absence of trees' shade) hence only less labile and non-labile portion remains therein. Our results were very similar to those obtained by Benbi *et al.* (2012). In their study, agroforestry system was significantly higher regarding percentage of very labile and labile C, but non-labile C was higher in rice-wheat system, however, these systems didn't differ regarding less labile C fraction. Our findings are similar to those observed by Majumder *et al.* (2008) for rice based cropping systems under hot humid tropics of India, under rice-berseem cropping system, the less labile and recalcitrant fractions (fraction 3 and fraction 4) constituted almost 55% of the total organic carbon (TOC). The greater proportion of organic carbon existing in less labile and recalcitrant forms in rice-wheat system, it might be attributed due to the reduced rate of carbon oxidation in these soils that are submerged for 3 months during the rice cultivation (Jenkinson 1988; Watanabe 1984). Consequences of slower decomposition of carbon substrates in submerged soils than in aerated soils, plant fraction that are more resistant to microbial degradation such as lignins may gradually accumulate in the organic matter of paddy soils (Colberg 1988; Tate 1979).

4.2.10 Active and passive Carbon pools

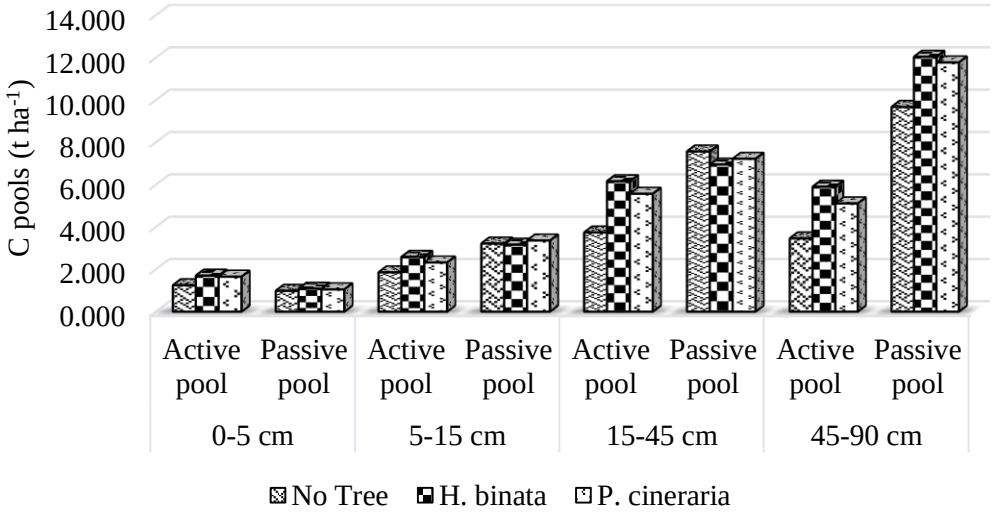
Tree species were found significant regarding active carbon pool at 0-5 cm and 45-90 cm soil depths. Anjan based agroforestry system (active C pool- 1.70 t ha^{-1} at 0-5 cm and 5.91 t ha^{-1} at 45-90 cm) was found significant over 'no tree' system but it was not significant over Khejri based agroforestry system. However, Anjan based system was significant over both Khejri based system and sole cropping system regarding active C pool at 5-15 cm and 15-45 cm depths, and values for the pool were 2.58 t ha^{-1} at 5-15 cm and 6.16 t ha^{-1} at 15-45 cm. Fig-4.5 represents active and passive pools of organic C in various land use systems.

Crops, but not the trees, were found significant regarding passive C pool at 0-5 cm, 5-15 cm and 15-45 cm. However, tree species were significantly different at 45-90 cm depth regarding passive C pool. The passive C pool was represented highest by Mungbean (*V. radiata*) at 0-5 cm depth (1.13 t ha^{-1}), by moth bean (*V. aconitifolia*) at 5-15 cm depth (3.47 t ha^{-1}) and by Mungbean (*V. radiata*) at 15-45 cm depth (8.25 t ha^{-1}). The highest passive C pool at 45-90 cm depth was represented by Anjan based system (12.04 t ha^{-1}) which was significant over sole cropping system but not over Khejri plantation based system.

Under Anjan tree based and Khejri tree based agroforestry systems, the two easily-oxidisable fractions of soil carbon viz. fraction 1 and fraction 2 constituted almost 45-50% of total organic carbon (TOC). The rest of total organic carbon (TOC) occurred in less labile and

recacitrant fractions, which is almost 50-55% assigned to the 'passive pool' of soil organic carbon (SOC). But in sole cropping system, active pool was only 35-40% and the rest was passive one. These carbon pools gives an idea about the easiness of availability of food for microbes. As active C pool represented higher by Anjan tree plantation system, which tells greater availability of easily decomposable C source for the soil microbial population which is not so in sole cropping system. Soil carbon pool in an ecosystem (as suggested by Benbi *et al.*, 2012) is influenced by the balance between the carbon inputs derived from root biomass, litter fall and root exudates and outputs through heterotrophic respiration. Our results were also supported by those obtained by Chauhan *et al.*, 2011; Tandon *et al.*, 1991; and Ralhan *et al.*, 1996). The region having Poplar trees plantation, supply 2.3 t C ha^{-1} y^{-1} through roots and leaves (Chauhan *et al.*, 2011) and also add 2.9–3.3 t ha^{-1} of litter fall every year (Tandon *et al.*, 1991; Ralhan *et al.*, 1996).

Fig.-4.5: Long term influence of different agroforestry systems on active and passive pools of organic carbon



Our results were also supported by Barreto *et al.* (2011) who observed that labile carbon fraction constitutes a larger fraction, 54–59%, of the total organic carbon (TOC) in soils under agroforestry systems in Brazil.

4.2.11 Labiality Index (LI) of Soil Organic Carbon

Labiality Index (LI) suggests the susceptibility of OM to decomposition.

Labiality Index (LI) was found significant at 15-45 cm depth only, but not at 0-5 cm, 5-15 cm and 45-90 cm depths. LI was also found significantly higher for Anjan tree plantation when averaged over all four depths (0-5 cm, 5-15 cm 15-45 cm and 45-90 cm). Labiality Index (LI) at 15-45 cm depth was highest (1.457) for Anjan tree plantation system followed by Khejri plantation system (1.336) and lowest (1.060) for 'sole cropping' system. Among the crops Pearl millet (*P. glucum*) was highest 1.350 at 15-45 cm and moth bean (*V. aconitifolia*) was highest at 0-90 cm depth regarding Labiality Index (LI).

4.2.12 Recalcitrance Index (RI-1 & RI-2) of Soil Organic Carbon

Recalcitrance Index (RI-1) was calculated by dividing passive carbon pool with active carbon pool. Neither the tree nor the crop was significant at 0-5 cm and 45-90 cm depths. At 5-15, 15-45 and 0-90 cm depths, RI-1 was highest for sole cropping system (1.78, 1.86 and 1.80, respectively) and was significant over Anjan and Khejri tree planted systems. Crops were found significant at 15-45 cm and 0-90 cm depths only, and in both the cases, values were highest for moth bean (1.60 and 1.67, respectively).

Recalcitrance Index (RI-2) was calculated by dividing non-labile C with TOC. Regarding RI-2, only tree species at only 15-45 cm depth was significant. At this depth, RI-2 for sole cropping system was highest (0.444) which was significant over Anjan tree plantation system only but not over Khejri plantation system. Fig-4.6 and fig.4.7 are representing Recalcitrance Index-1 (RI-1) and Recalcitrance Index-2 (RI-2) of organic C, respectively, in various land use systems.

Labiality Index (LI) and Recalcitrance Index are just the ratios which represent the susceptibility (Labiality Index) or resistance (Recalcitrance Index) of a system to lose organic carbon when the system is put under intensive cultivation.

Fig.-4.6: Long term influence of different agroforestry systems on Recalcitrance Index-1 (RI-1) of Soil Organic Carbon

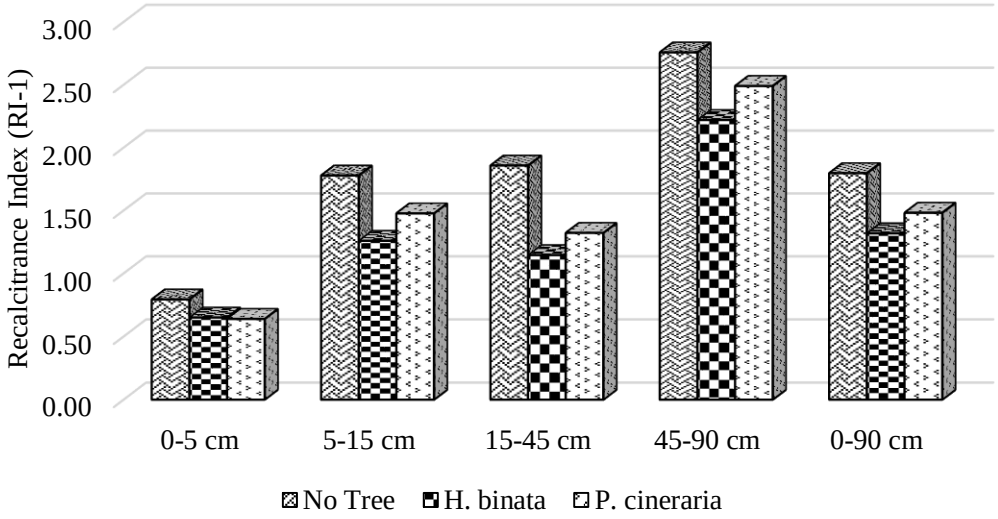
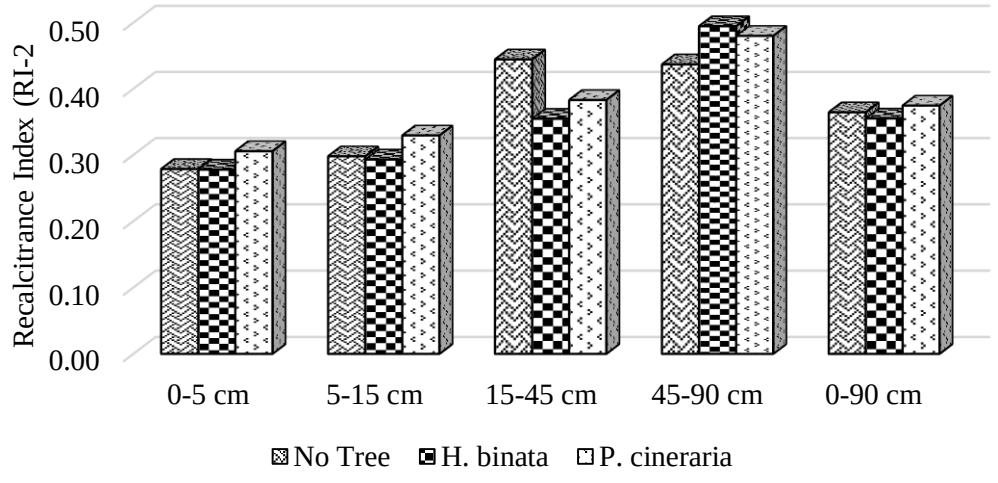


Fig.-4.7: Long term influence of different agroforestry systems on Recalcitrance Index-1 (RI-2) of Soil Organic Carbon



4.3 Influence of tree based agroforestry systems on biological properties of soil

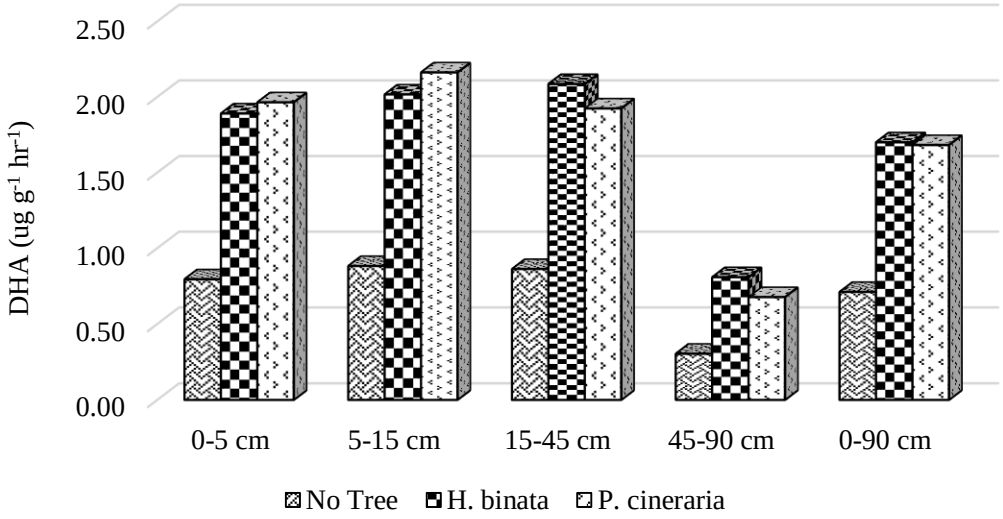
Biological properties of soil are supposed to be among most important properties affecting growth and development of higher plants and can be used as an indirect index of soil fertility. Dehydrogenase Activity (DHA) and Microbial biomass carbon (MBC) is an indication of activity of biological community in soil. In our study, dehydrogenase activity (DHA) in the

soil samples was estimated using spectrophotometric method (Casida *et al.*, 1964) and MBC was determined by irradiation method and expressed in terms of ug C/g soil.

4.3.1 Dehydrogenase Activity

Dehydrogenase activity is a relative index of microbial activity of soil which basically depends on the food material available there, average temperature of surrounding and moisture content of soil. Both the tree species showed substantial increase in DHA in soil over the sole cropping (no tree) treatment. DHA was observed to be very similar at first three depths i.e. 0-5 cm, 5-15 cm and 15-45 cm (though highest at 5-15 cm), but lower at 45-90 cm depth (fig.-4.8 and table-4.10). In furrow slice, both trees and crops are significant, but at later depths only trees are significant. Legumes are much better in increasing DHA (microbial activity) than that of pearl millet. At first two depths Khejri was found to be better regarding DHA followed by Anjan tree plantation and sole cropping at last but at later depths Anjan leads Khejri plantation. The DHA (ug/g soil/hour) in furrow slice ranged from 0.46 in pearl millet in sole cropping to 2.39 in mung bean under Khejri plantation with average of 1.62. A study conducted by Yadav *et al.* (2011) comparing traditional agroforestry systems with cropping systems. They found significant increase ($p < 0.01$) in dehydrogenase activity due to agroforestry systems (multi-purpose trees/MPTs) compared to non-agroforestry systems (conventional cropping systems). Increase was higher in Khejri planted system than the system comprising of *Acacia nilotica* (L.), *A. leucophloea* (Roxb.) and *Dalbergia sissoo* (Roxb.). Similar results were also observed by Chander *et al.* (1998) who compared cropping with agroforestry (comprising of *D. sissoo* trees). DHA was significantly higher in trees plantation than no-tree system. The activity increased with increasing density of planting of trees. In sequence, Prasad and Mertia (2005) in CAZRI, Jodhpur compared dehydrogenase activity between trees' rhizosphere (six tree species) and non- rhizospheric soil. They also found significantly higher DHA in all the trees' rhizospheric soil over non-rhizosphere.

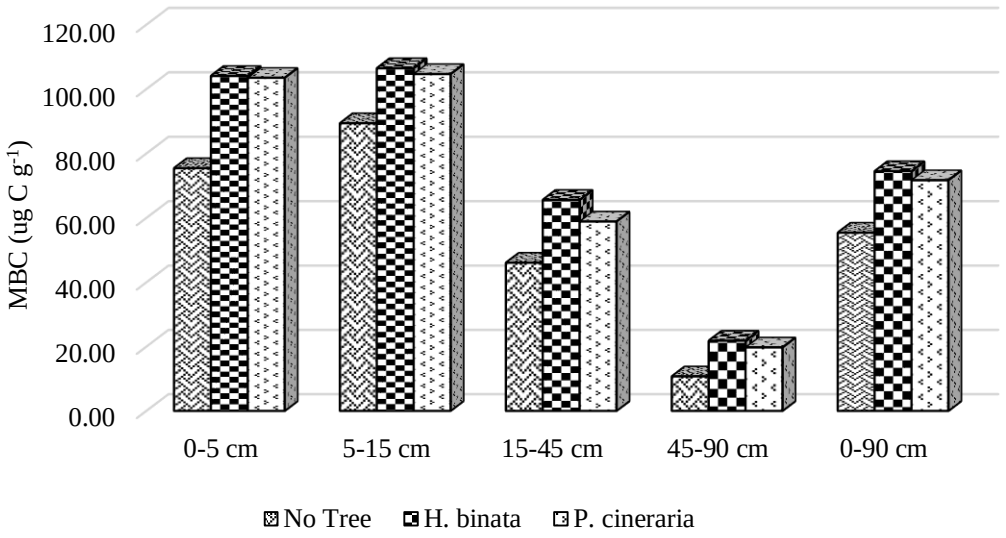
Fig.-4.8: Long term influence of different agroforestry systems on DHA (ug g^{-1} hr^{-1})



4.3.2 Microbial biomass carbon (MBC)

MBC was determined using irradiation method in three steps viz. 1. killing of microbes (by irradiation), 2. extraction of cell constituents (using 0.5 N K_2SO_4), and 3. determination of carbon content (using $K_2Cr_2O_7$). Results of MBC are very similar to that of hot water soluble carbohydrate (HWCh). MBC shows about similar values in furrow slice but thereafter decreases with depth. Both the tree species substantially increased the MBC over sole cropping treatment. Between the two tree-based agroforestry systems, Anjan plantation is somewhat better than Khejri plantation as MBC is very much associated with organic carbon and carbohydrate contents of medium (here soil). Legumes are better than pearl millet in increasing MBC same as HWC and HWCh. Data pertaining to MBC are represented in fig.-4.9 and table-4.11. Average MBC in furrow slice (averaged over 0-5 cm and 5-15 cm) is highest for Anjan tree system (105.30 ug C/g soil) followed by Khejri plantation (104.08 ug C/g soil) and lowest value of MBC was showed by sole cropping system (82.44 ug C/g soil). Benbi *et al.* (2012) also found similar results. They found agroforestry to significantly increase the MBC over maize-wheat and rice-wheat system. The reason behind was explained by them as greater addition of organic carbon to soil in agroforestry system resulted in increase in microbial activity of soil.

Fig.-4.9: Long term influence of different agroforestry systems on MBC (ug C g^{-1})



4.4 Tree Above-ground biomass (C_{AG}) assessment

The tree Above-ground biomass was estimated using the equation developed by Kuyah *et al.*, 2012 (for P. cineraria) and by Singh and Singh, 2015 (for *H. binata*). Diameter of trunk at breast height (DBH) was measured (1.3 meters above the ground) and was used in calculating the above ground biomass of respective trees. Tree biomass, Carbon sequestered by trees and CO_2 captured by trees are represented in table-4.24, 4.25 and 4.26, respectively. Above ground tree biomasses recorded were 19.37 t ha^{-1} for *H. binata* (Anjan) based system, 15.77 t ha^{-1} for *P. cineraria* (Khejri) based system and 0.00 t ha^{-1} for sole cropping system.

4.5 Tree Below-ground biomass (C_{BG}) assessment

C_{BG} was estimated from above ground biomass by multiplying with a certain factor say "0.24" for H. binata (Singh and Singh, 2015) and "0.27" for P. cineraria (Kuyah *et al.*, 2012).

Average tree biomass (Above-ground + Below-ground) for Anjan tree system, as calculated here, is 23.62 t ha^{-1} and for Khejri system is 20.03 t ha^{-1}. Obviously, it is 0.00 t ha^{-1} in 'no tree' system.

Data pertaining to above-ground, below-ground, and total tree biomass are represented in table-4.24.

4.6 Crop biomass (C_{CB}) assessment

Roots also serves as an important sink of carbon same as shoot. Both the tree species (*Prosopis cineraria* and Hardwickia binata) have deep (phreatophytic) root systems, largely lying below 50 – 60 cm and do not interfere with cultivation of the annual crops. Horizontal spread of roots of both the species was greater in comparison to the crown (canopy) spread (Tanwar *et al.*, 2018, and Singh and Singh, 2015).

The rooting area of H. binata was 1.25 times greater than the canopy area and was bell shape in structure. Also, the dry weight of root was 24 percent of the above ground biomass for same. The increased horizontal spread of roots in both the species beyond their canopy zones may be to access the minimal resources available in dry areas and is peculiar characteristic of the species adopted to these areas. Also, deep rooting pattern of the trees suggests suitability of same to agroforestry system (Tanwar *et al.*, 2018). Importance of Khejri can be seen in its recognition as 'state tree of Rajasthan', 'kalpavriksha of the desert', 'king of desert', and 'wonder tree'. Beside all these benefits, Khejri (being a leguminous tree) fixes atmospheric nitrogen enhancing the fertility of soil at the same time (Sarolia *et al.*, 2019).

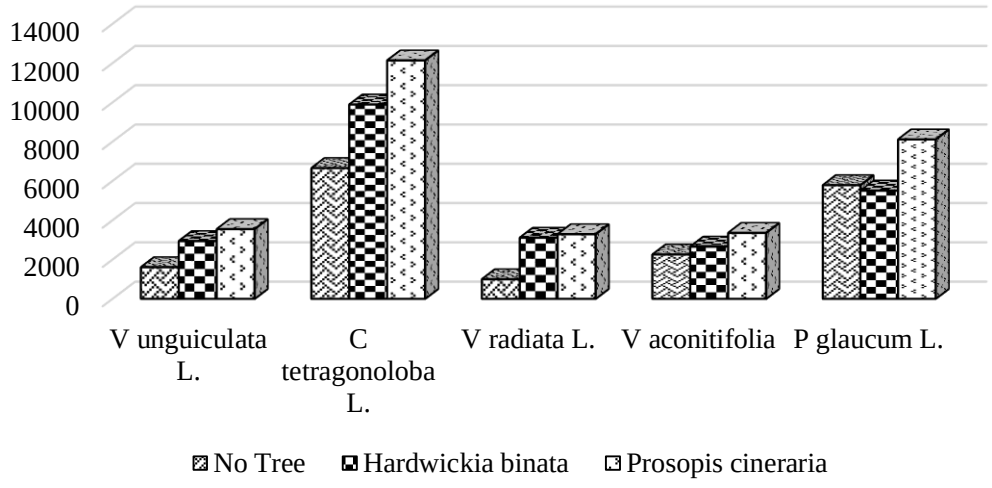
Over 70% of roots in pulses are distributed within 0 - 60 cm soil profile at late-flower stage and largest proportion (nearly 50%) is found in top 20 cm of soil. Around 85 percent (%) of roots in pulses are classified as `extra fine` (with diameter <0.4 mm) (Sarolia *et al.*, 2019).

The root : shoot ratio in our experiment was determined by weighing the harvested portions (root and shoot) of crop plants after air and oven drying. In this study, an average root : shoot ratios of 0.35 for pulses (average of cowpea, cluster bean, mung bean, and moth bean) and 0.18 for cereal (pearl millet) were found. Our results were very similar with that obtained by Williams et al. (2013) and Rao, Theertham & O, Ito. (1998). Williams et al. (2013) found average root shoot ratio for cereal (wheat) ranging from 0.14 to 0.17 and Rao, Theertham & O, Ito. (1998) found average root shoot ratio of 0.31 for pulses (pigeon pea, chickpea and groundnut). The root biomass was found out from shoot (stover) biomass using root : shoot ratio. Root and shoot biomass were combined with grain yield to obtain total organic material produced annually which further used to find out annual rate of carbon (C) and CO_2 capture.

An average 50% carbon in vegetation is expected to find out C amounts and this C is converted to CO_2 using molecular formula of these two.

The crops' grain yield (average of all the crops form a particular tree species), as represented in table-4.27, was recorded highest in Khejri based AF system (1021.14 kg ha^{-1}) followed by Anjan based system (799.73 kg ha^{-1}) and lowest in 'no tree' system (662.43 kg ha^{-1}). Table-4.28, Table-4.29, Table-4.30 represent the data pertaining to Stover yield (kg ha^{-1}), root biomass (kg ha^{-1}) and total crop biomass (kg ha^{-1}), respectively. Total crop biomass (Grain + Stover + Root) was recorded highest in Khejri based system (6088.42 kg ha^{-1}) followed by Anjan based system (4821.52 kg ha^{-1}) and sole cropping system at the last (3461.17 kg ha^{-1}). Though the C stock status is higher for Anjan based system but the reasons for lower yields in the same than that of the Khejri based system may thought to be excessive shading by Anjan trees which prevents light to reach to crop plants which results in lower photosynthesis and consequently lower dry matter production. Table-4.31, table-4.32, table-4.33, table-4.34, table-4.35, table-4.36, table-4.37 and table-4.38 represent carbon sequestered and CO_2 captured by different portions of crops in various agroforestry systems. Fig.4.10 represents crop biomass yields in various land use systems.

Fig.-4.10: Long term influence of different agroforestry systems on total carbon sequestered by crops (Grain + Stover + Root) (2019-20) (kg ha^{-1})



4.7 Total Organic Carbon Stock (C_S or TOC-soil) Assessment in soil

Percent soil organic carbon was converted to Total Organic Carbon (TOC) stock (t ha^{-1}) using the following formula...

C_S (t ha^{-1}) = %OC x p x D x 100

Where, p = Bulk density of soil (Mg m^{-3}), and

D = depth of soil (m)

At all depths, Anjan based system was somewhat better than Khejri system and both of them were far better than 'no tree system' regarding C_S. The TOC-soil up to 90 cm depth is 39.33 t ha^{-1} in Anjan system, 37.82 t ha^{-1} in Khejri system and 31.49 t ha^{-1} in 'no tree' system.

4.8 Total Carbon Stock of the system (TOC-system)

Total carbon stock is the sum of all sorts of carbon estimated above...

TOC-system (t ha^{-1}) = C_{AG} + C_{BG} + C_{CB} + C_S

Where, C_{AG} - Above-ground tree biomass (tonne per ha)

C_{BG} - Below-ground tree biomass (tonne per ha)

C_{CB} - Crop biomass (tonne per ha)

C_S - Soil carbon stock (tonne per ha)

The data for the same are represented in table-4.39.

TOC-soil followed a trend in contrary to that of TOC-soil i.e. Khejri > Anjan > sole cropping (no tree). It was 155.26 t ha^{-1} Khejri based system 140.15 t ha^{-1} Anjan based system 86.87 t ha^{-1} 'sole cropping' system. This is because of higher production of crops under Khejri based system.

4.9 Estimation of carbon sequestration potential (CSP)

Carbon sequestration potential (CSP) of system was calculated by multiplying the TOC stock in a system by a factor of 3.67 (Chiemela *et al.*, 2018).

The data for the same are represented in table-4.39.

CSP were calculated as 569.81 t ha^{-1} for Khejri plantation system, 514.34 t ha^{-1} for Anjan plantation system and 318.81 t ha^{-1} for 'sole cropping' system.

4.10 Estimation of carbon trade potential

Carbon trading potential = TOC in system (tonne ha^{-1}) x Price per ton of Carbon

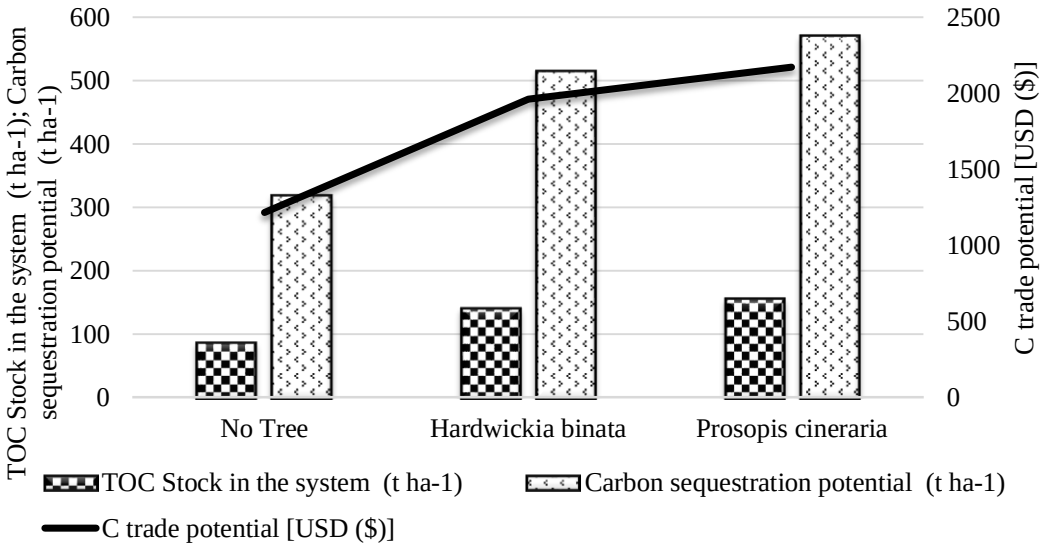
As of now India has not fixed a price; but many companies are using different price of carbon for their internal purposes. Here, we are using the price used by Google i.e. USD 14 per metric ton (or tonne) of carbon which is further converted to Indian Rupee.

1 United States Dollar = 74.89 Indian Rupee (As on 30 Jul, 2020; 3:53 pm UTC).

The data for the same are represented in table-4.39 and fig.4.11 is representing TOC stock (t ha^{-1}), C sequestration potential (t ha^{-1}) and C trade potential (US$) of different agroforestry systems.

Carbon trading potential of the systems, as calculated in Indian Rupee (Rs.), at present is ` 1,62,785.98 for Khejri based system, ` 1,46,937.28 for Anjan based system and ` 91,077.77 for sole cropping.

Fig.-4.11: Long term influence of different agroforestry systems on TOC stock, sequestration potential and C trade potential



This difference among different agroforestry systems regarding carbon sequestration potential and carbon trading potential represents the dominance of trees in agroforestry systems in sequestering higher amounts of carbon, increasing crop yields and simultaneously benefitting farmers in increasing their livelihood.

Table-4.1: Long term influence of crops under different agroforestry systems on bulk density of soil (g cm^{-3})

Depth	Crop	Tree species			Mean	ANOVA		
		No Tree	*H. binata*	*P. Cineraria*		T	C	T×C
0-5 cm	*V. unguiculata* L.	1.43	1.43	1.43	**1.43**	NS	NS	NS
	C. tetragonoloba L.	1.44	1.42	1.43	**1.43**			
	V. radiata L.	1.42	1.43	1.43	**1.43**			
	V. aconitifolia	1.42	1.43	1.44	**1.43**			
	P. glaucum L.	1.44	1.44	1.43	**1.43**			
	Mean	**1.43**	**1.43**	**1 .43**				
5-15 cm	*V. unguiculata* L.	1.43	1.42	1.43	**1.43**	NS	NS	NS
	C. tetragonoloba L.	1.43	1.43	1.43	**1.43**			
	V. radiata L.	1.44	1.43	1.44	**1.44**			
	V. aconitifolia	1.43	1.43	1.44	**1.43**			
	P. glaucum L.	1.43	1.44	1.45	**1.44**			
	Mean	**1.43**	**1.43**	**1.44**				
15-45 cm	*V. unguiculata* L.	1.48	1.47	1.47	**1.47**	NS	NS	NS
	C. tetragonoloba L.	1.46	1.48	1.48	**1.48**			
	V. radiata L.	1.48	1.48	1.48	**1.48**			
	V. aconitifolia	1.47	1.48	1.49	**1.48**			
	P. glaucum L.	1.47	1.48	1.48	**1.48**			
	Mean	**1.47**	**1.48**	**1.48**				
45-90 cm	*V. unguiculata* L.	1.56	1.57	1.55	**1.56**	NS	NS	NS
	C. tetragonoloba L.	1.55	1.57	1.53	**1.55**			
	V. radiata L.	1.56	1.55	1.56	**1.56**			
	V. aconitifolia	1.56	1.55	1.55	**1.55**			
	P. glaucum L.	1.57	1.54	1.54	**1.55**			
	Mean	**1.56**	**1.56**	**1.54**				
0-90 cm	*V. unguiculata* L.	1.56	1.57	1.55	**1.56**	NS	NS	NS
	C. tetragonoloba L.	1.55	1.57	1.53	**1.55**			
	V. radiata L.	1.56	1.55	1.56	**1.56**			
	V. aconitifolia	1.56	1.55	1.55	**1.55**			
	P. glaucum L.	1.57	1.54	1.54	**1.55**			
	Mean	**1.56**	**1.56**	**1.54**				

*significant at $p < 0.05$; NS= non-significant; T –Tree species; C-Crop.

Table-4.2: Long term influence of crops under different agroforestry systems on soil pH (0-15 cm depth)

Crops	Tree Species			**Mean**
	No Tree	*Hardwickia binata*	*Prosopis cineraria*	
Vigna unguiculata L.	7.24	7.39	7.42	**7.35$_{a}$**
Cymopsis tetragonoloba L.	7.45	7.37	7.46	**7.43$_{ab}$**
Vigna radiata L.	7.55	7.28	7.12	**7.32$_{a}$**
Vigna aconitifolia	7.71	7.48	7.58	**7.59$_{c}$**
Pennisetum glaucum L.	7.50	7.52	7.52	**7.52$_{bc}$**
Mean	**7.49$_{A}$**	**7.41$_{A}$**	**7.42$_{A}$**	
CD $_{0.05}$	Tree	Crop	Tree x Crop	
	NS	0.13*	0.22*	

*significant at $p < 0.05$; NS= non-significant; Means followed by the same letters are non-significant ($p < 0.05$)

Table-4.3: Long term influence of crops under different agroforestry systems on electrical conductivity (dS m^{-1}) of soil (0-15 cm depth)

Crop	Tree Species			**Mean**
	No Tree	*Hardwickia binata*	*Prosopis cineraria*	
Vigna unguiculata L.	0.62	0.63	0.63	**0.62$_{a}$**
Cymopsis tetragonoloba L.	0.60	0.62	0.65	**0.62$_{a}$**
Vigna radiata L.	0.60	0.60	0.63	**0.61$_{a}$**
Vigna aconitifolia	0.61	0.63	0.63	**0.63$_{a}$**
Pennisetum glaucum L.	0.66	0.62	0.64	**0.64$_{b}$**
Mean	**0.62$_{A}$**	**0.62$_{A}$**	**0.64$_{B}$**	
CD $_{0.05}$	Tree	Crop	Tree x Crop	
	0.01*	0.01*	0.03*	

*significant at $p < 0.05$; NS= non-significant; Means followed by the same letters are non-significant ($p < 0.05$)

Table-4.4: Long term influence of crops under different agroforestry systems on oxidisable organic carbon (%)

Depth	Crop	Tree species			Mean	ANOVA		
		No Tree	*H. binata*	*P. Cineraria*		T	C	T×C
0-5 cm	*V. unguiculata* L.	0.197	0.276	0.259	**0.244**	0.018*	0.024*	NS
	C. tetragonoloba L.	0.227	0.300	0.262	**0.263**			
	V. radiata L.	0.256	0.272	0.271	**0.266**			
	V. aconitifolia	0.240	0.286	0.260	**0.262**			
	P. glaucum L.	0.187	0.265	0.256	**0.236**			
	Mean	**0.221**	**0.280**	**0.262**				
5-15 cm	*V. unguiculata* L.	0.273	0.300	0.249	**0.274**	0.017*	0.022*	NS
	C. tetragonoloba L.	0.252	0.289	0.300	**0.280**			
	V. radiata L.	0.253	0.278	0.251	**0.261**			
	V. aconitifolia	0.228	0.279	0.290	**0.266**			
	P. glaucum L.	0.222	0.272	0.235				
	Mean	**0.246**	**0.284**	**0.265**	**0.265**			
15-45 cm	*V. unguiculata* L.	0.157	0.215	0.169	**0.180**	0.019*	NS	NS
	C. tetragonoloba L.	0.159	0.178	0.188	**0.175**			
	V. radiata L.	0.139	0.196	0.178	**0.171**			
	V. aconitifolia	0.131	0.217	0.176	**0.174**			
	P. glaucum L.	0.124	0.194	0.173	**0.164**			
	Mean	**0.142**	**0.200**	**0.177**				
45-90 cm	*V. unguiculata* L.	0.117	0.131	0.126	**0.125**	0.013*	NS	NS
	C. tetragonoloba L.	0.096	0.141	0.128	**0.122**			
	V. radiata L.	0.103	0.135	0.118	**0.119**			
	V. aconitifolia	0.104	0.123	0.120	**0.116**			
	P. glaucum L.	0.092	0.105	0.126	**0.108**			
	Mean	**0.103**	**0.127**	**0.124**				
0-90 cm	*V. unguiculata* L.	0.178	0.224	0.191	**0.197**	0.008*	0.011*	NS
	C. tetragonoloba L.	0.165	0.219	0.210	**0.198**			
	V. radiata L.	0.179	0.217	0.193	**0.196**			
	V. aconitifolia	0.173	0.221	0.207	**0.200**			
	P. glaucum L.	0.136	0.206	0.170	**0.171**			
	Mean	**0.166**	**0.217**	**0.194**				

*significant at $p < 0.05$; NS= non-significant; T –Tree species; C-Crop.

Table-4.5: Long term influence of crops under different agroforestry systems on soil available N (kg ha^{-1}) (0-15 cm depth)

Crop	Tree Species			Mean
	No Tree	*Hardwickia binata*	*Prosopis cineraria*	
Vigna unguiculata L.	83.63	83.63	108.71	**91.99$_a$**
Cymopsis tetragonoloba L.	71.08	83.63	117.08	**90.60$_a$**
Vigna radiata L.	79.45	91.99	96.17	**89.20$_a$**
Vigna aconitifolia	96.17	96.17	142.17	**111.50$_a$**
Pennisetum glaucum L.	87.81	66.90	100.35	**85.02$_a$**
Mean	**83.63$_A$**	**84.46$_A$**	**112.90$_B$**	
CD $_{0.05}$	Tree	Crop	Tree x Crop	
	17.95*	NS	NS	

*significant at $p < 0.05$; NS= non-significant; Means followed by the same letters are non-significant ($p < 0.05$)

Table-4.6: Long term influence of crops under different agroforestry systems on soil available P (kg ha^{-1}) (0-15 cm depth)

Crop	Tree Species			Mean
	No Tree	*Hardwickia binata*	*Prosopis cineraria*	
Vigna unguiculata L.	12.24	6.14	7.74	**8.71**
Cymopsis tetragonoloba L.	8.51	13.25	9.64	**10.46**
Vigna radiata L.	5.61	11.47	15.68	**10.92**
Vigna aconitifolia	8.87	8.75	5.67	**7.76**
Pennisetum glaucum L.	5.61	9.87	9.40	**8.29**
Mean	**8.17**	**9.90**	**9.62**	
CD $_{0.05}$	Tree	Crop	Tree x Crop	
	NS	NS	NS	

*significant at $p < 0.05$; NS= non-significant

Table-4.7: Long term influence of crops under different agroforestry systems on soil available K (kg ha^{-1}) (0-15 cm depth)

Crop	Tree Species			Mean
	No Tree	*Hardwickia binata*	*Prosopis cineraria*	
Vigna unguiculata L.	184.58	240.13	209.66	**211.46$_a$**
Cymopsis tetragonoloba L.	186.37	215.04	256.26	**219.22$_a$**
Vigna radiata L.	186.37	215.04	209.66	**203.69$_a$**
Vigna aconitifolia	186.37	211.46	231.17	**209.66$_a$**
Pennisetum glaucum L.	213.25	224.00	184.58	**207.27$_a$**
Mean	**191.39$_A$**	**221.13$_B$**	**218.27$_B$**	
CD $_{0.05}$	Tree	Crop	Tree x Crop	
	25.03*	NS	NS	

*significant at $p < 0.05$; NS= non-significant

Table-4.8: Long term influence of crops under different agroforestry systems on hot water soluble carbon (HWC) (ug C g^{-1})

Depth	Crop	Tree species			Mean	ANOVA		
		No Tree	*H. binata*	*P. Cineraria*		T	C	T×C
0-5 cm	*V. unguiculata* L.	332.71	402.23	352.57	**362.50**	44.33*	NS	NS
	C. tetragonoloba L.	283.05	372.43	432.02	**362.50**			
	V. radiata L.	263.18	412.16	402.23	**359.19**			
	V. aconitifolia	273.12	432.02	422.09	**375.74**			
	P. glaucum L.	263.18	402.23	352.57	**339.33**			
	Mean	**283.05**	**404.21**	**392.29**				
5-15 cm	*V. unguiculata* L.	317.55	300.15	317.55	**311.75**	37.13*	47.93*	NS
	C. tetragonoloba L.	247.95	334.95	334.95	**305.95**			
	V. radiata L.	239.25	361.05	213.15	**271.15**			
	V. aconitifolia	247.95	326.25	247.95	**274.05**			
	P. glaucum L.	204.45	308.85	247.95	**253.75**			
	Mean	**251.43**	**326.25**	**272.31**				
15-45 cm	*V. unguiculata* L.	160.95	160.95	213.15	**178.35**	NS	NS	NS
	C. tetragonoloba L.	160.95	187.05	187.05	**178.35**			
	V. radiata L.	143.55	178.35	187.05	**169.65**			
	V. aconitifolia	160.95	256.65	178.35	**198.65**			
	P. glaucum L.	152.25	213.15	204.45	**189.95**			
	Mean	**155.73**	**199.23**	**194.01**				
45-90 cm	*V. unguiculata* L.	143.55	169.65	204.45	**172.55**	34.65*	NS	NS
	C. tetragonoloba L.	143.55	117.45	160.95	**140.65**			
	V. radiata L.	82.65	213.15	152.25	**149.35**			
	V. aconitifolia	65.25	213.15	169.65	**149.35**			
	P. glaucum L.	108.75	204.45	160.95	**158.05**			
	Mean	**108.75**	**183.57**	**169.65**				
0-90 cm	*V. unguiculata* L.	238.68	256.06	271.92	**255.56**	27.59*	NS	NS
	C. tetragonoloba L.	208.87	255.14	278.74	**247.58**			
	V. radiata L.	182.15	284.65	238.66	**235.15**			
	V. aconitifolia	186.81	302.66	254.50	**247.99**			
	P. glaucum L.	177.19	260.74	227.50	**221.81**			
	Mean	**198.74**	**271.85**	**254.27**				

*significant at $p < 0.05$; NS= non-significant; T –Tree species; C-Crop

Table -4.9: Long term influence of crops under different agroforestry systems on hot water soluble carbohydrate (HWCh) (ug C g^{-1})

Depth	Crop	Tree species			Mean	ANOVA		
		No Tree	*H. binata*	*P. Cineraria*		T	C	T×C
0-5 cm	*V. unguiculata* L.	33.86	41.09	37.45	**37.46**	3.23*	4.17*	NS
	C. tetragonoloba L.	32.78	41.29	38.99	**37.69**			
	V. radiata L.	30.57	36.73	36.27	**34.52**			
	V. aconitifolia	33.09	38.83	37.70	**36.54**			
	P. glaucum L.	28.73	30.78	31.19	**30.23**			
	Mean	**31.80**	**37.74**	**36.32**				
5-15 cm	*V. unguiculata* L.	29.96	40.37	34.98	**35.10**	3.49*	4.51*	NS
	C. tetragonoloba L.	31.14	41.35	37.96	**36.81**			
	V. radiata L.	29.14	36.32	34.57	**33.34**			
	V. aconitifolia	31.39	36.73	38.22	**35.45**			
	P. glaucum L.	25.85	29.55	30.01	**28.47**			
	Mean	**29.50**	**36.86**	**35.15**				
15-45 cm	*V. unguiculata* L.	18.16	19.54	15.54	**17.75**	NS	NS	NS
	C. tetragonoloba L.	13.64	19.29	17.34	**16.76**			
	V. radiata L.	14.82	18.47	16.77	**16.69**			
	V. aconitifolia	14.77	18.11	16.57	**16.48**			
	P. glaucum L.	15.34	17.44	17.13	**16.64**			
	Mean	**15.35**	**18.57**	**16.67**				
45-90 cm	*V. unguiculata* L.	7.08	14.72	14.16	**11.99**	1.54*	NS	NS
	C. tetragonoloba L.	12.36	15.39	13.59	**13.78**			
	V. radiata L.	12.52	14.11	13.13	**13.25**			
	V. aconitifolia	10.26	14.88	12.21	**12.45**			
	P. glaucum L.	12.00	14.47	12.41	**12.96**			
	Mean	**10.84**	**14.71**	**13.10**				
0-90 cm	*V. unguiculata* L.	22.26	28.93	25.53	**25.57**	2.13*	2.74*	NS
	C. tetragonoloba L.	22.48	29.32	26.96	**26.25**			
	V. radiata L.	21.76	26.40	25.18	**24.45**			
	V. aconitifolia	22.37	27.13	26.17	**25.22**			
	P. glaucum L.	20.48	23.05	22.68	**22.07**			
	Mean	**21.87**	**26.97**	**25.30**				

*significant at $p < 0.05$; NS= non-significant; T –Tree species; C-Crop

Table-4.10: Long term influence of crops under different agroforestry systems on total organic carbon (TOC) (%) in soil

Depth	Crop	Tree species			Mean	ANOVA		
		No Tree	*H. binata*	*P. Cineraria*		T	C	T×C
0-5 cm	*V. unguiculata* L.	0.333	0.359	0.405	**0.366**	0.023*	0.030*	NS
	C. tetragonoloba L.	0.343	0.406	0.378	**0.376**			
	V. radiata L.	0.337	0.412	0.388	**0.379**			
	V. aconitifolia	0.302	0.405	0.379	**0.362**			
	P. glaucum L.	0.250	0.364	0.338	**0.317**			
	Mean	**0.313**	**0.389**	**0.378**				
5-15 cm	*V. unguiculata* L.	0.391	0.423	0.380	**0.398**	0.016*	0.020*	NS
	C. tetragonoloba L.	0.391	0.423	0.419	**0.411**			
	V. radiata L.	0.351	0.395	0.412	**0.386**			
	V. aconitifolia	0.345	0.408	0.416	**0.390**			
	P. glaucum L.	0.290	0.362	0.347	**0.333**			
	Mean	**0.354**	**0.402**	**0.395**				
15-45 cm	*V. unguiculata* L.	0.247	0.278	0.287	**0.271**	0.011*	0.014*	NS
	C. tetragonoloba L.	0.263	0.278	0.287	**0.276**			
	V. radiata L.	0.268	0.329	0.309	**0.302**			
	V. aconitifolia	0.262	0.324	0.302	**0.296**			
	P. glaucum L.	0.239	0.270	0.255	**0.255**			
	Mean	**0.256**	**0.296**	**0.288**				
45-90 cm	*V. unguiculata* L.	0.198	0.250	0.238	**0.229**	0.011*	0.014*	NS
	C. tetragonoloba L.	0.183	0.265	0.231	**0.226**			
	V. radiata L.	0.168	0.239	0.238	**0.215**			
	V. aconitifolia	0.191	0.258	0.260	**0.236**			
	P. glaucum L.	0.176	0.250	0.230	**0.219**			
	Mean	**0.183**	**0.252**	**0.239**				
0-90 cm	*V. unguiculata* L.	0.293	0.327	0.328	**0.316**	0.011*	0.014*	NS
	C. tetragonoloba L.	0.295	0.343	0.329	**0.322**			
	V. radiata L.	0.281	0.344	0.337	**0.320**			
	V. aconitifolia	0.275	0.348	0.339	**0.321**			
	P. glaucum L.	0.239	0.311	0.293	**0.281**			
	Mean	**0.276**	**0.335**	**0.325**				

*significant at $p < 0.05$; NS= non-significant; T –Tree species; C-Crop

Table-4.11: Long term influence of crops under different agroforestry systems on TOC stock (t ha^{-1}) in soil

Depth	Crop	Tree species			Mean	ANOVA		
		No Tree	*H. binata*	*P. Cineraria*		T	C	T×C
0-5 cm	*V. unguiculata* L.	2.37	2.56	2.89	**2.61**	0.17*	0.21*	NS
	C. tetragonoloba L.	2.46	2.89	2.70	**2.68**			
	V. radiata L.	2.39	2.95	2.78	**2.71**			
	V. aconitifolia	2.14	2.90	2.72	**2.59**			
	P. glaucum L.	1.79	2.61	2.41	**2.27**			
	Mean	**2.23**	**2.78**	**2.70**				
5-15 cm	*V. unguiculata* L.	5.60	6.02	5.45	**5.69**	0.22*	0.29*	0.50*
	C. tetragonoloba L.	5.61	6.05	6.00	**5.89**			
	V. radiata L.	5.04	5.65	5.95	**5.55**			
	V. aconitifolia	4.95	5.83	6.00	**5.59**			
	P. glaucum L.	4.17	5.19	5.02	**4.79**			
	Mean	**5.08**	**5.75**	**5.68**				
15-45 cm	*V. unguiculata* L.	10.99	12.23	12.63	**11.95**	0.51*	0.66*	NS
	C. tetragonoloba L.	11.54	12.31	12.77	**12.21**			
	V. radiata L.	11.92	14.66	13.76	**13.45**			
	V. aconitifolia	11.56	14.39	13.46	**13.14**			
	P. glaucum L.	10.55	11.99	11.36	**11.30**			
	Mean	**11.31**	**13.12**	**12.80**				
45-90 cm	*V. unguiculata* L.	13.94	17.70	16.61	**16.08**	0.78*	1.01*	NS
	C. tetragonoloba L.	12.79	18.70	15.91	**15.80**			
	V. radiata L.	11.81	16.71	16.64	**15.06**			
	V. aconitifolia	13.40	18.02	18.10	**16.51**			
	P. glaucum L.	12.40	17.27	15.94	**15.20**			
	Mean	**12.87**	**17.68**	**16.64**				
0-90 cm	*V. unguiculata* L.	32.90	38.51	37.58	**36.33**	1.16*	1.50*	NS
	C. tetragonoloba L.	32.41	39.96	37.39	**36.58**			
	V. radiata L.	31.17	39.97	39.13	**36.76**			
	V. aconitifolia	32.05	41.14	40.28	**37.82**			
	P. glaucum L.	28.91	37.06	34.73	**33.57**			
	Mean	**31.49**	**39.33**	**37.82**				

*significant at $p < 0.05$; NS= non-significant; T –Tree species; C-Crop

Table-4.12: Long term influence of crops under different agroforestry systems on various fractions (%) of organic carbon in 0-5 cm soil

Depth	Crop	Tree species			Mean	ANOVA		
		No Tree	*H. binata*	*P. Cineraria*		T	C	T×C
Very Labile	*V. unguiculata* L.	0.121	0.177	0.143	**0.147**	0.012*	0.015*	NS
	C. tetragonoloba L.	0.131	0.179	0.188	**0.166**			
	V. radiata L.	0.154	0.196	0.186	**0.179**			
	V. aconitifolia	0.158	0.181	0.167	**0.169**			
	P. glaucum L.	0.114	0.160	0.158	**0.144**			
	Mean	**0.135**	**0.179**	**0.168**				
Labile	*V. unguiculata* L.	0.041	0.061	0.085	**0.062**	0.019*	NS	NS
	C. tetragonoloba L.	0.056	0.056	0.046	**0.053**			
	V. radiata L.	0.035	0.041	0.051	**0.042**			
	V. aconitifolia	0.029	0.055	0.062	**0.048**			
	P. glaucum L.	0.037	0.082	0.069	**0.063**			
	Mean	**0.040**	**0.059**	**0.063**				
Less Labile	*V. unguiculata* L.	0.035	0.038	0.032	**0.035**	0.012*	NS	NS
	C. tetragonoloba L.	0.040	0.065	0.028	**0.044**			
	V. radiata L.	0.068	0.035	0.034	**0.046**			
	V. aconitifolia	0.053	0.050	0.031	**0.045**			
	P. glaucum L.	0.036	0.023	0.028	**0.029**			
	Mean	**0.046**	**0.042**	**0.031**				
Non Labile	*V. unguiculata* L.	0.136	0.083	0.146	**0.122**	NS	NS	NS
	C. tetragonoloba L.	0.116	0.105	0.116	**0.113**			
	V. radiata L.	0.080	0.140	0.117	**0.112**			
	V. aconitifolia	0.062	0.119	0.119	**0.100**			
	P. glaucum L.	0.063	0.099	0.082	**0.081**			
	Mean	**0.091**	**0.109**	**0.116**				

*significant at $p < 0.05$; NS= non-significant; T –Tree species; C-Crop

Table-4.13: Long term influence of crops under different agroforestry systems on various fractions (%) of organic carbon in 5-15 cm soil

Depth	Crop	Tree species			Mean	ANOVA		
		No Tree	*H. binata*	*P. Cineraria*		T	C	T×C
Very Labile	*V. unguiculata* L.	0.102	0.112	0.091	**0.101**	0.013*	NS	NS
	C. tetragonoloba L.	0.088	0.122	0.131	**0.114**			
	V. radiata L.	0.088	0.110	0.096	**0.098**			
	V. aconitifolia	0.062	0.108	0.114	**0.095**			
	P. glaucum L.	0.085	0.095	0.095	**0.091**			
	Mean	**0.085**	**0.109**	**0.105**				
Labile	*V. unguiculata* L.	0.041	0.081	0.054	**0.059**	0.017*	NS	NS
	C. tetragonoloba L.	0.044	0.080	0.048	**0.057**			
	V. radiata L.	0.054	0.045	0.082	**0.060**			
	V. aconitifolia	0.048	0.060	0.052	**0.054**			
	P. glaucum L.	0.036	0.090	0.044	**0.057**			
	Mean	**0.045**	**0.071**	**0.056**				
Less Labile	*V. unguiculata* L.	0.130	0.107	0.105	**0.114**	NS	NS	NS
	C. tetragonoloba L.	0.120	0.087	0.121	**0.109**			
	V. radiata L.	0.112	0.123	0.073	**0.103**			
	V. aconitifolia	0.118	0.111	0.124	**0.118**			
	P. glaucum L.	0.101	0.087	0.096	**0.095**			
	Mean	**0.116**	**0.103**	**0.104**				
Non Labile	*V. unguiculata* L.	0.118	0.123	0.131	**0.124**	NS	NS	NS
	C. tetragonoloba L.	0.139	0.134	0.118	**0.131**			
	V. radiata L.	0.098	0.117	0.161	**0.125**			
	V. aconitifolia	0.117	0.128	0.126	**0.124**			
	P. glaucum L.	0.069	0.089	0.112	**0.090**			
	Mean	**0.108**	**0.118**	**0.130**				

*significant at $p < 0.05$; NS= non-significant; T –Tree species; C-Crop

Table-4.14: Long term influence of crops under different agroforestry systems on various fractions (%) of organic carbon in 15-45 cm soil

Depth	Crop	Tree species			Mean	ANOVA		
		No Tree	*H. binata*	*P. Cineraria*		T	C	T×C
Very Labile	*V. unguiculata* L.	0.048	0.087	0.087	**0.074**	0.010*	NS	NS
	C. tetragonoloba L.	0.050	0.091	0.074	**0.072**			
	V. radiata L.	0.039	0.082	0.095	**0.072**			
	V. aconitifolia	0.058	0.081	0.108	**0.083**			
	P. glaucum L.	0.046	0.100	0.081	**0.076**			
	Mean	**0.048**	**0.088**	**0.089**				
Labile	*V. unguiculata* L.	0.037	0.049	0.027	**0.038**	NS	NS	NS
	C. tetragonoloba L.	0.046	0.053	0.039	**0.046**			
	V. radiata L.	0.072	0.056	0.041	**0.056**			
	V. aconitifolia	0.024	0.054	0.031	**0.036**			
	P. glaucum L.	0.037	0.042	0.043	**0.041**			
	Mean	**0.043**	**0.051**	**0.036**				
Less Labile	*V. unguiculata* L.	0.072	0.030	0.052	**0.051**	NS	NS	NS
	C. tetragonoloba L.	0.061	0.035	0.075	**0.057**			
	V. radiata L.	0.029	0.058	0.043	**0.043**			
	V. aconitifolia	0.048	0.083	0.037	**0.056**			
	P. glaucum L.	0.042	0.051	0.049	**0.048**			
	Mean	**0.050**	**0.051**	**0.051**				
Non Labile	*V. unguiculata* L.	0.090	0.112	0.121	**0.108**	NS	0.027*	NS
	C. tetragonoloba L.	0.106	0.099	0.098	**0.101**			
	V. radiata L.	0.127	0.133	0.131	**0.130**			
	V. aconitifolia	0.132	0.106	0.125	**0.121**			
	P. glaucum L.	0.115	0.076	0.081	**0.091**			
	Mean	**0.114**	**0.105**	**0.111**				

*significant at $p < 0.05$; NS= non-significant; T –Tree species; C-Crop

Table-4.15: Long term influence of crops under different agroforestry systems on various fractions (%) of organic carbon in 45-90 cm soil

Depth	Crop	Tree species			Mean	ANOVA		
		No Tree	*H. binata*	*P. Cineraria*		T	C	T×C
Very Labile	*V. unguiculata* L.	0.019	0.067	0.059	**0.048**	0.007*	NS	0.016*
	C. tetragonoloba L.	0.022	0.067	0.052	**0.047**			
	V. radiata L.	0.031	0.053	0.045	**0.043**			
	V. aconitifolia	0.016	0.060	0.059	**0.045**			
	P. glaucum L.	0.030	0.045	0.045	**0.040**			
	Mean	**0.024**	**0.058**	**0.052**				
Labile	*V. unguiculata* L.	0.023	0.023	0.011	**0.019**	NS	NS	NS
	C. tetragonoloba L.	0.035	0.016	0.018	**0.023**			
	V. radiata L.	0.025	0.019	0.026	**0.023**			
	V. aconitifolia	0.030	0.023	0.011	**0.021**			
	P. glaucum L.	0.024	0.030	0.026	**0.027**			
	Mean	**0.027**	**0.022**	**0.018**				
Less Labile	*V. unguiculata* L.	0.075	0.041	0.056	**0.057**	NS	NS	NS
	C. tetragonoloba L.	0.039	0.058	0.059	**0.052**			
	V. radiata L.	0.047	0.063	0.047	**0.052**			
	V. aconitifolia	0.058	0.040	0.051	**0.050**			
	P. glaucum L.	0.038	0.030	0.055	**0.041**			
	Mean	**0.051**	**0.046**	**0.054**				
Non Labile	*V. unguiculata* L.	0.082	0.119	0.112	**0.104**	0.018*	NS	NS
	C. tetragonoloba L.	0.087	0.125	0.102	**0.105**			
	V. radiata L.	0.065	0.104	0.120	**0.096**			
	V. aconitifolia	0.086	0.134	0.140	**0.120**			
	P. glaucum L.	0.083	0.145	0.104	**0.111**			
	Mean	**0.081**	**0.125**	**0.116**				

*significant at $p < 0.05$; NS= non-significant; T –Tree species; C-Crop

Table-4.16: Long term influence of crops under different agroforestry systems on various fractions (%) of organic carbon in 0-90 cm soil

Depth	Crop	Tree species			Mean	ANOVA		
		No Tree	*H. binata*	*P. Cineraria*		T	C	T×C
Very Labile	*V. unguiculata* L.	0.072	0.111	0.095	**0.093**	0.005*	0.007*	NS
	C. tetragonoloba L.	0.073	0.115	0.111	**0.100**			
	V. radiata L.	0.078	0.110	0.106	**0.098**			
	V. aconitifolia	0.074	0.108	0.112	**0.098**			
	P. glaucum L.	0.069	0.100	0.095	**0.088**			
	Mean	**0.073**	**0.109**	**0.104**				
Labile	*V. unguiculata* L.	0.036	0.053	0.044	**0.044**	0.006*	NS	0.014*
	C. tetragonoloba L.	0.045	0.051	0.038	**0.045**			
	V. radiata L.	0.046	0.040	0.050	**0.045**			
	V. aconitifolia	0.033	0.048	0.039	**0.040**			
	P. glaucum L.	0.033	0.061	0.046	**0.047**			
	Mean	**0.039**	**0.051**	**0.043**				
Less Labile	*V. unguiculata* L.	0.078	0.054	0.061	**0.064**	NS	NS	NS
	C. tetragonoloba L.	0.065	0.061	0.071	**0.066**			
	V. radiata L.	0.064	0.070	0.049	**0.061**			
	V. aconitifolia	0.069	0.071	0.061	**0.067**			
	P. glaucum L.	0.054	0.048	0.057	**0.053**			
	Mean	**0.066**	**0.061**	**0.060**				
Non Labile	*V. unguiculata* L.	0.107	0.109	0.128	**0.114**	0.014*	NS	NS
	C. tetragonoloba L.	0.112	0.116	0.109	**0.112**			
	V. radiata L.	0.093	0.123	0.132	**0.116**			
	V. aconitifolia	0.099	0.122	0.128	**0.116**			
	P. glaucum L.	0.082	0.102	0.095	**0.093**			
	Mean	**0.099**	**0.115**	**0.118**				

*significant at $p < 0.05$; NS= non-significant; T –Tree species; C-Crop

Table-4.17: Long term influence of different tree species on active and passive carbon pools (t ha^{-1}) at 0-5 cm and 5-15 cm soil depths

Depth	C pool	Crop	Tree species			Mean	ANOVA		
			No tree	*H. binata*	*P. cineraria*		T	C	TxC
0-5cm	Active pool	*V. unguiculata* L.	1.16	1.69	1.62	**1.49**	0.10*	NS	NS
		C. tetragonoloba L.	1.34	1.68	1.67	**1.56**			
		V. radiata L.	1.34	1.69	1.70	**1.58**			
		V. aconitifolia	1.32	1.69	1.64	**1.55**			
		P. glaucum L.	1.09	1.74	1.62	**1.48**			
		Mean	**1.25**	**1.70**	**1.65**				
	Passive	*V. unguiculata* L.	1.22	0.87	1.27	**1.12**	NS	0.24*	NS
		C. tetragonoloba L.	1.12	1.21	1.03	**1.12**			
		V. radiata L.	1.06	1.25	1.08	**1.13**			
		V. aconitifolia	0.81	1.21	1.08	**1.04**			
		P. glaucum L.	0.71	0.87	0.79	**0.79**			
		Mean	**0.98**	**1.08**	**1.05**				
5-15cm	Active pool	*V. unguiculata* L.	2.04	2.75	2.07	**2.29**	0.21*	NS	0.46*
		C. tetragonoloba L.	1.89	2.88	2.58	**2.45**			
		V. radiata L.	2.03	2.22	2.57	**2.27**			
		V. aconitifolia	1.58	2.41	2.39	**2.13**			
		P. glaucum L.	1.74	2.66	2.01	**2.13**			
		Mean	**1.86**	**2.58**	**2.32**				
	Passive	*V. unguiculata* L.	3.56	3.27	3.38	**3.41**	NS	0.40*	NS
		C. tetragonoloba L.	3.72	3.17	3.43	**3.44**			
		V. radiata L.	3.01	3.43	3.37	**3.27**			
		V. aconitifolia	3.37	3.42	3.60	**3.47**			
		P. glaucum L.	2.43	2.54	3.02	**2.66**			
		Mean	**3.22**	**3.17**	**3.36**				

Table-4.18: Long term influence of different tree species on active and passive carbon pools (t ha^{-1}) at 15-45 cm and 45-90 cm soil depths

Depth	C pool	Crop	Tree species			Mean	ANOVA		
			No tree	*H. binata*	*P. cineraria*		T	C	TxC
15-45 cm	Active C pool	V. unguiculata L.	3.79	5.96	5.00	**4.92**	0.48*	NS	NS
		C. tetragonoloba L.	4.22	6.37	5.07	**5.22**			
		V. radiata L.	3.43	6.16	6.02	**5.20**			
		V. aconitifolia	3.63	6.01	6.23	**5.29**			
		P. glaucum L.	3.64	6.32	5.54	**5.17**			
		Mean	**3.74**	**6.16**	**5.57**				
	Passive C pool	V. unguiculata L.	7.20	6.26	7.63	**7.03**	NS	0.69*	1.20*
		C. tetragonoloba L.	7.32	5.95	7.71	**6.99**			
		V. radiata L.	8.50	8.50	7.74	**8.25**			
		V. aconitifolia	7.93	8.38	7.23	**7.85**			
		P. glaucum L.	6.91	5.67	5.82	**6.13**			
		Mean	**7.57**	**6.95**	**7.23**				
45-90cm	Active C pool	V. unguiculata L.	2.96	6.35	4.86	**4.72**	0.85*	NS	NS
		C. tetragonoloba L.	3.25	5.85	4.79	**4.63**			
		V. radiata L.	3.64	6.35	5.44	**5.14**			
		V. aconitifolia	3.24	5.81	4.83	**4.63**			
		P. glaucum L.	4.22	5.17	5.66	**5.02**			
		Mean	**3.46**	**5.91**	**5.11**				
	Passive C pool	V. unguiculata L.	11.17	11.35	11.75	**11.42**	1.07*	NS	NS
		C. tetragonoloba L.	9.55	12.85	11.12	**11.17**			
		V. radiata L.	8.93	11.68	11.69	**10.77**			
		V. aconitifolia	10.16	12.21	13.27	**11.88**			
		P. glaucum L.	8.56	12.10	11.03	**10.56**			
		Mean	**9.67**	**12.04**	**11.77**				

Table-4.19: Long term influence of crops under different agroforestry systems on Labiality Index (LI) of SOC

Depth	Crop	Tree species			Mean	ANOVA		
		No Tree	*H. binata*	*P. Cineraria*		T	C	T×C
0-5 cm	*V. unguiculata* L.	1.451	1.920	1.551	**1.641**	NS	NS	NS
	C. tetragonoloba L.	1.524	1.764	1.809	**1.699**			
	V. radiata L.	1.796	1.725	1.792	**1.771**			
	V. aconitifolia	1.932	1.719	1.731	**1.794**			
	P. glaucum L.	1.847	1.837	1.896	**1.860**			
	Mean	**1.710**	**1.793**	**1.756**				
5-15 cm	*V. unguiculata* L.	1.288	1.434	1.270	**1.330**	NS	NS	NS
	C. tetragonoloba L.	1.214	1.447	1.459	**1.373**			
	V. radiata L.	1.419	1.377	1.275	**1.357**			
	V. aconitifolia	1.159	1.363	1.369	**1.297**			
	P. glaucum L.	1.477	1.524	1.350	**1.450**			
	Mean	**1.311**	**1.429**	**1.345**				
15-45 cm	*V. unguiculata* L.	1.174	1.574	1.289	**1.346**	0.094*	0.121*	NS
	C. tetragonoloba L.	1.160	1.484	1.373	**1.339**			
	V. radiata L.	0.881	1.269	1.265	**1.138**			
	V. aconitifolia	1.030	1.338	1.378	**1.249**			
	P. glaucum L.	1.057	1.618	1.375	**1.350**			
	Mean	**1.060**	**1.457**	**1.336**				
45-90 cm	*V. unguiculata* L.	0.905	1.159	1.072	**1.045**	NS	NS	NS
	C. tetragonoloba L.	0.909	1.096	1.080	**1.028**			
	V. radiata L.	1.163	1.333	1.071	**1.189**			
	V. aconitifolia	0.859	1.032	0.954	**0.948**			
	P. glaucum L.	1.081	0.909	1.220	**1.070**			
	Mean	**0.983**	**1.106**	**1.079**				
0-90 cm	*V. unguiculata* L.	0.178	0.224	0.191	**0.197**	0.048*	0.062*	NS
	C. tetragonoloba L.	0.165	0.219	0.210	**0.198**			
	V. radiata L.	0.179	0.217	0.193	**0.196**			
	V. aconitifolia	0.173	0.221	0.207	**0.200**			
	P. glaucum L.	0.136	0.206	0.170	**0.171**			
	Mean	**0.166**	**0.217**	**0.194**				

*significant at $p < 0.05$; NS= non-significant; T –Tree species; C-Crop

Table-4.20: Long term influence of crops under different agroforestry systems on Recalcitrance Index-1 (RI-1) of SOC

Depth	Crop	Tree species			Mean	ANOVA		
		No Tree	*H. binata*	*P. Cineraria*		T	C	T×C
0-5 cm	*V. unguiculata* L.	1.07	0.52	0.79	0.79	NS	NS	NS
	C. tetragonoloba L.	0.86	0.74	0.62	0.74			
	V. radiata L.	0.78	0.75	0.64	0.72			
	V. aconitifolia	0.62	0.73	0.66	0.67			
	P. glaucum L.	0.64	0.51	0.49	0.55			
	Mean	0.79	0.65	0.64	0.69			
5-15 cm	*V. unguiculata* L.	1.76	1.21	1.64	1.53	0.26*	NS	NS
	C. tetragonoloba L.	2.04	1.12	1.39	1.52			
	V. radiata L.	1.52	1.55	1.33	1.47			
	V. aconitifolia	2.13	1.42	1.51	1.69			
	P. glaucum L.	1.45	1.00	1.51	1.32			
	Mean	1.78	1.26	1.48	1.51			
15-45 cm	*V. unguiculata* L.	1.96	1.05	1.54	1.51	0.19*	0.43*	NS
	C. tetragonoloba L.	1.75	0.96	1.54	1.42			
	V. radiata L.	1.41	1.41	1.29	1.37			
	V. aconitifolia	2.22	1.41	1.16	1.60			
	P. glaucum L.	1.95	0.91	1.08	1.31			
	Mean	1.86	1.15	1.32	1.44			
45-90 cm	*V. unguiculata* L.	3.84	1.88	2.47	2.73	NS	NS	NS
	C. tetragonoloba L.	2.36	2.25	2.35	2.32			
	V. radiata L.	2.00	2.33	2.60	2.31			
	V. aconitifolia	3.18	2.17	2.79	2.71			
	P. glaucum L.	2.40	2.47	2.25	2.38			
	Mean	2.76	2.22	2.49	2.49			
0-90 cm	*V. unguiculata* L.	2.16	1.16	1.61	1.64	0.08*	0.10*	NS
	C. tetragonoloba L.	1.75	1.27	1.47	1.50			
	V. radiata L.	1.43	1.51	1.46	1.47			
	V. aconitifolia	2.04	1.43	1.53	1.67			
	P. glaucum L.	1.61	1.22	1.33	1.39			
	Mean	1.80	1.32	1.48	1.53			

*significant at $p < 0.05$; NS= non-significant; T –Tree species; C-Crop

Table-4.21: Long term influence of crops under different agroforestry systems on Recalcitrance Index-2 (RI-2) of SOC

Depth	Crop	Tree species			Mean	ANOVA		
		No Tree	*H. binata*	*P. Cineraria*		T	C	T×C
0-5 cm	*V. unguiculata* L.	0.405	0.233	0.361	0.333	NS	NS	NS
	C. tetragonoloba L.	0.325	0.259	0.307	0.297			
	V. radiata L.	0.231	0.334	0.301	0.289			
	V. aconitifolia	0.206	0.291	0.315	0.271			
	P. glaucum L.	0.226	0.271	0.245	0.247			
	Mean	0.279	0.278	0.306	0.287			
5-15 cm	*V. unguiculata* L.	0.303	0.289	0.347	0.313	NS	NS	NS
	C. tetragonoloba L.	0.353	0.318	0.283	0.318			
	V. radiata L.	0.257	0.295	0.391	0.314			
	V. aconitifolia	0.340	0.315	0.303	0.319			
	P. glaucum L.	0.236	0.248	0.323	0.269			
	Mean	0.298	0.293	0.329	0.307			
15-45 cm	*V. unguiculata* L.	0.361	0.405	0.421	0.396	0.070*	NS	NS
	C. tetragonoloba L.	0.400	0.356	0.341	0.366			
	V. radiata L.	0.476	0.402	0.420	0.433			
	V. aconitifolia	0.507	0.328	0.415	0.417			
	P. glaucum L.	0.478	0.283	0.318	0.360			
	Mean	0.444	0.355	0.383	0.394			
45-90 cm	*V. unguiculata* L.	0.405	0.474	0.471	0.450	NS	NS	NS
	C. tetragonoloba L.	0.470	0.470	0.444	0.461			
	V. radiata L.	0.381	0.434	0.503	0.439			
	V. aconitifolia	0.455	0.521	0.538	0.505			
	P. glaucum L.	0.473	0.574	0.444	0.497			
	Mean	0.437	0.495	0.480	0.470			
0-90 cm	*V. unguiculata* L.	0.368	0.350	0.400	0.373	NS	NS	NS
	C. tetragonoloba L.	0.387	0.351	0.344	0.361			
	V. radiata L.	0.336	0.366	0.404	0.369			
	V. aconitifolia	0.377	0.364	0.393	0.378			
	P. glaucum L.	0.353	0.344	0.332	0.343			
	Mean	0.364	0.355	0.374	0.365			

*significant at $p < 0.05$; NS= non-significant; T –Tree species; C-Crop

Table-4.22: Long term influence of crops under different agroforestry systems on dehydrogenase enzyme activity (DHA) ug g^{-1} $hour^{-1}$

Depth	Crop	Tree species			Mean	ANOVA		
		No Tree	*H. binata*	*P. Cineraria*		T	C	T×C
0-5 cm	*V. unguiculata* L.	0.86	1.82	2.01	**1.56**	0.10*	0.13*	NS
	C. tetragonoloba L.	0.93	2.01	2.08	**1.67**			
	V. radiata L.	0.79	1.91	2.09	**1.60**			
	V. aconitifolia	0.74	2.07	2.16	**1.66**			
	P. glaucum L.	0.65	1.64	1.49	**1.26**			
	Mean	**0.79**	**1.89**	**1.96**				
5-15 cm	*V. unguiculata* L.	0.84	2.00	2.16	**1.66**	0.16*	0.21*	NS
	C. tetragonoloba L.	1.13	2.24	2.21	**1.86**			
	V. radiata L.	1.02	2.13	2.39	**1.84**			
	V. aconitifolia	0.97	2.29	2.32	**1.86**			
	P. glaucum L.	0.46	1.42	1.74	**1.21**			
	Mean	**0.88**	**2.02**	**2.16**				
15-45 cm	*V. unguiculata* L.	0.76	2.05	1.98	**1.60**	0.12*	NS	NS
	C. tetragonoloba L.	0.92	1.84	2.00	**1.58**			
	V. radiata L.	0.97	2.20	1.85	**1.67**			
	V. aconitifolia	0.87	2.18	1.81	**1.62**			
	P. glaucum L.	0.79	2.17	1.99	**1.65**			
	Mean	**0.86**	**2.09**	**1.92**				
45-90 cm	*V. unguiculata* L.	0.31	0.90	0.79	**0.67**	0.13*	NS	NS
	C. tetragonoloba L.	0.21	0.83	0.66	**0.57**			
	V. radiata L.	0.30	0.78	0.49	**0.52**			
	V. aconitifolia	0.31	0.60	0.81	**0.57**			
	P. glaucum L.	0.39	0.93	0.63	**0.65**			
	Mean	**0.30**	**0.81**	**0.68**				
0-90 cm	*V. unguiculata* L.	0.69	1.69	1.73	**1.37**	0.08*	0.10*	NS
	C. tetragonoloba L.	0.80	1.73	1.74	**1.42**			
	V. radiata L.	0.77	1.76	1.70	**1.41**			
	V. aconitifolia	0.72	1.79	1.77	**1.43**			
	P. glaucum L.	0.57	1.54	1.46	**1.19**			
	Mean	**0.71**	**1.70**	**1.68**				

*significant at $p < 0.05$; NS= non-significant; T –Tree species; C-Crop

Table-4.23: Long term influence of crops under different agroforestry systems on microbial biomass carbon MBC (ug C g^{-1})

Depth	Crop	Tree species			Mean	ANOVA		
		No Tree	*H. binata*	*P. Cineraria*		T	C	T× C
0-5 cm	*V. unguiculata* L.	76.06	111.85	108.87	**98.92**	7.71*	9.95*	NS
	C. tetragonoloba L.	73.08	99.92	105.88	**92.96**			
	V. radiata L.	85.01	114.83	102.90	**100.91**			
	V. aconitifolia	79.04	102.90	105.88	**95.94**			
	P. glaucum L.	64.13	90.97	93.95	**83.02**			
	Mean	**75.46**	**104.09**	**103.50**				
5-15 cm	*V. unguiculata* L.	86.97	102.23	108.33	**99.18**	9.34*	12.06*	NS
	C. tetragonoloba L.	93.07	102.23	111.38	**102.23**			
	V. radiata L.	93.07	129.69	102.23	**108.33**			
	V. aconitifolia	90.02	111.38	108.33	**103.25**			
	P. glaucum L.	83.92	86.97	93.07	**87.99**			
	Mean	**89.41**	**106.50**	**104.67**				
15-45 cm	*V. unguiculata* L.	47.30	65.61	62.56	**58.49**	9.12*	11.78*	NS
	C. tetragonoloba L.	44.25	65.61	50.35	**53.40**			
	V. radiata L.	56.46	86.97	62.56	**68.66**			
	V. aconitifolia	47.30	62.56	65.61	**58.49**			
	P. glaucum L.	35.09	47.30	53.40	**45.27**			
	Mean	**46.08**	**65.61**	**58.90**				
45-90 cm	*V. unguiculata* L.	8.66	15.59	19.06	**14.44**	7.23*	NS	NS
	C. tetragonoloba L.	12.13	19.06	19.06	**15.59**			
	V. radiata L.	15.59	43.32	19.06	**23.68**			
	V. aconitifolia	8.66	12.13	22.53	**14.44**			
	P. glaucum L.	8.66	19.06	19.06	**15.59**			
	Mean	**10.74**	**21.83**	**19.75**				
0-90 cm	*V. unguiculata* L.	54.74	73.82	74.70	**67.75**	6.41*	8.28*	NS
	C. tetragonoloba L.	54.76	71.70	71.67	**66.04**			
	V. radiata L.	60.79	93.70	71.68	**75.39**			
	V. aconitifolia	56.25	72.24	75.58	**68.02**			
	P. glaucum L.	47.95	61.07	64.87	**57.96**			
	Mean	**54.90**	**74.50**	**71.70**				

*significant at $p < 0.05$; NS= non-significant; T –Tree species; C-Crop

Table-4.24: Tree Biomass in different agroforestry systems

Particulars	***H. binata***	***P. cineraria***
Age of Plantation (years)	16	16
Planting density (nos. ha^{-1})	400	400
Diameter at breast height (DBH) (cm)	12.87	11.77
Above Ground Tree Biomass (kg $tree^{-1}$)	48.41	39.42
Above Ground Tree Biomass (tonne ha^{-1})	19.37	15.77
Below Ground Tree Biomass (kg $tree^{-1}$)	10.77	10.64
Below Ground Tree Biomass (tonne ha^{-1})	4.31	4.26
Total Tree Biomass (kg $tree^{-1}$)	59.05	50.06
Total Tree Biomass (tonne ha^{-1})	**23.62**	**20.03**

Table-4.25: C sequestered by trees in different agroforestry systems

Particulars	***H. binata***		***P. cineraria***	
	Annual	16 years	Annual	16 years
Above Ground Biomass (kg $tree^{-1}$)	1.51	24.21	1.23	19.71
Above Ground Biomass (tonne ha^{-1})	0.61	9.68	0.49	7.88
Below Ground Biomass (kg $tree^{-1}$)	0.34	5.38	0.33	5.32
Below Ground Biomass (tonne ha^{-1})	0.13	2.15	0.13	2.13
Total Tree Biomass (kg $tree^{-1}$)	1.85	29.53	1.56	25.03
Total Tree Biomass (tonne ha^{-1})	**0.74**	**11.81**	**0.63**	**10.01**

Table-4.26: CO_2 captured by trees in different agroforestry systems

Particulars	*H. binata*		*P. cineraria*	
	Annual	16 years	Annual	16 years
Above Ground Biomass (kg tree^{-1})	5.55	88.75	4.52	72.26
Above Ground Biomass (tonne ha^{-1})	2.22	35.50	1.81	28.91
Below Ground Biomass (kg tree^{-1})	1.23	19.74	1.22	19.51
Below Ground Biomass (tonne ha^{-1})	0.49	7.90	0.49	7.80
Total Tree Biomass (kg tree^{-1})	6.77	108.25	5.74	91.77
Total Tree Biomass (tonne ha^{-1})	**2.71**	**43.30**	**2.29**	**36.71**

Table-4.27: Long term influence of different agroforestry systems on grain yield of crops (2019-20) (kg ha^{-1})

Crop	Tree Species			
	No Tree	***Hardwickia binata***	***Prosopis cineraria***	**Mean**
Vigna unguiculata L.	415.75	760.01	1146.19	**773.98**
Cymopsis tetragonoloba L.	1031.34	1312.22	1448.02	**1263.86**
Vigna radiata L.	323.00	437.29	615.08	**458.46**
Vigna aconitifolia	426.94	406.01	542.36	**458.44**
Pennisetum glaucum L.	1115.13	1083.09	1354.02	**1184.08**
Mean	**662.43**	**799.73**	**1021.14**	
CD $_{0.05}$	Tree	Crop	Tree x Crop	
	20.25*	26.14*	45.28*	

*significant at $p < 0.05$; NS= non-significant

Table-4.28: Long term influence of different agroforestry systems on Stover yield of crops (2019-20) (kg ha^{-1})

Crop	Tree Species			
	No Tree	***Hardwickia binata***	***Prosopis cineraria***	**Mean**
Vigna unguiculata L.	884.47	1615.02	1779.29	**1426.26**
Cymopsis tetragonoloba L.	4167.39	6355.08	7917.12	**6146.53**
Vigna radiata L.	500.01	1980.33	1979.26	**1486.53**
Vigna aconitifolia	1353.82	1667.03	2084.40	**1701.75**
Pennisetum glaucum L.	3958.46	3750.32	5729.09	**4479.29**
Mean	**2172.83**	**3073.56**	**3897.83**	
CD $_{0.05}$	Tree	Crop	Tree x Crop	
	81.86*	105.69*	183.05*	

*significant at $p < 0.05$; NS= non-significant

Table-4.29: Long term influence of different agroforestry systems on root biomass of crops (2019-20) (kg ha^{-1})

Crop	Tree Species			
	No Tree	***Hardwickia binata***	***Prosopis cineraria***	**Mean**
Vigna unguiculata L.	309.57	565.26	622.75	**499.19**
Cymopsis tetragonoloba L.	1458.59	2224.28	2770.99	**2151.29**
Vigna radiata L.	175.00	693.12	692.74	**520.29**
Vigna aconitifolia	473.84	583.46	729.54	**595.61**
Pennisetum glaucum L.	712.52	675.06	1031.24	**806.27**
Mean	**625.90**	**948.23**	**1169.45**	
CD $_{0.05}$	Tree	Crop	Tree x Crop	
	25.25*	32.60*	56.47*	

*significant at $p < 0.05$; NS= non-significant

Table-4.30: Long term influence of different agroforestry systems on crop biomass (Grain + Stover + Root) (2019-20) (kg ha^{-1})

Crop	Tree Species			Mean
	No Tree	*Hardwickia binata*	*Prosopis cineraria*	
Vigna unguiculata L.	1609.79	2940.29	3548.23	**2699.44**
Cymopsis tetragonoloba L.	6657.32	9891.58	12136.14	**9561.68**
Vigna radiata L.	998.02	3110.74	3287.08	**2465.28**
Vigna aconitifolia	2254.60	2656.49	3356.31	**2755.80**
Pennisetum glaucum L.	5786.12	5508.46	8114.34	**6469.64**
Mean	**3461.17**	**4821.52**	**6088.42**	
CD $_{0.05}$	Tree	Crop	Tree x Crop	
	125.64*	162.20*	280.95*	

*significant at $p < 0.05$; NS= non-significant

Table-4.31: Long term influence of different agroforestry systems on carbon sequestered by grain of crops (2019-20) (kg ha^{-1})

Crop	Tree Species			
	No Tree	*Hardwickia binata*	*Prosopis cineraria*	Mean
Vigna unguiculata L.	207.88	380.01	573.09	**386.99**
Cymopsis tetragonoloba L.	515.67	656.11	724.01	**631.93**
Vigna radiata L.	161.50	218.65	307.54	**229.23**
Vigna aconitifolia	213.47	203.00	271.18	**229.22**
Pennisetum glaucum L.	557.57	541.55	677.01	**592.04**
Mean	**331.22**	**399.86**	**510.57**	
CD $_{0.05}$	Tree	Crop	Tree x Crop	
	10.13*	13.07*	22.64*	

*significant at $p < 0.05$; NS= non-significant

Table-4.32: Long term influence of different agroforestry systems on carbon sequestered by Stover of crops (2019-20) (kg ha^{-1})

Crop	Tree Species			
	No Tree	***Hardwickia binata***	***Prosopis cineraria***	**Mean**
Vigna unguiculata L.	442.24	807.51	889.65	**713.13**
Cymopsis tetragonoloba L.	2083.70	3177.54	3958.56	**3073.27**
Vigna radiata L.	250.00	990.17	989.63	**743.27**
Vigna aconitifolia	676.91	833.51	1042.20	**850.87**
Pennisetum glaucum L.	1979.23	1875.16	2864.54	**2239.64**
Mean	**1086.42**	**1536.78**	**1948.92**	
CD $_{0.05}$	Tree	Crop	Tree x Crop	
	40.93*	52.84*	91.53*	

*significant at $p < 0.05$; NS= non-significant

Table-4.33: Long term influence of different agroforestry systems on carbon sequestered by roots of crops (2019-20) (kg ha^{-1})

Crop	Tree Species			
	No Tree	***Hardwickia binata***	***Prosopis cineraria***	**Mean**
Vigna unguiculata L.	154.78	282.63	311.38	**249.60**
Cymopsis tetragonoloba L.	729.29	1112.14	1385.50	**1075.64**
Vigna radiata L.	87.50	346.56	346.37	**260.14**
Vigna aconitifolia	236.92	291.73	364.77	**297.81**
Pennisetum glaucum L.	356.26	337.53	515.62	**403.14**
Mean	**312.95**	**474.12**	**584.73**	
CD $_{0.05}$	Tree	Crop	Tree x Crop	
	12.63*	16.30*	28.24*	

*significant at $p < 0.05$; NS= non-significant

Table-4.34: Long term influence of different agroforestry systems on total carbon sequestered by crops (Grain + Stover + Root) (2019-20) (kg ha^{-1})

Crop	Tree Species			
	No Tree	***Hardwickia binata***	***Prosopis cineraria***	**Mean**
Vigna unguiculata L.	804.90	1470.15	1774.11	**1349.72**
Cymopsis tetragonoloba L.	3328.66	4945.79	6068.07	**4780.84**
Vigna radiata L.	499.01	1555.37	1643.54	**1232.64**
Vigna aconitifolia	1127.30	1328.25	1678.15	**1377.90**
Pennisetum glaucum L.	2893.06	2754.23	4057.17	**3234.82**
Mean	**1730.58**	**2410.76**	**3044.21**	
CD $_{0.05}$	Tree	Crop	Tree x Crop	
	62.82	81.10	140.47	

*significant at p < 0.05; NS= non-significant

Table-4.35: Long term influence of different agroforestry systems on CO_2 sequestered by grain of crops (2019-20) (kg ha^{-1})

Crop	Tree Species			
	No Tree	***Hardwickia binata***	***Prosopis cineraria***	**Mean**
Vigna unguiculata L.	762.14	1393.22	2101.13	**1418.83**
Cymopsis tetragonoloba L.	1890.61	2405.50	2654.44	**2316.85**
Vigna radiata L.	592.12	801.63	1127.54	**840.43**
Vigna aconitifolia	782.65	744.27	994.24	**840.39**
Pennisetum glaucum L.	2044.20	1985.47	2482.12	**2170.60**
Mean	**1214.34**	**1466.02**	**1871.89**	
CD $_{0.05}$	Tree	Crop	Tree x Crop	
	37.12*	47.92*	83.01*	

*significant at p < 0.05; NS= non-significant

Table-4.36: Long term influence of different agroforestry systems on CO_2 sequestered by Stover of crops (2019-20) (kg ha^{-1})

Crop	Tree Species			
	No Tree	***Hardwickia binata***	***Prosopis cineraria***	**Mean**
Vigna unguiculata L.	1621.37	2960.58	3261.71	**2614.55**
Cymopsis tetragonoloba L.	7639.45	11649.82	14513.27	**11267.51**
Vigna radiata L.	916.59	3630.25	3628.28	**2725.04**
Vigna aconitifolia	2481.75	3055.91	3821.02	**3119.56**
Pennisetum glaucum L.	7256.46	6874.89	10502.28	**8211.21**
Mean	**3983.12**	**5634.29**	**7145.31**	
CD $_{0.05}$	Tree	Crop	Tree x Crop	
	150.07*	193.74*	335.56*	

*significant at $p < 0.05$; NS= non-significant

Table-4.37: Long term influence of different agroforestry systems on CO_2 sequestered by roots of crops (2019-20) (kg ha^{-1})

Crop	Tree Species			
	No Tree	***Hardwickia binata***	***Prosopis cineraria***	**Mean**
Vigna unguiculata L.	567.48	1036.20	1141.60	**915.09**
Cymopsis tetragonoloba L.	2673.81	4077.44	5079.64	**3943.63**
Vigna radiata L.	320.81	1270.59	1269.90	**953.76**
Vigna aconitifolia	868.61	1069.57	1337.36	**1091.85**
Pennisetum glaucum L.	1306.16	1237.48	1890.41	**1478.02**
Mean	**1147.37**	**1738.26**	**2143.78**	
CD $_{0.05}$	Tree	Crop	Tree x Crop	
	46.30*	59.77*	103.52*	

*significant at $p < 0.05$; NS= non-significant

Table-4.38: Long term influence of different agroforestry systems on total CO_2 sequestered by crops (Grain + Stover + Root) (2019-20) (kg ha^{-1})

Crop	Tree Species			
	No Tree	***Hardwickia binata***	***Prosopis cineraria***	**Mean**
Vigna unguiculata L.	2950.99	5390.00	6504.44	**4948.48**
Cymopsis tetragonoloba L.	12203.87	18132.76	22247.36	**17528.00**
Vigna radiata L.	1829.51	5702.46	6025.72	**4519.23**
Vigna aconitifolia	4133.01	4869.75	6152.62	**5051.79**
Pennisetum glaucum L.	10606.82	10097.84	14874.81	**11859.82**
Mean	**6344.84**	**8838.56**	**11160.99**	
CD $_{0.05}$	Tree	Crop	Tree x Crop	
	230.32*	297.34*	515.02*	

*significant at $p < 0.05$; NS= non-significant

Table-4.39: Long term influence of crops under different tree species on carbon stock, carbon stock potential, and carbon prices

Particulars	Tree Species		
	No Tree	**Hardwickia binata**	**Prosopis cineraria**
Above Ground Biomass (t ha^{-1})	0.00	19.37	15.77
Below Ground Biomass (t ha^{-1})	0.00	4.31	4.26
crop biomass produced in 16 years (t ha^{-1})	55.38	77.14	97.41
TOC Stock in the soil at 0-90 cm (t ha^{-1})	31.49	39.33	37.82
TOC Stock in the system (t ha^{-1})	86.87	140.15	155.26
Carbon sequestration potential (t ha^{-1})	318.81	514.34	569.81
C trade potential USD ($)	1216.15	1962.04	2173.67
C trade potential (Indian Rupee) (`)	**91,077.77**	**1,46,937.28**	**1,62,785.98**

Chapter V

Summary and Conclusion

The arid zone of India covers about 12% of the country's total geographical area (TGA). The Thar Desert (Great Indian Desert) is a large arid region in the north-western part of the Indian subcontinent. About 85% of the Thar Desert is located within India and remaining 15% in Pakistan (Sinha *et al.,* 1996). The hot arid region is characterized mainly by scarce natural resources with an inhospitable climate. Rainfall varies from less than 100 mm to 400 mm, and is highly erratic and unpredictable. Livestock is the major source of survival of the people because cropping is not a secure and definite proposal (Behera *et al.,* 2016). The erosion of top soil by wind is a wide spread problem.

Agroforestry is one of the key paths towards the prosperity of poor people suffering from hunger, malnutrition, extreme poverty and deterioration of the environment in the areas that have been bypassed by the Green revolution. Presence of trees within a landscape affects its hydrological characteristics, just as deforestation increases the run-off. Agroforestry is thus the most feasible option to tackle land degradation and to bring about eco-restoration and also to sustain soil resources (Gupta *et al.*, 2009). Therefore, the present study entitled **"Carbon sequestration potential of tree based agroforestry systems in the arid region of India"** was undertaken to evaluate the above and below ground carbon sequestration potential agroforestry systems, changes in carbon pools and enzyme activities, change in available nutrients, and to evaluate the effect of agroforestry systems on yield of intercrops.

The study was carried out at ARS, Fatehpur, SKN Agriculture University, Jobner taking two factors in the experiment, factor-1 is 'tree species' at three levels and factor-2 is 'crop species' which is at 5 levels. Hence, there are 15 treatment combinations (3 tree species X 5 crop species) which are replicated trice. The samples were collected twice (at flowering stage and after harvesting of the crops) and used for various chemical and biological soil properties. The following pertinent points were derived from the investigation:

- Bulk density of soil was not found to be significant at any particular depth but on an average it showed an increasing trend with depth ranging from 1.43 g cc^{-1} at 0-5 cm to 1.55 g cc^{-1} at 45-90 cm.

- The electrical conductivity (EC) of soil was found to be lower and soil is non-saline. Among the crops, all the pulses showed slightly lower values of EC as compared to the cereal (Pearl millet). It ranged from 0.60 to 0.66 dSm^{-1} with an average of 0.63 dSm^{-1}.
- *H. binata* system was highest in SOC status followed by *P. cineraria* system and sole cropping system had the lowest SOC. SOC was found to be higher under legumes and slightly lower under cereal (pearl millet). *H. binata* increased SOC status over *P. cineraria* and all the legumes increased SOC status over pearl millet, because of their (of *H. binata* and of legumes) dense foliage. In the furrow slice (0-15 cm), lowest value of SOC i.e. 0.187% was found in pearl millet under 'No tree' system and highest value i.e. 0.300% was found in cluster bean under *'H. binata'*, cowpea under *'H. binata'*, and cluster bean under *'P. cineraria'* system.
- *Prosopis cineraria* agroforestry system had significantly higher N content over both sole cropping system and *Hardwickia binata* (Anjan) based agroforestry system. Among the crops, *Vigna aconitifolia* (moth bean) had higher available N content over all other crops. The nitrogen content ranged from 66.90 kg/ha in pearl millet (*Pennisetum glaucum* L.) under 'Anjan tree (*H. binata*)' system to 142.17 kg/ha in moth bean under Khejri plantation with an average of 93.66 kg/ha.
- None of the factors (trees, crops, and interaction of these two) was found to be significantly different regarding soil P content. However, among the observed cases mung bean (*Vigna radiata* L.) and pearl millet (*Pennisetum glaucum* L.) under 'no tree' system were lowest in available P content (5.61 kg P/ha) and mung bean under Khejri plantation was highest in available P content (15.68 kg P/ha).
- Lowest value of available K was observed in cowpea (*Vigna unguiculata* L.) under 'no tree' system and pearl millet under Khejri plantation i.e. 184.58 kg K/ha and highest in cluster-bean under Khejri plantation (256.26 kg K/ha).
- Trend of variation of HWC is nearly similar to that of oxidisable organic carbon (OC) and goes on decreasing with depth in all cases. In furrow slice (average of 0-15 cm), pearl millet in sole cropping (no tree system) showed lowest value of HWC i.e. 204.45 ug C g^{-1} soil and highest value i.e. 432.02 ug C g^{-1} soil was shown by moth bean under Anjan trees and cluster bean under Khejri trees. On an average, all the legumes are relatively higher in HWC as compared to pearl millet (cereal).

- Hot water soluble carbohydrate (HWCh) followed a very similar trend of change to that of HWC. Anjan tree based agroforestry system is higher followed by Khejri planted system and sole cropping system to the least. The lowest value of HWCh in furrow slice (25.85 ug C/g soil) was observed in pearl millet in sole cropping and highest (41.35 ug C/g soil) in cluster bean under Anjan tree plantation.
- Anjan tree (*H. binata*) system had 0.335%, Khejri tree (*P. cineraria*) system had 0.325% and sole cropping (no tree) system had 0.276% of TOC in soil. When averaged over all depths, pulse crops increased TOC percent over cereal crop (pearl millet).
- Up to 90 cm soil depth TOC in Anjan tree system was found to be slightly higher (39.33 t ha^{-1}) than Khejri tree system (37.82 t ha^{-1}) and much higher than sole cropping system (31.49 t ha^{-1}). Pulse crops increased TOC stock in furrow slice (0-15 cm) over cereal crop (pearl millet).
- Percent very labile C (fraction-1) was significantly higher in *H. binata* (32.5%) and *P. cineraria* (31.95%) plantation but percent less labile C (fraction-3) was higher in no tree system (24.02%) as compared to both the tree plantation.
- Anjan based agroforestry system (active C pool- 1.70 t ha^{-1} at 0-5 cm and 5.91 t ha^{-1} at 45-90 cm) was found significant over sole cropping but it was not significant over Khejri based agroforestry system. However, Anjan based system was significant over both Khejri based system and sole cropping system regarding active C pool at 5-15 cm and 15-45 cm depths.
- The passive C pool was represented highest by mung bean (*V. radiata*) at 0-5 cm depth (1.13 t ha^{-1}), by moth bean (*V. aconitifolia*) at 5-15 cm depth (3.47 t ha^{-1}) and by mung bean (*V. radiata*) at 15-45 cm depth (8.25 t ha^{-1}).
- Up to 90 cm soil depth, LI was also found significantly higher for Anjan based plantation (0.217) than for Khejri based plantation (0.194) and sole cropping system (0.166).
- At 5-15 cm, 15-45 cm and 0-90 cm depths, RI-1 was highest for sole cropping system (1.78, 1.86 and 1.80, respectively) and was significant over Anjan and Khejri tree planted systems. Neither the tree nor the crop was significant at 0-5 cm and 45-90 cm depths.

- Regarding RI-2, sole cropping system was significantly higher (0.444) which was significant over Anjan tree plantation at 15-45 cm soil depth.
- Both the tree species showed substantial increase in DHA in soil over the sole cropping (no tree) treatment. Legumes are much better in increasing DHA (microbial activity) than that of pearl millet. The DHA (ug/g soil/hour) in furrow slice ranged from 0.46 in pearl millet in sole cropping to 2.39 in mung bean under Khejri plantation with average of 1.62.
- Results of MBC are very similar to that of hot water soluble carbohydrate (HWCh). Between the two tree-based agroforestry systems, Anjan plantation is somewhat better than Khejri plantation as MBC is very much associated with organic carbon and carbohydrate contents of medium (here soil). Average MBC in furrow slice (averaged over 0-5 cm and 5-15 cm) is highest for Anjan tree system (105.30 ug C/g soil) followed by Khejri plantation (104.08 ug C/g soil) and lowest value of MBC was showed by sole cropping system (82.44 ug C/g soil).
- Above ground tree biomasses recorded were 19.37 t ha^{-1} for *H. binata* (Anjan) based system, 15.77 t ha^{-1} for *P. cineraria* (Khejri) based system and 0.00 t ha^{-1} for sole cropping system.
- Average tree biomass (Above-ground + Below-ground) for Anjan tree system, as calculated here, is 23.62 t ha^{-1} and for Khejri system is 20.03 t ha^{-1}. Obviously, it is 0.00 t ha^{-1} in 'no tree' system.
- The grain yield (average of all the crops form a particular tree species) was recorded highest in Khejri based AF system (1021.14 kg ha^{-1}) followed by Anjan based system (799.73 kg ha^{-1}) and lowest in 'no tree' system (662.43 kg ha^{-1}).
- Total crop biomass (Grain + Stover + Root) was recorded highest in Khejri based AF system (6088.42 kg/ha) followed by Anjan based system (4821.52 kg/ha) and lowest in 'no tree' system (3461.17 kg/ha).
- The TOC-soil up to 90 cm depth is 39.33 t ha^{-1} in Anjan system, 37.82 t ha^{-1} in Khejri system and 31.49 t ha^{-1} in 'no tree' system.
- TOC-soil followed a trend in contrary to that of TOC-soil i.e. Khejri > Anjan > sole cropping (no tree). It was 155.26 t ha^{-1} Khejri based system 140.15 t ha^{-1} Anjan based system 86.87 t ha^{-1} 'sole cropping' system.

- CSP were calculated as 569.81 t ha^{-1} for Khejri plantation system, 514.34 t ha^{-1} for Anjan plantation system and 318.81 t ha^{-1} for 'sole cropping' system.
- Carbon trading potential of the systems, as calculated in Indian Rupee (Rs.), at present is `1,62,785.98 for Khejri based system, ` 1,46,937.28 for Anjan based system and ` 91,077.77 for sole cropping.

Finally, from this study, it can be concluded that presence of trees in farmer's fields adds a lot of organic material to the soil. This material is full of nutrients which are inaccessible to the roots of field crops. The trees also provide partial shade to the crop plants and soil which helps in reducing evapotranspiration losses and consequently reduces water requirement of crops. Certainly, there is shading effect of trees which may reduce net photosynthesis, therefore, further research is needed to know what density of trees in best for getting maximum benefit without yield losses, which tree species is/are suitable for particular crops or which crop species is/are suitable for growing under particular tree species.

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