CARBON DYNAMICS STUDIES IN AGROFORESTRY SYSTEMS OF WESTERN HIMALAYA

Thesis

by

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Submitted in partial fulfilment of the requirements
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Affectionately dedicated
to my Parents

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CERTIFICATE-I

This is to certify that the thesis entitled **"Carbon Dynamic Studies in Agroforestry Systems of Western Himalaya"**, submitted in partial fulfilment of the requirements for the award of degree of **MASTER OF SCIENCE** in **AGROFORESTRY** to Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan (H.P.) is a bonafide research work carried out by **Mr. Sanjeev Kumar (F-2001-6-M)** under my guidance and supervision. No part of this thesis has been submitted for any other degree or diploma.

The assistance and help received during the course of investigations have been fully acknowledged.

Place : Nauni, Solan
Dated : 29th December, 2003

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CERTIFICATE-II

This is to certify that the thesis entitled **"Carbon Dynamic Studies in Agroforestry Systems of Western Himalaya"**, submitted by **Mr. Sanjeev Kumar (F-2001-6-M)** to Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan (H.P.), in partial fulfilment of the requirements for the award of degree of **MASTER OF SCIENCE** in **AGROFORESTRY** has been approved by the Student's Advisory Committee after an oral examination of the same in collaboration with the external examiner.

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(Sanjeev Kumar)

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ABBREVIATIONS USED IN THE THESIS

\$	Dollar
%	Per cent
AF	Agroforestry
AFs	Agroforestry systems
AH	Agri-horticulture
AHS	Agri-horti-silviculture
approx	Approximately
AS	Agri-silviculture
BD	Bulk density
CD	Critical difference
CH_4	Methane
cm	Centimeter
CO_2	Carbon dioxide
DOE	Department of energy
g	gram
GHGs	Green house gasses
HP	Horti-pastoral
IPCC	Intergovernmental panel for climate change
Kg/m2	Kilogram per square meter
Km	Kilometer
m	Meter
m.a.m.s.l	meter above mean sea level
MAP	Mean Annual precipitation
MAT	Mean Annual Temperature
N	Nitrogen
N_2O	Nitrous oxide
NE	North East
NG	Natural grassland
°C	Degree Celsius
OC	Organic carbon
P	Phosphorus
Pg	Petagram
PgC	Peta gram carbon
SOC	Soil Organic carbon
SOM	Soil organic matter
SP	Silvi-pastoral
UNFCCC	United Nations Frame Work Conventioin of Climate Change GHG Green House gas
USA	United States of America
USDA NRCS	United State Department Of Agriculture, National Resource Conservation Services
CSP	Carbon sequestration potential
WANA	West Asia and North Africa
gcm^{-3}	Gram per centimeter cube
$Mgha^{-1}$	Mega gram per hectare
tCh^{-1}	Tonne Carbon hectare
$TgCyr^{-1}$	Teragram Carbon per year
yr^{-1}	Per year
ha	hectare (10,000 m^2)

INTRODUCTION

1

INTRODUCTION

Global climate change, caused by increased emissions of greenhouse gases (GHGs) is likely to affect the agro ecosystems. The concentration of major contributing gases viz., Carbon dioxide, Nitrus oxide and Methane (CO_2, N_2O and CH_4) has considerably increased over the last century and is set to rise further. Among these, continuous increase in CO_2 levels of atmosphere has serious implications for agriculture, forests as well as environment. It is accumulating in the atmosphere at a rate of 3.5 Pg per annum, the largest proportion of which resulting from the burning of fossil fuels and conversion of tropical forests to agricultural production (Paustian *et al.*, 2000). Scientific evidences suggest that increased atmospheric CO_2 could have some positive effects such as improved plant productivity (Idso and Kimball, 2001; Keutgen and Chen, 2001). However, negative changes in the global climate (rising temperatures, higher frequency of droughts and floods) are often the most consequential processes associated with an increased concentration of CO_2 in the atmosphere (USDA NRCS, 2000).

The debate on atmospheric build up of GHGs and their role in global warming by conference of the parties to the United Nations Frame work Convention of Climate Change (UNFCCC) in 1997, in Kyoto, Japan culminated in urging the participating countries to find ways of reducing GHGs concentration in the atmosphere. Carbon reduction targets could be achieved through two major processes: (i) reducing anthropogenic emissions of CO_2, and (ii) creating and/or enhancing carbon sinks in the biosphere.

Current terrestrial (plant and soil) carbon is estimated at 2000±500 Pg, which represents 25 % of global carbon stocks (DOE, 1999). The sink option for CO_2 mitigation is based on the assumption that this figure can be significantly increased if various biomes are judiciously managed and/or manipulated. Among these the carbon sequestration potential of three biomes viz. agricultural lands, biomass croplands and deserts and degraded lands has been estimated as 0.85-0.90, 0.50-0.80 and 0.80-1.30 Pg year^{-1}, respectively (that might be sustained for a period of 25-50 years). The primary method to increase carbon sequestration in agricultural lands biome has been advocated as high-level management whereas for biomass croplands as well as deserts and degraded lands, high-level manipulation (DOE, 1999). The carbon sequestration potential of tropical agroforestry systems is estimated between 12 and 228 Mg ha^{-1} with a median value of 95 Mg ha^{-1}. Therefore, based on earth's area that is suitable for practice (585-1215 X 10^{6} ha), 1.1-2.2 Pg C could be stored in the terrestrial ecosystems over the next 50 years (Albrecht and Kandji, 2003).

Removing atmospheric carbon and storing it in terrestrial biosphere is one of the options, which have been proposed to compensate greenhouse gas emissions. Agricultural lands are believed to be a major potential sink and could absorb large quantities of carbon if trees are reintroduced to these systems and judiciously managed together with crops and/or animals. Thus, the importance of agroforestry as a landuse system is receiving wider recognition not only in terms of agricultural sustainability but also in issues related to carbon sequestration or climate change.

The amount of carbon sequestered largely depends on the agroforestry system put in place, the structure and function of which are, to a great extent, determined by environmental and socio-economic factors. Other factors influencing carbon storage in agroforestry systems include tree species and system management. Agroforestry systems are complex and varied like simple windbreaks, boundary planting, hedgerow inter-cropping, improved fallows, silvipasture systems, and very complex agroforests (also known as multistrata tree gardens or analogue forests) and homegardens those involve a high plant diversity. Most of these agroforestry systems, if not all, have the potential to sequester carbon. With adequate management of trees in cultivated lands and pastures, a significant fraction of the atmospheric carbon could be stored in plant biomass and in soils.

In agroforestry systems carbon sequestration is a dynamic process and can be divided into phases. At establishment, many systems are likely to be source of GHGs. These follow a quick accumulation phase and a maturation period when tonnes of carbon is stored in boles, stems, and roots of trees and in soils. At the end of rotation period, when the trees are harvested and land returned to cropping (sequential systems), part of carbon will be released back to atmosphere (Dixon, 1995). In case of simultaneous systems like hedgerow inter-cropping, silvi-pasture systems and agri-silviculture systems fate of carbon will be different. Therefore, effective sequestration can only be considered if there is a positive net carbon balance from an initial stock after a few decades (Feller *et al.*, 2001).

Realistically, carbon storage in plant biomass is only feasible in the perennial agroforestry systems (perennial tree- crop combinations, agroforests, wind breaks etc.), which allow full tree growth and where the woody component represents an important part of the total biomass. One comparative advantage of these systems is that sequestration does not have to end at wood harvest. It can continue way beyond if boles, stems or branches are processed in any form of long lasting products. Alternatively the wood can serve as fuel, in which case an important part of plant stored carbon returns to the atmosphere. While carbon sequestration *per se* may be insignificant in the later scenario, producing firewood from arable or grazed lands using energy plantation systems may still present good opportunities in CO_2 mitigation through: (i) protection of existing forests and other natural land scapes, (ii) the reduction of fossil fuel energy consumption by using wood as energy sources and, (iii) the conservation of soil productivity (Kursten and Burschel, 1993; Cooper *et al.*, 1996; Kursten, 2000). Adequate understanding of these secondary effects of agroforestry requires more research.

Restoring degraded croplands and pastures is an effective way of storing carbon in the soil. There is a strong evidence that soil levels can be considerably increased at a global scale if management options that improve land productivity are pursued. For such options to be successful, they will have to increase inputs (primary production) while reducing losses through the processes of decomposition, leaching and erosion. Agroforestry trees improve land cover in agricultural fields in addition to providing carbon inputs e.g. root biomass, litter and pruning to the soil. This often reduces soil erosion, which is a crucial process in carbon dynamics. It has also been speculated that most significant increase in carbon stocks occur in fine textured soils, where carbon is better protected through soil aggregation (Ingram and Fernades, 2001). But one must be aware that soils have a finite sink capacity of 0.4-0.6 Pg C per year over 50-100 years (Paustian *et al.*, 2000; Ingram and Fernades, 2001). If above ground and soil carbon are considered together, 1.1-2.2 Pg C could be sequestered annually over 50 years, which, as estimates suggest, would offset about 10-15% of the current annual carbon emissions (Dixon, 1995).

Soil management strategies for carbon sequestration include three approaches. First management of soil to maintain higher than existing levels of soil organic matter. Secondly, to manage carbon degraded soils so as to restore soil organic matter levels. Wastelands in India cover more than 63.85 M ha, of which 70% is carbon degraded. Agroforestry land management practices and systems are highly suitable for rejuvenating these lands. Third, enlarging soil organic matter pools by improving soil fertility. Soil processes could be managed so that litter production exceeds decomposition. Another approach could be to increase passive or inert fraction of soil organic pool. This can be achieved through the increase of sub-soil organic carbon and micro-aggregation. Sub-soil organic carbon can be increased by growing deep-rooted plants (trees/crops) and deep ploughing. Using soil conditioners, long chain polymers and earthworms can increase micro-aggregation. Eco-friendly farming practices like organic farming, precision farming and agroforestry has a great potential to enrich soil with organic carbon through sequestering carbon in soils. Research efforts are needed to quantify the carbon sequestration capacity of these practices.

Looking at contributions, agroforestry landuse systems can make, in solving current climatic problems, it can be easily inferred that agroforestry is one among a range of strategies. It can be justified for many other reasons too. First, increasing soil carbon greatly benefits agricultural productivity and sustainability. Second, given the improbability of obtaining any single mitigating method, adding modest contributions together appears to be a more realistic way of achieving CO_2 reduction targets. Third, the financial costs of carbon sequestration through agroforestry appear to be much lower (approx. \$ 1-69/ Mg C; median \$ 13/Mg C) than through other CO_2 mitigating options. These costs could be easily offset by the monetary benefits from agricultural products and trading in carbon credits (Albrecht and Kandji, 2003).

In India agroforestry is being promoted as an alternate landuse system to deal with the problems related to landuse sustainability and environmental amelioration yet its real potential needs scientific evidences. Numerous agroforestry systems both natural as well as planted developed in different agroclimatic regions of the country have been found highly productive and environmentally suitable. North-West Himalayan region also have variety of land management practices and systems of agroforestry nature. Promising among these have been modified and planted on University farm. Therefore, present study on carbon dynamics studies in agroforestry systems of Western Himalaya is a maiden attempt in this direction and involved the following two objectives.

1) Determine existing carbon stocks in different agroforestry systems.

2) Determine relative carbon sequestration potential of agroforestry systems.

REVIEW OF LITERATURE

2

REVIEW OF LITERATURE

Carbon sequestration refers to the provision of long term storage of carbon in the terrestrial biosphere, underground or the ocean so that the build up of CO_2 concentration in the atmosphere will reduce or slow in order to improve environmental conditions and check the processes of environmental degradation especially through agriculture, horticulture and forestry land management operation both on arable and non-arable lands. Scientific integration of these major land management systems result into a distinct and a separate landuse known as 'Agroforestry'. This new land management system termed, as agroforestry has been found more productive and sustainable than other existing landuse systems particularly under medium and small holders conditions. It also holds good promise to enhance plant-soil carbon pools by sequestering carbon from the atmospheric carbon dioxide. However, to elucidate the potential of agroforestry practices or systems to enhance biomass productivity and store the carbon sequestered for long time either in biomass or soil needs scientific evidences. The scientific work on the subject is of very recent origin. The available literature from the sources accessible have been reviewed under the following heads:

2.1 Carbon sequestration and its mitigations through plant biomass

2.2 Carbon sequestration and its mitigation through soils

2.1 Carbon sequestration and its mitigation through plant biomass

Tree based landuse systems could sequester carbon in soils and vegetation and improve nutrient cycling within the system. The association of trees with the grasses in the silvipastoral systems revealed that an increased inputs of plant residues into the soil played a significant role to improve nutrient cycling and biological productivity in the tree-based systems. Increased biological production will lead to greater carbon storage in the vegetation and soil along with an enhanced nitrogen uptake by the plants (B Kaur *et al.*, 2002). The commercial plantations known as clonal plantations promoted by pulp and paper industry have high rate of survival and productivity (average 25 tonnes ha^{-1}annum^{-1}) with fairly uniform growth. Under farm forestry the industry in India is promoting plantation activity at an average rate of 40,000 ha per annum. The carbon sequestration potential of these plantations work out to 2.0 million tonne resulting in CO_2 mitigation of 7.2 million tonne, with an approximate carbon credit value of US$ 6.0 million (Rs. 30 crore). These plantations apart from serving as effective carbon sink, also provide several other environmental benefits such as conservation of natural forests and biodiversity, prevention of soil and water erosion, increasing green cover and improving the socio-economic conditions of rural poor (Kulkarni 2003).

Kotto-Same-J *et al.* (1997) identified three alternatives to slash and burn agriculture and evaluated them in terms of carbon sequestration. The alternatives were: Commercial cassava cultivation, improved forest conversion and stratified agroforestry. These alternative landuse had the potential to reduce carbon losses over slash and burn practices by 10, 55 and 75 Mg C ha^{-1}, respectively and also differs greatly in potential to alleviate rural poverty, protect biodiversity and reduce deforestation. Singh *et al.* (2000) found that farm forestry plantations have sequestered nearly 20 million tonne of carbon. Therefore, farm forestry is the major instrument for increasing carbon sequestration while supplying wood and non-wood products to meet both domestic and market requirements.

Malhi *et al.* (1999) studied the climatic influence on the carbon dynamics of boreal, temperate and tropical forests by presenting a new synthesis of micro-meteriological, eco-physiological and forestry data. They concluded that there have been significant advances in determining the carbon balance of forests, but there are still critical uncertainties remaining particularly in the behavior of soil carbon stocks. Houghton *et al.* (1987) reported that deforestation in the tropics is responsible for an annual net release of carbon to the atmosphere, estimated for 1980 at 0.5 - 4.2 X 10^{15}g. Comparative carbon release from fossil fuel combustion in 1980 was 5.2 X 10^{15} g. The wide range of estimates for the tropical biota and soils has been primarily caused by different estimates of the rate of deforestation.

Conversion of natural forests to agriculture in the humid tropics lead to a reduction in ecosystem carbon storage due to removal of above ground biomass and a gradual subsequent reduction in soil organic carbon. Whereas forest conversion to well managed grasslands may lead to increased soil carbon storage, after an initial decline (Van *et al.*, 1997). Katagiri *et al.* (1992) reported that dry weight of dead organic matter including dead standing trees was 4.1 to 16.8 per cent of the total above ground biomass in Sanbe forest, Shimane Japan. *Quercus serrata* and *Castancca crenato* comprised the principal broad leave species. Forests show the best mitigation potential followed by agroforestry, plantations and agriculture. Agroforestry interventions in the farming sector appear to be the most suitable landuse strategy. Degradation of soil has its adverse effect on soil carbon. Causes of soil degradation, adopted from world resources in 1992 for the Asian region showed 40 per cent contribution from deforestation, 27 per cent from industrialization and agricultural activities, and 26 per cent from overgrazing and 6 per cent from over exploitation (Jha and Gupta 2003).

The amount of carbon sequestered largely depends on the agroforestry system put in place, the structure, and function of which are, to a great extent, determined by environmental and socio-economic factors. Other factors influencing carbon storage in agroforestry systems include tree species and system management (Albrecht and Kandji 2003). Planting fallow trees for 12 - 22 months in West Kenya resulted in carbon inputs ranging from 1.35 - 16.5 Mg ha^{-1} in the soil. Beer *et al.* (1990) gave a detailed breakdown of biomass production over 10 years in two tree combinations in Costa Rica:

Cacao (*Theobroma cacao*), laurel (*Cordia alliadora*) and Cacao-Poro (*Erythrina poeppigiana*). Based on these data, whole system carbon stocks were calculated by averaging the annual biomass production in the two periods and multiplying the out put by 0.5 (Kursten and Burschel 1993). Thus, 11 Mg C ha^{-1} yr^{-1} was stored over 10 years in the system including 6 Mg C ha^{-1} yr^{-1} in the shade trees. Biomass estimates by Jensen (1993) in Java showed that 16 Mg C ha^{-1} could be stored if rice fields were transformed into homegardens.

In a carbon sequestration trial in Mexico, live fence trees were reported to store 24 - 36 Mg C ha^{-1} during a cycle of 25 - 30 years (de Jong *et al.*, 1995). A comprehensive study on the production and carbon sequestration potential of *Leucaena leucocephala* during the fallow phase of the Naalad system was carried out by Lasco and Suson (1999) using a 6 years old model fallow. Above ground *Leucaena* biomass increased from 4 Mg ha^{-1} in the first year to 64 Mg ha^{-1} in the sixth year (end of the fallow). Carbon in the under story soils and woody debris was estimated at 25 per cent of the above ground carbon. Overall, the authors calculated average carbon storage of 16 Mg ha^{-1} over the six years period.

The carbon storage potential of agroforestry systems was estimated between 12 and 228 Mg ha^{-1} with a median value of 95 Mg ha^{-1} (Albrecht and Kandji, 2003). Growing trees can improve soil quality, albeit at a slow rate, and sequester carbon in soil and biomass. Kair (*Capparis deciduas*), one such tree is adaptable to the dry lands of North-West India (Gupta *et al.*, 1989).

Baggio and Heuveldop (1984) studied the potential of *Calliandra calothyrsus* as a live fence species in Costa Rica. At 10 months, the total biomass produced was 3 - 4 Mg dry matter Km^{-1} of fence (2 Mg carbon sequestered per Km). Biomass production in boundary planting can be highly variable - dependent on environmental and soil characteristics. Live fences of

Gliricidia sepium monitored on a 4-years cycle produced a total biomass of 7 Mg Km^{-1} yr^{-1} (35 Mg C ha^{-1} yr^{-1}) when pruned every 4 months and 9.5 Mg Km^{-1} yr^{-1} (50 Mg C ha^{-1} yr^{-1}) when pruned every six months (Romero *et al.*, 1991). In a carbon sequestration trial in Mexico, live fence trees were reported to store 24-36 Mg C ha^{-1} during a cycle of 25-30 years (de Jong *et al.*, 1995).

Farm forestry plantations raised on farmer's fields are mainly on marginal and sub-marginal lands with low levels of soil carbon. However, the soil carbon in such area rises quite rapidly and can reach levels of normal forest soils in a period of 15 to 25 years (Sampson and Sedja 1997). Planted forests are known to take up and store carbon at high rate compared to other world land covers, storage rates commonly range from 1 to 8 Mg C ha^{-1} yr^{-1} and typical mean carbon storage over a rotation period is from 50 to 80 Mg C ha^{-1} (Winjum and Sehroeder 1995).

2.2 Carbon sequestration and its mitigation through soils

2.2.1 General status

Agricultural practices can render a soil either a sink or a source of the atmospheric CO_2 with direct influence on the green house effect (Lugo and Brown 1993; Lal *et al.*, 1998). Oldeman (1994) estimated the area of strongly degraded soils throughout the world. Assuming that 25 per cent of all degraded areas are strongly and extremely degraded, the total area of such land is estimated at 411 Mha. If such lands can be planted to fast growing trees with a biomass production potential of 2-4 Mg $ha^{-1}yr^{-1}$, total biomass production of these soils is 0.8-1.6 Pg.

Total organic matter accumulated in soils constitutes a major portion of the world's fixed carbon reserves. Bohn (1976) estimated that the soil contains approx. 30 X 10^{14} Kg organic carbon. Distribution of this organic matter among soil type is highly variable and generally not easily predictable from aboveground vegetation types. The quantity of organic material retained within the soil matrix is the differences between total biomass production and decomposition.

Trees are known to maintain soil organic matter and nutrient cycling through the addition of litter and root residues into the soil. There is a large potential of sequestering carbon in soil and vegetation by adopting suitable agroforestry systems on salt affected soils (Singh and Singh 1997). In Haryana India, Bhojvaid and Timmer (1998) reported a large increase in soil organic carbon content by reclamation of sodic soils through growing *Prosopis juliflora*.

Tiessen *et al.* (1992) studied the carbon sequestration and turn over in semi arid savannas and dry forests. Study was conducted at North East Brazil and West Africa. In NE Brazil approximately 40 per cent of the land have near climax native vegetation < 10 per cent of the area is planted annually, but about 3 - 4 times that area was affected by shifting cultivation which had an average cycle of 5 years arable use, followed by 20 years or more recovery. Standing biomass of native cuttings shown nearly the full global range with 2-50 MgC ha^{-1}. Litter fall around 1-2 MgCha^{-1} yr^{-1} was partially decomposed and partially consumed by animals resulting in low average soil C levels near 8 g Kg^{-1} or 20 Mg C ha^{-1} under cultivation. Carbon sequestration was decreased and soils loose approximately half their carbon stock, before being abandoned. In West Africa between 50-70 per cent of the land was under a management regime with minimal carbon returns to the soils. Overgrazing and over exploitation for fuel wood has resulted in land degradation. Short fallow periods on cultivated land have caused serious decline in soil carbon stocks. Both carbon sequestration and stocks area, therefore, lower in West Africa than in NE Brazil.

Lal (2002a) studied the carbon sequestration in dry land ecosystems of West Asia and North Africa (WANA) and reported that the region has a land area of 1.7 billion ha and a population of 600 million.

Desertification and soil degradation are severe problems in the region. The problem of drought stress is exacerbated by low and erratic rainfall and soils of limited available water holding capacity and organic carbon content of <0.5 per cent. The soil organic carbon pool of most soils has been depleted by soil degradation and widespread use of subsistence and exploitative farming systems. The historic loss of a soil organic carbon pool for the region may be 6-12 Pg compared with the global loss of 66-90 Pg. Assuming that 60 per cent of the historic loss can be resequestered, the total soil carbon sink capacity of the WANA region may be 3-7 Pg. This potential may be realized through adoption of measures to control desertification, restore degraded soils and ecosystems and improve soil and crop management techniques, that can enhance the soil organic carbon pool and improve soil quality. The strategies of soil carbon sequestration include integrated nutrient management and recycling, controlled grazing and growing improved fodder species on rangeland. Through adoption of such measures, the potential of soil carbon sequestration in the WANA region is 0.2 - 0.4 Pg C yr^{-1}. Lal (2002b) also advocated that restoration of degraded soils and ecosystems is an important strategy for enhancing biomass production, improve soil quality and increase the soil carbon pool.

Lal (2002b) reported that the most soils in the mid Western USA have lost 30 to 50 per cent of their original pool or 25 to 40 Mg C ha^{-1} upon conversion from natural to agricultural ecosystems. About 60 to 70 per cent of the carbon thus depleted can be resequestered through adoption of recommended soil and crop management practices. The gross rate of soil organic carbon sequestration ranges from 500 - 800 Kg ha^{-1} yr^{-1} in cold and humid regions and 100 - 300 Kg ha^{-1} yr^{-1} in dry and warm regions. And there is also a large potential to sequester soil inorganic carbon in arid and semi arid regions.

Bronson *et al.* (1998) observed that despite straw removed in the low producing rainfed regions and straw burning in the productive and irrigated areas, carbon levels are constant in tropical and subtropical Asia. In clayey acid upland soils carbon levels are usually higher than in the rice-rice, rice-wheat soils of the South and South-Eastern regions. In both regions agroforestry appears effective in sequestering soil organic carbon. Smith *et al.* (1997) studied the potential for carbon sequestration in European soils and reported only limited potential to increase soil carbon stocks over the next century by addition of animal manure, sewage sludge or straw (<15 Tg C Yr^{-1}) but greater potential through extensification of agriculture or through afforestation of surplus arable lands. Extensification is estimated to increase the total soil carbon stock of European Union by 17 per cent; afforestation of 30 per cent of present arable land would increase soil carbon stock by about 8 per cent over a century and would substitute upto 30 Tg C yr^{-1}. Gupta and Rao (1994) stated that the present stock of carbon in the Indian soils (24.3 Pg) could be increased to 34.9 Pg. Thus there is a potential of 10.6 Pg for sequestering additional carbon.

2.2.2 Depth wise distribution of soil organic carbon pool

The soil organic carbon pool in the top 1 m depth of world soils ranges between 1462 and 1576 Pg. It is nearly three times that in the above ground biomass and approximately double that in the atmosphere; 32% of this in contributed by soils in the tropics. (Eswaran *et al.*, 1993). Kern and Johnson (1993) reviewed data from 17 fields comparing no tillage with conventional tillage plots in USA and observed that soil organic carbon gains were 27 per cent for the 0 - 8 cm layer, 16 per cent for the 8-15 cm layer and no gains for depth >15 cm. In tropical zones a significant impact on soil organic concentration has been observed for the 0-10 cm layer (Bayer *et al.*, 2000 and Lal 1976).

Joao Carlos *et al.* (2001) studied the carbon sequestration rates for a tillage chronosequence and concluded that the carbon sequestration rates for no tillage was 80.6 g cm^{-2} yr^{-1} for the 0-20 cm depth. The no tillage carbon sequestration potential for South Brazil was estimated as 9.37 Tg C yr^{1}. Ross *et al.* (1999) found that the total and microbial carbon and nitrogen declined consistently with profile depth. Microbial carbon and nitrogen ratios differed little among soil profile depths and ecosystems. In 0 to 10 cm depth mineral soil, CO_2 - C production, metabolic quotients and net nitrogen mineralization were all highest in the pasture samples.

Batjes *et al.* (1999) reported that the mean carbon densities to a depth of 1m range from 4.0 Kg m^{-2} for coarse textured Arenosols to 72.4 Kg m^{-2} for the poorly drained Histosols of the Latin America. Mean carbon density for the mineral soils excluding Arenosols and Andosols (30.5 Kg cm^{-2}) was 9.8 Kg m^{-2}. In total the top 1 m holds 66.9 Pg C and 6.9 Pg N. Approximately 52 per cent of the carbon pool was held in the top 30 cm of the soil, the layer which was most prone to changes upon landuse conversion and deforestation.

The results of study on deforestation and soil management experiments conducted at Ibadan and Okomu in Nigeria revealed that tillage and intensive cropping followed by deforestation usually decrease soil organic carbon by 25 - 60% for the top 0 to 5cm depth. Cropping system that maintained a favourable soil organic carbon level in the soil were characterized by high total and below ground root biomass and relatively narrow ratios of carbon to nitrogen, phosphorus and sulphur. The rate of soil organic carbon sequestration was extremely high under Glycine and Melinin grasses (Lal et al., 1998).

Zueng Sang *et al.* (1997) tested 172 soil pedons from cultivated and forestlands of Taiwan to calculate organic carbon pools. They found total organic carbon of 347 Tg from the soil surface, to a depth of 100 cm. As estimated the organic carbon in soils was 196 Tg in the upper 50 cm from the surface. They also reported that the mean soil organic carbon storage in the upper 30 cm depth of different cultivated soils ranged from 2.8 Kg m^{-2} in Oxisols to 18.3 Kg m^{-2} in Andisols and in forest soils ranged from 3.83 Kg m^{-2} in Entisols to 36.9 Kg m^{-2} in Histosols.

Mbagwu *et al.* (1998) investigated the distribution of organic carbon, total carbohydrates and humic acids in water stable aggregates of forest and cultivated soils in South East Nigeria. Gracia *et al.* (1999) studied the effect of slash and burn management on soil aggregates, organic carbon and nitrogen in a tropical deciduous forest of USA. They reported that macro aggregates were an important source of soil organic carbon and soil organic nitrogen in forest soils and accounted for approximately 80 per cent of the total carbon and nitrogen content. They also stated that slash and burn activities did not destroy micro aggregates but the soil organic carbon associated with micro aggregates decreased by 32 per cent due to combustion during burning. Kowalenko and Iwarson (1978) observed that CO_2 evolution was greater from clay loam soil (6.2 Kg CO_2 ha^{-1} day^{-1}) than sandy soil (3.3 CO_2 Kg ha^{-1} day^{-1}).

Carbon sequestration and its mitigation potential in soils Ruecker *et al.* (1998) observed in Eastern Spain that natural tree establishment on degraded soils significantly increased soil organic carbon content in the 0-10 cm layer after 30 years of growth. In North-Eastern Sudan Alstad and Vetaas (1994) observed improvement in soil quality under the stand of *Acacia tortilis*. Garg (1998) observed that establishment of mesquite (*Prosopis juliflora*) plantation on salt affected soils in North-Western India increased soil organic carbon pool from 10 Mg ha^{-1} to 45 Mg ha^{-1} over an eight-year period. Matar *et al.* (1992) showed that judicious application of P to soils of arid region improve water use efficiency, enhance biomass production and improve crop yield.

In Saudi Arabia, Shahin *et al.* (1998) observed that introducing alfa-alfa in rotation with wheat grown on a sandy soil decreased soil salinity and increased soil organic carbon content three fold as compared with continuous wheat. In Algeria, Roose (1996) observed beneficial effects of improved crop rotations and silvipastoral systems on soil and water conservation and enhancements of soil quality. In Syria, Ryan (1998) reported a significant increase in soil organic carbon content by elimination of fallow and application of recommended rates of fertilizers.

When Medicago was grown in a long-term rotation, increase in soil organic carbon content was observed to 1 m depth, probably because of its deep root system (White *et al.*, 1994; Ryan 1998). Adoption of conservation tillage and mulch farming techniques can lead to improvement in the soil organic carbon pool. Experiment conducted in Southern Spain by Murillo *et al.* (1998) demonstrated that conservation tillage was effective in increasing soil organic carbon content.

In Western Nigeria, Lal (1996) observed that the soil organic carbon (SOC) of the surface 10 cm layer declined by about 50 per cent within 10 years after deforestation and cultivation. In the Ivory Coast, Traore and Harris (1995) reported that the soil organic carbon content declined steadily with duration of cultivation. In Australia, Dalal and Carter (2000) reported that the SOC pool in the 10 cm layer decreased with cultivation duration from 7.5-22.1 to 4.4-10.2 Mg C ha^{-1}. The rate of loss was lower in coarse textured soils. In Argentina, Rosell and Galantini (1998) reported a decrease in soil organic carbon content from 2.71 - 1.54 per cent after 11 years of cultivation.

Lal and Logan (1995) estimated the SOC loss from the tropical ecosystem caused by a wide range of agricultural activities. Estimates of the historic SOC loss included 2-13 Pg C by deforestation. The current rate of SOC loss was 90-219 Tg C $year^{-1}$ because of tropical deforestation, 3.8 - 9.2 Tg Cyr^{-1} by shifting cultivation, 112 - 276 Tg Cyr^{-1} by annual burning of grasslands, 38 - 92 Tg Cyr^{-1} by plowing of cropland, 55 - 133 Tg Cyr^{-1} from pastures and 2-3 Tg Cyr^{-1} from cultivation of peat soils.

Galantini and Rosell (1997) reported that rotation of mixed pasture (5.5 years) and annual crops (4.5 years) in Argentina maintained 17.3 Mg ha^{-1} of SOC compared with 11.2 Mg ha^{-1} in continuous cultivation with a wheat - sunflower rotation. In another study, Miglierina *et al.* (1993, 1996) observed a high SOC content in wheat - grassland and wheat-alfalfa rotation especially with a conservation tillage system. Barber (1994) in eastern Bolivia observed that subsoiling and incorporation of cover crops in rotation enhanced quality of degraded soils. In Maharashtra, India, Lomte *et al.* (1993) reported that intercropping sorghum with legumes and application of manure increased soil organic carbon content and aggregation.

In northern Nigeria, Abubaker (1996) monitored the impact of duration of fallowing on changes in SOC content. The mean SOC content of the surface soil was 0.94 per cent for two years fallow, 1.13 per cent for five years fallow, 1.42 per cent for ten years fallow and 1.44 per cent for fifteen years fallow. There was also improvement in SOC content of the subsoil. The SOC content reached 95 per cent of the equilibrium level within ten years of fallowing. The data from a 30 years fallowing experiment conducted in eastern Spain showed that SOC content stayed more or less constant at a low level for several years. Subsequently, there occurred a significant increase in SOC content in the top 0.1 m layer and a slight increase in the 0.2 to 0.3 cm depth. The data showed a notable increase in SOC content to occur after 20 years of fallowing. Although natural vegetative regeneration can enhance soil quality (Ruecker *et al.*, 1998).

Mando (1997) monitored the effectiveness of mulch and termite activity in the rehabilitation of soil structure in Burkina Faso. Termite activity improved structure, soil water regime, biomass production and SOC content. Badanur *et al.* (1990) reported that application of sorghum stubbles and safflower stalks on vertisols in Karnataka, India improved soil structure and increased soil organic carbon content. In degraded red soils of South China, Li *et al.* (1994) observed that application of organic material to degraded soils enhanced SOC content. In a 12-year hedge - row inter cropping trial on a Nigerian Alfisol. *Gliricidia sepium* and *Leucaena leucocephala* increased surface soil organic carbon by 15 per cent (2.38 Mg C ha^{-1}) compared to sole crops (Kang *et al.*, 1999). A 12 per cent increase in SOC (0.23 Mg C ha^{-1}) has also been observed after 5 years of hedge - row intercropping with *Ingaedulis* in a typic Paleudulf in Peru (Alegre and Rao 1996).

In Nigeria, Jaiyeoba (1998) monitored changes in soil properties following conversion of Savannah woodland into *Pinus oocarpa* and *Eucalyptus camaldulensis* plantations. The SOC content of 0 - 0.15 m depth declined during initial stages of tree establishment and increased thereafter to a steady equilibrium value, attained in about 16 years. The initial decline was apparently due to the near absence of ground cover and low biomass production. According to Ball *et al.* (1999); low or zero CO_2 fluxes under no tillage are associated with reduced gas diffusivity and air filled porosity, while increased CO_2 emission with ploughing is due to degassing of soil CO_2.

MATERIALS AND METHODS

3

MATERIAL AND METHODS

The present investigation entitled "Carbon Dynamics studies in Agroforestry Systems of Western Himalaya" were conducted at the Dr. Y.S. Parmar University of Horticulture and Forestry, Nauni, Solan (HP) during 2002-2003. The details about experimental site, materials used and methodology adopted in undertaking these studies are given below:

3.1 Site description

3.1.1 Location

Nauni is located at an elevation of 1250 m a.m.s.l. 15 Km South East of Solan, representing $30^0 51'$ N latitude and $76^0 11'$ E longitude (Survey of India Toposheet No. 55 F/1). It falls in the mid hill zone of Himachal Pradesh.

3.1.2 Climate

The climate of the area is transitional between subhumid subtropical to subtemperate with maximum temperature rising upto 37.8^0C during summer. The mean annual temperature is 19.8 ^{0}C. May and June are the hottest months where as December and January are the coldest months. The annual rainfall ranges between 800-1300 mm of which 75 per cent is received during mid June to Mid September.

Table 1: Locality factors of the study area

Latitude	30°51' N
Longitude	76°11'E
Altitude	1250 m a.m.s.l
Climate type	Subhumid subtropical
MAT	19.8^{0}C
MAP	1150 mm
Soil type	Inceptisols and typic entrochrepts
Texture	Gravelly sandy loam
Parent material	Sandstone, Conglomerate, boulders, dolomite and calcareous.
Soil pH	7.0

3.2 Experimental Methodology

3.2.1 Agroforestry systems used 6

System type	**System unit**
Natural grass land (NG)	* Pure grasses
Horti-pastoral system (HP)	*Prunus salicina* + grasses
Silvi-pastoral system (SP)	*Leucaena leucocephala* + *Grewia optiva* + Grasses
Agri-silviculture system (AS)	*Bauhinia* varigata +*Grewia optiva* + Wheat
Agri-horticulture system (AH)	*Prunus persica*+ Wheat
Agri-horti-silviculture system (AHS)	*Prunus salicina* + *Morus alba* (M-5) + Wheat

* Each AF system was taken as one treatment

3.2.2 Soil depths (cm)

D1	0-10
D2	10-20
D3	20-30
D4	30-40

3.2.3 Replication 3

3.2.4 Design : Split plot

Six Agroforestry systems formed main plot treatments and sampling depth as sub plots.

Table 2. Experimental details indicating specific tree-crop combination and their distribution

Agroforestry system type	Code	Tree-crop combination	Plot size (m) L X B	Net cropped area (ha)	Area under trees (ha)	Area under grasses (ha)	No. of trees (ha^{-1})	Year of planting
Natural grass land	NG	Grass	50 X 10	-	-	1.0	-	-
Horti-pastoral	HP	Plum + grass	50 X 10	-	-		286	1985
Silvi-pastoral	SP	Leuceana + Grewia + grass	50 X 10	-	0.2	0.8	2500 (1:1)*	1990
Agri-silviculture	AS	Grewia + Bauhinia + Wheat	50 X 10	0.9	0.1	-	400 (1:1)*	1990
Agri-horticulture	AH	Peach + Wheat	50 X 10	0.9	0.1	-	200	1990
Agri-horti-silviculture	AHS	Plum + Morus + Wheat	50 X 10	0.9	0.1	-	332 (1:3)*	1990

* Figures in parentheses are ratios for tree species planted in a system type.

3.3 Observation recorded

3.3.1 Plants

3.3.1.1 Aboveground biomass

- Tree
- Crops
- Grasses
- Surface litter

3.3.1.2 Belowground biomass

- Fine roots

3.3.2 Soils

- Soil organic carbon
- Bulk density
- Carbon inventory

3.4 Procedures adopted

Aboveground biomass was estimated by non-destructive method for different plant parts viz., stem, branch, leaf and roots.

3.4.1 Stem biomass

To estimate stem biomass all the trees falling in the plot (50 x 10 m) were enumerated. The diameter at breast height was measured with

Caliper and height with Ravi's multimeter. Form factor was calculated with Spiegel relaskope to find out the tree volume using the formula given by Pressler (1865) and Bitterlich (1984).

$$f = 2h_1/3h$$

Where f - form factor

h_1- height at which diameter is half of dbh.

h- total height

Volume was calculated by Pressler formula (1865)

$$V = f \times h \times g$$

Where V- volume

f- form factor

h- total height

g- basal area

$g = \pi r^2$ or $\pi (dbh/2)^2$

r- radius, dbh- diameter at breast height

Specific gravity

The stem cores were taken to find out specific gravity which was used further to determine the biomass of the stem using maximum moisture method (Smith, 1954).

$$Gf = \frac{1}{\frac{Mn\text{-}Mo}{Mo} + \frac{1}{Gso}}$$

Where,

G_f specific gravity based on gross volume

M_n weight of saturated volume sample

M_0 weight of oven-dried sample

GS_0 average density of wood substances equal to 1.53.

Thus, the weight of the wood was estimated using the formula i.e. mass per unit volume.

Mass = average specific gravity of stem wood x volume.

3.4.2 Branch Biomass

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

$$B_{dwi} = B_{fwi}/1+M_{cbdi}$$

Where

B_{dwi}- oven dry weight of branch

B_{fwi}- fresh/green weight of branches

M_{cbdi}- Moisture content of branch on dry weight basis

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

$$B_{bt}= n_1bw_1 + n_2bw_2 + n_3bw_3 = \sum_{i=1}^{n} nibwi$$

Where

B_{bt}- branch biomass (fresh/dry) per tree

n_i- number of branches in the i^{th} branch group

b_{wi}- average weight of branch of i^{th} group

i = 1,2,3, ….. refers to branch group

3.4.3 Leaf biomass

Leaves from the branches were removed, weighed and oven dried separately to a constant weight at 80 ± 5°C (Chidumaya, 1990).

3.4.4 Tree biomass

The total tree biomass was the sum of stem biomass, branch biomass and leaf biomass. The tree biomass was converted into carbon by a factor of 0.45 (Woomer, 1999).

3.4.5 Crop biomass

Crop biomass was estimated using 1 m x 1 m quadrates. All the crop plants occurring within the borders of the quadrate were cut at ground level and collected samples were weighed, sub sampled and oven dried at 65 ± 5 °C to a constant weight. The crop biomass was converted into carbon by multiplying with a factor of 0.45 (Woomer, 1999)

3.4.6 Grass biomass

Grass biomass was estimated using 1 m x 1 m quadrates. The total grass biomass occurring within the borders of the quadrate were cut at ground level and collected samples were weighed, sub sampled and oven dried at 65 ± 5°C to a constant weight. The grass biomass was converted into carbon by multiplying with a factor of 0.45 (Woomer, 1999).

3.4.7 Surface litter

Surface litter was collected within a 50 x 50 cm frame centrally placed within each quadrate. Samples were weighed, sub sampled and oven dried at 65 ± 5 °C to a constant weight, weighed, ground and ashed. Ash-corrected dry weight was assumed to contain 45 per cent of carbon.

3.4.8. Root biomass

Root samples were collected from an area of 20 cm within each quadrate upto a depth of 40 cm. The roots and soil from the hole were placed in the bags for further laboratory analysis. The samples were dispersed in water and passed through a 2 mm sieve. Roots were collected from the sieve and washed in water without distinguishing live and dead roots. Roots were oven dried at 65 ± 5 °C to a constant weight, weighed, ground and ashed. Ash corrected dry weight was assumed to contain 45 per cent carbon.

3.5 Soil analysis

3.5.1 Collection and preparation of samples

Soil samples were collected by dividing each main plot area into five sub areas each 10 x 10 m. Soil samples for each sub area were obtained by digging five profiles of 20 X 50 cm (sub-surface area) by 50 cm deep. Composite samples from all sub area were obtained for each depth. Samples were air dried in shade, ground with wooden pestle, passed through 2 mm sieve and stored in cloth bags for further laboratory analysis. The following physio-chemical attributes of soils were determined.

S.No.	**Parameters**	**Method employed**
1.	Bulk density (g cm^{-3})	Specific gravity method
2.	Organic carbon (%)	Walkley and Black (1934)

3.5.2 Carbon inventory

The soil organic carbon pool inventory expressed as Mega grams per ha^{-1} (Mgha^{-1}) for a specific depth was computed by multiplying the soil organic carbon (g kg^{-1}) with bulk density (g cm^{-3}) and depth (cm)(Joao Carlos *et al.*, 2001).

3.6 Statistical analysis

The data obtained were subjected to statistical analysis using split plot of experimentation as per the procedure suggested by Gomez and Gomez (1984) wherever, the effects exhibited significance at 5 per cent level of probability, the critical difference (CD) was calculated. Analysis was carried out on computer using the package "STATISTICS".

EXPERIMENTAL RESULTS

4

EXPERIMENTAL RESULTS

Agroforestry systems due to their structure, function, and tree species included and the management to which the system is put reflects wide variability both in productivity and the carbon stored in a defined agro-climatic region. The biomass production levels obtained and the carbon stored in the biomass through the different agroforestry systems have been described in this chapter under the following heads:

4.1 Biomass production levels of different agroforestry systems

4.1.1 Aboveground biomass

4.1.2 Belowground biomass

4.2 Carbon stocks in different agroforestry systems

4.2.1 Aboveground biomass carbon stocks

4.2.2 Belowground biomass carbon stocks

4.3 CO_2 mitigation by agroforestry systems

4.3.1 Aboveground

4.3.2 Belowground

4.4 Soil physico-chemical properties

4.4.1 Bulk density

4.4.2 Soil organic carbon

4.4.3 Soil organic carbon (SOC) stocks inventory

4.4.4 Soil organic carbon (SOC) pool inventory

4.5 Total carbon stocks

4.1 Biomass production levels of different agroforestry systems

Six agroforestry systems including natural grasslands studied have shown significant variations in their total biomass production levels. The biomass produced has been apportioned among different above-and belowground parts for each component of a system.

4.1.1 Aboveground biomass

The data in Table 3 shows the variations in biomass levels of stem, branch, leaf and whole tree for the woody perennial component as well as for crop, grass and litter. Stem biomass was highest in SP system followed by AHS. Agroforestry system types: AS and AH as well as AH and HP showed statistically non-significant biomass values between themselves. However, HP system produced the minimum stem biomass. Branch biomass was also significantly higher in SP system, but reflected a trend different to that of stem biomass among the different systems. Contrary to stem biomass the second highest value for branch biomass was shown by HP system, as in case of stem biomass AHS system showed the second highest value. Similar to stem and branch biomass, leaf biomass was also highest in SP system. It was followed by AHS. However, minimum amount of leaf biomass was in AH system.

Whole tree biomass was significantly higher in SP system with a value of 53.48 tonnes ha^{-1}. It was followed by AHS, AS, HP and AH. Agroforestry systems namely AS, AH and HP showed statistically alike biomass values. Similarly AHS and AS did not show any statistically significant difference with each other.

Variation in crop (wheat) biomass were statistically significant yet AH and AHS systems produced exactly equal amount (2.87 tonnes ha^{-1}) of biomass. Grass biomass was significantly higher in NG system than the

Table 3. Biomass production levels of different agroforestry systems (tonnes ha^{-1}).

System Components	Natural grassland (NG)	Horti-pastoral (HP)	Silvi-pastoral (SP)	Agri-silviculture (AS)	Agri-horticulture (AH)	Agri-horti-silviculture (AHS)	$CD_{0.05}$
Above ground							
Stem	0	4.20	27.02	7.83	6.41	11.19	2.27
Branch	0	7.34	20.73	6.49	4.98	4.41	2.58
Leaf	0	1.51	5.36	1.51	1.03	1.79	1.21
Whole Tree	**0**	**13.07**	**53.48**	**15.49**	**12.41**	**17.31**	**4.28**
Crop	0	0	0	2.44	2.87	2.87	0.28
Grass	2.08	1.52	1.93	0	0	0	0.38
Litter	2.74	2.64	3.34	1.66	1.42	1.44	0.21
Total	**4.83**	**17.22**	**58.74**	**19.59**	**16.70**	**21.93**	**4.27**
Below ground							
Fine roots	0.97	1.03	0.98	0.94	0.93	1.04	NS
Grand Total	**5.79**	**18.25**	**59.72**	**20.53**	**17.63**	**22.97**	**4.22**

biomass. It produced under agroforestry system types namely HP and SP. Litter biomass was significantly higher in SP system followed by NG and HP with their respective value of 3.34, 2.74 and 2.64 tonnes ha^{-1}. AH system showed the minimum litter biomass (1.42 tonnes ha^{-1}), which was statistically similar to the value shown by AHS. Similarly litter biomass levels were also statistically non-significant between AS and AHS.

The total aboveground biomass followed the trend almost similar to the stem biomass among the different systems. It was significantly higher in SP system followed by AHS, AS, HP and AH, with their respective values of 58.74, 21.93, 19.59, 17.22 and 16.70 tonnes ha^{-1}. NG system produced the lowest value of 4.83 tonnes ha^{-1}.

4.1.2 Belowground biomass

The belowground biomass observed as fine roots was highest in AHS followed by HP with their respective values of 1.04 and 1.03 tonnes ha^{-1}, although statistically alike. The remaining systems also showed almost similar amounts of fine roots biomass, which were statistically non-significant with one another.

Total above -and belowground biomass was highest in SP system having a value of 59.72 tonnes ha^{-1}. It was followed by AHS (22.97) and AS (20.53) whereas the minimum was observed under natural grasslands (5.79 tonnes ha^{-1}).

4.2 Carbon stocks in different agroforestry systems

Carbon in plant biomass obtained from a particular agroforestry system type through both above- and belowground components has been termed as current carbon stock of the system. The variability in carbon stocks, among the different systems has been described agroforestry system wise in both above -and belowground components separately, while considering the variations in total i.e. whole systems value.

4.2.1 Aboveground carbon stocks

The data presented in Table 4 shows the present carbon stocks in different plant part i.e. tree stem, branch, leaf and fine roots as well as whole tree and other components of a system like crop and grasses including litter. Carbon stocks for whole system have also been shown in the table. For different plants parts viz. tree stem, branch and leaf. SP system had the highest stem carbon, which was followed by AHS, AS, AH, and HP systems. All the systems showed significantly higher carbon stock values over HP (1.89 tonnes ha^{-1}). The variation in stem carbon between AS and AH as well as AH and HP was however, non-significant between themselves. Branch carbon was significantly higher in SP system followed by HP, AS, AH and AHS with their respective values 9.33, 3.30, 2.92, 2.24 and 1.99 tonnes ha^{-1}. The minimum value was under AHS system. Similar to branch carbon, leaf carbon was also highest in SP system (2.41 tonnes ha^{-1}), which was followed by HP. The minimum value (0.46 tonnes ha^{-1}) was under AH system, although statistically alike to HP, AS and AHS.

Whole tree carbon stocks were significantly higher in SP system with a value of 24.07 tonnes ha^{-1}. It was followed by AHS, AS, HP and AH systems. Agroforestry system type namely AH showed the lowest value of 5.59 tonnes ha^{-1} which was statistically similar to the carbon stock values shown by system types viz. HP, AS and AHS. The respective values for later three systems were 5.88, 6.97 and 7.63 tonnes ha^{-1}, respectively (Table 4).

Among the six agroforestry system types studied, crop (wheat) component was present in three arable landuse systems viz. AS, AH and AHS only. The carbon stocks varied significantly between these three landuse systems. AS system had significantly lowest value of 1.10 tonnes ha^{-1},

Table 4. Carbon stocks in different agroforestry systems (tonnes ha^{-1}).

System Components	Natural grassland (NG)	Horti-pastoral (HP)	Silvi-pastoral (SP)	Agri-silviculture (AS)	Agri-horticulture (AH)	Agri-horti silviculture (AHS)	$CD_{0.05}$
Above ground							
Stem	0	1.89	12.16	3.52	2.89	5.04	1.02
Branch	0	3.30	9.33	2.92	2.24	1.99	1.16
Leaf	0	0.68	2.41	0.68	0.46	0.81	0.55
Whole Tree	**0**	**5.88**	**24.07**	**6.97**	**5.59**	**7.63**	**1.93**
Crop	0	0	0	1.10	1.29	1.29	0.13
Grass	0.94	0.68	0.87	0	0	0	0.17
Litter	1.23	1.19	1.50	0.75	0.64	0.65	0.09
Total	**2.17**	**7.75**	**26.43**	**8.82**	**7.52**	**9.87**	**1.92**
Below ground							
Fine roots	0.44	0.46	0.44	0.42	0.42	0.47	NS
Grand Total	**2.61**	**8.21**	**26.87**	**9.24**	**7.93**	**10.34**	**1.90**

whereas AH and AHS systems depicted the same value of 1.29 tonnes ha^{-1}. The grass component was also present in the three -agroforestry system types in non-arable lands only. All the three systems had significantly varied carbon stock values with respect to the minimum value. The maximum was in NG (0.94 tonnes ha^{-1}) and the minimum (0.68 tonnes ha^{-1}) in HP system. Agroforestry system types NG and SP behaved statistically alike.

Litter carbon stock was significantly higher in SP system with its maximum value of 1.50 tonnes ha^{-1} (Table 4). It was followed by NG and HP showing the values of 1.23 and 1.19 tonnes ha^{-1}. Agroforestry system types *NG and HP albeit were statistically similar* but *significantly* lower than SP in their carbon stock values. The remaining three system types viz. AS, AH and AHS compared to NG, HP and SP showed lower carbon stock values. The carbon stock values for former three systems were 0.75, 0.64 and 0.65 tonnes ha^{-1}, wherein the later two were statistically alike.

A perusal of the data on total carbon stocks for different system types (Table 4) further revealed highest carbon storage through SP system. It was 26.43 tonnes ha^{-1}. This system stored about 12 times more carbon than NG and about 3.4 times of HP system. Similarly, carbon stored in SP system was about 3.00, 3.51 and 2.55 times higher over AS, AH and AHS systems, respectively. The variations in total current carbon stored in HP, AS and AH systems showed statistically non-significant differences with one another. The minimum amount (2.17 tonnes ha^{-1}) of carbon stored was in NG system, which was significantly lower than all the remaining systems total carbon.

4.2.2 Belowground carbon stocks

Data on carbon stored through fine roots referred to as below ground carbon stock of a system (Table 4) revealed least and non-significant differences between the system types. The highest current carbon stored value was albeit, shown by AHS (0.47 tonnes ha^{-1}) system and the lowest (0.42 tonnes ha^{-1}) by both AH and AS systems.

Further examination of the data for whole system carbon stocks depicted maximum value (26.87 tonnes ha^{-1}) in SP system, which was significantly higher than the values obtained for remaining systems. NG system showed the lowest value of 2.61 tonnes ha^{-1}. Carbon stored in system types viz. HP, AS and AH, having their respective values of 8.21, 9.24 and 7.93 tonnes ha^{-1} showed statistically non-significant differences with one another and hence, were found statistically similar. System types AS and AHS were also statistically similar.

4.3 CO_2 mitigation by agroforestry systems

4.3.1 Aboveground

The data presented in Table 5 shows the CO_2 mitigation potential of different agroforestry systems. Actual amount of CO_2 mitigated through each system and their components like tree stem, branch, leaf; annual crop, grass litter and fine roots have been analyzed and compared statistically. Variations thus, obtained between the systems have been described as below.

It is discernible from the CO_2 mitigation values in Table 5 that woody perennials - the dominant partner of the tree-crop association in each system type showed maximum CO_2 mitigation through stem. On comparison between the different systems types, it was seen that SP system had significantly higher CO_2 mitigation value of 44.50 tonnes ha^{-1} as stem CO_2 followed by AHS (18.43 tonnes ha^{-1}). The minimum value was found in HP system (6.92 tonnes ha^{-1}). The variation in stem CO_2 mitigation between AS and AH was albeit, non-significant. Branch CO_2 mitigation value was significantly higher in SP system followed by HP, AS, AH and AHS with their respective values 34.14, 12.09, 10.69, 8.20 and 7.26 tonnes ha^{-1},

Table 5. . CO_2 mitigation levels of different agroforestry systems (tonnes ha^{-1}).

System / Components	Natural grassland (NG)	Horti-pastoral (HP)	Silvi-pastoral (SP)	Agri-silviculture (AS)	Agri-horticulture (AH)	Agri-horti-silviculture (AHS)	$CD_{0.05}$
Above ground							
Stem	0	6.92	44.50	12.90	10.56	18.43	3.74
Branch	0	12.09	34.14	10.69	8.20	7.26	4.25
Leaf	0	2.49	8.83	2.49	1.70	2.95	1.99
Whole Tree	**0**	**21.53**	**88.08**	**25.51**	**20.44**	**29.00**	**7.05**
Crop	0	0	0	4.03	4.72	4.72	0.45
Grass	3.44	2.49	3.17	0	0	0	0.62
Litter	4.50	4.37	5.49	2.74	2.34	2.38	0.36
Total	**7.94**	**28.36**	**96.75**	**32.26**	**27.50**	**36.12**	**7.03**
Below ground							
Fine roots	1.60	1.68	1.62	1.55	1.54	1.71	NS
Grand Total	**9.54**	**30.06**	**98.36**	**33.81**	**29.04**	**37.83**	**6.95**

respectively. The minimum value was under AHS system yet, its value was statistically similar to those of AS and AH. Similar to branch CO_2 mitigation, leaf CO_2 mitigation was also highest in SP system (8.83 tonnes ha^{-1}). It was followed by AHS. However, minimum value (1.70 tonnes ha^{-1}) was under AH system. The values shown by HP, AS, AH and AHS were statistically non-significant with one another.

The amount of CO_2 mitigated through whole tree in each system was significantly higher in SP system with a value of 88.08 tonnes ha^{-1}. It was followed by AHS which was significantly higher than AH and HP but did not vary significantly with AS system. The lowest value was depicted by AH system yet statistically similar to HP. The respective values for these systems were 20.44 and 21.53 tonnes ha^{-1}.

The crop (wheat) component among the six agroforestry systems studied, was present in three arable landuse systems viz., AS, AH and AHS only. The amount of CO_2 mitigated varied significantly between these three landuse systems. AS system had the significantly lowest value of 4.03 tonnes ha^{-1}, whereas, AH and AHS systems depicted statistically alike values of 4.72 tonnes ha^{-1}. Grass a component which was present in the three agroforestry system types in non-arable lands viz. NG, HP and SP, only exhibited significantly higher CO_2 mitigation value in NG (3.44 tonnes ha^{-1}) system followed by SP having the value of 3.17 tonnes ha^{-1}. However, both yielded statistically similar values. HP system showed significantly lowest amount of CO_2 mitigated through grass component.

Litter, a common component of all the agroforestry systems evinced significantly higher amount of CO_2 mitigated through SP system showing its value of 5.49 tonnes ha^{-1}. It was followed by NG and HP with their respective values of 4.50 and 4.37 tonnes ha^{-1}. Agroforestry system types NG and HP were albeit, statistically similar but significantly lower than SP system in their CO_2 mitigation values. The remaining three system types viz. AS, AH and AHS compared to NG, HP and SP showed lower values. The amounts of CO_2 mitigated by former three systems were 2.74, 2.34 and 2.38 tonnes ha^{-1} and the difference between the later two systems was statistically non-significant.

Further perusal of the data on the amount of total CO_2 mitigated by aboveground components of different system types (Table 5) revealed significantly higher values in SP system. It was 96.75 tonnes ha^{-1}. This system mitigated about 12 times more CO_2 than NG and about 3.4 times of HP system. Similarly, CO_2 mitigation in SP system was about 3.00, 3.52 and 2.69 times higher over AS, AH and AHS systems, respectively. The variations in total CO_2 mitigation values among HP, AS, and AH systems were statistically non-significant with one another. The minimum (7.94 tonnes ha^{-1}) CO_2 mitigation was in NG system, which was significantly lower than all the remaining systems.

4.3.2 Belowground

Data on CO_2 mitigation through fine roots or below ground plant parts (Table 5) revealed least and non-significant differences between system types. The highest current CO_2 mitigation value was albeit, shown by AHS (1.71 tonnes ha^{-1}) system and lowest (1.54 tonnes ha^{-1}) by AH system.

The amount of CO_2 mitigated by an agroforestry system (total of above-and belowground) depicted maximum value (98.36 tonnes ha^{-1}) in SP system, which was significantly higher than the values obtained for remaining systems. NG system showed the lowest (9.54 tonnes ha^{-1}) value. The system types viz. HP, AS, AH and AHS having their respective values of 30.06, 33.81, 29.04 and 37.83 tonnes ha^{-1} showed statistically non-significant difference with one another and hence, were found statistically similar.

4.4 Soil physico-chemical properties

Soil physico-chemical properties studied were bulk density, per cent soil organic carbon (SOC) and soil organic carbon pool inventory. Total carbon stocks were determined for each of the system studied for comparison of the results. The results thus obtained are produced attribute wise as below:

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

A critical examination of the data presented in Table 6 inferred significant variations in the bulk density (BD) values for different agroforestry systems. AH system showed the significantly higher value of 1.22 among all the systems. It was followed by AHS and AS showing their respective values of 1.17 and 1.13 albeit, the differences among all the three were statistically non-significant with one another. The lowest bulk density value of 0.95 g cm^{-3} was found in SP system.

It was further perused from the data in Table 6 that bulk density values for three non arable agroforestry system types viz. SP, HP and NG compared to arable land agroforestry system types i.e. AH, AS and AHS were lower. It was also deduced from the data that agroforestry system type involving fruit tree as one of the functional unit in place of the forest/fodder tree both in arable as well as non-arable lands had slightly higher bulk density values. Among the three non-arable landuse systems NG system exhibited the maximum value, which was significantly higher than the SP but statistically similar to that of HP. The results thus indicated that inclusion of woody perennials in natural grasslands decreased the bulk density of soils.

Variations in the bulk density of soils at different depths of soil profile have shown significant differences in their values (Table 6). The data indicated that bulk density of surface soils (0-10 cm) was the lowest (1.06), which increased gradually with an increase in soil depth and attained its maximum value of 1.15 at 20 -30 cm. The increase in bulk density at 10 -20 cm depth over 0 -10 cm, although was statistically non -significant yet at deeper depths of 20-30 and 30-40 cm a significant increase in bulk density over 0-10 cm depth was evident. The interaction effects between agroforestry landuse system x soil depths were non-significant. The maximum bulk density (1.27) however, was noticed in AH system at 30-40 cm depth, whereas minimum (0.90) in SP system at 0-10 cm depth.

4.4.2 Per cent Organic carbon

Soil organic carbon (SOC) was influenced significantly due to various agroforestry systems. Data in Table 5 revealed that soil organic carbon was higher under SP system (3.38) which was followed by NG (1.73) and AHS (1.67). The AH system showed lowest (1.03) soil organic carbon. Contrary to the bulk density, soil organic carbon was highest in SP system followed by NG and HP systems indicating that inclusion of forest trees increased the soil organic carbon but that of fruit trees decreased its value over natural grasslands. The decrease though was statistically non-significant. Trend for SOC change in agroforestry landuse systems in arable lands viz. AS and AH wherein SOC in AS was higher than AH was almost similar. It was further interesting to note that simultaneous integration of both forest and fruit trees (AHS) caused significant increase in SOC content over their individual combinations i.e. AH and AS. The SOC content in AHS, HP and NG was statistically at par with one another.

Soil organic carbon at different soil depths in a profile also depicted significant variations in its content (Table 7). An examination of the mean values has shown that surface soils had the maximum (2.49) SOC value. It decreased with the increase in soil depth gradually resulting into the lowest value of 1.27 at 30-40 cm soil depth. The two soil depths 10-20 and 20-30 cm did not show statistically significant differences in SOC values, albeit a gradual decrease was evident. The interaction effects between the agroforestry landuse system X profile depths were also significant and depicted maximum (4.70) SOC in SP system at 0-10 cm soil depth. It was followed by NG and HP systems at the same depth. The lowest SOC (0.77) value was exhibited by the AH system at 30-40 cm soil depth.

4.4.3 Soil organic carbon stocks (tonnes ha^{-1})

Soil organic carbon stocks were calculated by multiplying the organic carbon with weight of the soil for a particular depth and expressed as

Table 6. Effect of agroforestry systems on the bulk density at different profile depths (g cm^{-3}).

Agroforestry systems	0-10	10-20	20-30	30-40	Mean
Natural Grassland (NG)	1.07	1.14	1.16	1.12	1.12
Horti-pastoral (HP)	1.04	1.11	1.13	1.15	1.11
Silvi-pastoral (SP)	0.90	0.94	0.97	0.97	0.95
Agri-silviculture (AS)	1.08	1.10	1.17	1.21	1.13
Agri-horticulture (AH)	1.16	1.22	1.24	1.27	1.22
Agri-horti-silviculture (AHS)	1.10	1.13	1.26	1.20	1.17
Mean	**1.06**	**1.11**	**1.15**	**1.15**	

$CD_{0.05}$

System : 0.10

Depth : 0.05

System X Depth: NS

Table 7. Percent organic carbon under different agroforestry systems

Agroforestry systems	0-10	10-20	20-30	30-40	Mean
Natural Grassland (NG)	2.77	1.30	1.74	1.13	1.73
Horti-pastoral (HP)	2.55	1.42	1.33	1.00	1.57
Silvi-pastoral (SP)	4.70	3.48	2.73	2.62	3.38
Agri-silviculture (AS)	1.27	1.17	1.15	0.98	1.14
Agri-horticulture (AH)	1.32	1.06	0.97	0.77	1.03
Agri-horti-silviculture (AHS)	2.37	1.67	1.50	1.14	1.67
Mean	**2.49**	**1.68**	**1.57**	**1.27**	

$CD_{0.05}$

System : **0.25**

Depth : **0.13**

System X Depth : 0.245

tonnes ha^{-1}. The various agroforestry systems influenced SOC stocks significantly. A critical examination of data in Table 8 indicated that SP system showed significantly higher (31.71 tonnes ha^{-1}) SOC stock. NG and AHS systems showing their respective SOC stocks of 19.20 and 18.81 followed the SP system. The former systems were statistically alike. AH system exhibited lowest SOC stock of 12.28 among all the six landuse systems, albeit statistically alike with AS system (13.37).

Soil organic carbon stocks at different depths of a profile also had significant variations in their content (Table 8). Analyses of mean values have shown that surface soils had the maximum (25.54 tonnes ha^{-1}) and significantly higher SOC stock values over the remaining. It decreased with the increase in soil depth gradually resulting into the lowest value of 14.05 tonnes ha^{-1} at 30-40 cm soil depth. The SOC stocks at 10-20 and 20-30 cm soil depths did not show statistically significant difference in their variation, albeit a gradual decrease was evinced.

The interaction effects between the agroforestry landuse systems X soil depths were also significant. Maximum (42.24 tonnes ha^{-1}) SOC stock was in SP system at 0-10 cm soil depth. It was followed by NG and HP systems at the same depth. The lowest SOC stock of 9.31 was in AH system at 30-40 cm soil depth.

4.4.4 Soil organic carbon pool inventory (Mg ha^{-1})

Soil organic carbon pool inventory for a particular system was determined by multiplying bulk density (g cm^{-3}), organic carbon (g kg^{-1}) and depth (cm), which was expressed as Mg ha^{-1}. Data in Table 9 revealed that the soil organic carbon pool under SP system was maximum (317.38) and significantly higher than all other systems. It was followed by NG (190.2) and AHS (185.2) both of these, however did not differ significantly with each other. The AH system showed lowest (124.8 Mg/ha) value of SOC pool.

The SOC pool also experienced significant variations, due to different landuse systems in its vertical distribution. It was maximum (255.2) in surface soils (0-10 cm) and decreased significantly to a value of 179.5 in 10-20 cm soil depth. Thereafter, a gradual but non-significant decrease occurred showing its lowest value of 140 in 30-40 cm soil depth.

The interaction effects between agroforestry landuse systems X soil depths were non -significant. The maximum value of SOC pool (423.0 Mg/ha) was albeit, observed in SP system at 0-10 cm depth, whereas minimum (97.49) in AH system at 30-40 cm depth.

4.5 Total carbon stocks for different agroforestry systems

Total carbon stocks for a particular system was determined by the addition of plant carbon and the soil carbon stocks upto a particular soil depth. The data presented in Table 10 revealed highest carbon stocks under SP system. It was 101.69 tonnes ha^{-1} upto 20 cm soil depth. This system stored 2.17 times more carbon than NG system and 2.01 times more than HP system. Similarly carbon stock in SP system was 2.78, 2.85 and 1.87 times higher over AS, AH and AHS systems, respectively. The minimum (35.74 tonnes ha^{-1}) carbon stock was in AH system, which was almost equal to AS system, though slightly less. It was further revealed from the data in Table 8 that soil carbon stocks upto 0-20 cm soil depth were lower in AS and AH systems i.e. the systems planted in arable lands, whereas NG, HP and SP systems in non-arable lands showed considerably higher values of carbon stock. One system type on arable lands i.e. AHS had almost similar amount of carbon to that of NG and HP planted in non-arable lands. Their respective values were 43.97, 44.33 and 42.31 tonnes ha^{-1}. Comparing the average plant carbon stocks among the systems in arable and non-arable lands, it was found that AH system (7.93 tonnes ha^{-1}) in arable lands, whereas NG (2.61 tonnes ha^{-1}) in non-arable lands produced the minimum values. In general, the NG system had the lowest plant carbon stocks among all the system types. Total carbon stocks i.e. plant plus soil carbon in (0-20 cm soil depth) for

Table 8. Soil organic carbon stocks under different agroforestry systems (tonnes ha^{-1}).

Agroforestry systems	0-10	10-20	20-30	30-40	Mean
Natural Grassland (NG)	29.58	14.75	19.89	12.57	19.20
Horti-pastoral (HP)	26.50	15.81	14.91	11.42	17.16
Silvi-pastoral (SP)	42.24	32.58	26.57	25.45	31.71
Agri-silviculture (AS)	14.11	13.22	14.45	11.69	13.37
Agri-horticulture (AH)	15.21	12.60	11.98	9.31	12.28
Agri-horti-silviculture (AHS)	25.26	18.35	17.45	13.84	18.81
Mean	**25.54**	**17.89**	**17.54**	**14.05**	

$CD_{0.05}$

System : 3.45

Depth : 1.57

System X Depth : 3.57

Table 9. Effect of agroforestry landuse systems on soil organic carbon pool (Mg ha^{-1}) distribution.

Agroforestry systems	0-10	10-20	20-30	30-40	Mean
Natural Grassland (NG)	296.2	147.5	198.9	118.0	190.2
Horti-pastoral (HP)	264.9	158.1	149.2	114.3	171.7
Silvi-pastoral (SP)	423.0	325.8	265.7	255.0	317.38
Agri-silviculture (AS)	139.6	132.2	144.4	116.9	133.3
Agri-horticulture (AH)	152.1	129.6	119.9	97.5	124.8
Agri-horti-silviculture (AHS)	256.2	183.5	162.9	138.4	185.2
Mean	**255.2**	**179.5**	**173.5**	**140.0**	

$CD_{0.05}$

System	:	50.70
Depth	:	33.30
System X Depth:		NS

Table10. **Carbon stocks (tonnes ha^{-1}) of different agroforestry landuse systems considering belowground carbon upto 20cm profile depth.**

Landuse system	Plant C Stocks	Soil C Stocks	Total	Soil : Plant
Non-arable lands				
Natural Grassland (NG)	2.61	44.33	46.94	16.99
Horti-pastoral (HP)	8.21	42.31	50.52	5.15
Silvi-pastoral (SP)	26.87	74.82	101.69	2.79
Arable lands				
Agri-silviculture (AS)	9.24	27.33	36.57	2.96
Agri-horticulture (AH)	7.93	27.81	35.74	3.51
Agri-horti-silviculture (AHS)	10.34	43.97	54.31	4.25

different agroforestry systems followed the following decreasing order: SP>AHS>HP>NG>AS>AH.

Similarly the total carbon stocks among the different systems considering belowground profile depth upto 40 cm were higher in SP system (153.71 tonnes ha^{-1}) and minimum under AH system (57.04 tonnes ha^{-1}). Here, again agroforestry system type viz. SP, NG and HP in non-arable lands had higher amounts of carbon than AS and AH systems planted in arable lands. Albeit, AHS in arable lands had more carbon stocks than had the NG and HP in non-arable lands (Table 11). The different agroforestry landuse systems showed the following decreasing order of their total carbon stock: SP>AHS>NG>HP>AS>AH. It was revealed from the data in Table 10 and 11 that total carbon stocks in different agroforestry systems followed almost similar order of abundance or reduction. The highest and lowest values in each case, whether belowground carbon stocks were considered upto 20 cm profile depth or 40 cm, were shown by the same system types i.e. SP and AH, respectively. In case of profile depth 40 cm, however HP and NG systems types substituted their places with each other with respect to their order observed in profile depth 0-20 cm. In the former case NG occupied the third highest place, whereas HP the fourth which was just opposite in the later case.

4.5.1 Loss and gain in the different agroforestry systems

The data in Table 12 shows the carbon stocks in different agroforestry systems relative to NG system. The data also shows the change in current carbon stocks of different systems when the belowground carbon stocks values are accounted either upto 20 cm profile depth only or upto 40 cm profile depth from the surface. The values shown are the calculated values of their actual ones. The actual value of NG system has been considered as 100 and respective values for other systems thus have been calculated and absolute loss or gain in the carbon stocks of different agroforestry systems over NG has been obtained.

The data indicated that AS and AH systems had the lower values i.e. 77.91 and 76.14 tonnes ha^{-1} whereas SP, AHS and HP systems had higher carbon stocks of 216.64, 115.70 and 107.63 tonnes ha^{-1}, respectively than the NG, when soil profile depth was considered from 0-20 cm. On the other hand, if soil profile depth is extended upto 40 cm from the surface, agroforestry systems namely HP, AS and AH showed less carbon stocks where as SP and AHS indicated the higher carbon stocks values. In the former case AS and AH showed the net loss of 22.09 and 23.84 tonnes ha^{-1}, respectively, whereas SP, AHS and HP system types showed net gains of 116.64, 15.70 and 7.63 tonnes ha^{-1}, respectively over the NG. Similarly, in the later case that is, if the profile depth extended upto 40 cm, HP, AS and AH shows respective net losses of -3.20, -21.03 and -28.16 tonnes ha^{-1}. The SP and AHS system had the net gains of 93.59 and 7.80 tonnes ha^{-1} of carbon in this profile depth.

4.5.2 Above- and belowground distribution of carbon stocks in different agroforestry systems

Above-and belowground current carbon stocks in different agroforestry systems (Table 13) were observed to vary considerably within and between different systems. The data have shown that NG system had 2.17 tonnes ha^{-1} of aboveground carbon stock compared to 77.23 tonnes ha^{-1} of belowground. The SP system had 26.44 tonnes ha^{-1} of aboveground carbon stock and 127.27 tonnes ha^{-1} of belowground carbon which showed the highest above-and belowground carbon stock among all the system types. It was further observed from the data that AS and AH system types had almost similar carbon stock values both above (8.82 and 7.52 tonnes ha^{-1}) and belowground (53.88 and 50.18 tonnes ha^{-1}) though AS system exhibited slightly higher values. On the other hand, aboveground carbon stocks in HP system were similar to AH system but relatively lower than AS system. However, belowground carbon stock in HP system (69.11 tonnes ha^{-1}) was considerably higher than AS and AH. The respective values of the belowground carbon stock for later two systems were 53.88 and 50.18 tonnes ha^{-1}.

Table 11. Carbon stocks (tonnes ha^{-1}) of the different agroforestry landuse systems considering belowground carbon upto 40cm profile depth

Landuse system	Plant C Stocks	Soil C Stocks	Total	Soil : Plant
Non-arable lands				
Natural Grassland (NG)	2.61	76.79	79.40	29.42
Horti-pastoral (HP)	8.21	68.65	76.86	8.36
Silvi-pastoral (SP)	26.87	126.84	153.71	4.72
Arable lands				
Agri-silviculture (AS)	9.24	53.46	62.70	5.79
Agri-horticulture (AH)	7.93	49.11	57.04	6.19
Agri-horti-silviculture (AHS)	10.34	75.25	85.59	7.28

Table 12. Relative* loss or gain in the system carbon stocks (tonnes/ha) of different agroforestry systems

System	A**	B**
Natural Grassland (NG)	100.00 (± 0.00)	100.00 (± 0.00)
Horti-pastoral (HP)	107.63 (+7.63)	96.80 (-3.2)
Silvi-pastoral (SP)	216.64 (+116.64)	193.59 (96.59)
Agri-silviculture (AS)	77.91 (-22.09)	78.97 (-21.03)
Agri-horticulture (AH)	76.14 (-23.86)	71.84 (-28.16)
Agri-horti-silviculture (AHS)	115.70 (+15.70)	107.80 (+7.80)

* Actual loss or gain is calculated considering the value of NG system as 100.

** Column A includes the belowground values upto 20 cm profile depth whereas column B upto 40 cm profile depth.

Table 13. Above-and belowground carbon stocks (tonnes ha^{-1}) in different agroforestry systems.

System Components	Natural grassland	Horti-pastoral (HP)	Silvi-pastoral (SP)	Agri- silviculture (AS)	Agri- horticulture (AH)	Agri-horti - silviculture (AHS)
Above ground						
Tree	0.00	5.88	24.07	6.97	5.59	7.63
Crop	0.00	0.00	0.00	1.10	1.29	1.29
Grass	0.94	0.68	0.87	0.00	0.00	0
Litter	1.23	1.19	1.50	0.75	0.64	0.65
Total (A)	**2.17**	**7.75**	**26.44**	**8.82**	**7.52**	**9.57**
Below ground						
Fine roots	0.44	0.46	0.44	0.42	0.42	0.47
Soil (0 -10 cm)	29.58	26.50	42.24	14.11	15.21	25.26
Soil (10-20 cm)	14.75	15.81	32.58	13.22	12.60	18.35
Soil (20-30 cm)	19.89	14.91	26.57	14.45	11.98	17.45
Soil (30-40 cm)	12.57	11.42	25.45	11.69	9.31	13.84
Total (B)	**77.23**	**69.11**	**127.27**	**53.88**	**50.18**	**76.02**
Total (A+B)	**79.40**	**76.86**	**153.71**	**62.70**	**57.04**	**85.59**
Below: aboveground	35.59	8.92	4.81	6.11	6.67	7.94

Table 14 . CO_2 mitigation by different agroforestry systems (tonnes ha^{-1}).

System / Components	Natural grassland	Horti-pastoral (HP)	Silvi-pastoral (SP)	Agri- silviculture (AS)	Agri- horticulture (AH)	Agri-horti - silviculture (AHS)
Above ground						
Tree	0	21.53	88.08	25.51	20.44	29.00
Crop	0	0	0	4.03	4.72	4.72
Grass	3.44	2.49	3.17	0	0	0
Litter	4.50	4.37	5.49	2.74	2.34	2.38
Total (A)	**7.94**	**28.36**	**96.75**	**32.26**	**27.50**	**36.12**
Below ground						
Fine roots	1.60	1.68	1.62	1.55	1.54	1.71
Soil (0 -10 cm)	108.26	96.99	154.60	51.64	55.67	92.45
Soil (10-20 cm)	53.99	57.87	119.24	48.39	46.12	67.61
Soil (20-30 cm)	72.80	54.57	97.25	52.89	43.85	63.87
Soil (30-40 cm)	46.01	41.80	93.15	42.79	34.08	50.65
Total (B)	**282.66**	**252.91**	**465.86**	**197.26**	**181.26**	**276.29**
Total (A + B)	**290.6**	**281.27**	**562.61**	**229.52**	**208.76**	**312.41**
Below: aboveground	35.60	8.92	4.82	6.12	6.59	7.65

AH system showed the lowest belowground carbon stock among all the systems. It was also seen from the data that belowground carbon stock in AHS (76.02) system was almost equal to NG (77.23) however aboveground carbon stock in AHS system (7.52) was about 3.47 times higher than NG (2.17 tonnes ha^{-1}) system. The ratio of below : aboveground carbon stocks for different agroforestry systems was observed to be highest (35.59) in NG system where as the minimum(4.81) in SP. Considering the above ratio different systems can be arranged in the following ascending order: SP < AS < AH < AHS < HP < NG with their respective values of 4.81 < 6.11 < 6.67 < 7.94 < 8.92 < 35.59.

4.5.3 CO_2 mitigation (tonnes ha^{-1})

CO_2 mitigation by different agroforestry systems (Table 14) varied considerably within and between different systems. The data have shown that NG system mitigated 7.94 tonnes of CO_2 through aboveground biomass compared to 282.66 tonnes ha^{-1} through belowground fine roots soils. Similarly the SP system mitigated 96.75 tonnes ha^{-1} through aboveground biomass and 465.86 tonnes ha^{-1} a through belowground fine roots and soils. This system exhibited the highest mitigation level among all the systems. A further perusal of the data reveal that AS and AH systems both had almost similar CO_2 mitigation levels both above (32.26 and 27.50 tonnes ha^{-1}) and belowground (197.26 and 181.26 tonnes ha^{-1}) though AS system exhibited slightly higher values. On the other hand, CO_2 mitigation through aboveground biomass in HP system revealed values almost similar to AH system, but relatively lower than AS system. However, belowground CO_2 mitigation in HP (252.91 tonnes ha^{-1}) was considerably higher than AS and AH system, with their respective values of 197.26 and 181.26 tonnes ha^{-1}. AH system showed the lowest belowground CO_2 mitigation levels among all thse systems. The data also indicated that belowground CO_2 mitigation levels in AHS (276.29 tonnes ha^{-1}) system was almost equal to NG (282.66 tonnes ha^{-1}) however, aboveground CO_2 mitigation levels in AHS system (36.12 tonnes ha^{-1}) was about 4.41 times higher than NG (7.94 tonnes ha^{-1}) system.

DISCUSSION

5

DISCUSSION

The results obtained from the present investigations have been discussed in this chapter, establishing a cause and effect relationship wherever necessary or feasible in the light of available literature, under the following heads:

5.1 Biomass production levels

5.2 Carbon stocks in different agroforestry systems

5.3 Soil physico-chemical properties

5.4 Total carbon stocks

5.1 Biomass production levels

The biomass produced has been apportioned as above -and belowground biomass for each agroforestry system type. Aboveground biomass has further been partitioned for woody perennials in stem, branch and leaf biomass. Table 3 contained the data on changes in biomass levels of woody perennials stem, branch and leaf as well as for other components viz. crop, grass and their litter. Stem biomass was significantly highest in SP system followed by AHS. The lowest stem biomass was produced by HP system. Agroforestry system types AS, AH and AH, HP produced statistically non-significant biomass values among themselves. Branch biomass though highest in SP system yet, its second highest value was observed under HP system. This was contrary to the trend observed for stem biomass for which second highest value was under AHS system. The leaf biomass followed the trend just similar to stem biomass showing its highest value under SP system followed by AHS whereas the minimum was under AH system.

The stem, branch and leaf biomass depends upon number of factors viz., growth habit of the tree species, soil on which it grows, age of the tree, its management and also its compatibility with the associated crop plant species. The highest stem biomass obtained under SP system can be explained to the fact that in this system the tree species namely *Leucaena leucocephala* and *Grewia optiva* were planted at high density in mixture (2500 trees/ha) and were managed using pollarding technique. The system had the highest number of trees per hectare among all the systems. Therefore more number of stems per hectare in SP system over the remaining resulted into higher stem; branch and leaf biomass. Pollarding of these trees also increased the branch number and ultimately more branch biomass. The second highest stem biomass value was under AHS system integrating plum and mulberry as woody perennials. The significantly higher stem biomass in this system over AS, AH and HP reflected the influence of systems structure i.e. species involved and tree management practices.

It was further observed that despite total number of trees per hectare in AS system (400) was more than AHS (332), the stem biomass was higher in AHS. This has happened as the trees viz. *Grewia optiva* and *Bauhinia varigata* under AS system were managed using pollarding at 0.5 m and 1 m for Grewia, whereas 3 m for Bauhinia, thus producing lower stem biomass per tree compared to the tree species namely plum and mulberry planted in AHS system. In AHS system plum trees were maintained as natural trees. These were managed using light pruning only. Mulberry the fodder species was pollarded at 1m height. Both produced higher stem biomass per tree than Grewia and Bauhinia (Appendix-II). The stem biomass per tree of Grewia planted in AS system was about 4 times less than the stem biomass per tree of plum in AHS system. Contrary to the results shown by AHS system i.e. despite having less number of trees per hectare produced more stem biomass over AS system other system types viz. HP and AH having less number of trees per hectare over AHS system produced less biomass. The results are obvious considering the difference in number of trees. Secondly HP system was in non-arable lands whereas AHS on arable lands and hence, difference in soil -site quality also must have influenced the tree growth. The influence of site and species is discernible from the higher stem biomass in AH system in arable lands involving peach as woody component over HP system in non-arable lands involving plum as woody perennial. Here, also the number of trees per hectare were more in HP (286) system over AH (200) system. The age of the trees in HP system was also more i.e. five years older than peach trees in AH system. Therefore, it can be inferred that factors of soil site quality, species and its management influence the biomass production, the most and should be regarded of paramount importance in agroforestry.

Further perusal of the data in Table 3 for branch and leaf biomass shows that although SP system produced significantly higher branch and leaf biomass over the remaining systems but second highest value for branch biomass was shown by HP system. This may have occurred due to the different branching habit of the species, the variation in soil fertility on which they were growing and also the plant management. Plum trees grown in the HP system on non-arable lands produced lower stem biomass and higher branch biomass compared to its values in AHS system on arable lands in which it produced higher stem biomass and lower branch biomass (Appendix-II). The findings thus, indicated that although the woody perennials were common in both the systems. Soil site played the dominant role owing to which in non-arable lands plum trees were more branched compared to the individuals of this species in arable lands. Secondly, in AHS system crown management was little different and intensive to minimize its adverse influence on associated field crops. Hence crown management was also a factor that influenced the branch biomass. The lower branch biomass of AHS system can also be ascribed to the less number of plum trees (83 only) in this system over HP. However, the total number of trees (fruits and fodder trees) was more i.e. 332. The other species involved in AHS system was mulberry. But to reduce the competition for growth resources and to improve the microclimate especially to reduce shade of the tree component over the companion crop, mulberry trees were pollarded at 1m height, which reduced the branch biomass under AHS system.

The AHS system further showed the second highest value for the leaf biomass over the remaining systems except SP, which showed significantly highest leaf biomass among all the systems. This may be attributed to the different leaf size, number of leaves/branch coupled with the variations in soil fertility on which the trees were growing. The whole tree biomass exhibited different trends than shown by biomass of components under each agroforestry system. The highest whole tree biomass was in SP followed by AHS, AS, HP and the least value was shown by AH. The system types AH, AS and HP however did not differ significantly with one another. The relatively higher whole tree biomass in AHS system over the remaining except SP can be ascribed to the fact that plum trees in AHS system growing on arable lands produced about 3 times more stem biomass per tree than the plum in HP system planted on non-arable lands, despite plum trees in AHS system were younger by 5 years. It may also have happened as AHS system involved two woody perennials, one fruit and one fodder species.

The crop biomass was significantly higher in AH and AHS system over the AS. The variations in the crop biomass can be explained due to the tree -crop interaction effects. The reduced crop biomass in AS system involving two fodder tree species viz., *Grewia* and *Bauhinia* may have occurred due to more competition for resources like nutrients, moisture and light compared to the tree species i.e. peach in AH system and plum plus mulberry in AHS system. The fruit species constituting the AH and AHS system received regular application of fertilizers which may have minimized the competition for nutrients between the woody and non-woody components of the system. Secondly peach and plum both being the fruit trees are deciduous in nature. Thus may not have influenced the relative illumination significantly during the germination and initial active growth period of the wheat crop. Conversely Grewia trees planted in AS system had full canopy during the germination and initial active growth period of wheat, hence may have created competition for light. Grass biomass was significantly higher in NG system than HP system but it was statistically at par with SP. The significantly lower grass biomass in HP system may be due to the adverse influence of plum tree on the associated grass species, owing to their large

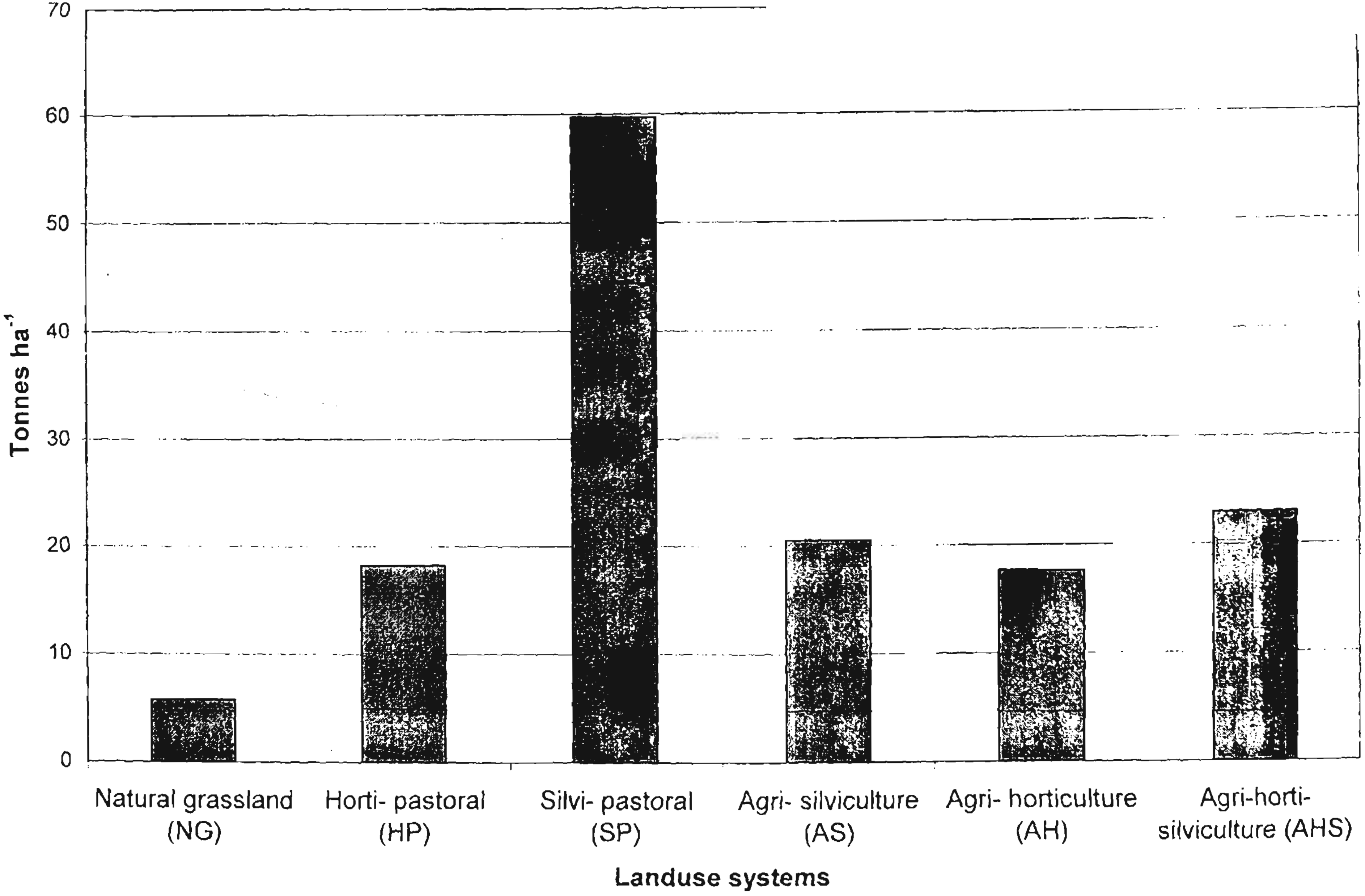

Fig.1. Biomass production levels of agroforestry systems (tonnes ha^{-1})

crown area compared to the fodder tree species viz., *Leucaena* and *Grewia optiva* which were managed using intensive pollarding resulting into lesser crown area. In addition the total area under these two systems viz., SP and HP under grass component was relatively lesser than the NG system.

The surface litter fall ranged from 1.42 to 3.34 tonnes ha^{-1}, the value being maximum in case of SP system followed by natural grassland and lowest in AH system. The higher amounts of surface litter under SP system may be due to higher leaf biomass production.

Belowground biomass measured as fine root biomass did not show significant differences among the various agroforestry systems. The fine root biomass was highest in AHS followed by HP with their respective values of 1.04 and 1.03 tonnes ha^{-1} although statistically alike. The AH system showed the lowest value. The lower values in AH and AS systems in belowground biomass could be ascribed to the death of roots, their detachment from the plants, and their mineralization as reported by Aggarwal *et al., 1*978. This happened because of their life cycle completion and presumable after this period old roots of many species die and their decomposition start at fast rate due to congenial soil temperature and abundance of microbes (Aggarwal *et al., 1*978; Singh and Yadava, 1974 and Ras Bihari Sah, 2002).

Considering both above- and belowground biomass it can be inferred from the Fig. 1 that SP system produced the maximum biomass followed by AHS, AS, HP and AH. The respective values for the above system were 59.72, 22.97, 20.53, 18.25 and 17.63 tonnes ha^{-1}. Natural grassland showed the least biomass of 5.79 tonnes ha^{-1}. The above finding clearly indicates the high biomass production potential of SP system among the current six system types may be planted on arable or non-arable lands. However, among the arable land systems AHS system showed the maximum biomass production potential and relatively can be regarded a promising agroforestry system.

The results discussed above clearly quantify the influence of agroforestry systems structure, land type and management on biomass production levels. Few other authors during the recent past have also reported variations in biomass production levels of woody perennials grown under different agroforestry systems. Nayak (1996) found that aboveground biomass influenced due to species and density. Deshmukh (1998) similarly reported that management practices also affects the biomass production of the fodder trees grown under different agroforestry systems. He found that pollarding height affects the biomass production of shoots and leaves. The difference in productivity of agroforestry systems due to marked differences in soil conditions, phenology of dominant plant species (Gupta and Singh, 1981); better root net working as well as efficient and economical use of limited resources for maintaining higher photosynthetic activities, leaf area index, better light interceptions and water use efficiency (Sehgal, 1999) have been reported earlier too.

5.2 Biomass carbon stocks in different agroforestry systems

The biomass carbon stock in a particular agroforestry system depends up on its structure, functional components and the management. Table 4 shows the carbon stored in different components of the system both above- and below ground. The data have indicated a significant variations in the carbon stored by different components of the system namely: tree- (stem, branch, leaf), annual crop, grass their litter and fine roots below the ground. The highest stem carbon was found in SP system followed by AHS, AS, AH and the minimum in HP system. The branch and leaf carbon was significantly higher in SP system. However, the second highest value in branch carbon was shown by AHS system. The second highest value in case of leaf carbon followed the trend similar to stem carbon showing the second highest value in AHS system. The higher carbon stock in the stem biomass of SP system, whereas minimum in HP system may be explained owing to the more number of trees in SP system then the HP .The number of trees in SP system was 2500 whereas in HP.

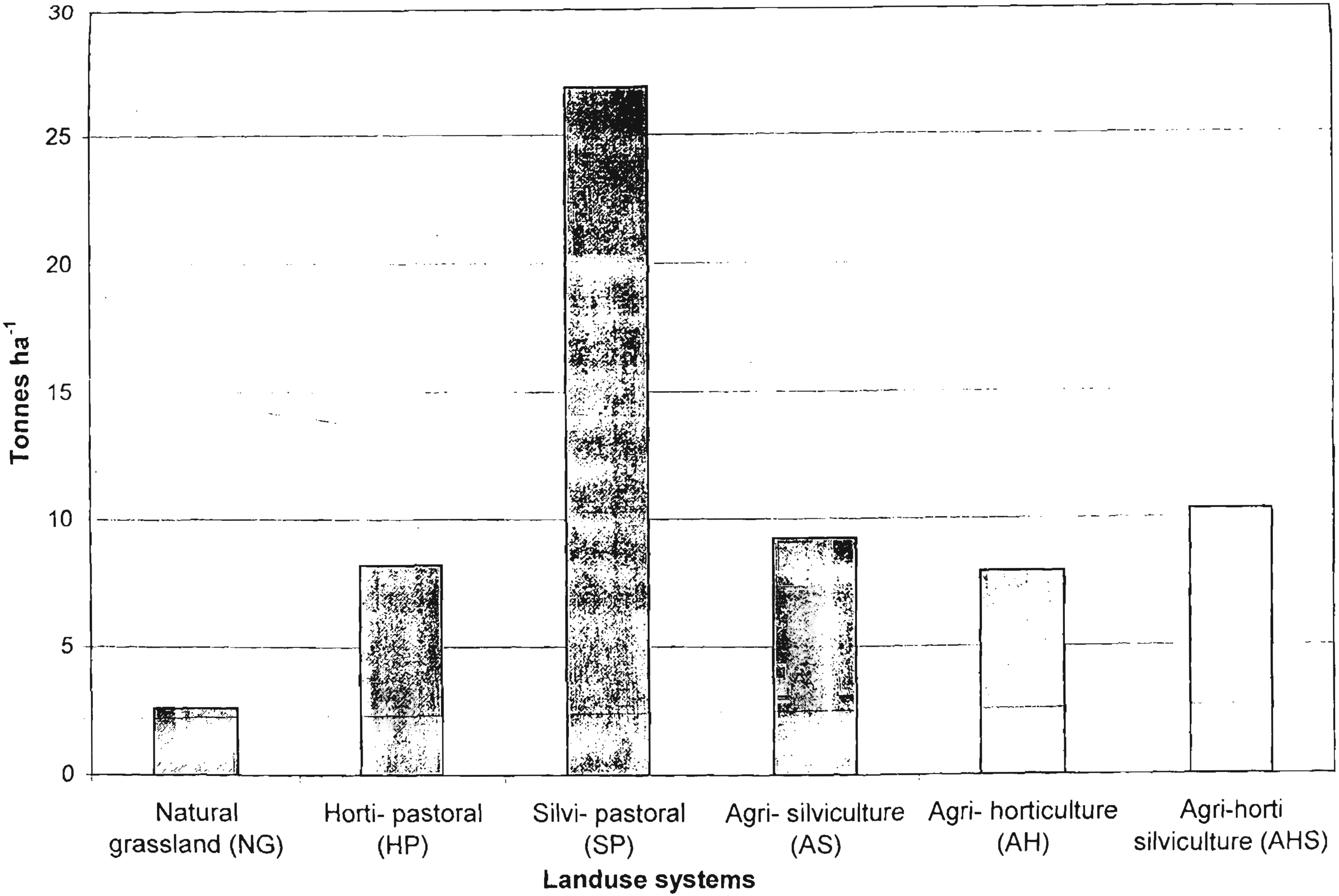

Fig. 2. Biomass carbon stocks in different agroforestry systems (tonnes ha^{-1})

The data further elucidate that AHS system despite having the less number trees (332) than AS (400) had significantly higher carbon stocks in stem then the AS. Similarly, the AH system having 200 number of trees compared to 286 in HP system. The significantly higher carbon stocks in AHS system over the AS can be explained due to the higher biomass produced per tree namely, plum and morus over *Grewia* and *Bauhinia* in AS system namely. The per tree stem biomass in AHS system for plum and Morus was 43.99 and 30.27Kg, respectively whereas per tree stem biomass for *Grewia* and *Bauhinia* in AS system was 10.37 and 28.77 Kg per tree, respectively. The variation in the biomass per tree may have occurred : (1) due to the change in species involved in the system and (2) the tree management imposed due to the system requirement. In AS system *Grewia* and *Bauhinia* both being fodder trees were pollarded at a height of 0.5m and 3m respectively. On the other hand plum being a fruit tree in AHS system has been managed as a natural tree with light pruning.

The highest carbon stocks in case of AH system compared to HP can again be ascribed to the biomass production potential of tree species involved and its management. In AH system peach formed the fruit component whereas in HP it was plum. Peach tree produced about 2.17 times more stem biomass than the plum, therefore, despite the lower number of trees in AH system over the HP the stem carbon stock were significantly higher in AH system.

Whole tree carbon stock was also higher in SP system followed by AHS and the minimum in AH system. The variations were mainly due to the difference in stem and branch biomass of the system. The aboveground carbon stocks were also observed to be dominated by the whole tree carbon stock values. Belowground (fine roots) carbon stocks did not vary significantly among the various systems and have shown the following increasing trend: NG<AH<HP<AS<AHS<SP, with their respective carbon stock values of 2.61<7.93<8.21<9.24<10.34<26.87, respectively. In general total carbon stocks (above -and belowground were highest in SP followed by AHS, AS, HP, AH and NG (Fig. 2).

It is deduced from the above discussion that variability in the carbon stocks of different agroforestry system types depends primarily on its complexity. Albrecht and Kandji (2003) have also reported that carbon variability in plant biomass can be high within complex agroforestry systems and productivity depends on several factors including the age, the structure and the way system is managed. Beer *et al.* (1990) gave a detailed breakdown of biomass production over 10 years in two tree combinations in Costa Rica: cacao (*Theobroma cacao*)-laurel (*Cordia alliadora*) and cacao-poro (*Erythrina poeppigiana*). Based on these data, whole system carbon stocks were calculated by averaging the annual biomass production in the two periods defined by the authors (0-5 years and 6-10 years) and multiplying the output by 0.5 (Kursten and Burschel, 1993). Thus, 11 Mg C ha^{-1} per year was stored over 10 years in the system including 6 Mg C ha^{-1} per year in the shade trees. 60 Mg C ha^{-1} is clearly higher than storage values estimated by Kursten and Burschel (1993) on similar systems (7-25 Mg C ha^{-1}), even if these authors did not consider belowground carbon. However, this corresponds perfectly to the carbon sequestration capacity of agroforestry calculated by Houghton *et al.* (1991) for America and Asia. Biomass estimates by Jensen (1993) in Java showed that 16 Mg C ha^{-1} could be stored if rice fields were transformed into home gardens.

5.3 SOIL PHYSICO- CHEMICAL PROPERTIES

5.3.1 Bulk Density

The data presented in Table 6 on bulk density of soils have shown significant variation. AH system showed significantly higher value of 1.22 among all the systems. The high value of bulk density in the soils are ascribed to the lower soil organic carbon content. Findings are in line with Karan *et al.*, 1991, who reported higher values of bulk density in cultivated soils due to low organic carbon content. The lowest bulk density was under

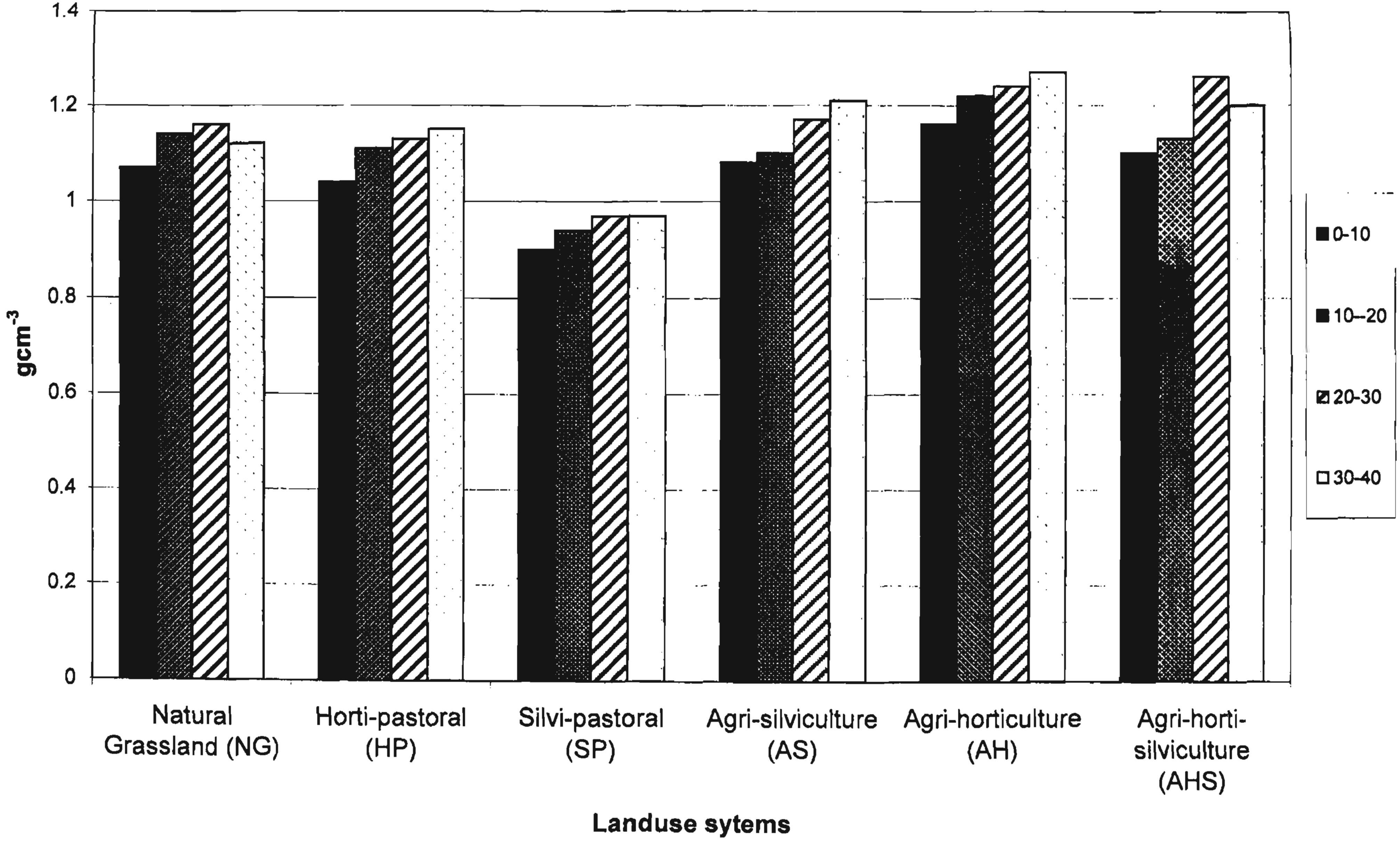

Fig.3. Effect of agroforestry systems on the bulk density at different profile depth (cm)

SP system that could be related to high organic matter as contended by Anil Kumar (2001) and Kaushal (1992). This has been further corroborated with present findings, too, wherein soils under SP system exhibited the maximum of 3.38% organic carbon (Table 7).

Bulk density in general increased with the increase in soil depth. Deeper depths Fig. 3 have higher values than the shallower ones. The lower bulk density values in upper layers of soil profile may have resulted from the dilution of soil matrix(mineral matter) with lesser denser material(organic matter) and improvement in soil aggregation. Improvement in aggregation encouraged a fluffy and porous condition in soil which results in low bulk density value. The reduction of bulk density of soil due to increase in soil organic carbon has been amply reported in literature (Soane 1975, Coote and Ramsay 1983, Sharma and Aggarwal 1984, Sharma *et al 1995* and Lav Bhushan 1998). The ability of trees and biomass from trees to maintain or improve soil physical properties is well documented (Young 1997). Torquebiaw and Kwesiga(1996) showed that 2 year fallows with *Sesbenia sesban* can decrease soil bulk density and resistance to penetration and increase water infiltration on an Alfisol in eastern Zambia. Similarly Hulugalle and Kang 1990, in a study that included *Leuceana leucocephala* on an Oxic Paleustalf found that bulk density values were superior in the hedgerow plots as compared to the control without tree. It was also noticed from the data that bulk density values for three agroforestry systems in non-arable lands viz. SP, HP and NG were lower than agroforestry system types viz. AH, AS and AHS in arable lands. The low bulk density in soils under SP, HP and NG systems was due to their higher soil organic carbon content. The current studies further revealed that agroforestry system types integrating fruit trees as woody perennials in place of fodder/forest tree had higher bulk density values. The above findings indicated that fruit tree based agroforestry system types compared to forest tree based systems have less potential to improve upon the physico-chemical properties of the soil e.g. bulk density in the current studies.

It was also deduced from the data (Table-6) that inclusion of woody perennials improve the physical conditions of the soils in pasture lands compared to the soils in pasture/grasslands without trees. This was evident from higher bulk density values of soils under NG system than the soils under SP system.

5.3.2 Soil organic carbon

Data in Table 7 revealed that soil organic carbon was higher under SP system (3.38 %), which was followed by NG (1.73 %), and AHS (1.67 %). the AH system showed lowest (1.03) soil organic carbon. The increased organic carbon content in soils under SP system may be ascribed to more leaf litter accumulation and root turn over from trees (Zegeye,1991).

The carbon fixed by the plant is the primary source of organic matter input into the soil, which provides substrate for microbial process and accumulation of soil organic matter. The belowground allocation of photosynthetes is also an important factor for improving soil organic carbon content (B Kour *et al* 2002). The result from the present studies also revealed a maximum accumulation of soil organic carbon in surface (2.49) soils which decreased with the increase in soil depth (Fig. 4) Therefore, in deeper profile depths soil organic carbon content was less compared to surface layer. The greater accumulation of soil organic carbon on the surface is due to the incorporation of leaf litter and addition of decayed roots to the upper layers . Similar results i.e. reduction in organic carbon content with the increase in soil depth have also been reported by Nair and Chamuah (1988) and Minhas *et al.* (1997). Organic carbon content is affected by leaf litter, high rate of turnover of minute rootlets, death and decomposition of roots and exudation of organic chemicals and hence organic carbon of soil will also increase (Huck, 1983 and Waisel *et al.*, 1991).

The high soil organic carbon under tree based system can be attributed to increased mineralization under tree than in open. The results are in line with the findings of Kater et al (1992), Rhodes (1995) and Sood (1999).

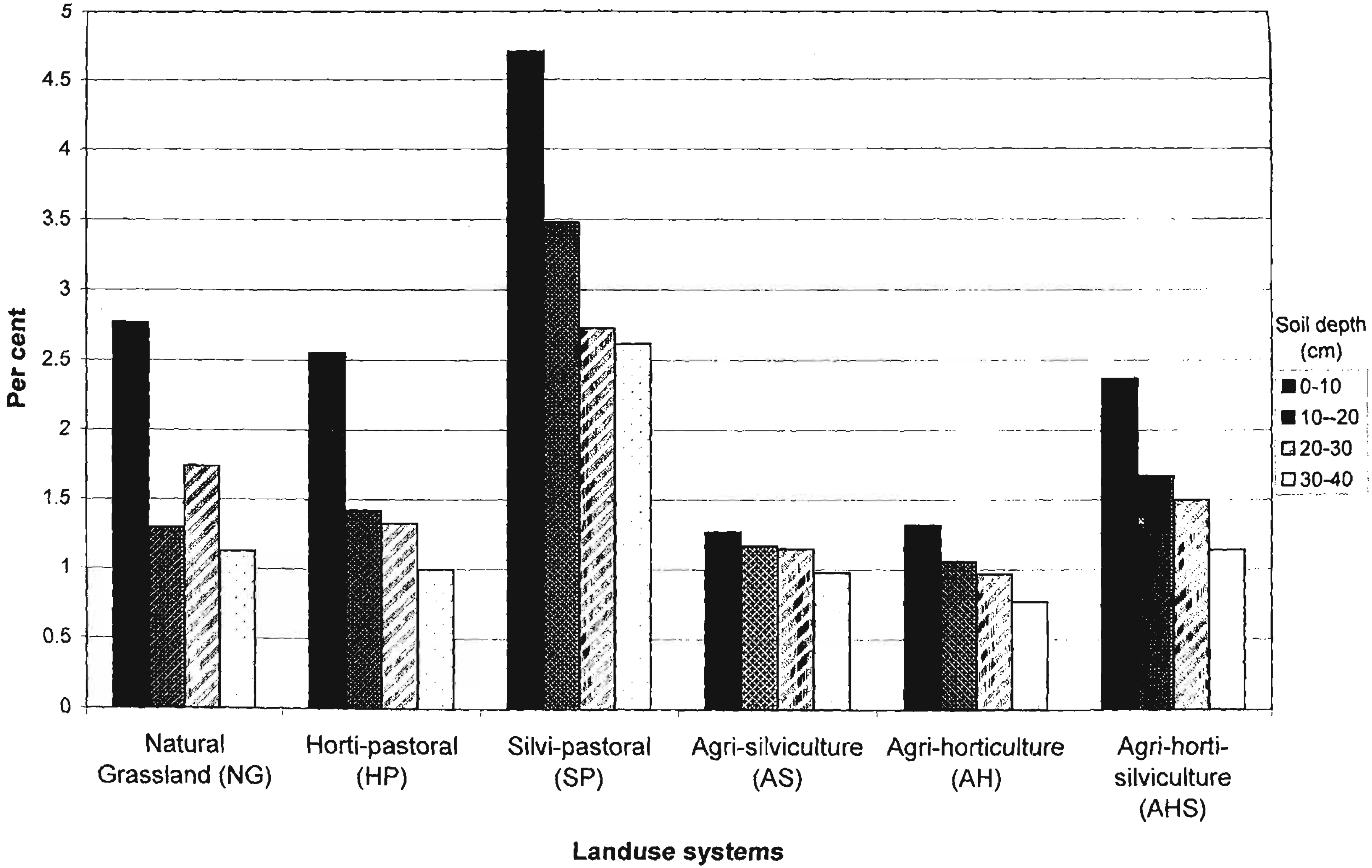

Fig. 4. Per cent organic carbon under different agroforestry systems

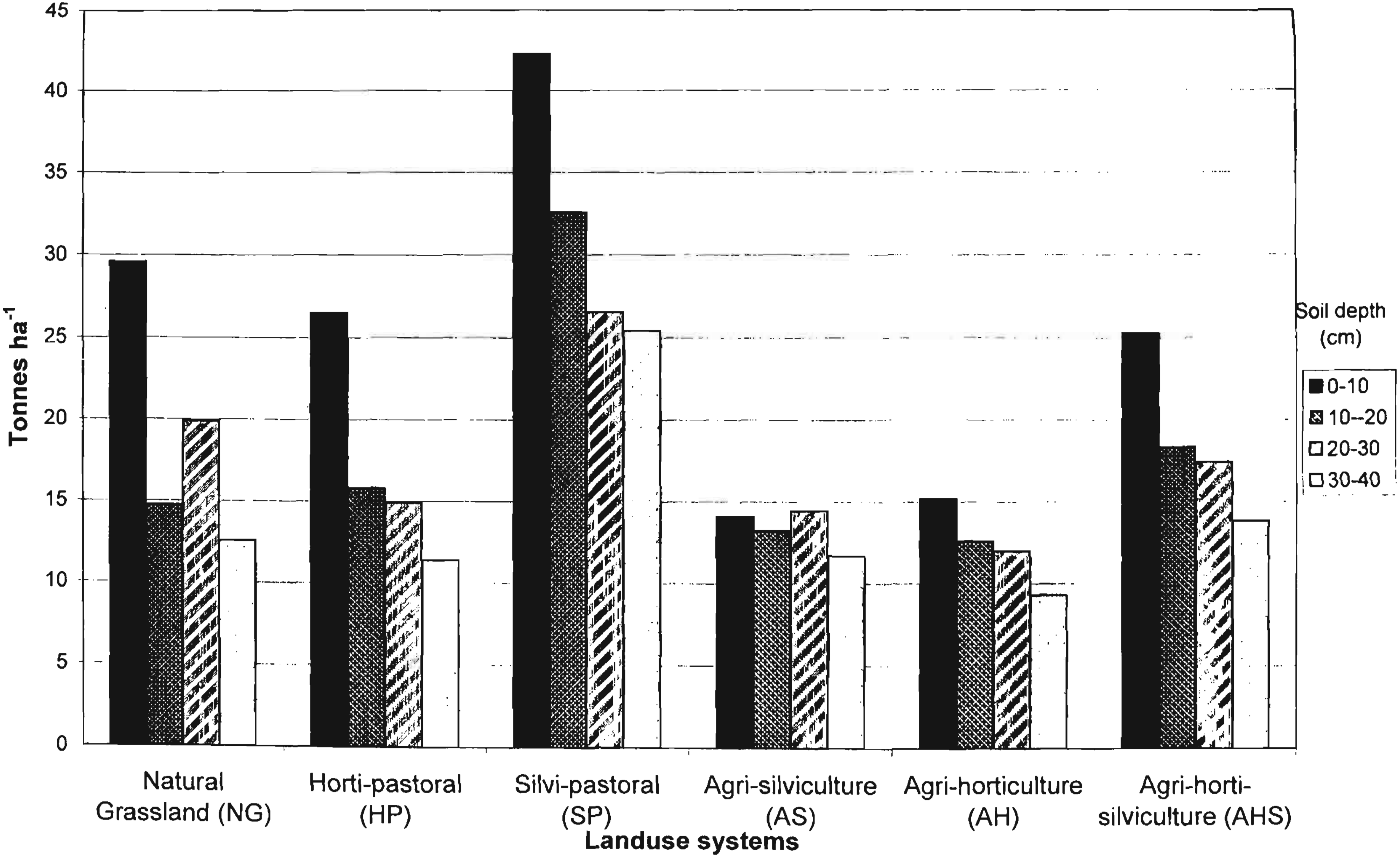

Fig. 5. Soil organic carbon stocks under different agroforestry systems

The highest organic carbon was recorded for *Leuceana* based SP system. It may be due to the accumulation of leaf litter on the surface of site. Similar results were found by Anil Kumar (2001).

The studies clearly indicated that in surface depth there was significantly higher organic carbon than subsurface depth. The continuous addition of higher amounts of plant litter in surface might have resulted in higher organic carbon content in the surface than the subsurface soils. These results are well supported by the findings of Banerjee and Badola (1980), Gupta et al (1991), Kaushal (1992), Saralch (1994), Bhola (1995), Nayak (1996) and Saralach (1999). The efficacy of different species in improving organic carbon content is a function of annual leaf litter production and its rate of decomposition. The effect of trees on soil organic matter varies among trees species and soil (Kang et al 1994). Mordelet et al (1993), reported higher soil organic carban under tree clumps than in open grassland. Soil changes under trees, may be species specific and also dependent on size and age of the trees and site condition (Belsky et al 1993; Kater *et al.*, 1992; Campbell *et al.*, 1994 and Depomier et al (1992).

5.3.3 Soil organic carbon stocks

Soil organic carbon stocks were determined by multiplying organic carbon with the soil weight for a particular depth. The data presented in Fig. 5 shows its highest values under SP system whereas NG and AHS systems followed it. AH system had the lowest value of carbon stock. This may have occurred due to the higher accumulation of plant litter under this system compared to the other (Table 3). The abundant litter and / or pruned biomass returned to the soil, combined with the decay of roots contribute to the improvement of organic matter under complex agroforestry systems. (Beer *et al.*, 1990; Lehmann *et al.*, 1998; Rao *et al.*, 1998; Kumar *et al.*, 2001). A 15 per cent increase in surface soil organic carbon stocks under *Leucaena leucocephala* based hedgerow inter-cropping was also reported by Kang et al (1999). Several studies of tree planting on degraded soils by Drechsel *et al.* (1991); Onim *et al.* (1990); Impala., (2001); Boye., (2000); Ndufa., (2001) and

Nyvert., (2001) have also shown increased soil organic carbon stock after a few season of planting. Low amounts of soil organic carbon stocks under AH and AS systems may be due to intensive cropping as reported by Lal *et al.* (1998). Lower density of perennial component may also be responsible for lower amounts of soil organic carbon under these systems.

5.3.4 Soil organic carbon pool

Agroforestry systems influenced the soil organic carbon pools significantly. The data Fig. 6 have shown that soil organic carbon pool in soils under SP system type was higher than those under AH and AS systems in the top 0-10 cm layer. It varied with the depth of soil profile and was determined taking into account bulk density and soil organic carbon content. The bulk density was highest under AH system and lowest under SP system, on the other hand the organic carbon was highest under SP system and lowest under AH system. The increase or decrease in the soil organic carbon pool was associated with the bulk density and organic carbon content of the soil for a particular depth. The higher amount of soil organic carbon may be attributed to the reduced rate of decomposition of organic material. The soil organic carbon pool decreases with the increase in soil depth. The greater accumulation of organic carbon in the surface is due to the incorporation of leaf litter and addition of decayed roots to the upper layer. The results are in line with the findings of Joao Carlos (2001), Nair and Chamuah (1988) and Minhas *et al.* (1997).

5.4 Total carbon stocks

Total carbon stocks include plant carbon of an agroforestry system plus soil carbon up to a particular depth component wise i.e., tree, crop, grass, litter, fine roots and various soil layers carbon stocks have been shown in Fig. 7. Whereas cumulative values for systems components and different soil layers are shown in Fig. 8 and 9. An examination of Fig. 8 revealed that SP system had the maximum carbon stock. It was followed by AHS and HP systems. The minimum value was obtained in AH system. The

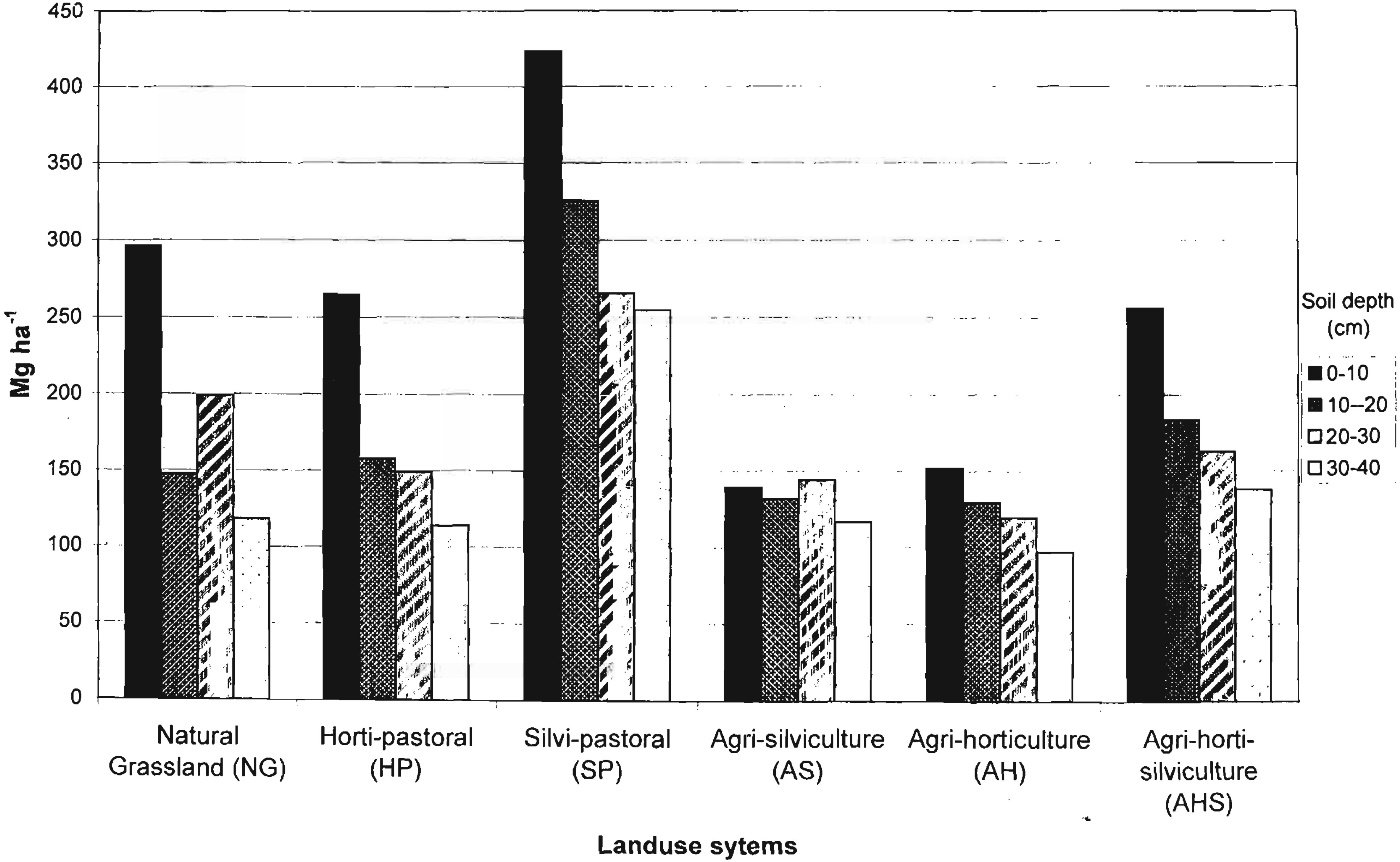

Fig. 6. Effect of agroforestry landuse systems on soil organic carbon pool distribution

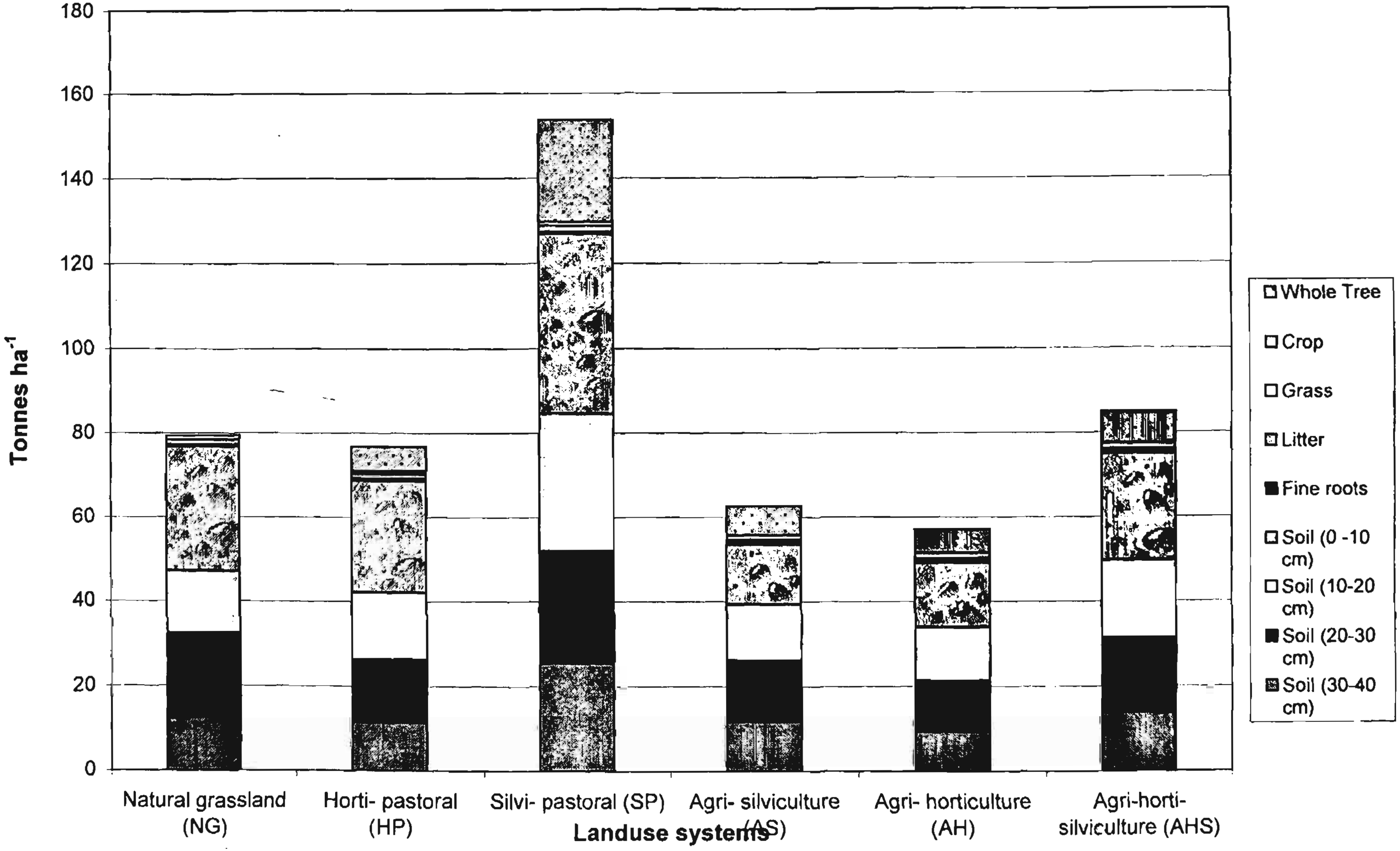

Fig. 7. Carbon stock under different agroforestry systems

results indicated that SP system had 2.17 times more carbon stock than NG system and 2.85 times than AH system.

The studies further revealed that agroforestry systems in arable land viz. AS and AH had the lowest soil carbon stocks 0-20 cm soil depth that resulted in their lowest total carbon stocks too. The plant carbon stocks, however in these two systems were either almost equal to or greater than the HP system. The findings thus indicated that AS and AH system types if practiced using current management system and tree - crop species composition will contribute less toward soil carbon stocks than HP system. The possible reasons may be that being in arable lands both the systems experienced more competition for available resources. Secondly regular tilling of the soil for cultivating annual crops, depleted the soil carbon pool more compared to HP, where no tilling is done. AHS system on the other hand had higher total carbon stocks, both plant as well as soils, despite being under going the similar tillage practices as AS and AH. Such a phenomenon thus revealed that integration of fruit and forest tree species together and simultaneously than either of these species alone or separately alongwith field crops contribute more toward the build-up of total carbon stocks. This may also be due to the reason that trees on agricultural fields simulate the natural forest conditions. The system functions more alike to closed nutrient cycle than the open nutrient cycle.

Different agroforestry systems on the basis of total carbon stock (0-20 cm soil depth) obeyed the following decreasing order: SP > AHS> HP> NG> AS > AH (Fig. 8). Results were almost similar if soil depth was 0- 40 cm (Fig. 9). In this case different agroforestry systems observed the following descending order: SP>AHS>NG>HP>AS>AH. The highest and lowest values in both cases were shown by same system types. A slight change was observed in later case i.e. profile depth 0-40 cm wherein NG system swapped the third place with HP system. The findings also indicated that total carbon stocks increased when profile depth was 0-40 cm in place of 0-20 cm. The results are obvious owing to increased soil volume in consideration.

The above findings are almost in conformity with those of Lal *et al.* (1998) who reported decrease in soil organic carbon due to cropping practices in Nigerian soil where cropping decreased soil organic carbon by 25-60 per cent for the top 0 to 5 cm depth. The higher amounts of total carbon stocks under SP system may be due to regular addition of biomass on the surface soil over the years that contributed to the buildup of soil organic matter and nutrient stocks in the soil. It favors the high biomass production as reported by Lehmann *et al.* (1998); Rao *et al.* (1998) and Kumar *et al.* (2001). Rueckar *et al.* (1998); Alstad and Vetass., (1994) and Garg, (1998) also observed the increase in total carbon stocks for the tree stands on the degraded soil. The total carbon stocks, if soil depth is 0 to 20 cm ranged from 35.74 - 101.69 tonnes ha^{-1} and 57.04-153.71 tonnes ha^{-1} if soil depth is extended up to 40 cm from the surface. The data in Table 10 and 11 showing the soil: plant ratio for carbon stocks have indicated that plant biomass contained much less amount of carbon and larger amounts were in soils. Among the different systems, NG system showed its highest soil: plant ratio 16.99 which was reduced to 2.79 in SP system. The reduction in the above ratio thus revealed that more carbon can be sequestered through vegetation in NG by the planting of trees similarly to the HP system. The findings have shown that soil: plant ratio of carbon stocks in SP, AS and AH systems concides with global carbon stocks distribution between vegetation and soil on land. Globally soil contains much larger amount of carbon i.e. about three times than the vegetation carbon stocks. The Royal Society London (2001) has reported that vegetation contains 550 ± 100 Pg of carbon whereas soil contain a much larger amounts of 1750 ± 250 Pg carbon. The ratio of soil carbon to vegetation carbon has been reported to be about 5 in boreal forest but <1 in moist tropical forest. (The carbon sequestration potential of tropical agroforestry systems was estimated between 12 and 228 Mg ha^{-1} with a median value of 95 Mg ha^{-1} by Albrecht and Kandji (2003), too. The present finding thus are in line with the above. Shrouder (1994) also estimated that median carbon storage by agroforestry practices was 9, 21 and 50 Mg C ha^{-1} in semi arid, sub humid and humid eco-zone, respectively.)

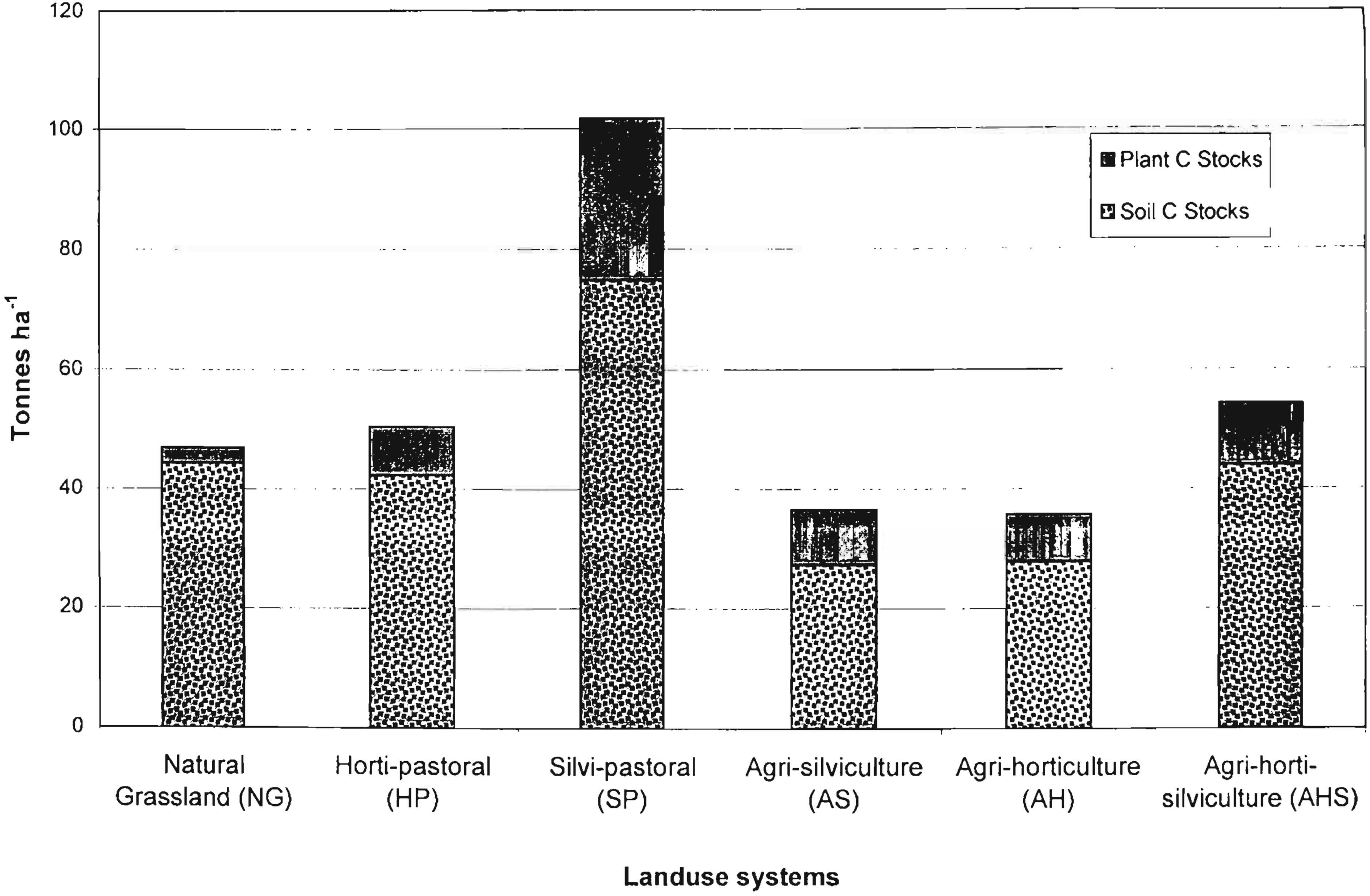

Fig. 8. Carbon stocks for different agroforestry systems upto 0-20 cm depth

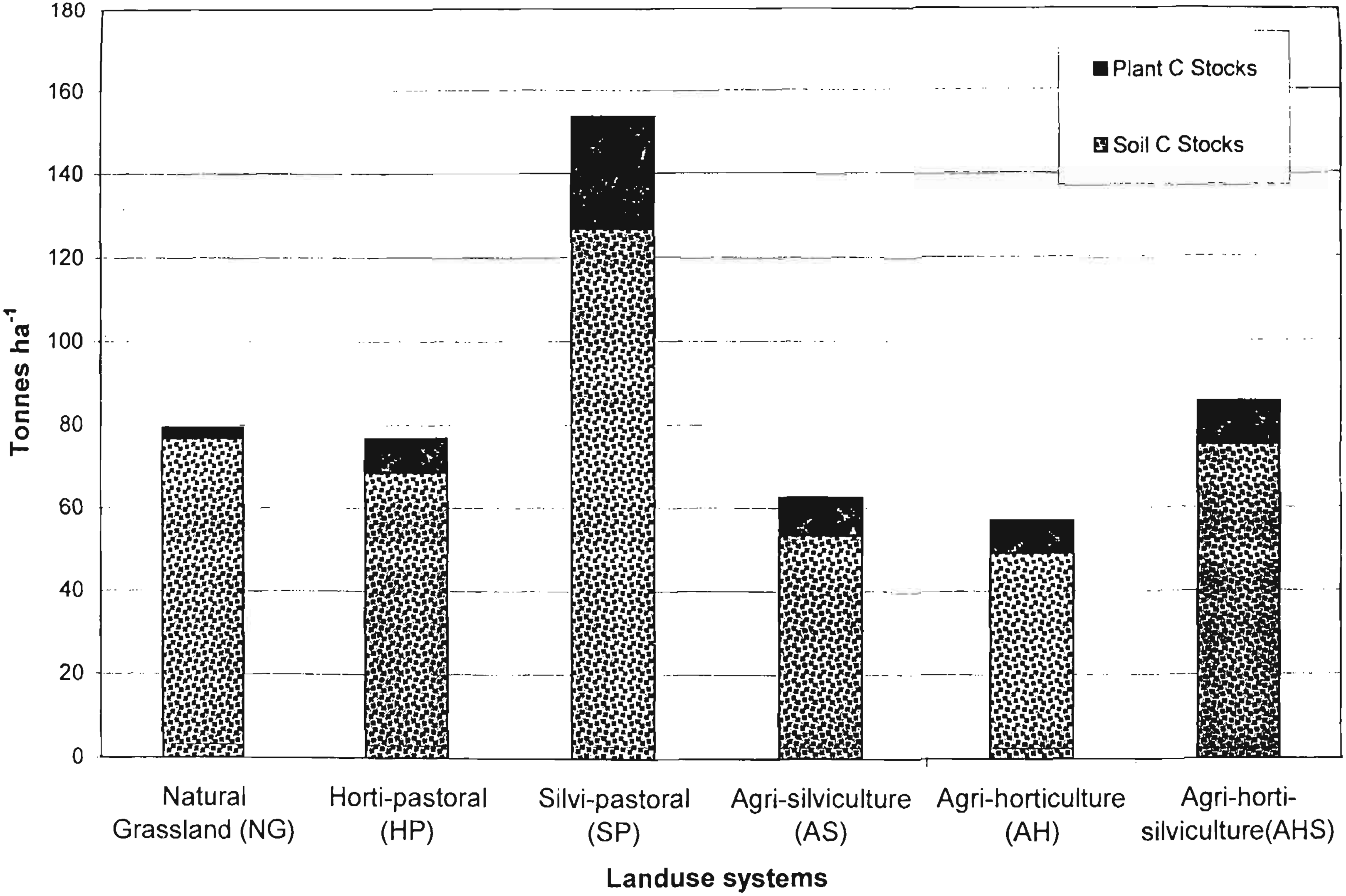

Fig. 9. Carbon stocks for the different agroforestry landuse systems upto 0-40 cm soil depth

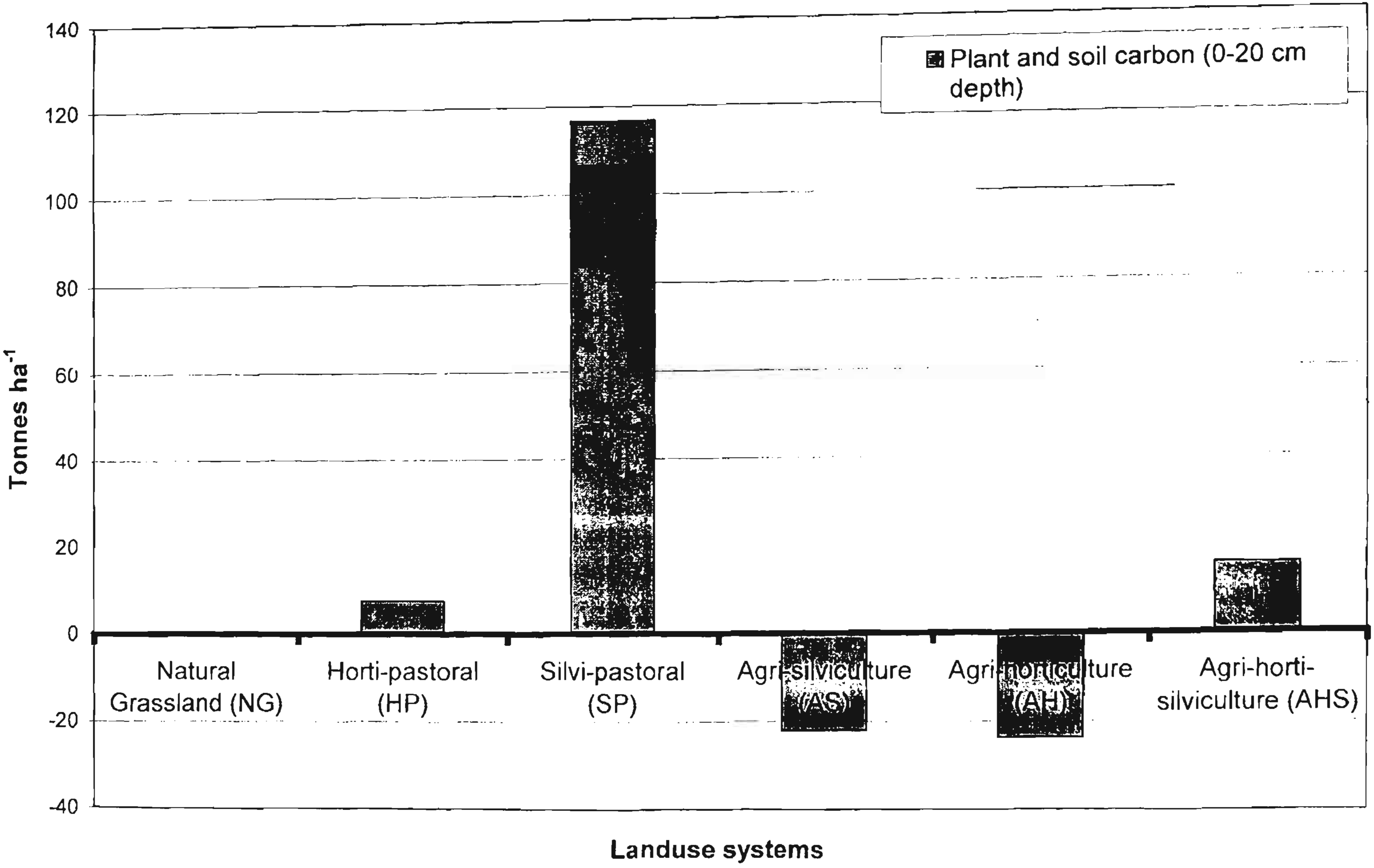

Fig. 10. Relative loss or gain in total system's carbon by different agroforestry systems (tonnes ha^{-1}). Soil depth is 0-20 cm.

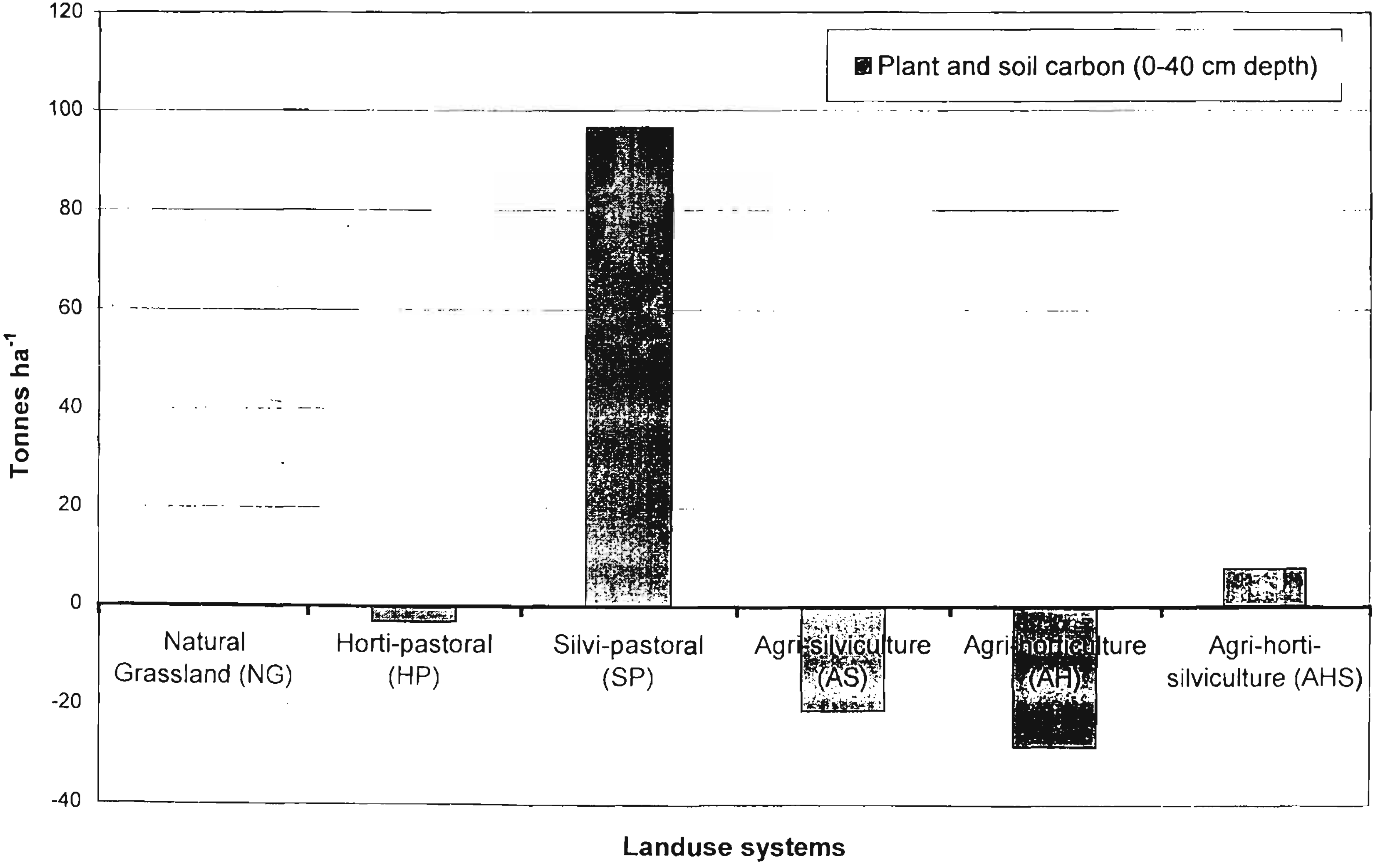

Fig. 11. Relative loss or gain in total system's carbon by different agroforestry systems affected by agroforestry systems (tonnes ha^{-1}). Soil depth is 0-40 cm.

5.4.1 Relative loss or gain in system carbon stocks (tonnes ha^{-1})

The net loss or gain in total carbon stocks of different agroforestry systems has been calculated over the actual value of NG system considered as 100 and presented in Fig. 10 and 11. It was observed from the figure that SP, HP and AHS system had net gains in the total carbon stock with respect to NG if the soil profile layer is considered upto 20 cm depth from the surface. The Agroforestry systems namely AS and AH on the other hand have shown net losses in their total carbon stocks. Which indicates that agroforestry system involving single woody perennials tree species either fruit or fodder on agricultural land have lower potential to sequester the carbon compared to non-arable land agroforestry systems. The finding also revealed that the total carbon stocks can be enhanced by integrating fruit and forest tree species together on the agricultural lands as was evident from the net gains shown by AHS system.

5.4.2 Relative carbon sequestration potential

The relative net gain and loss in total carbon stocks of different agroforestry systems were further used to find out the carbon sequestration potential(CSP) of each system taking the value of NG as 1. The data thus obtained (Table 15) have inferred that CSP of SP system was 2.17 times higher than the NG, if the soil organic carbon stocks are limited upto 20 cm profile depth only. It was followed by AHS system with its CSP of 1.15. AS and AH system were observed to have lowest CSP. The trend was exactly similar even if the soil organic stocks are extended upto 40 cm profile depth from the surface. In general 0 to 20 cm soil depth exhibited higher CSP.

5.4.3 CO_2 mitigation by different agroforestry systems

CO_2 mitigated by various agroforestry systems through their total biomass as well as both biomass plus soil (Table 14) have indicated significant variations. The data on total CO_2 mitigation (biomass plus soils) have evinced that SP system mitigated. 562.61 tonnes of CO_2 which was the maximum among all the systems (Table 14). It was followed by AHS system with a value of 312.41 tonnes ha^{-1} AH system had the lowest CO_2 mitigation level of 181.26 tonnes ha^{-1}. It was further discernible from the data that agroforestry in arable lands except AH system had mitigated low levels of CO_2 compared to system on non-arable land, however, AHS system had shown its superiority even over the NG and HP systems in non - arable lands. This has indicated that while agroforestry systems on non- arable lands can mitigate higher amount of CO_2, the agroforestry systems like AHS, has greater potential to mitigate CO_2 levels on agricultural lands.

The potential of various land management activities to mitigate global emission of CO_2 by increasing the carbon sink potential of forestry and agriculture, or reducing emission resource. Estimate provided by IPCC suggest that a maximum mitigation of 100 Pg carbon could achieved between 2000 and 2050, out of which change in agricultural management could sequester 33 percent in addition potential of agroforestry has been projected to about 7 percent of the total global potential of forestry and agriculture.

Table 15. Relative* carbon sequestration potential of different agroforestry systems

System	A**	B**
Natural Grassland (NG)	1.00	1.00
Horti-pastoral (HP)	1.08	0.97
Silvi-pastoral (SP)	2.17	1.94
Agri-silviculture (AS)	0.78	0.79
Agri-horticulture (AH)	0.76	0.71
Agri-horti-silviculture (AHS)	1.15	1.07

* Carbon sequestration potential calculated considering the value of NG system 1.

** Column A includes the belowground values upto 20 cm profile depth whereas column B upto 40 cm profile depth.

SUMMARY AND CONCLUSIONS

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SUMMARY AND CONCLUSIONS

The present investigations entitled "Carbon Dynamics Studies in Agroforestry Systems of Western Himalaya" were carried out at Dr. Y. S. Parmar University of Horticulture and Forestry, Nauni, Solan (HP) during 2002-2003. The experiment was laid in split plot design using six landuse systems viz. natural grassland (NG), horti-pastoral (HP), silvi-pastoral (SP), agri-silviculture (AS), agri-horticulture (AH) and agri-horti-silviculture (AHS). Each agroforestry landuse system was replicated thrice. Agroforestry system formed main plot and soil sampling depth as sub plot. The plot size was 50 m X 10 m.

The data were recorded on above-and belowground biomass of all the system components viz. trees, crop, and grasses. Litter biomass was also measured. The aboveground biomass of woody perennials was apportioned into stem, branch and leaf by non-destructive method. Stem biomass was estimated by multiplying the volume of stem with specific gravity. Crop and grass biomass was estimated using 1m x 1m quadrate. Soil samples were collected by dividing each main plot area into five sub-areas. Soil attributes viz. bulk density and organic carbon content were determined later carbon pool inventory and carbon stocks were calculated.

The results have indicated that different landuse systems had significant variations in their total biomass production levels. Comparing the various landuse systems for their biomass production levels over natural grasslands, it was 3.15 times more in horti-pastoral, 10.31 times in silvi-pastoral, 3.55 times in agri-silviculture, 3.05 times in agri-horticulture and 3.97 times in agri-horti-silviculutre system. Thus, silvi-pastoral (SP) system gave higher biomass over all the systems. Agri-horti-silviculture (AHS) system produced the second highest biomass value among all the landuse systems.

The whole system biomass carbon stocks depicted maximum value (26.87 tonnes ha^{-1}) in SP system which was significantly higher than the remaining systems. NG system showed the lowest value of 2.61 tonnes ha^{-1}. The carbon stored in system types viz. horti-pastoral, agri-silviculture, agri-horticulture and agri-horti-silviculture was 8.21, 9.24, 7.93 and 10.34 tonnes ha^{-1}, respectively.

The amount of CO_2 mitigated by an agroforestry landuse system depicted higher value in silvi-pastoral system followed by agri-horti-silviculture, agri-silviculture, horti-pastoral and agri-horticulture. Natural grasslands showed the least amount of CO_2 mitigation potential.

The soil bulk density was higher under agri-horticulture system, and the lowest was under silvi-pastoral system. The bulk density depicted an increasing trend with the increase in soil depth. The bulk density values for non-arable agroforestry system types viz. silvi-pastoral, horti-pastoral and natural grasslands compared to arable land agroforestry system types i.e. agri-silvicultue, agri-horticulture and agri-horti-silviculture were lower.

Soil organic carbon (SOC) was influenced significantly due to various agroforestry systems. Soil organic carbon was higher under silvi-pastoral system and the lowest was under agri-horticulture system. The soil organic carbon was maximum in surface soils (0-10 cm) whereas minimum was in soils at 30-40 cm profile depth. Soil organic carbon pool was also maximum in silvi-pastoral system followed by natural grasslands and agri-horti-silviculture. The minimum soil organic carbon pool was in agri-horticutlure system.

The total carbon stocks (plant + soil) were highest under silvi-pastoral system. Agroforestry systems in arable lands viz. agri-silviculture and agri-horticulture both had the lowest soil carbon stocks. Different agroforestry systems on the basis of total carbon stock (0-20 cm soil depth) obeyed the following decreasing order: silvi-pastoral>agri-horti-silviculture>horti-pastoral>natural grassland>agri-silviculture>agri-horticulture. Results were almost similar for soil depth upto 40 cm. The following descending order: Silvi-pastoral> Agri-horti-silviculture> Natural grassland > Horti-pastoral >Agri-silviculture > Agri-horticulture was observed for 0-40 cm soil profile depth. The total carbon stocks increased when profile depth was 0-40 cm in place of 0-20 cm.

The agroforestry landuse systems namely silvi-pastoral, horti-pastoral and agri-horti-silviculture have shown net gain in the total carbon stock with respect to natural grassland. If the soil profile layer is considered upto 20 cm depth from the surface, the agroforestry system types, namely agri-silviculture and agri-horticulture showed net loss in their total carbon stocks. On the other hand, if the soil profile depth is extended upto 40 cm from the surface, horti-pastoral, agri-silviculture and agri-horticulture showed their respective net losses whereas the silvi-pastoral and agri-horti-silviculture system showed the net gains in carbon. Total above- and belowground carbon stocks in different agroforestry systems was highest for silvi-pastoral system. The agri-horticulture system showed the lowest belowground carbon stocks among all the systems. The ratio of below: aboveground carbon stocks was observed to be highest (35.59) in natural grassland system, whereas the minimum (4.81) in silvi-pastoral. In general total carbon stocks ranged from 57.04 tonnes ha^{-1} under agri-horticulture system to 153.71 tonnes ha^{-1} under silvi-pastoral system. Their CO_2 mitigation levels arranged from 208.76 tonnes ha^{-1} to 562.61 tonnes ha^{-1}. The carbon sequestration potential (CSP) of different agroforestry systems with respect to natural grasslands whose value was taken as 1, was 2.17, 1.15, 1.08, 0.78 and 0.76 for SP, AHS, HP, AS and AH systems, respectively.

CONCLUSION

Carbon dynamics studies in agroforestry systems to determine existing carbon stocks of different agroforestry systems and their relative carbon sequestration potential involved 5 agroforestry system types viz., horti-pastoral, silvi-pastoral, agri-silviculture, agri-horticulture and agri-horti-silviculture and one natural grassland system. The results obtained revealed the following salient findings:

- Biomass production level both below- and aboveground was highest (59.72 tonnes ha^{-1}) in silvi-pastoral system whereas minimum (5.79 tonnes ha^{-1}) in natural grassland.
- Agri-horti-silviculture system produced the second highest biomass level among the different systems despite having less number of trees (332 ha^{-1}) over agri-silviculture which contained 400 number of trees per hectare.
- Comparison of different agroforestry systems for total carbon stock (Plant + Soil) revealed the superiority of silvi-pastoral system followed by agri-horti-silviculture system. The respective values for these two systems were 101.69 and 54.31 tonnes ha^{-1}.
- The soil : plant ratio of total carbon stock for different agroforestry systems was highest (16.99) in natural grassland whereas minimum (4.791) in silvi-pastoral system.
- The CO_2 mitigation was highest in silvi-pastoral (562 tonnes ha^{-1}) followed by agri-horti-silviculture, natural grassland, horti-pastoral, agri-silviculture. The minimum value was in agri-horticulture system.
- Soil organic carbon pool was also maximum in silvi-pastoral system followed by Natural grasslands and agri-horti-silviculture. The minimum Soil organic carbon pool was in agri-horitculture system.

- Relative carbon sequestration potential of different agroforestry systems considering the value of natural grasslands system as 1 was highest in silvi-pastoral system followed by agri-horti-silviculture and horti-pastoral. On the basis of relative carbon sequestration potential different agroforestry systems showed the following descending order : silvi-pastoral > agri-horti-silviculture > horti-pastoral > agri-silviculture > agri-horticulture.

Considering the relative biomass levels, and total carbon stocks it can be concluded that structural composition of the agroforestry system and the management influences the carbon storage as well as CO_2 mitigation potential of agroforestry systems the most, in addition to the number and quantity of woody perennials involved in the system. Further taking into account the relative biomass levels and total current carbon stocks for different agroforestry systems, it can be concluded that silvi-pastoral system wherein trees were planted at high density (2500 plants ha^{-1}) and pollarded/lopped at 1/3 m height can be a better system for CO_2 mitigation in general. However, in arable lands agri-horti-silviculture system shall be a better system for this purpose.

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APPENDICES

Appendix 1. Meteorological data

Month	Temperature (°C)		Relative humidity (%)	Rainfall (mm)
	Maximum	Minimum		
2002				
August	27.9	19.9	81.5	302
September	26.6	15.3	76	230.6
October	26.4	10.4	57	15
November	23.9	6.1	54.5	Nil
December	20.7	3.5	57	Nil
2003				
Month	**Temperature (°C)**		**Relative humidity (%)**	**Rainfall (mm)**
	Maximum	**Minimum**		
January	19.9	1.8	57.5	39.6
February	19.6	5	67	101.6
March	23.5	8.3	57.5	57.6
April	29.2	12.3	49.5	43.4
May	31.8	15.6	38	33
June	37.8	16.0	56.0	102.6
July	31.5	18.5	85	318.2
August	28.7	20.0	85	320.2

Source: Meteorological Observatory, Department of Soil Science and Water Management, Dr. Y. S. Parmar University of Horticulture and Forestry, Nauni-Solan (HP) 173 230 INDIA

Appendix-II. Biomass produced per tree (Kg/tree) by different woody perennials under agroforestry systems

Component / Species	Stem Biomass	Branch Biomass	Leaf Biomass	Whole Tree	Biomass production (Yr^{-1})
Plum (AHS)	43.99	19.27	6.22	69.48	5.35
Morus (AHS)	30.27	12.20	5.08	47.55	3.66
Grewia (AS)	10.37	13.95	3.47	27.79	2.14
Bauhinia (AS)	28.77	16.81	4.06	49.64	3.82
Peach (AH)	32.05	24.88	5.15	62.08	4.78
Plum (HP)	14.74	25.65	5.29	45.68	2.54
Leuceana (SP)	2.86	3.40	1.47	7.73	0.60
Grewia (SP)	18.75	13.18	3.12	35.05	2.70

Appendix III. Biomass produced, carbon sequestered and CO_2 mitigation by of woody perennials in agroforestry systems.

Parameters / Species	*Biomass Levels	*Carbon sequestered	*CO_2 Mitigated	CO_2** mitigation potential
Plum (AHS)	69.48	31.27	114.43	8.80
Morus (AHS)	47.55	21.40	78.32	6.02
Grewia (AS)	27.79	12.51	45.77	3.52
Bauhinia (AS)	49.64	22.34	81.76	6.29
Peach (AH)	62.08	27.94	102.25	7.87
Plum (HP)	45.68	20.56	75.24	4.18
Leuceana (SP)	7.73	3.48	12.73	0.98
Grewia (SP)	35.05	15.77	57.73	4.44

* Values are Kg per Tree.
** Values are per tree per annum.

Appendix-IV-A. Analysis of variance table for stem biomass under different agroforestry systems

Source	Df	Sum of square	Mean sum of square	F	P
System	5	1321.1	264.22	169.55	0.000
Replication	2	1.3003	0.6502	0.42	0.6699
S X R	10	15.584	1.5584		
Total	17	1338.0			
Grand average	1	1604.0			

Appendix-IV-B. Analysis of variance table for branch biomass under different agroforestry systems

Source	df	Sum of square	Mean sum of square	F	P
System	5	743.91	148.78	73.81	0.000
Replication	2	0.6033	0.3017	0.15	0.8629
S X R	10	20.158	2.0158		
Total	17	764.67			
Grand average	1	965.36			

Appendix-IV-C. Analysis of variance table for leaf biomass under different agroforestry systems

Source	df	Sum of square	Mean sum of square	F	P
System	5	49.944	9.9889	22.56	0.000
Replication	2	0.0973	0.04865	0.11	0.8970
S X R	10	4.4270	0.4427		
Total	17	54.469			
Grand average	1	62.720			

Appendix-IV-D. Analysis of variance table for whole tree biomass under different agroforestry systems

Source	df	Sum of square	Mean sum of square	F	P
System	5	4925.5	985.09	177.71	0.000
Replication	2	3.6031	1.8015	0.32	0.7299
S X R	10	54.434	5.5434		
Total	17	4984.5			
Grand average	1	6278.3			

Appendix-IV-E. Analysis of variance table for crop biomass under different agroforestry systems

Source	df	Sum of square	Mean sum of square	F	P
System	5	33.766	6.7532	294.61	0.000
Replication	2	0.09391	0.04696	2.05	0.1796
S X R	10	0.2292	0.02292		
Total	17	34.089			
Grand average	1	33.402			

Appendix-IV-F. Analysis of variance table for grass biomass under different agroforestry systems

Source	df	Sum of square	Mean sum of square	F	P
System	5	15.770	3.1541	72.46	0.000
Replication	2	0.1114	0.05572	1.28	0.3199
S X R	10	0.4353	0.04353		
Total	17	16.317			
Grand average	1	15.235			

Appendix-IV-G. Analysis of variance table for surface litter biomass under different agroforestry systems

Source	df	Sum of square	Mean sum of square	F	P
System	5	9.5022	1.9004	138.46	0.000
Replication	2	0.018611	0.009306	0.68	0.5235
S X R	10	0.13726	0.013726		
Total	17	9.6581			
Grand average	1	87.296			

Appendix-IV-H. Analysis of variance table for aboveground biomass under different agroforestry systems

Source	df	Sum of square	Mean sum of square	F	P
System	5	5079.5	1015.9	184.85	0.000
Replication	2	5.8850	2.9425	0.54	0.6013
S X R	10	54.956	5.4956		
Total	17	5140.3			
Grand average	1	9659.6			

Appendix-IV-I. Analysis of variance table for belowground (fine roots) biomass under different agroforestry systems

Source	df	Sum of square	Mean sum of square	F	P
System	5	0.02970	0.005940	0.81	0.5655
Replication	2	0.04011	0.02005	2.75	0.1117
S X R	10	0.07291	0.007291		
Total	17	0.1427			
Grand average	1	17.395			

Appendix-IV-J. Analysis of variance table for total biomass under different agroforestry systems

Source	df	Sum of square	Mean sum of square	F	P
System	5	5081.2	1016.2	189.21	0.000
Replication	2	6.7789	3.3895	0.63	0.5519
S X R	10	53.710	5.3710		
Total	17	5141.7			
Grand average	1	10497.0			

Appendix-V-A. Analysis of variance table for stem carbon under different agroforestry systems

Source	df	Sum of square	Mean sum of square	F	P
System	5	272.64	54.529	32.24	0.000
Replication	2	0.25063	0.12532	0.76	0.4914
S X R	10	1.6412	0.16412		
Total	17	274.52			
Grand average	1	278.24			

Appendix-V-B. Analysis of variance table for branch carbon under different agroforestry systems

Source	df	Sum of square	Mean sum of square	F	P
System	5	154.80	30.961	157.28	0.000
Replication	2	0.20068	0.10034	0.51	0.6155
S X R	10	1.9685	0.19685		
Total	17	156.97			
Grand average	1	167.20			

Appendix-V-C. Analysis of variance table for leaf carbon under different agroforestry systems

Source	df	Sum of square	Mean sum of square	F	P
System	5	11.035	2.2070	45.05	0.0000
Replication	2	0.11941	0.059703	1.22	0.3360
S X R	10	0.48993	0.048993		
Total	17	11.644			
Grand average	1	11.528			

Appendix-V-D. Analysis of variance table for whole tree carbon under different agroforestry systems

Source	df	Sum of square	Mean sum of square	F	P
System	5	1020.1	204.03	316.41	0.000
Replication	2	0.047500	0.023750	0.04	0.9640
S X R	10	6.4482	0.64482		
Total	17	1026.6			
Grand average	1	1091.8			

Appendix-V-E. Analysis of variance table for crop carbon under different agroforestry systems

Source	df	Sum of square	Mean sum of square	F	P
System	5	6.8599	1.3720	288.35	0.000
Replication	2	0.019012	0.009506	2.00	0.1862
S X R	10	0.04758	0.0047581		
Total	17	6.9265			
Grand average	1	6.7872			

Appendix-V-F. Analysis of variance table for grass carbon under different agroforestry systems

Source	df	Sum of square	Mean sum of square	F	P
System	5	3.1838	0.63676	74.30	0.000
Replication	2	0.02190	0.010950	1.28	0.3205
S X R	10	0.08570	0.008570		
Total	17	3.2914			
Grand average	1	3.0752			

Appendix-V-G. Analysis of variance table for surface litter carbon under different agroforestry systems

Source	df	Sum of square	Mean sum of square	F	P
System	5	1.9515	0.39030	135.10	0.000
Replication	2	0.004044	0.002022	0.70	0.5194
S X R	10	0.028889	0.0028889		
Total	17	1.9844			
Grand average	1	17.781			

Appendix-V-H. Analysis of variance table for aboveground carbon under different agroforestry systems

Source	df	Sum of square	Mean sum of square	F	P
System	5	1053.9	210.78	339.95	0.000
Replication	2	0.036011	0.018006	0.03	0.9715
S X R	10	6.2003	0.62003		
Total	17	1060.1			
Grand average	1	1730.3			

Appendix-V-I. Analysis of variance table for belowground carbon under different agroforestry systems

Source	df	Sum of square	Mean sum of square	F	P
System	5	0.0053833	0.0010767	0.74	0.6134
Replication	2	0.0082333	0.0041167	2.81	0.1073
S X R	10	0.014633	0.0014633		
Total	17	0.028250			
Grand average	1	3.5112			

Appendix-V-J. Analysis of variance table for total biomass carbon under different agroforestry systems

Source	df	Sum of square	Mean sum of square	F	P
System	5	1055.5	211.09	347.05	0.000
Replication	2	0.069211	0.034606	0.06	0.9450
S X R	10	6.0825	0.60825		
Total	17	1061.6			
Grand average	1	1886.6			

Appendix-VI-A. Analysis of variance table for stem CO_2 mitigation under different agroforestry systems

Source	df	Sum of square	Mean sum of square	F	P
System	5	3652.2	730.45	332.32	0.000
Replication	2	3.3646	1.6823	0.77	0.4906
S X R	10	21.980	2.1980		
Total	17	3677.6			
Grand average	1	3727.9			

Appendix-VI-B. Analysis of variance table for branch CO_2 mitigation under different agroforestry systems

Source	**df**	**Sum of square**	**Mean sum of square**	**F**	**P**
System	5	2073.7	414.73	157.69	0.000
Replication	2	2.6857	1.3429	0.51	0.6150
S X R	10	26.300	2.6300		
Total	17	2102.6			
Grand average	1	2239.6			

Appendix-VI-C. Analysis of variance table for leaf CO_2 mitigation under different agroforestry systems

Source	**df**	**Sum of square**	**Mean sum of square**	**F**	**P**
System	5	106.69	21.338	8.64	0.000
Replication	2	5.6967	2.8483	1.15	0.3541
S X R	10	24.686	2.4686		
Total	17	137.07			
Grand average	1	133.77			

Appendix-VI-D. Analysis of variance table for tree CO_2 mitigation under different agroforestry systems

Source	**df**	**Sum of square**	**Mean sum of square**	**F**	**P**
System	5	13666.0	2733.1	316.42	0.000
Replication	2	0.63373	0.31687	0.04	0.9641
S X R	10	86.377	8.6377		
Total	17	13753.0			
Grand average	1	14626.0			

Appendix-VI-E. Analysis of variance table for crop CO_2 mitigation under different agroforestry systems

Source	df	Sum of square	Mean sum of square	F	P
System	5	91.871	18.374	288.88	0.000
Replication	2	0.25301	0.12651	1.99	0.1874
S X R	10	0.63606	0.063606		
Total	17	92.760			
Grand average	1	90 900			

Appendix-VI-F. Analysis of variance table for grass CO_2 mitigation under different agroforestry systems

Source	df	Sum of square	Mean sum of square	F	P
System	5	42.645	8.529	74.41	0.000
Replication	2	0.29114	0.14557	1.27	0.3225
S X R	10	1.1463	0.11463		
Total	17	44.082			
Grand average	1	41.193			

Appendix-VI-G. Analysis of variance table for surface litter CO_2 mitigation under different agroforestry systems

Source	df	Sum of square	Mean sum of square	F	P
System	5	26.107	5.2215	136.39	0.000
Replication	2	0.054978	0.027489	0.72	0.5112
S X R	10	0.38282	0.038282		
Total	17	26.545			
Grand average	1	238.34			

Appendix-VI-H. Analysis of variance table for aboveground CO_2 mitigation under different agroforestry systems

Source	df	Sum of square	Mean sum of square	F	P
System	5	14132.0	2826.5	338.74	0.000
Replication	2	0.1627	0.081356	0.01	0.9903
S X R	10	83.441	8.3441		
Total	17	14216.0			
Grand average	1	23107.0			

Appendix-VI-I. Analysis of variance table for belowground CO_2 mitigation under different agroforestry systems

Source	df	Sum of square	Mean sum of square	F	P
System	5	0.071378	0.014276	0.73	0.06171
Replication	2	0.11188	0.055939	2.86	0.1042
S X R	10	0.19559	0.019559		
Total	17	0.37884			
Grand average	1	46.980			

Appendix-VI-J. Analysis of variance table for CO_2 mitigation under different agroforestry systems

Source	df	Sum of square	Mean sum of square	F	P
System	5	14130.0	2825.9	346.68	0.000
Replication	2	0.9643	0.48216	0.06	0.9429
S X R	10	81.514	8.1514		
Total	17	14212.0			
Grand average	1	25286.0			

Appendix-VII. Analysis of variance table for soil bulk density under different agroforestry systems

Source	df	Sum of square	Mean sum of square	F	P
System	5	0.5193	0.1039	8.33	0.0025
Replication	2	0.007057	0.003528	0.28	0.7594
S X R	10	0.12470	0.01247		
Depth	3	0.11472	0.03824	6.24	0.0016
S X D	15	0.02930	0.001953	0.32	0.9896
S X D X R	36	0.2250	0.006125		
Total	71	1.0156			
Grand average	1	89.843			

Appendix-VIII. Analysis of variance table for soil organic carbon under different agroforestry systems

Source	df	Sum of square	Mean sum of square	F	P
System	5	43.059	8.6117	112.24	0.0000
Replication	2	0.038231	0.019116	0.25	0.7842
S X R	10	0.76725	0.076725		
Depth	3	14.788	4.9292	135.65	0.0000
S X D	15	5.4378	0.36252	9.98	0.0000
S X D X R	36	1.3082	0.036338		
Total	71	65.398			
Grand average	1	221.93			

Appendix-IX. Analysis of variance table for soil organic carbon pool under different agroforestry systems

Source	df	Sum of square	Mean sum of square	F	P
System	5	19521.0	3904.1	12.58	0.0005
Replication	2	7018.5	3509.2	1.13	0.3607
S X R	10	31025.0	3102.5		
Depth	3	80323.0	26774.0	11.05	0.0000
S X D	15	50720.0	3381.4	1.39	0.2022
S X D X R	36	87263.0	2424.0		
Total	71	451560.0			
Grand average	1	2373100.0			

Appendix-X. Analysis of variance table for soil organic carbon stocks under different agroforestry systems

Source	df	Sum of square	Mean sum of square	F	P
System	5	291.49	58.298	40.56	0.0000
Replication	2	0.13136	0.065681	0.05	0.9555
S X R	10	14.372	1.4372		
Depth	3	126.93	42.310	78.23	0.0000
S X D	15	44.589	2.9726	5.50	0.0000
S X D X R	36	19.470	0.54083		
Total	71	496.99			
Grand average	1	2529.8			

Appendix XI. Coarse sand particle of soil at different depth under different Agroforestry systems

Depth / Landuse Systems	0-10 cm	10-20 cm	20-30 cm	30-40 cm
NG	23.45	23.30	23.25	26.70
HP	23.55	23.10	22.75	27.70
SP	11.20	15.75	15.60	17.60
AS	23.25	21.40	24.40	24.25
AH	23.28	22.20	24.60	23.75
AHS	22.65	21.70	24.90	24.44

Appendix-XII. Fine sand particle of soil at different depth under different Agroforestry systems.

Depth / Landuse Systems	0-10 cm	10-20 cm	20-30 cm	30-40 cm
NG	28.55	20.70	16.75	23.30
HP	28.45	20.90	17.25	22.30
SP	20.80	20.25	14.40	13.40
AS	32.75	36.60	27.60	27.75
AH	33.72	35.80	27.40	28.25
AHS	32.35	37.30	26.10	27.56

Appendix-XIII. Silt fractions of soil at different depth under different Agroforestry systems.

Depth / Landuse Systems	0-10 cm	10-20 cm	20-30 cm	30-40 cm
NG	33	35	40	33
HP	32	36	40	32
SP	44	46	46	48
AS	28	24	24	30
AH	27	23	25	31
AHS	29	24	24	30

Appendix-XIV. Clay particle of soil at different depth under different Agroforestry systems.

Depth / Landuse Systems	0-10 cm	10-20 cm	20-30 cm	30-40 cm
NG	15	19	20	17
HP	16	20	20	18
SP	24	18	24	21
AS	16	18	24	18
AH	16	19	23	17
AHS	16	17	25	18

Appendix-XV. Specific gravity of stem wood of different tree species growing under different agroforestry systems

Species	Specific gravity
Bahuhnia variegata	0.812
Grewia optiva	1.015
Prunus sellisina	1.401
Leucaena leucucephala	1.035
Morus alba	2.433
Prunus persica	1.697

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ABSTRACT

Agroforestry landuse systems have been perceived as a potential carbon sinks and can contribute substantially to mitigate the global climate change hence, "Carbon dynamics studies in agroforestry systems of Western Himalaya" involving five agroforestry systems viz. horti-pastoral (HP), silvi-pastoral (SP), agri-horticulture (AH), agri-silviculture (AS), agri-horti-silviculture (AHS) and one natural grassland (NG) system were undertaken at Nauni (30° 51'N and 76°11'E), Solan (H.P.). The region represent sub-humid sub-tropical to sub-temperate climate with an altitude of 1250 m amsl. The experiment was laid in split plot design. Each landuse system was replicated thrice. Existing carbon stocks and relative carbon sequestration potential of above six landuse systems were evaluated. Different landuse systems had significant variation in their total biomass production levels. Comparing the various landuse systems, for their biomass production levels over NG, it was 3.15 times more in HP, 10.31 times in SP, 3.55 times in AS, 3.05 times in AH and 3.97 times in AHS. The SP system produced the highest biomass whereas minimum in NG. The AHS system produced the second highest biomass among the different systems despite having less number of trees. The total carbon stocks (plant + soil) revealed the superiority of SP system followed by AHS system, with their respective values of 101.69 and 54.31 tonnes ha^{-1}. Soil organic carbon pool was also maximum in SP system followed by NG and AHS system. The minimum soil organic carbon pool was in AH system. Relative carbon sequestration potential of different agroforestry systems considering the value of NG as 1 was highest in SP system and minimum was under AH system. The finding evinced that SP system can be better option for CO_2 mitigation in general. However, in arable land, AHS system shall be a better system for this purpose.

19/10/04

Signature of Major Advisor **Signature of the Student**

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