CARBON STORAGE POTENTIAL OF INTENSIVE SILVOPASTURE SYSTEMS IN HUMID TROPICS OF KERALA

By

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(2010-20-111)

THESIS

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DECLARATION

I, hereby declare that this thesis entitled **"Carbon storage potential of intensive silvopasture systems in humid tropics of Kerala"** is a bonafide record of research done by me during the course of research and that the thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or other similar title, of any other University or Society.

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CERTIFICATE

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Varsha K.M

Dedicated to my loving parents and sister

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SYMBOLS AND ABBREVIATIONS

ANOVA	Analysis of variance
BD	Bulk Density
C	Carbon
CDM	Clean Development Mechanism
cm	Centimeter
CSP	Carbon Sequestration Potential
DM	Dry Matter
DMRT	Duncan's Multiple Range Test
et al	And others
Fig.	Figure
GHG	Greenhouse gas
g cm^{-3}	gram per centimeter cube
ha	Hectare
HN	Hybrid Napier
i.e.	That is
IPCC	Intergovernmental Panel on Climate Change
K	Potassium
kg	Kilogram
kg ha^{-1}	Kilogram per hectare
MPT	Multipurpose tree
MRT	Mean residence time
N	Nitrogen
NS	Non significant
P	Phosphorus
ppm	parts per million
pH	Soil reaction
SCS	Soil carbon sequestration
SOC	Soil Organic Carbon

SPSS	Statistical Package for the Social Sciences
SSSA	Soil Science Society of America
t ha^{-1}	tons per hectare
UNFCCC	United Nations Framework Convention on Climate Change

INTRODUCTION

CHAPTER 1

INTRODUCTION

Dairy farming is a notable pathway towards poverty alleviation for a large number of small and marginal farmers and agricultural labourers in Kerala and also a major contributor to gross state domestic product. Being a milk deficit state, prospects for dairy farming is also high. However, high cost of feeds and scarcity of quality fodder are the major constraints limiting the growth of dairy sector in the state. Introducing ideal silvopastoral systems with trees, grasses and legumes in farm lands, wastelands or in homesteads is one of the promising ways for reducing the existing gap in fodder production and boosting milk production in Kerala.

However, apart from fodder production, silvopastoral systems have the potential to offer many ecosystem services and environmental benefits. Global climate change caused by rising levels of carbon dioxide (CO_2) and other greenhouse gases is recognized as a serious environmental issue of the twenty-first century. The role of land use systems in stabilizing the CO_2 levels and increasing the carbon sink potential has attracted considerable scientific attention in the recent past, especially after the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC). The UNFCCC defines carbon sequestration as the process of removing carbon from the atmosphere and depositing it in a reservoir. It entails the transfer of atmospheric carbon dioxide and its secure storage in long-lived pools (UNFCCC, 2007). It has increasingly been recognized that agroforestry practices such as silvopasture have importance as a carbon sequestration strategy because of carbon storage potential in the multiple plant species and soil (Nair and Nair, 2003). For small holder agroforestry systems in the tropics, potential carbon sequestration rates range from 1.5 Mg C ha^{-1} yr^{-1} to 3.5 Mg C ha^{-1} yr^{-1} (Montagnini and Nair, 2004). As a leading tree-based system especially in the tropics, agroforestry has been suggested as one of the most appropriate land-management systems for mitigating atmospheric CO_2 (Dixon, 1995).

Silvopastoral systems can better sequester carbon in soil and biomass and help to improve soil conditions. Carbon sequestration is the important benefit that silvopasture can generate by storing atmospheric carbon dioxide in the form of tree biomass. Added tree cover on pasturelands is expected to increase carbon storage.

Considering the productive and protective functions of silvopasture systems, intensive 3-tier and 2-tier silvopasture models involving fodder grass hybrid napier (HN), fodder tree mulberry and fodder legume stylosanthus, suitable to humid tropical conditions and integrating well with the existing cropping systems of Kerala have been developed for year round fodder self- sufficiency and balanced nutrition. However, in addition to production aspects, there is also a need to quantify the ecosystem services in terms of carbon storage potential, for reducing carbon emissions for climate change mitigation. Loreau *et al.* (2002) reported that high tree diversity should reduce temporal instabilities caused by climate change and other disturbances. Agroforestry is also important in enhancing farmers' adaptive capacity in reducing the vulnerability of agricultural systems to climate change or climate variability (Boye and Albrecht, 2005). Silvopastoral systems involve integration of trees in combination with fodder crops; there is greater scope for abatement of GHG emissions through carbon sequestration in tree biomass and soil. However, this aspect is one of the promising, but least studied ecological service of silvopasture systems. Since subsistence farmers are the major practitioners of these silvopasture systems, there is an opportunity for them to benefit economically from these systems when the C sequestered is sold through the clean development mechanism (CDM) projects. This however requires information on aboveground and belowground carbon storage potential of silvopastoral system which is lacking.

As compared to pure agricultural systems, agroforestry systems contribute towards improved nutrient cycling and sustainability through greater mineralization of nutrients from unavailable reserves, addition of nutrients in plant litter/tree residues, more closed nutrient cycles as a result of greater uptake by plant roots and less leaching losses and achieving a balanced supply of nutrients including micronutrients. Hence the present study is envisaged with the following objectives:-

- To evaluate the carbon storage potential of 2 year old intensive 3-tier silvopasture systems, in comparison with 2-tier silvopasture systems, fodder grass/legume/tree monocultures, and open lands.

- To investigate the soil fertility changes associated with various cropping systems.

REVIEW OF LITERATURE

CHAPTER 2

REVIEW OF LITERATURE

Land degradation is on continuous increase primarily due to increase in human and animal population pressure on a limited land resource. The problem of over grazing is present in the entire country. The increasing grazing pressure on natural vegetation has resulted into acceleration of erosion processes and loss of soil fertility. Land degradation and along with the poor forest productivity has resulted in huge deficits of timber and fuel wood. The development of wastelands through the establishment and management of silvopasture not only checks land degradation forces but also facilitates the production of vital human needs. One of the major advantages of silvopasture system is carbon sequestration. Carbon sequestration is the process of removing carbon from the atmosphere and depositing it in a reservoir.

The present study is aimed to find out carbon storage potential of intensive silvopasture systems in humid tropics of Kerala and also find out the soil fertility changes associated with various cropping systems. In this context, an attempt has been made in ensuring sections to review the literature on relevance of silvopasture system, environmental services of silvopasture system with special reference to carbon sequestration and soil nutrient dynamics.

2.1 Relevance of silvopasture systems in humid tropics of Kerala

Insufficient quantity and quality nutrition is one of the major hindrances in livestock production in Kerala (Ajith *et al.*, 2012). Intensive fodder production in the farm lands, wastelands or homesteads through a silvopasture system of combination of trees, grasses and legumes in a sustainable manner is a possible alternative to attain fodder self sufficiency, year-round production and balanced nutrition. Recent studies conducted at Vellanikkara showed that intensively managed silvopasture systems with mulberry+ hybrid napier+ stylosanthus in an area of 7 cents (280 sq m) with ample light, is sufficient for meeting the fodder requirements of a single cattle with daily milk yield of 8 litres (Raj *et al.*, 2014).

The suitability of mulberry (*Morus alba*) as a promising fodder tree by virtue of its nutritive foliage and ability to withstand severe pruning has already been reported (Pye-Smith, 2010). Hybrid napier (*Pennisetum purpureum* X *Pennisetum typhoides*) varieties, CO 3 and CO 4 are the most popular fodder grass varieties among the farmers of Kerala due to their fast growing nature and higher productivity from a limited land area. Stylosanthus (*Stylosanthes guianensis*) is a protein rich leguminous fodder recommended for Kerala (KAU, 2011). However, in addition to fodder production, tree-based pasture system has greater potential to store more stable carbon in the soil compared with the treeless system and thereby contribute towards climate change mitigation.

2.2 Environmental services of silvopasture systems

Silvopasture practice is an agroforestry technology combining trees, forage, and shrubs with livestock operation. Silvopastoral systems have been promoted as win-win technologies to enhance productivity and provide environmental services (Gobbi and Ibrahim, 2004). In silvopasture, grasses conserve soil and moisture and provide forage. The legumes benefit soil by nitrogen fixation and in the mixture they help growth of grasses and trees besides improving the forage quality. The system works well with the improvement in land productivity by 2.5 times compared with the traditional system of land use (Singh, 1990). Many researchers have noted that silvopasture practices provide environmental benefits such as water quality improvement, soil conservation, wildlife habitat protection, and aesthetics (Alavalapati and Nair, 2001; Clason and Sharrow, 2000; Garrett *et al.*, 2000 and Kurtz, 2000). These environmental benefits are largely attributed to tree and other vegetation cover on cattle ranches. Besides the above environmental benefits, trees and vegetation cover complement livestock operations by providing shade to cattle (Kurtz, 2000; Clason and Sharrow, 2000 and Pimentel *et al.*, 1995).

Another factor that is not accounted for in many studies of silvopastoral systems is the amount of grass consumed by the grazing animals and the carbon deposited on soil via manure deposits. For example, sheep consumed a total of 30.5 Mg ha^{-1} forage in pastures and 22 Mg ha^{-1} of forage in silvopasture and deposited 9 and 7 Mg ha^{-1} manure in those two respective systems cited in study in Oregon (Sharrow and Ismail, 2004). When forests are converted to treeless system they lose soil organic carbon (SOC). The conversion of forest to agricultural system results in depletion of SOC by 20-50% (Post and Mann, 1990; Davidson and Ackerman, 1993). Trumbore *et al.* (1995) reported that, when tropical dry forest in eastern Amazonia were converted to pasture it lost 13 g SOC m^{-2} $year^{-1}$ from the top 10 cm soil. In another part of eastern Amazonia, when tropical moist forest was converted to pasture it lost 30 g SOC m^{-2} $year^{-1}$ from the top 40 cm soil (Desjardins *et al.*, 1994).

Water quality benefits of maintaining trees and other vegetation on farms and ranches are realized by reducing pollution, runoff, maintaining long-term water cycle, and recharging ground water aquifers (Wu *et al.*, 2001; Stednick, 1996). In addition to the agricultural production issues arising from combining trees and pastures, over the past decade or so there has been increasing interest in the role of agroforestry, including silvopastoral systems, as a means of sequestering atmospheric carbon to mitigate the effects of this greenhouse gas (Albrecht and Kandji, 2003; Montagnini and Nair, 2004; Oelbermann *et al.*, 2004). The advantage of agroforestry systems compared to forests is that the land can remain in agricultural use whilst sustaining a greater phytomass than a purely arable or pastoral system.

2.3 Carbon sequestration

Global warming is undoubtedly one of the major environmental issues of this century. This phenomenon is affecting global climate by increasing earth's temperature and is caused primarily by the increase in atmospheric concentrations of greenhouse gases (GHGs) (Intergovernmental Panel on Climate Change (IPCC), 2007), the most common of which is carbon dioxide (CO_2).Global climate change caused by rising levels of CO_2 and other greenhouse gases is recognized as a serious environmental issue of the twenty-first century. The role of land use systems in stabilizing the CO_2 levels and increasing the carbon sink potential has attracted considerable scientific attention in the recent past, especially after the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC). The UNFCCC defines carbon sequestration as the process of removing carbon from the atmosphere and depositing it in a reservoir. It entails the transfer of atmospheric carbon dioxide and its secure storage in long-lived pools (UNFCCC, 2007). A carbon sink absorbs CO_2 from the atmosphere, and stores it as carbon; in the case of a growing forest, carbon storage is in the form of wood and other vegetation and soil carbon.

Young fast-growing forests absorb carbon dioxide more rapidly than older forests. An old forest is characterized by slow-growing trees and carbon losses due to death and decay that may translate to a net loss of carbon over time. As explained by Sedjo (2001), a carbon sink such as an old forest "may not be capturing any new carbon but can continue to hold large volumes of carbon as biomass over long periods of time." It is estimated that without the removal of CO_2 from the atmosphere via carbon sinks, the present concentration of CO_2 would be considerably higher (450 ppm) (Gillon, 2001). Carbon sinks can help offset environmental damage of energy intensive activities. Carbon sequestration has been suggested as a means to help mitigate the increase in atmospheric carbon dioxide concentration.

Ecosystem carbon stocks are represented by five carbon pools: carbon stored in live tree biomass (above ground and below ground), carbon stored in dead woody material (standing and down), carbon stored in understory biomass (live, dead, above and below ground), carbon stored in forest floor, and carbon stored in mineral soil (Bradford and Kastendick, 2010).

2.4 C sequestration potential of silvopasture systems

Silvopastoral systems can better sequester carbon in soil and biomass and help to improve soil conditions. Carbon sequestration is the important benefit that silvopasture can generate by storing atmospheric carbon dioxide in the form of tree biomass. Added tree cover on pasturelands is expected to increase carbon storage. Under the Kyoto Protocol, it is likely that carbon credits can be obtained for new or expanded tree cover in silvopasture (Sedjo, 2001; Cannell, 1999).

It has increasingly been recognized that agroforestry practices such as silvopasture have importance as a carbon sequestration strategy because of carbon storage potential in the multiple plant species and soil (Nair and Nair, 2003). Agroforestry are believed to have a higher potential to sequester carbon than pastures or field crops growing under similar ecological condition (Roshetko *et al.*, 2002; Kirby and Potvin, 2007). Conversion of pasture land to silvopasture has the potential to enhance rooting depth and distribution, quantity, and quality of organic matter input and thereby carbon sequestration potential (Haile *et al.*, 2008). Several studies have reported agro-ecosystems to contain approximately 12% of the world terrestrial carbon (Dixon, 1995). For small holder agroforestry systems in the tropics, potential C sequestration rates range from 1.5 Mg C ha^{-1} yr^{-1} to 3.5 Mg C ha^{-1} yr^{-1} (Montagnini and Nair, 2004). As a leading tree-based system especially in the tropics, agroforestry has been suggested as one of the most appropriate land-management systems for mitigating atmospheric CO_2 (Dixon, 1995; Albrecht and Kandji, 2003; Montagnini and Nair, 2004).

Wright *et al.* (2001) estimated that the goal of assimilating 3.3 Pg C $year^{-1}$ would require 670-760 M ha area of improved maize cultivation, whereas this goal can be achieved by adoption of 460 M ha of agroforestry. They even suggested that agroforestry is the only system that could realistically be implemented to mitigate the atmospheric CO_2 through terrestrial C sequestration. Estimation of C stocks all over the world indicated that, with the proper implementation of agroforestry at the global scale, 1.1 to 2.2 Pg C can be removed from the atmosphere within 50 years (Albrecht and Kandji, 2003). Trees can contribute substantially to soil C sequestration (Sanchez *et al.*, 1985; Lal *et al.*, 1999; Nair *et al.*, 2008).

2.5 Carbon sequestration in above and below ground biomass

Carbon sequestration occurs in two major segments of agroforestry: - above ground and below ground. On average, the above ground parts and the soil (including roots and other living biomass) are estimated to hold roughly one-thirds and two-thirds, respectively, of the total carbon stored in the tree based land use systems (Lal, 2010). Based on the notion that tree incorporation in crop lands and pastures would result in greater net carbon storage above and below ground (Palm *et al.*, 2004; Haile *et al.*, 2008).These system could outperform carbon sequestration of either forest or pastures as they have both forest and grassland mechanisms of carbon captured that can minimize carbon sequestration both above and below ground. In general trees store about 50-60% of the carbon in the above ground biomass whereas pasture grasses store only 10% above ground, the rest being allocated below ground (Houghton and Hackler 2000; Sharrow and Ismail 2004). These authors observed that the silvopastoral system sequestered an additional 0.74 Mg C ha^{-1} year^{-1} and 0.52 Mg C ha^{-1} year^{-1} than the plantation and pasture, respectively. Individual trees in the silvopastoral systems grew faster than in conventional forests on the same site, allowing silvopastoral trees to store more carbon. Tree-based land-use systems have greater soil carbon sequestration potential (CSP) than agronomic crops (Post and Mann, 1990). Trees have the potential of producing larger quantities of aboveground and belowground biomass compared to shrubs or herbs. More biomass results in increased production of aboveground litter and belowground root activity and these make trees an important factor for SOC sequestration (Lemma *et al.*, 2007). Inclusion of trees in a treeless system changes some functional mechanisms such as total productivity, rooting depth and distribution, and litter quantity and quality (Gill and Burke, 1999; Jackson *et al.*, 2000; Jobbagy and Jackson, 2000). According to Montagnini and Nair (2004), the tree components of agroforestry systems are potential sinks of atmospheric C due to their fast growth and productivity, high and long-term biomass stock, and extensive root system. By adding trees in the agricultural systems, agroforestry can increase the C storage capacity of the system (Kursten, 2000). Research indicates that by adding trees in grassland or pasture systems the SOC content can be increased considerably (Reyes-Reyes *et al.*, 2002; Yelenik *et al.*, 2004; Haile *et al.*, 2008). Forests are land use systems with high tree population and play a major role in C sequestration (Lal, 2005). Forest ecosystems store more than 80% of all terrestrial aboveground C and more than 70% of all SOC (Batjes, 1996; Six *et al.*, 2002). Production of larger quantities of aboveground and belowground biomass compared to shrubs or herbs makes trees more efficient in promoting soil C sequestration (Brady and Weil, 2007). More biomass results in increased production of aboveground litter and belowground root activity. Many authors have also reported that integration of trees into agricultural landscapes can increase the C storage potential considerably within belowground biomass (BGB), which is thought to be a viable approach for soil carbon sequestration (Nair *et al.*, 2010; Bambrick *et al.*, 2010; Kuyah *et al.*, 2012). The total amount of C stored in above and below ground biomass and soil was 5.8 and 8.2 Mg C ha^{-1} greater in silvopasture than pasture and Douglas fir plantation. Estimates of aboveground C-sequestration potential (CSP) are based on the assumption that 45% to 50% of branch and 30% of foliage dry weight constitute C (Shepherd and Montagnini, 2001; Schroth *et al.*, 2002).

Roots of the perennial vegetation in silvopastoral systems shifts C deeper into the soil profile, compared to conventional pastures or row crops. Paudel *et al.* (2011) observed significantly greater percentages of C in soils under a cottonwood (*P.deltoi*des Bortr.ex Marsh.) and grass silvopasture compared to maize-soybean rotation in Missouri. In the same study area, Kumar *et al.* (2010) observed significantly greater root mass in the 1m soil profile in tree grass areas than the pasture grass, clearly indicating the potential to deposit C deeper in the soil profile in silvopasture compared to pastures. The spatial distribution of C, both above- and below-ground, can vary depending on the design of the silvopastoral systems and management practices. SOC derived from the tree component was significantly greater near the trees in a slash pine (*Pinus elliottii* Englem) and bahiagrass (*Paspalum notatum* Fluegge) silvopasture compared to open pasture areas in Florida (Haile *et al.*, 2010). SOC were 1,033, 1,376 and 1,318 Mg ha^{-1} to a 1.25 m depth in open pasture, center of the pasture alley, and in-between trees in tree row, respectively. Strategies to enhance C sequestration in silvopasture may include selection of complementary tree, shrub, and pasture grasses with optimal biomass accrual, deep rooting habits, and greater below ground C accumulation potential.

2.6 Soil carbon sequestration

Soil plays a major role in global C sequestration (Lal, 2002). Henderson (1995) reported that about 755 of total terrestrial C is stored in the world's soils. The global soil carbon pool has been estimated to contain more than four times as much carbon as in the biotic pool and about three times as much as in the atmospheric pool (Lal, 2004). The total soil C pool of 2,300 Pg is three times the atmospheric pool of 770 Pg and 3.8 times the vegetation pool of 610 Pg; a reduction in soil C pool by 1Pg is equivalent to an atmospheric enrichment of CO_2 by 0.47 ppmv (Lal, 2001). Bohn (1976) estimated that about 30×10^{14} kg of organic carbon is present in the soils. The Soil Science Society of America (SSSA) recognizes that C is sequestered in soils in two ways: direct and indirect (Soil Science Society of America, 2001): "Direct soil C sequestration occurs by inorganic chemical reactions that convert CO_2 into soil inorganic C compounds such as calcium and magnesium carbonates." Indirect plant C sequestration occurs as plants photosynthesize atmospheric CO_2 into plant biomass. Some of this plant biomass is indirectly sequestered as SOC during decomposition processes. The amount of C sequestered at a site reflects the long-term balance between C uptake and release mechanisms. Because those flux rates are large, changes such as shifts in land cover and/ or land use practices that affect pools and fluxes of SOC have large implications for the C cycle and the earth's climate system.

The SOC varies with the land-use system (Post and Mann, 1990; Davidson and Ackerman, 1993). Depending on land-use type, changes in vegetation change the SOC accumulation. Changes beneficial to SOC are: increase in the rate of organic matter production, changes in the decomposability of organic matter that increase organic C, placing of organic matter deeper in the soil, and enhancing physical protection and aggregation (Post and Kwon, 2000). Soil organic matter (SOM) is defined as the summation of plant and animal residues at various stages of decomposition, cells and tissues of soil organisms, and well decomposed substances (Brady and Weil, 2007). This soil organic matter (SOM) represents a significant carbon store and can remain in the soil for extended periods as a part of soil aggregates. It is also the largest pool of plant nutrients.

The fraction of soil organic matter that is so "protected" from further rapid decomposition is very important from the point of view of soil carbon sequestration (SCS) (Saha *et al.,* 2010). Amount of C diverted towards soil organic matter is greatly influenced by the amount of belowground C allocation. This pool of C in the soil is the largest storage site in the global C cycle (Mellilo *et al.,* 1990; Schlesinger, 1990). Thus increased allocation to belowground through root production, turnover and exudation is important for sequestering C under conditions of increasing atmospheric CO_2 concentration (Curtis *et al.,* 1995; van Veen, 1991). Most soils under the managed ecosystems contain a lower SOC pool than their counterparts under natural ecosystems owing to the depletion of the SOC pool in cultivated soils. The most rapid loss of the SOC pool occurs in the first 20-50 years of conversion from natural to agricultural ecosystems in temperate regions and 5-10 years in the tropics (Lal, 2001). In general, cultivated soils normally contain 50-75 per cent of the original SOC pool. The depletion of the SOC pool is caused by oxidation or mineralization, leaching and erosion. Soil organic C contains a variety of fractions that differ in decomposability and are very heterogeneous in structure. The turnover of SOC is intimately linked with organic-matter quality (Agren *et al.,* 1996; Martens, 2000). Distinctive components of SOC have different residence times, ranging from labile to stable forms (Carter, 1996). This concept has led to the suggestion that SOC can be viewed as having an active, labile pool (mean residence times [MRTs] approx. 1–2 y), a slow pool (MRTs approx. 25 y), and a passive, recalcitrant pool (MRTs approx. 100–1000 y) (Parton *et al.*, 1988; Jenkinson, 1990; Schimel *et al.*, 1994; Torn *et al.*, 2005). Further, protection of SOC by silt and clay particles is well established (Sorensen, 1972; Ladd *et al.*, 1985; Feller and Beare, 1997; Hassink, 1997; von Lutzow *et al.*, 2006, 2007). It is also known that aggregation increases in less disturbed systems and that organic material within the soil aggregates, especially the microaggregates, has lower decomposition rate than that located outside the aggregates (Elliott and Coleman, 1988; Six *et al.*, 2000). Thus, soil C sequestration implies increasing the concentration/pools of SOC through land-use conversion and adoption of recommended management practices (RMPs) in agricultural, pastoral and forestry ecosystems and restoration of degraded and drastically disturbed soils. Formation of charcoal and use of biochar as a fertilizer is another option (Fowles, 2007).

Roots make a significant contribution to SOC (Strand *et al.*, 2008). About 50% of the C fixed in photosynthesis is transported belowground and partitioned among root growth, rhizosphere respiration, and assimilation to soil organic matter (Lynch and Whipps, 1990; Nguyen, 2003). Increased production and turnover rates of roots lead to increased SOC accumulation following root decomposition (Matamala *et al.*, 2003). Roots are the sources of SOC in deeper soil depth, where they are better protected. Some trees have rooting depth as deep as 60 m or more (Akinnifesi *et al.*, 2004). The deeper root development accumulates C at lower depths and the soil at lower depths is better protected from the disturbances leading to longer residence time. Minimal physical disturbance and reduced microbial activity caused by lack of supply of fresh C, increases the mean residence time (MRT) of SOC at deeper depths (Fontaine, 2007).

2.7 Soil fertility status

2.7.1 Influence of silvopasture system on soil physical properties

Many researchers have observed improved soil moisture in silvopastures compared to open pasture (Smith, 1942; Ovalle *et al.*, 1989). In Patagonia, silvopastoral systems were found to be more productive than traditional pastures due to more exhaustive use of water resources (Gyenge et al., 2002). Leaf water was greater in grasses growing under tree canopies compared with grasses growing in open pastures (Gyenge *et al.,* 2002). Shallow rooted grasses exploited small rainfall events while the deep rooted trees exploited reserves of water not available to grasses, showing no reaction to small rainfall events (Gyenge *et al.*, 2002). The authors concluded that silvopastoral systems use water resources that otherwise are lost from the system. Their work supports the resource sharing theory of competitive partitioning. Similar effects on water relations were reported for a southern African savanna, in which the grass layer obtained most of its water from the topsoil (Knoop and Walker, 1985; Ong and Leakey 1999). Pasture cultivation for eight years continuously changed the bulk density of cultivated soil (White *et al.*, 1976). Page and williard (1946) found that cultivation of grasses increased the pore space and soil bulk density. Anderson and Gantzer (1989) noticed the soil physical properties after 100 years of continous cultivation of pasture crops and reported that annual addition of organic matter by way of decomposition of plant parts decreased the bulk density by an average of 0.12g/cm^3. In general, bulk density (BD) increased with increase in soil depth. Many reports suggest such increase in bulk density with soil depth (Jangra *et al.*, 2010; Singh *et al.,* 2010 and Tumwebaze *et al.,* 2012). The top soil in tropical areas is usually low in bulk density owing to the highly weathered soil rich in litter and organic matter which turns harder with increasing soil depth. Pandey and Pathak (1975) stressed on higher compaction and deflocculation of soil particles (which considerably restricts the capillary pores) to be an important reason for higher values of bulk density in the treeless control site. The higher evapotranspiration capacity associated with plantation forest and shrub vegetation results in a lower soil moisture content (Chenet *et al.,* 2010). Research has demonstrated that inclusion of trees within agricultural systems can improve water quality (Lowrance 1992).

Soil physical properties, namely infiltration rate, pore space and water holding capacity improved with tree planting. Soil organic carbon and available nutrients increased, while soil pH decreased with tree planting. Soils planted with *Acacia nilotica* and *A. auriculiformis* had the lowest soil pH (Devevaranavadgi *et al.*, 2000). Malik *et al.* (1996) studied the changes in some physical and chemical properties of the soil in an agri-silvicultural system with multipurpose tree species in Tarai region of Uttar Pradesh. Soil pH showed a decrease while planting of trees increased the soil organic carbon, cation exchange capacity and available plant nutrients. The differences among different tree species were not considerable and the beneficial effects of the trees were more evident in the surface soil horizons than the sub surface horizons.

Tomar *et al.* (1998) reported the impacts of multipurpose trees (MPT) on physical properties of soil under different agroforestry systems in western Himalaya and the result showed significant differences between plots in percentage water content and water holding capacity, but there was no consistent pattern of response to the presence of trees, or to distance from the trees, or with soil depth or season. Soil pH values tended to be slightly lower in the plots with MPTs.

2.7.2 Silvopasture systems on soil nutrients

As compared to pure agricultural systems, agroforestry systems contribute towards improved nutrient cycling and sustainability through greater mineralization of nutrients from unavailable reserves, addition of nutrients in plant litter/tree residues, more closed nutrient cycles as a result of greater uptake by plant roots and less leaching losses and achieving a balanced supply of nutrients including micronutrients. Puri *et al.*, 1994 studied the productivity of *Cicer arietinum* (chick pea) under a *Prosopis cineraria* agroforestry system in the arid regions of India and revealed that soil N, P and K, soil moisture and organic carbon were higher under tree canopies than tree less plots. It was concluded that *P. cineraria* benefits chickpea growth and yield due to improvement of soil fertility and conservation of moisture. In a study to know the effects of the multipurpose tree, *Prosopis cineraria* on physico-chemical properties of soil were investigated in Hisar district, which suggested that in arid regions, this species can conserve moisture, improve soil fertility and increase the production of agricultural crops in agroforestry systems.

Jha (1990) studied silvopastoral system at Ranchi, the experiments showed increase of organic carbon, available K and pH of soil. Organic carbon, available P and available K and pH recorded were 0.4%, 29 kg/ha, 100 kg/ha and 5.8 respectively. After three years level of organic carbon, available P, available K, pH recorded were 0.49 %, 46 kg/ha, 179 kg/ha and 6.5 respectively. Nitrogen synthesized by legumes act more evenly and gradually than that of nitrogenous fertilizers (Kanodia and Patil, 1983). Singh (1994) suggested that intercropping systems are important in the management of soil fertility. The incorporation of forage legumes in inter/ mixed cropping systems of grasses has both direct and indirect effects on soil fertility. The direct effect is in terms of N fixation by legumes. The indirect effect is that the nutrient requirements are specific to each crop. As such, the soil is not continuously depleted in particular nutrient. Leaf nutrient concentration, degree of nutrient reabsorption prior to leaf abscission, and litter fall mass determine the amount of nutrients recycled in litter. The chemical quality of litter inputs then regulates organic matter decomposition and the formation of stable and labile soil organic matter pools (Patron *et al.*, 1988). Legume tree species form one of the most evident functional groups by its potential for the symbiotic fixation of atmospheric N and, even independent of this capacity, by the high levels of N in their tissues, which is in accordance with their N-demanding strategy (McKey, 1994). Hence, both above and below ground litter in-puts from legume trees are thought to enhance soil's biological activity and nutrient release from organic matter. According to this, and among other reasons, legume tree species are widespread in production systems, including agroforestry systems in the tropics. Silvopastoral systems can be an alternative for the management of soil nutrients of tropical pastures, though the selection of tree species becomes critical for successful results (Galicia and García-Oliva, 2004; Rhoades, 1997).

Nutrient uptake and removal by the soil and vegetation in a wooded ecosystem (either through tree plantings in pastures or grazing cattle in wooded settings) has been shown to prevent agricultural upland outputs from reaching stream channels. Forested areas function as bioassimilative transformers, changing the chemical composition of compounds. Under oxygenated soil conditions, resident bacteria and fungi mineralize runoff-derived nitrogen which is then available for uptake by soil bacteria and plants. Livestock-created nutrients moving to streams and ground water are reduced due to absorption by roots. Greater infiltration of nutrient-transporting water occurs within forested areas than in cultivated soil. Processes involved include retention of sediment-bound nutrients in surface runoff, uptake of soluble nutrients by vegetation and microbes, and absorption of soluble nutrients by organic and inorganic soil particles (Garrett *et al.* 1994). Leguminous crops (herbs, shrubs, or trees) play a critical role in natural ecosystems, agriculture, and agro-forestry, where their ability to fix nitrogen in symbiosis makes them excellent colonizers of low- N environment hence an economic and environmentally friendly species (Rejili *et al.*, 2012) .

MATERIALS AND METHODS

CHAPTER 3

MATERIALS AND METHODS

The present study entitled "Carbon storage potential of intensive silvopasture systems in humid tropics of Kerala" was carried out at Instructional farm, College of Horticulture Vellanikkara during the year 2013-2015. The main objective of the study was to assess the carbon storage potential of silvopasture systems in comparison with monoculture system and also investigate the soil fertility changes associated with different intercropping systems.

3.1 Location

The proposed study was conducted in existing 2-year old 3-tier and 2-tier silvopasture systems and fodder grass/ tree/ herbaceous legume monoculture systems established during May 2013 at Instructional Farm, College of Horticulture, Vellanikkara.

3.2. Climate and Soil

Vellanikkara experiences a warm humid climate with a mean rainfall of 2817.1mm (2 year average from May 2013- May 2015) (Fig. 1). The area is benefited both by the southwest and northeast monsoons, with a greater share (68-72%) from southwest monsoon. The mean maximum temperature ranged from 29.10 to 36.07^0 C in the months of July and March respectively. While the mean minimum temperature varied from 22.03^0 C to 25.7^0 C in the months of December and April respectively. The soil of experimental site was deep well drained sandy clay loam of Ultisol order (Typic Plinthustult – Vellanikkara series midland laterite – Ustic moisture regimes (dry period – February to May) and Isohyperthermic temperature regimes). The soil physico-chemical properties at the beginning of the experiment were as follows: pH: 5.52, total N: 0.13%, total P: 804.46 kg ha^{-1} total K: 799.06 kg ha^{-1}available N: available P (Bray): 18 kg ha^{-1}, exchangeable K: 190.4 kg ha^{-1} and organic C: 1.50%, deficient in Ca and Mg and

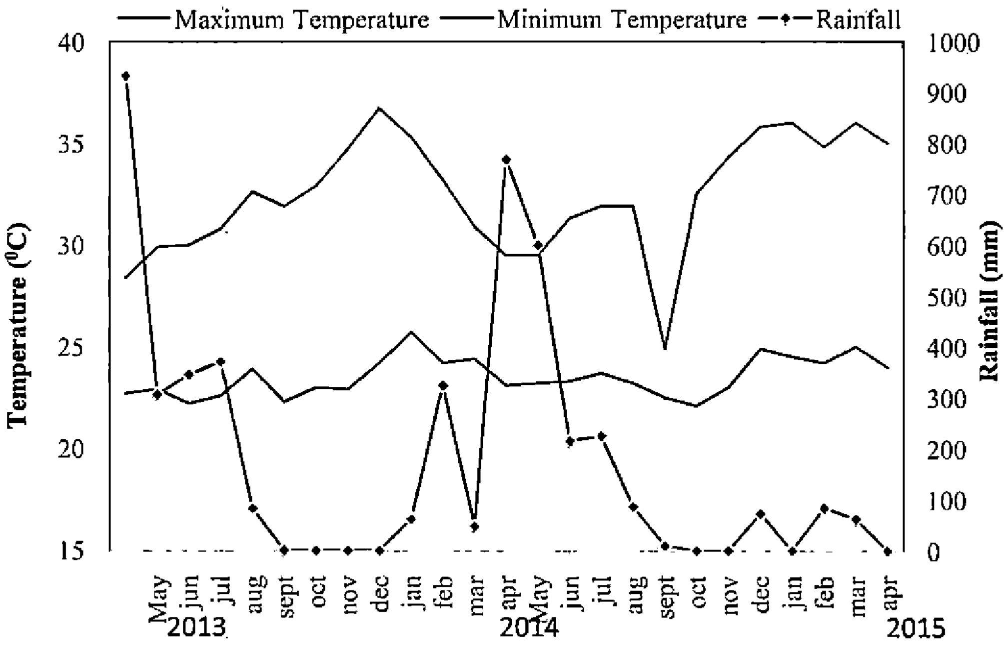

Fig. 1. Mean monthly rainfall and temperature data from May 2013- May 2015 at Vellanikkara, Kerala.

sufficient in available sulphur. All micronutrients except boron were found to be sufficient in the soil.

3.3 Materials

3.3.1 Crops

Fodder grass hybrid napier, fodder tree mulberry and herbaceous fodder legume stylosanthus were the component crops in silvopasture and monoculture systems.

3.3.1.1 Mulberry

The leaves of the multipurpose perennial shrub, mulberry (*Morus indica*), traditionally used for silkworm rearing, is known for its high protein content with good amino acid profile, high digestibility, high mineral content, low fibre content and very good palatability (Sanchez, 1985). The high biomass yield of the plant together with its low tannin content make it an attractive fodder resource for ruminants particularly, as a supplement to low quality basal diets. Being a potential fodder tree suited to the agro climatic conditions of Kerala, mulberry variety V1 (Victoria 1, a cross of S-30 and Berc 776 mulberry cultivars), released from Central Sericultural Research and Training Institute, Mysore, Karnataka was the fodder tree selected for this study.

3.3.1.2 Hybrid napier grass

Hybrid napier is the most preferred grass fodder in Kerala, owing to its fast growing nature and higher productivity from a limited land area. Hybrid napier, variety CO 4 was the fodder grass used, which was developed by Tamil Nadu Agricultural University, Coimbatore, India, This is a cross between Bajra cereal Cumbu CO 8 and Napier grass F.T.461 with a yield range of 380-400 t ha^{-1}. It produces more tillers with soft and juicy stem, free from pest and disease and non-lodging. It can be cultivated throughout the year under irrigated conditions. This is a very high yielding grass variety with productivity of 350-400 t ha^{-1} with protein content of 8% to 11%. It is propagated using cuttings.

3.3.1.3 Stylosanthus

Stylosanthus is a protein rich leguminous fodder (crude protein- 15-18 %) with shade and drought tolerance recommended for humid tropics of Kerala (KAU, 2011). *Stylosanthes hamata cv. Verano,* was the variety used in this study.

3.3.2 Manures and fertilizers

Manures and fertilizers were applied in both the years as per the annual requirements of each crop based on state recommendations (mulberry- fertilizers @ 300:120:120 kg ha^{-1} of N: P_2O_5: K_2O in five split doses + Farm yard manure (FYM) 20 t ha^{-1} basal; hybrid napier - FYM@ 25 t ha^{-1}, and P_2O_5 and K_2O @ 50 kg ha^{-1} basal, N @ 200 kg ha^{-1} in two or three split doses; stylosanthus - 20, 80 and 30 kg of N, P_2O_5 and K_2O per ha (KAU, 2011);. Urea (46 % N), rock phosphate (20 % $P_2 O_5$) and muriate of potash (60% $K_2 O$) were used as chemical sources of nitrogen, phosphorus and potassium respectively.

3.4 Methods

3.4.1 Design and layout of the experiment

Design	:	RBD (Randomized block design)
Treatments	:	7
Replications	:	3
Plot size	:	20m x 10m (200 sq m)

3.4.2 Treatment details

The experiment consisted of two- year old 3-tier (grass+ tree+ herbaceous legume) and 2- tier (grass+ tree/ legume) silvopasture systems (Plate 1) and fodder monoculture systems (Plate 2) established at Instructional Farm, COH on May 2013, and the details of which are given below.

T_1- Hybrid napier +mulberry+ stylosanthus (3-tier system)

T_2- Hybrid napier + mulberry (2-tier system)

T_3- Hybrid napier + stylosanthus (2-tier system)

T_4- Fodder grass monoculture (Hybrid napier, variety CO 4)

T_5- Mulberry monoculture

T_6- Stylosanthus monoculture

T_7- Absolute control (Open plot with natural grass vegetation)

The layout plan of the experiment is shown in Fig. 2. Three – tier silvopastoral system consisted of grass intercropped in between tree and legume sub plots in 1:3:1 ratio on area basis, two- tier systems contained grass + tree/ legume in 3: 2 ratios on area basis, whereas the entire 200 sq m (5 cents) was planted with either grass, or legume or tree for monoculture treatments. The above ratio and the plot size was selected to satisfy the fodder and protein requirements of cross-breed lactating cows of Kerala with an yield potential of 6- 8litres of milk.

3.4.3 Field culture

All the fodder production systems were established during May 2013. The field area was ploughed twice and the layout was done allocating a plot size of 20 m x 10 m (200 sq m) for each treatment. Within each plot, subplots were demarcated for trees, grasses and legumes and each component was planted at high density as single species. Within subplots ridges and furrows were taken at recommended spacing for planting hybrid napier (60 cm x 60 cm), and stylosanthus (30 cm x15cm) (KAU, 2011). Trees were closely planted at a spacing of 60 cm x 60 cm, and maintained as hedge rows of 1m height for preventing

3- tier silvopsature system **2-tier HN+ stylosanthus**

2- tier HN+mulberry

Plate 1. 3- tier, 2- tier silvopasture systems

Mulberry monoculture **HN monoculture**

Stylosanthus monoculture

Plate 2. Different fodder monoculture systems

shading effect on grasses and legumes and for the ease of harvest. All recommended cultivation practices for crops were followed as per the Package of Practices Recommendation of Kerala Agricultural University.

3.4.3.1 Harvesting

All the crops are perennial and were harvested at standard intervals for 2 years to study biomass accumulation pattern and for carbon analysis. The crops were harvested as: hybrid napier (1st harvest at 75 days and subsequent at 30 days interval), stylosanthus (1st harvest after 3 months and later at 45 days interval) and mulberry (1st harvest 6 months after planting and then at trimonthly intervals). Trees were harvested at a height of 1 m above ground level, stylosanthus and hybrid napier at 15 cm height.

3.5 Observations

3.5.1 Above ground harvested biomass (collected from previous harvest observations)

3.5.1.1 Annual green fodder yield from different systems

Observations on fodder yield from each harvest were taken by random sampling using a quadrat (1 sq. m) from each plot as well as from all tiers within the silvopasture plots (Plate 3). In monoculture plots, forage from three random quadrats in the central zone of the plot was harvested and their fresh weights recorded in the field. For silvopasture plots, three samples each were taken randomly from all the component subplots, weighed and pooled to get the total yield from the system. Thereafter, yield from all harvests in a year was pooled to get annual yields and using the net harvested area and fresh weight, fodder yield was scaled up to a hectare basis.

3.5.1.2. Annual dry fodder yield per hectare

After harvesting, the biomass from each fodder bank was weighed fresh. Biomass from trees was separated into leaf and stem and their fresh weights determined. Three sub-samples (of approximately 500 g each) taken from the whole fresh biomass samples of grasses and legumes, and leaf and stem samples of trees were oven-dried at 70^0C for 48 hours for dry matter (DM) determination. The annual fresh fodder yields were multiplied with the dry matter content and expressed as dry fodder yield per hectare.

3.5.1.3. Pooled fodder yield from various systems over 2 year period

The sum total of annual green fodder and dry fodder yield during 1st and 2nd year from different systems were pooled for getting overall fresh and dry fodder yield per hectare for 2 years.

3.5.2 Above ground fresh and dry standing biomass

Observations on fresh standing biomass were taken from the same quadrats used for taking harvested biomass observations (Plate 4). The left over standing biomass from hybrid napier, mulberry and stylosanthus in various plots at the end of the 2-year period was collected through destructive sampling and their fresh weight determined in the same manner as that of harvested biomass and scaled to hectare basis. Then sub samples taken from the fresh standing biomass samples were oven-dried at 70^0C for 48 hours for dry matter (DM) determination and estimation of dry standing biomass per hectare for various systems.

3.5.3 Below ground root biomass and root depth

The soil below the quadrats used for making plant observation was excavated to 1 m depth to record the root biomass from 1cu.m volume of the soil (Plate 5). The roots were pulled out completely, washed to remove the soil and fresh weight determined. The mean fresh root weight of various crops was multiplied with the allotted area for each crop in the different systems and expressed as fresh root biomass production on hectare basis.

After recording root fresh weights, the sub samples were dried to constant weights at 70^0 C for dry matter determination and expressed on hectare basis.

Mulberry **Hybrid napier**

Stylosanthus

Plate 3. Harvested biomass observations of different fodder crops

Mulberry **Hybrid napier**

Stylosanthus

Plate 4. Standing biomass observations of different fodder crops using quadrat

Mulberry **Hybrid napier**

Stylosanthus

Plate 5. Root biomass observations of different fodder crops

The maximum length of the roots were also measured and expressed in centimeter.

3.6 Above and below ground carbon stock assessment

3.6.1 Plant carbon stocks

The oven dried plant samples (leaves, stem and roots for fodder trees; shoot and root for legumes and grasses) were ground thoroughly to pass through 2 mm sieve and used for analyzing the carbon concentrations in the various tissue types, by igniting in muffle furnace at 550^0 C for 6 hours (Gaur, 1975). Carbon content in the individual tissue types were multiplied with the corresponding component dry biomass (Nair *et al.*, 2010) and summed up to calculate the overall plant carbon stocks of various systems. This was also computed on hectare basis.

3.6.2 Soil carbon stocks

The soil sampling was done from the same 1 sq m quadrats which were used for making plant observations. The soil below the quadrats was excavated to 1 m depth, and soil samples were collected from five soil depths (0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm and 80-100 cm) from each plot as well as from all tiers in silvopasture plots. In case of 3-tier and 2-tier silvopasture plots triplicate samples were collected from all the tiers at different depths, with sample size in proportion to their area and mixed to get the composite sample. Sub sample from the composite sample were used for carbon analysis by using Walkely and Black's permanganate oxidation method (Walkely and Black, 1934). Also, triplicate soil samples were collected at different depths from grass/tree/legume monoculture plots and open control plots to get the composite sample and subsamples used for analysis.

Soil samples were collected separately from all the soil depths using a core sampler for estimation of bulk density. For 3-tier and 2-tier silvopasture plots, the bulk density was calculated at each depth by taking the average of all the tiers in proportion to the area. Soil mass for each soil depth was computed from the bulk density and soil C sequestration calculated for each soil depth by multiplying soil mass with soil organic C-content (%) (Anderson and Ingram, 1989). Soil carbon stocks in individual soil depths were summed up to get the overall soil carbon sequestration under various systems.

3.7 Soil analysis

To study the comparative changes in soil physical properties (Plate 6) and nutrient contents of silvopasture and monoculture systems, triplicate samples drawn from composite samples at various depths as detailed above were analysed for soil temperature, moisture, pH, bulk density, water holding capacity and soil total and available N, P and K contents following standard analytical methods.

3.7.1 Soil physical properties

3.7.1.1 Bulk density

Bulk density was estimated by taking out a core of undisturbed soil by using a core sampler. The core was taken out without pressing the cylinder too hard on soil so that the natural bulk density of soil may not get disturbed. The soil was oven dried and weight was determined. The volume of soil was calculated by measuring the volume of cylinder ($\pi r^2 h$). The bulk density was calculated by dividing the oven dry weight of soil samples (g) by volume of soil.

3.7.1.2 Soil moisture

Soil moisture was estimated by collecting fresh soil samples from the field in moisture can and dried in an oven at 105^0C until constant weight was obtained. The quantity of moisture lost was determined gravimetrically and expressed on oven dry basis.

$$\text{Soil moisture percent on dry basis} = \frac{\text{Fresh weight (g) - Dry weight (g)}}{\text{Dry weight (g)}} \times 100$$

Bulk density

Soil temperature

Plate 6. Estimation of soil physical properties

3.7.1.3 Water holding capacity (WHC)

A known quantity of soil was allowed to fully saturate and equilibrate with water and from the water held in the soil after free draining, the water holding capacity was determined (Jackson, 1958).

$$\text{WHC on dry basis (\%)} = \frac{\text{Saturated weight (g) - Dry weight (g)}}{\text{Dry weight (g)}} \times 100$$

3.7.1.4 Soil temperature

Soil temperature at different depths was estimated by using soil thermometer during the month of May.

3.7.1.5 Soil pH

Soil p^H was calculated using an aqueous suspension of soil (soil and water in 1:2.5 ratio) using an Elico p^H meter (Model Li 613) as described by Jackson (1973).

3.7.2 Soil nutrient analysis

3.7.2.1 Total nitrogen

The total nitrogen content in the soil was determined by digesting 1g of soil in 5ml of sulphuric acid in presence of digestion mixture (Na_2SO_4: $CuSO_4$: Selenium in 10: 4: 1 ratio) and the N content in the digest was determined by microkjeldhal method (Jackson, 1958)

3.7.2.2 Available nitrogen

Available nitrogen in soil was determined by alkaline permanganate method (Subbiah and Asija, 1956).

3.7.2.3 Total phosphorus

Total phosphorus was extracted by di-acid digestion and then estimated colorimetrically by vanadomolybdate (blue colour) method. The extracted P was estimated using spectrophotometry.

3.7.2.4 Available phosphorus

Available phosphorus was extracted using Bray-I extractant (Bray and Kurtz, 1945) and the P content was colorimetrically assayed (Chloromolybdic acid blue colour method). The reducing agent was ascorbic acid (Jackson, 1973).

3.7.2.5 Total potassium

Total potassium was extracted by di-acid digestion (9:4 mixture HNO3: $HclO_4$) and potassium in soil extract was estimated by flame photometer method.

3.7.2.6 Available potassium

Available potassium was determined by flame photometry using 1N neutral normal ammonium acetate solution as the extractant (Jackson, 1973).

All nutrient concentrations were expressed on oven dry basis

3.8 Statistical analysis

The data were subjected to statistical analysis by analysis of variance (ANOVA) in SPSS version 20.0 (SPSS Inc.,USA) to ascertain the significance of various parameters. The Duncan's Multiple Range Test (DMRT) was used to test the differences among treatment means at 5% significance level.

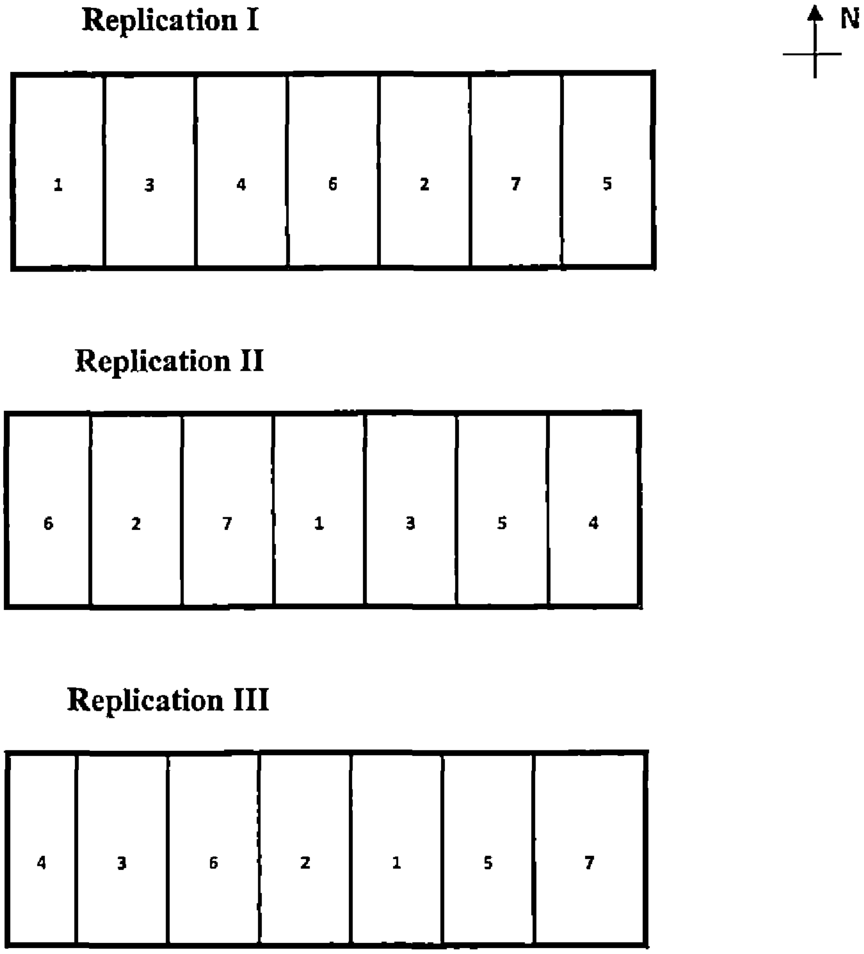

Fig. 2. Layout plan of field trials

Treatment combinations

T_1 – Hybrid napier +mulberry+ stylosanthus

T_2 - Hybrid napier + mulberry

T_3 - Hybrid napier + stylosanthus

T_4 - Fodder grass monoculture (Hybrid napier, variety CO 4)

T_5 - Mulberry monoculture

T_6. Stylosanthus monoculture

T_7. Open plot

RESULTS

CHAPTER 4

RESULTS

The two year study on carbon storage potential of intensive silvopasture systems at Vellanikkara revealed vital information on harvested biomass, standing biomass, root biomass and carbon storage potential of various silvopasture and monoculture systems and on soil physical and nutrient properties. The salient results are presented hereunder.

4.1 Harvested biomass

4.1.1 Harvested fresh fodder biomass

Tables 1 and 2 show the harvested fresh fodder biomass from silvopasture and monoculture systems during 1st year and 2nd year. The maximum harvested fresh fodder biomass during 1st year (123 Mg ha^{-1}) and 2nd year (261.15 Mg ha^{-1}) was recorded in hybrid napier monoculture and it was significantly superior to all other silvopasture and monoculture systems, followed by 2-tier system (hybrid napier+ mulberry) in both years (first year-93 Mg ha^{-1}; second year-198 Mg ha^{-1}). Lowest yield was recorded in stylosanthus monoculture (first year-25 Mg ha^{-1}; second year- 37 Mg ha^{-1}). The 3-tier system recorded 90.20 and 184.69 Mg ha^{-1} of yield where as the 2-tier system (hybrid napier + stylosanthus) recorded 88 and 171 Mg ha^{-1} fresh fodder biomass in 1st and 2nd year respectively. Harvested fresh fodder biomass during 1st and 2nd year in mulberry monoculture was 38 and 108 Mg ha^{-1} respectively.

Table 3 depicts the pooled harvested fresh fodder biomass over 2 years from silvopasture and monoculture systems. Among the two years, 2nd year recorded maximum harvested fresh fodder biomass in all treatments. Hybrid napier monoculture recorded the maximum value (384.11 Mg h^{-1}) over two years. Lowest harvested fresh fodder biomass was found in stylosanthus monoculture (62 Mg ha^{-1}).

Table 1. Harvested fresh fodder biomass from silvopasture and monoculture systems during 1st year.

Treatments	Fresh fodder yield in 1st year (Mg ha^{-1})			
	Hybrid napier	Mulberry	Stylosanthus	Total
T1	77.49^{b}	7.46^{c}	5.25^{c}	90.20^{c}
T2	78^{b}	15^{b}	0	93^{b}
T3	77.49^{b}	0	10.38^{b}	88^{d}
T4	123^{a}	0	0	123^{a}
T5	0	38^{a}	0	38^{e}
T6	0	0	25.03^{a}	25.03^{f}
T7	0	0	0	0
F value	< 0.05	< 0.05	< 0.05	< 0.05

* Significant at 0.05 level; values with the same superscripts do not differ significantly

Table 2. Harvested fresh fodder biomass from silvopasture and monoculture systems during 2nd year.

Treatments	Fresh fodder yield in 2nd year (Mg ha^{-1})			
	Hybrid napier	Mulberry	Stylosanthus	Total
T1	156.35^{b}	21.150^{c}	7.19^{c}	185^{c}
T2	156.41^{b}	41.36^{b}	0	198^{b}
T3	156.45^{b}	0	14.200^{b}	171^{d}
T4	261.15^{a}	0	0	261.15^{a}
T5	0	108^{a}	0	108^{e}
T6	0	0	37^{a}	37^{f}
T7	0	0	0	0
F value	< 0.05	< 0.05	< 0.05	< 0.05

* Significant at 0.05 level; values with the same superscripts do not differ significantly

Table 3. Pooled harvested fresh fodder biomass over two year period from silvopasture and monoculture systems.

Treatments	Pooled harvested fresh fodder biomass (Mg ha^{-1})		
	1st year	2nd year	Total over 2 years
T1	90.20^{c}	185^{c}	275^{c}
T2	93^{b}	198^{b}	290.41^{b}
T3	88^{d}	171^{d}	259^{d}
T4	123^{a}	261.150^{a}	384.11^{a}
T5	39^{e}	108^{e}	145.08^{e}
T6	25.03^{f}	37^{f}	62^{f}
T7	0	0	0
F value	< 0.05	< 0.05	< 0.05

* Significant at 0.05 level; values with the same superscripts do not differ significantly

4.1.2 Harvested dry fodder biomass

Tables 4 and 5 depict the harvested dry fodder biomass from silvopasture and monoculture systems during 1st and 2nd year. Among all silvopasture and monoculture systems, the hybrid napier monoculture recorded the maximum harvested dry fodder biomass in 1st year (16.39 Mg ha^{-1}) and 2nd year (35 Mg ha^{-1}) it was significantly superior to all other silvopasture and monoculture systems, followed by 2-tier system (hybrid napier+mulberry) in both the years. Lowest harvested dry fodder biomass in 1st year (7.44 Mg ha^{-1}) and 2nd year (11 Mg ha^{-1}) was recorded in stylosanthus monoculture. The 3-tier system recorded 14.10 and 29.24 Mg ha^{-1} of harvested dry fodder biomass in 1st and 2nd year respectively. The 2-tier system (hybrid napier + stylosanthus) recorded 13.41 and 25.07 mg ha^{-1} dry fodder biomass in 1st and 2nd year. Harvested dry fodder biomass from mulberry monoculture was 11.11 Mg ha^{-1}(1st year) and 32 Mg ha^{-1}(2nd year).

Table 6 depicts the pooled dry fodder biomass from silvopasture and monoculture systems over two years. Among the two years, 2nd year recorded maximum harvested dry fodder biomass in all treatments. Hybrid napier monoculture recorded the maximum value (51.20 Mg ha^{-1}) over two years followed by 2-tier system (hybrid napier+mulberry) with 48 Mg ha^{-1}. Lowest harvested dry fodder biomass was found in stylosanthus monoculture (18.35 Mg ha^{-1}). The 3-tier system and mulberry monoculture recorded 43.35 and 43 Mg ha^{-1} respectively and they were on par.

4.1.3 Carbon content in harvested biomass

Tables 7 and 8 reveal the carbon in harvested biomass from silvopasture and monoculture systems during 1st and 2nd year. Among all silvopasture and monoculture systems the maximum carbon in harvested biomass of 1st year (15.40 Mg ha^{-1}) and 2nd year (33 Mg ha^{-1}) was recorded in hybrid napier monoculture, followed by 2-tier system (hybrid napier+mulberry) in 1st (14 Mg ha^{-1}) and 2nd year (31 Mg ha^{-1}) . The lowest carbon during 1st (7 Mg ha^{-1}) and 2nd year (6.15 Mg ha^{-1}) was recorded in stylosanthus monoculture. The 3-tier system recorded 13.22 and 27 Mg ha^{-1} harvested carbon in 1st and 2nd year respectively. The 2-tier system (hybrid napier + stylosanthus) recorded 13 Mg ha^{-1} (1st year) and 22 Mg ha^{-1} carbon (2nd year). Carbon during 1st and 2nd year in mulberry monoculture was 10.30 and 30 Mg ha^{-1} respectively.

Among the two years, 2nd year recorded maximum harvested carbon in all treatments (Table 9). Hybrid napier monoculture recorded the maximum value (48.130 Mg ha^{-1}) over two years, followed by 2-tier HN+mulberry system (45 Mg ha^{-1}). Lowest harvested carbon over two years was recorded in stylosanthus monoculture (13.15 Mg ha^{-1}). The 3-tier system and mulberry monoculture recorded 40 Mg ha^{-1} and they were on par.

Table 4. Harvested dry fodder biomass from silvopasture and monoculture systems during 1st year.

Treatments	Fractional and total harvested dry fodder yield in 1st year (Mg ha^{-1})			
	Hybrid napier	Mulberry	Stylosanthus	Total
T1	10.32^{b}	2.21^{c}	2^{c}	14.10^{c}
T2	10.35^{b}	4.42^{b}	0	15^{b}
T3	10.33^{b}	0	3.08^{b}	13.41^{d}
T4	16.39^{a}	0	0	16.39^{a}
T5	0	11.11^{a}	0	11.11^{e}
T6	0	0	7.44^{a}	7.44^{f}
T7	0	0	0	0
F value	< 0.05	< 0.05	< 0.05	< 0.05

* Significant at 0.05 level; values with the same superscripts do not differ significantly

Table 5. Harvested dry fodder biomass from silvopasture and monoculture systems during 2nd year.

Treatments	Fractional and total harvested dry fodder biomass 2nd year (Mg ha^{-1})			
	Hybrid napier	Mulberry	Stylosanthus	Total
T1	21^{b}	6.26^{c}	2.13^{c}	29.24^{d}
T2	21^{b}	12.25^{b}	0	33.10^{b}
T3	21^{b}	0	4.22^{b}	25.07^{e}
T4	35^{a}	0	0	35^{a}
T5	0	32^{a}	0	32^{c}
T6	0	0	11^{a}	11^{f}
T7	0	0	0	0
F value	< 0.05	< 0.05	< 0.05	< 0.05

* Significant at 0.05 level; values with the same superscripts do not differ significantly

Table 6. Pooled harvested dry fodder biomass over two year period.

Treatments	Pooled harvested dry fodder biomass over two year period (Mg ha^{-1})		
	1^{st} year	2^{nd} year	Total over 2 years
T1	14.10^{c}	29.24^{d}	43.35^{c}
T2	15^{b}	33.10^{b}	48^{b}
T3	13.41^{d}	25.07^{e}	38.49^{d}
T4	16.39^{a}	35^{a}	51.20^{a}
T5	11.11^{e}	32^{c}	43^{c}
T6	7.44^{f}	11^{f}	18.35^{e}
T7	0	0	0
F value	< 0.05	< 0.05	< 0.05

* Significant at 0.05 level; values with the same superscripts do not differ significantly

Table 7. Carbon content in harvested biomass from silvopasture and monoculture systems during 1^{st} year.

Treatments	Fractional and total carbon during 1^{st} year(Mg ha^{-1})			
	Hybrid napier	Mulberry	Stylosanthus	Total
T1	10^{b}	2.05^{c}	1.46^{c}	13.22^{c}
T2	10^{b}	4.09^{b}	0	14^{b}
T3	10^{b}	0	3^{b}	13^{d}
T4	15.40^{a}	0	0	15.40^{a}
T5	0	10.30^{a}	0	10.30^{e}
T6	0	0	7^{a}	7^{f}
T7	0	0	0	0
F value	< 0.05	< 0.05	< 0.05	< 0.05

* Significant at 0.05 level; values with the same superscripts do not differ significantly

4.2 Standing biomass

4.2.1 Standing fresh fodder biomass

Table 10 shows the fresh standing biomass from silvopasture and monoculture systems. The maximum fresh standing biomass was recorded in mulberry monoculture (51 Mg ha^{-1}). The next best treatment was 2-tier HN and mulberry system (40.20 Mg ha^{-1}) and was significantly superior to 3-tier silvopasture systems with grass+ trees + legume. The lowest biomass was recorded in control open plot (4 Mg ha^{-1}). The stylosanthus and hybrid napier monoculture recorded 6 and 33 Mg ha^{-1} respectively. The three tier system recorded 31.16 Mg $ha^{-1}$of fresh standing biomass. The 2-tier system (hybrid napier+stylosanthus) recorded 6.31 Mg ha^{-1} of standing fresh fodder biomass.

4.2.2 Standing dry fodder biomass

Table 11 shows the dry standing biomass from silvopasture and monoculture systems which showed similar trend as that of fresh standing biomass. The maximum dry standing biomass of 22 Mg $ha^{-1}$was recorded in mulberry monoculture followed by 2 tier system HN+mulberry (15 Mg ha^{-1}), while the lowest value was recorded in open plot (1.5 Mg ha^{-1}). The hybrid napier and stylosanthus recorded 10.23 and 2 Mg ha^{-1} of standing dry fodder biomass. The 2-tier hybrid napier+stylosanthus and 3-tier recorded values of 7 and 11 Mg ha^{-1} of standing dry fodder biomass respectively.

4.2.3 Carbon content in standing biomass

Table 12 reveals the carbon in dry standing biomass from silvopasture and monoculture systems. Among all silvopasture and monoculture systems the maximum carbon in dry standing biomass was recorded in mulberry monoculture (21 Mg ha^{-1}) followed by 2-tier HN + mulberry system (14.01 Mg ha^{-1}). The lowest carbon was recorded in open plot (1.48 Mg ha^{-1}).The hybrid napier monoculture and stylosanthus monoculture recorded 9.41 and 2 Mg ha^{-1} respectively. The two tier system (hybrid napier+ stylosanthus) recorded 6.31 Mg ha^{-1} of carbon in dry standing biomass.

Table 10. Fresh standing biomass from silvopasture and monoculture systems.

Treatments	Fractional and total fresh standing biomass(Mg ha^{-1})			
	Hybrid napier	Mulberry	Stylosanthus	Total
T1	20^{b}	10.20^{c}	1.16^{c}	31.16^{d}
T2	20^{b}	20.40^{b}	0	40.20^{b}
T3	20^{b}	0	2.33^{b}	22.13^{e}
T4	33^{a}	0	0	33^{c}
T5	0	51^{a}	0	51^{a}
T6	0	0	6^{a}	6^{f}
T7		0	0	4^{g}
F value	< 0.05	< 0.05	< 0.05	< 0.05

* Significant at 0.05 level; values with the same superscripts do not differ significantly

Table 11. Dry standing biomass from silvopasture and monoculture systems.

Treatments	Fractional and total dry standing biomass (Mg ha^{-1})			
	Hybrid napier	Mulberry	Stylosanthus	Total
T1	6.13^{b}	4.36^{c}	$.350^{c}$	11^{c}
T2	6.13^{b}	9^{b}	0	15^{b}
T3	6.138^{b}	0	$.700^{b}$	7^{e}
T4	10.23^{a}	0	0	10.23^{d}
T5	0	22^{a}	0	22^{a}
T6	0	0	2^{a}	2
T7	0	0	0	1.55^{g}
F value	< 0.05	< 0.05	< 0.05	< 0.05

* Significant at 0.05 level; values with the same superscripts do not differ significantly

4.3 Root biomass

4.3.1 Fresh root biomass

Table 13 shows the fresh root biomass from silvopasture and monoculture systems. Similar to standing biomass trend, the maximum fresh root weight was recorded in mulberry monoculture (68 Mg ha^{-1}) followed by 2 tier HN+ mulberry system (30.09 Mg ha^{-1}). The lowest root weight was recorded in open plot (4 Mg ha^{-1}). The stylosanthus and hybrid napier monoculture recorded root biomass of 7 and 5.05 Mg ha^{-1} respectively. The three tier system recorded 18 Mg $ha^{-1}$of fresh root weight. The 2-tier system (hybrid napier+stylosanthus) recorded 6 Mg ha^{-1} of fresh root weight.

4.3.2 Dry root biomass

Table 14 depicts the dry root biomass from silvopasture and monoculture systems. The maximum dry root weight was recorded in mulberry monoculture (28 Mg ha^{-1}) followed by 2 tier HN + mulberry system (12.07 Mg ha^{-1}), while the lowest dry root weight was recorded in control open plot and hybrid napier monoculture (2 Mg ha^{-1}) and they were on par. The stylosanthus monoculture recorded 3 Mg ha^{-1} standing dry root weight. The 2-tier system (hybrid napier+stylosanthus) recorded 2.13 Mg ha^{-1} of dry root weight. The three tier system recorded 7.102 Mg ha^{-1} of dry root weight.

4.3.3 Carbon content in root biomass

Table 15 reveals the carbon content in dry root biomass from silvopasture and monoculture systems. The maximum carbon in root was recorded in mulberry monoculture (26 Mg ha^{-1}), followed by 2-tier system HN+ mulberry (11.32 Mg ha^{-1}). The lowest root carbon was recorded in open plot and hybrid napier monoculture (2 Mg ha^{-1}) and they were on par. The stylosanthus monoculture recorded 3 Mg $ha^{-1}$of carbon. The two tier system (hybrid napier+ stylosanthus) recorded 2.02 Mg ha^{-1} of carbon in root. The 3-tier system recorded 7 Mg ha^{-1} of carbon.

Table 12. Total carbon in dry standing biomass from silvopasture and monoculture systems.

Treatments	Fractional and total carbon in dry standing biomass (Mg ha^{-1})			
	Hybrid napier	Mulberry	Stylosanthus	Total
T1	6^{b}	4.18^{c}	$.332^{c}$	10.16^{c}
T2	6^{b}	8.37^{b}	0	14.019^{b}
T3	6^{b}	0	$.7^{b}$	6.31^{e}
T4	9.41^{a}	0	0	9.41^{d}
T5	0	21^{a}	0	21^{a}
T6	0	0	2^{a}	2^{f}
T7	0	0	0	1.48^{g}
F value	< 0.05	< 0.05	< 0.05	< 0.05

* Significant at 0.05 level; values with the same superscripts do not differ significantly

Table 13. Fresh root biomass from silvopasture and monoculture systems.

Treatments	Fractional and total fresh root biomass (Mg ha^{-1})			
	Hybrid napier	Mulberry	Stylosanthus	Total
T1	3.03^{b}	14^{c}	1.32^{c}	18^{c}
T2	3.03^{b}	27.06^{b}	0	30.09^{b}
T3	3.03^{b}	0	3^{b}	6^{d}
T4	5.05^{a}	0	0	5.05^{de}
T5	0	68^{a}	0	68^{a}
T6	0	0	7^{a}	7^{d}
T7	0	0	0	4^{e}
F value	< 0.05	< 0.05	< 0.05	< 0.05

* Significant at 0.05 level; values with the same superscripts do not differ significantly

Table 14. Dry root biomass from silvopasture and monoculture systems.

Treatments	Fractional and total dry root biomass (Mg ha^{-1})			
	Hybrid napier	Mulberry	Stylosanthus	Total
T1	1.06^{b}	.6^{c}	.6^{c}	7.10^{c}
T2	1.06^{b}	11.00^{b}	0	12.07^{b}
T3	1.06^{b}	0	1.06^{b}	2.13^{de}
T4	2^{a}	0	0	2^{e}
T5	0	28^{a}	0	28^{a}
T6	0	0	3^{a}	3^{d}
T7	0	0	0	2^{e}
F value	< 0.05	< 0.05	< 0.05	< 0.05

* Significant at 0.05 level; values with the same superscripts do not differ significantly

Table 15.Carbon content in dry root from silvopasture and monoculture systems.

Treatments	Total carbon content in dry root (Mg ha^{-1})			
	Hybrid napier	Mulberry	Stylosanthus	Total
T1	1^{b}	5.17^{c}	.6^{c}	7^{c}
T2	1^{b}	10.34^{b}	0	11.32^{b}
T3	1^{b}	0	1.04^{b}	2.02^{de}
T4	2^{a}	0	0	2^{e}
T5	0	26^{a}	0	26^{a}
T6	0	0	3^{a}	3^{d}
T7	0	0	0	2^{e}
F value	< 0.05	< 0.05	< 0.05	< 0.05

* Significant at 0.05 level; values with the same superscripts do not differ significantly

4.4 Soil carbon

4.4.1 Soil carbon content

Table 16 shows the organic carbon in soil at various depths from silvopasture and monoculture systems. Organic carbon was also calculated and compared between field and treeless open control up to 1m soil depth. The top 20 cm depth of the field was found to have comparatively higher values. For both silvopasture and monoculture systems percentage decline in organic carbon was observed with increasing depth. Soils under mulberry monoculture sequestered the maximum carbon throughout the entire profile depth with a mean value of 0.85 per cent and were significantly superior to all other systems. The second best treatment was the 2-tier system (hybrid napier+mulberry) with 0.73 per cent mean soil organic carbon (SOC). The control open system registered comparatively lower SOC than mulberry monoculture and HN +mulberry 2-tier systems, whereas it was comparatively superior to 3-tier and other treeless systems.

4.4.2 Soil carbon stocks

Table 17 shows the carbon stocks in the soil at various depths from silvopasture and monoculture systems. The top 0-20 cm depth was found to sequester maximum amount of carbon and the amount sequestered decreased with increase in depth except at stylosanthus monoculture. Among various treatments mulberry monoculture recorded the highest stocks of carbon at different depths. The total carbon stock (124.59 Mg ha^{-1}) was also highest in mulberry monoculture but was on par with that of controlled open system (124.16 Mg ha^{-1}) under natural vegetation. The second best system was HN+ mulberry 2-tier system which sequestered 107 Mg ha^{-1} of carbon in soil. The least carbon stock was recorded in stylosanthus monoculture (90.72 Mg ha^{-1}).

4.5 Carbon storage potential of various systems

Tables 18 and 19 reveal the total carbon storage potential of various systems. Mulberry monoculture systems captured the maximum (211.23 Mg ha^{-1}) quantity of carbon as compared to others. Out of the total carbon stocks, 39.85 Mg ha^{-1}(18.86 %) of carbon was captured by harvested biomass, which accounted for the labile carbon and 171.38 Mg ha^{-1} (81.13 %) of carbon was stored in above ground standing biomass, root biomass and in soil which accounted for the permanently stored carbon. The next best treatment was 2-tier system of HN and mulberry which captured 177.14 Mg ha^{-1} of carbon, out of which 132.33 Mg ha^{-1} (74.70 %) was permanent and the rest 44.79 Mg ha^{-1} (25.28 %) was labile. The lowest carbon was stored by the open plot (127.27 Mg ha^{-1}). The 3-tier system recorded 156.79 Mg ha^{-1} of carbon, in that 39.83 Mg ha^{-1} (25.40 %) of carbon was labile and 116.95 Mg ha^{-1} (74.59 %) was permanent.

Table 16. Soil carbon in silvopasture and monoculture systems.

Treatments	Soil carbon (%)					
	0-20cm	20-40 cm	40-60cm	60-80 cm	80-100 cm	Mean
T1	0.85^{c}	0.71^{c}	0.67^{c}	0.60^{c}	0.59^{c}	0.68^{d}
T2	0.93^{b}	0.75^{b}	0.72^{b}	0.64^{b}	0.63^{b}	0.73^{b}
T3	0.77^{d}	0.67^{d}	0.62^{d}	0.56^{d}	0.54^{de}	0.63^{f}
T4	0.85^{c}	0.70^{c}	0.62^{d}	0.57^{d}	0.56^{d}	0.66^{e}
T5	1.06^{a}	0.82^{a}	0.87^{a}	0.76^{a}	0.74^{a}	0.85^{a}
T6	0.65^{e}	0.62^{e}	0.63^{d}	0.55^{d}	0.52^{e}	0.60^{g}
T7	1.02^{a}	0.82^{a}	0.73^{b}	0.57^{d}	0.45^{f}	0.71^{c}
F value	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

* Significant at 0.05 level; values with the same superscripts do not differ significantly

Table 17. Soil carbon stocks in silvopasture and monoculture systems

Treatments	Soil carbon stocks (Mg ha^{-1})					
	0-20cm	20-40cm	40-60cm	60-80cm	80-100cm	Total
T1	22.75^{d}	20.71^{d}	20.29^{c}	18.77^{d}	17.59^{c}	100.12^{c}
T2	25.20^{c}	21.93^{c}	21.38^{b}	19.76^{c}	18.73^{b}	107^{b}
T3	20.37^{f}	19.53^{e}	19.12^{d}	17.74^{e}	16.45^{e}	93.21^{e}
T4	22.27^{e}	20.59^{d}	18.48^{e}	17.52^{f}	16.44^{e}	95.30^{d}
T5	29.81^{b}	24^{b}	25.70^{a}	23.01^{a}	22.07^{a}	124.59^{a}
T6	17.45^{g}	18.02^{f}	20.12^{c}	18.05^{d}	17.07^{d}	90.72^{f}
T7	32.97^{a}	26.85^{a}	25.99^{a}	20.98^{b}	17.37^{c}	124.16^{a}
F value	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

* Significant at 0.05 level; values with the same superscripts do not differ significantly

Table 18. Component wise carbon stocks in silvopasture and monoculture systems.

Treatments	Carbon content in various plant components (Mg ha^{-1})			Total Carbon (Mg ha^{-1})		Overall Carbon in various systems (Mg ha^{-1})
	Harvested biomass (labile carbon)	Dry standing biomass	Root biomass	Plant C	Soil C	
T1	39.83^c	10.16^c	6.67^c	56.67^d	100.12^d	156.79^c
T2	44.79^b	14.01^b	11.32^b	70.14^b	107^c	177.14^b
T3	34.6^d	6.31^e	2.02^{de}	42.93^e	93.21^f	136.14^e
T4	48.13^a	9.41^d	1.63^e	59.17^c	95.30^e	154.47^d
T5	39.85^c	20.93^a	25.86^a	86.64^a	124.59^a	211.23^a
T6	13.15^e	1.66^f	2.61^d	17.42^f	90.72^g	108.14^g
T7	0	1.48^g	1.63^e	3.11^g	124.16^b	127.27^f
F value	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

* Significant at 0.05 level; values with the same superscripts do not differ significantly

4.6 Soil fertility status

4.6.1 Soil physical properties

4.6.1.1 Bulk density

Table 20 shows the bulk density of soil at various depths from silvopasture and monoculture systems. The various treatments as well as soil depths significantly influenced the soil bulk density of various systems. In general, bulk density was lower in upper soil horizon (0-20 cm) than deeper layers. Comparing the mean values, the least and comparable bulk density (1.45 g cm^{-3}) was recorded in 2-tier system (hybrid napier+mulberry) and hybrid napier monoculture and they were on par. The open plot showed higher bulk density of mean value 1.75 g cm^{-3} followed by stylosanthus monoculture (1.51 g cm^{-3}). However, for all treatments except open plot and stylosanthus monoculture, there was a slight decrease in bulk density at the depth of 80-100 cm.

4.6.1.2 Soil pH

Table 21 depicts the pH value of soil at various depths in silvopasture and monoculture systems. The top 20-40 cm depth of the soil had comparatively higher p^H values than surface soil and lower depths. General trends showed a favourable improvement in soil pH in tree based systems, with the highest value in mulberry monoculture (7.28) followed by 2-tier HN+mulberry system (6.36). The lowest mean value (5.79) was recorded in open plot. The 3-tier system recorded the intermediate pH value of 6.11. At 0-20cm depth stylosanthus monoculture showed higher pH vaue (6.07) followed by open plot (5.73). The lowest pH value observed in 2-tier system (hybrid napier +mulberry) and hybrid napier monoculture were 5.21 and 5.15 respectively and they were on par.

4.6.1.3 Soil moisture

Table 22 shows the moisture content of soil at various depths in silvopasture and monoculture systems. It could be seen from the data that the soil moisture content was significantly higher in control open plot except 0-20 cm followed by all silvopasture systems. At 0-20 cm depth maximum soil moisture was recorded in stylosanthus monoculture (18.94 %) which was on par with 2-tier HN+ stylosanthus system (18.57 %) followed by hybrid napier monoculture (18.32%). The minimum soil moisture was recorded in mulberry monoculture at all depths except 60-80 cm. Comparing moisture content at different depths, stylosanthus based systems retained more moisture in surface layers, whereas higher moisture was found in sub surface soil in open control plot followed by silvopasture systems.

4.6.1.4 Water holding capacity

Table 23 gives the water holding capacity of soil at various depths from silvopasture and monoculture systems. The overall soil water holding capacity (WHC) was highest in mulberry monoculture (52.82%), followed by 2-tier hybrid napier+mulberry system (49.30%). Mulberry monoculture systems had higher WHC in sub surface layers, whereas in surface layer WHC was higher for stylosanthus (47.34 %), hybrid napier monoculture (47.20%), and 3-tier systems. The lowest mean WHC was observed in control open plot (45.92 %).

4.6.1.5 Soil temperature

Table 24 gives the soil temperature at various depths from silvopasture and monoculture systems. Significant difference was observed at 20-40 cm, 80-100 cm and overall mean values. The maximum mean temperature was observed in mulberry monoculture (32.93^0C) which was at par with 3- tier system, 2-tier system (hybrid napier+mulberry), open plot and stylosanthus monoculture, while the minimum soil temperature was recorded in 2-tier hybrid napier+stylosanthus system (32.04^0C) and hybrid napier monoculture (31.80^0 C) and they were on par.

Table 19. Labile and permanent carbon stocks in various silvopasture and monoculture systems.

Treatments	Overall Carbon stocks in various systems (Mg ha^{-1})	Labile carbon (Mg ha^{-1})	Permanent carbon (Mg ha^{-1})
T1	156.79^{c}	39.83 (25.40 %)	116.95 (74.59 %)
T2	177.14^{b}	44.79 (25.28 %)	132.33 (74.70 %)
T3	136.14^{e}	34.6 (25.41 %)	101.54 (74.58 %)
T4	154.47^{d}	48.13 (31.15 %)	106.34 (68.84 %)
T5	211.23^{a}	39.85 (18.86 %)	171.38 (81.13 %)
T6	108.14^{g}	13.15 (12.16 %)	94.99 (87.83 %)
T7	127.27^{f}	0	127.27 (99.99 %)
F value	<0.05	Not statistically analysed	

* Significant at 0.05 level; values with the same superscripts do not differ significantly

Table 20. Bulk density at various depths in silvopasture and monoculture systems.

Treatments	Bulk density(g cm^{-3})					
	0-20 cm	20-40 cm	40-60 cm	60-80 cm	80-100 cm	Mean
T1	1.33^{cd}	1.45^{b}	1.50^{cd}	1.54^{d}	1.48^{cd}	1.46^{cd}
T2	1.34^{c}	1.46^{b}	1.48^{de}	1.52^{e}	1.47^{de}	1.45^{d}
T3	1.32^{de}	1.45^{b}	1.52^{c}	1.57^{c}	1.49^{c}	1.47^{c}
T4	1.31^{e}	1.46^{b}	1.49^{de}	1.53^{de}	1.46^{e}	1.45^{d}
T5	1.39^{b}	1.46^{b}	1.47^{e}	1.50^{f}	1.47^{de}	1.46^{cd}
T6	1.34^{c}	1.43^{b}	1.57^{b}	1.62^{b}	1.62^{b}	1.51^{b}
T7	1.61^{a}	1.63^{a}	1.78^{a}	1.84^{a}	1.93^{a}	1.75^{a}
F value	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

* Significant at 0.05 level; values with the same superscripts do not differ significantly

Table 21. Soil pH as influenced by different systems and soil depths in silvopasture and monoculture systems.

Treatments	pH of soil at different depths					
	0-20 cm	20-40 cm	40-60 cm	60-80 cm	80-100 cm	Mean
T1	5.36^{d}	7.04^{c}	5.92^{d}	6.08^{c}	6.18^{c}	6.11^{c}
T2	5.21^{e}	7.28^{b}	6.13^{c}	6.53^{b}	6.64^{b}	6.36^{b}
T3	5.52^{c}	6.80^{de}	5.70^{f}	5.63^{de}	5.71^{e}	5.87^{e}
T4	5.15^{e}	6.84^{d}	5.21^{g}	5.73^{d}	5.80^{d}	5.74^{g}
T5	5.30^{d}	7.93^{a}	7.51^{a}	7.75^{a}	7.91^{a}	7.28^{a}
T6	6.07^{a}	6.75^{e}	6.43^{b}	5.48^{f}	5.59^{f}	6.06^{d}
T7	5.73^{b}	6.17^{f}	5.83^{e}	5.55^{ef}	5.66^{ef}	5.79^{f}
F value	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

* Significant at 0.05 level; values with the same superscripts do not differ significantly

Table 22. Soil moisture at different depths in silvopasture and monoculture.

Treatments	Soil moisture at different depths (%)					
	0-20 cm	20-40 cm	40-60 cm	60-80 cm	80-100 cm	Mean
T1	17.85^{c}	17.14^{c}	17.37^{bc}	16.14^{b}	17.85^{bc}	17.27^{bc}
T2	17.13^{d}	17.05^{c}	17.27^{bc}	16.15^{b}	18.40^{ab}	17.20^{bc}
T3	18.57^{ab}	17.23^{bc}	17.46^{bc}	16.13^{b}	17.31^{c}	17.34^{b}
T4	18.32^{bc}	17.91^{b}	17.64^{b}	15.82^{b}	19.03^{a}	17.74^{b}
T5	15.34^{e}	15.77^{d}	16.71^{c}	16.64^{ab}	17.46^{c}	16.38^{d}
T6	18.94^{a}	16.22^{d}	17.20^{bc}	16.60^{ab}	14.73^{d}	16.74^{cd}
T7	17.23^{d}	18.90^{a}	19.59^{a}	17.20^{a}	18.95^{a}	18.37^{a}
F value	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

* Significant at 0.05 level; values with the same superscripts do not differ significantly

Table 23. Water holding capacity of soil at different depths in silvopasture and monoculture systems.

Treatments	Water holding capacity of soil at different depths (%)					
	0-20cm	20-40cm	40-60cm	60-80cm	80-100cm	Mean
T1	46.99^{abc}	47.28^{c}	49.51^{c}	50.19^{bc}	46.16^{c}	48.02^{c}
T2	46.73^{abc}	48.54^{b}	50.21^{b}	50.57^{b}	50.45^{b}	49.30^{b}
T3	47.25^{ab}	46.01^{d}	48.81^{d}	49.81^{c}	41.87^{e}	46.75^{de}
T4	47.20^{ab}	45.93^{d}	47.65^{e}	49.25^{d}	44.75^{d}	46.95^{d}
T5	46.04^{bc}	52.46^{a}	54.04^{a}	52.55^{a}	59.00^{a}	52.82^{a}
T6	47.34^{a}	46.13^{d}	50.54^{b}	50.65^{b}	37.55^{f}	46.44^{ef}
T7	45.92^{c}	47.04^{cd}	45.90^{f}	49.85^{c}	42.55^{e}	46.25^{f}
F value	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

* Significant at 0.05 level; values with the same superscripts do not differ significantly

Table 24. Soil temperature at different depths in silvopasture and monoculture systems.

Treatments	Soil temperature at different depths (^{0}C)					
	0-20cm	20-40cm	40-60cm	60-80cm	80-100cm	Mean
T1	32.73	31.60^{ab}	31.93	32.13	32.33^{ab}	32.14^{ab}
T2	32.60	32.20^{ab}	32.00	32.40	32.06^{b}	32.25^{ab}
T3	32.86	31.00^{ab}	31.86	31.86	32.60^{ab}	32.04^{b}
T4	32.33	31.66^{ab}	31.33	32.00	31.66^{b}	31.80^{b}
T5	33.00	33.00^{a}	33.00	33.00	32.66^{ab}	32.93^{a}
T6	33.66	30.00^{b}	32.66	31.66	34.00^{a}	32.40^{ab}
T7	32.33	32.33^{a}	32.00	32.00	33.00^{ab}	32.33^{ab}
F value	ns	<0.05	ns	ns	<0.05	<0.05

* Significant at 0.05 level; ns non significant; values with the same superscripts do not differ significantly

4.6.2 Soil nutrient status

4.6.2.1 Total and available nitrogen content in soil

The various systems as well as soil depths significantly influenced the total nitrogen (Table 25) content in soil. Leguminous stylosanthus had a marked effect on total nitrogen pool. The stylosanthus monoculture system (573.98 kg ha^{-1}) recorded the highest total nitrogen content in soil and was comparable with all other systems except HN monoculture. Comparing various soil depths, it was observed that the total nitrogen declined with depth in all systems except those with stylosanthus, where in higher nitrogen accumulation was observed in sub surface layers. At 20-40 cm depth all silvopasture and monoculture systems were significantly superior to open system. The lowest mean total nitrogen was recorded in open plot (484.67 kg ha^{-1}).

Table 26 gives the available nitrogen content in soil at various depths in silvopasture and monoculture systems. In general, available nitrogen decreased with increase in depth except at 80-100cm depth. Among all treatments, mulberry monoculture recorded the highest mean available nitrogen (364.36 kg ha^{-1}) in all depths followed by 2-tier hybrid napier+mulberry system (254.75 kg ha^{-1}). The hybrid napier monoculture showed the lowest mean available nitrogen content (181.67 kg ha^{-1}). In general tree based systems favourably influenced the available nitrogen content in soil.

4.6.2.2 Total and available phosphorus content in soil

In all treatments except mulberry monoculture, stylosanthus monoculture and open plot, a gradual increase in total phosphorus concentration was noted in 0-60 cm depth and then it declined (table 27). The total phosphorus content at various depth as well as the overall mean was also highest for stylosanthus monoculture (1060.40 kg ha^{-1}), followed by 2-tier hybrid napier+stylosanthus system (937.92 kg ha^{-1}). Comparing the mean values the lowest and comparable total phosphorus was recorded in mulberry monoculture (614.67 kg ha^{-1}).

Table 28 shows the available phosphorus content in soil under various silvopasture and monoculture systems. In general for all systems, a gradual increase in concentration was noted for the initial 2 depths and then declined drastically. At 60-80cm all silvopasture and monoculture system recorded significantly lower P than the open system. The mean available phosphorus was higher in 2-tier HN+ mulberry system (10.52 kg ha^{-1}), followed by 3-tier system (9.31 kg ha^{-1}), while the lowest was observed in mulberry monoculture and open plot of about 2.17 and 1.28 kg ha^{-1} respectively.

4.6.2.3 Total and available potassium content in soil

Table 29 shows the total potassium in soil under various silvopasture and monoculture systems. Total potassium content was significantly higher in control open plot (799.06 kg ha^{-1}) in all depths except 20-60 cm, followed by stylosanthus monoculture. In 20-40 cm depth mulberry monoculture recorded the maximum value (629.71 kg ha^{-1}). The lowest value at 20-40 cm depth was for hybrid napier monoculture (101.63 kg ha^{-1}). At 40-60 cm depth hybrid napier monoculture recorded the maximum value (922.25 kg ha^{-1}) and the lowest value recorded in stylosanthus monoculture (708.93 kg ha^{-1}).The lowest mean total potassium content of 532.23 kg ha^{-1} was recorded in hybrid napier monoculture.

Among all treatments, mulberry monoculture recorded the highest mean available potassium (324.14 kg ha^{-1}) followed by stylosanthus monoculture (table 30). The lowest value of mean available potassium was recorded in 2-tier HN+stylosanthus system (91.64 kg ha^{-1}) and hybrid napier monoculture (82.24 kg ha^{-1}) and they were on par.

Table 25. Total nitrogen content in soil at various depths in silvopasture and monoculture systems.

Treatments	Total nitrogen (kg ha^{-1})					
	0-20 cm	20-40 cm	40-60 cm	60-80 cm	80-100 cm	Mean
T1	625.91^{c}	558.16^{a}	493.25^{b}	565.67^{c}	565.67^{c}	551.6^{ab}
T2	671.97^{b}	558.16^{a}	428.34^{d}	428.34^{e}	428.34^{e}	553.39^{ab}
T3	579.85^{d}	558.16^{a}	558.16^{a}	703.00^{b}	703.00^{b}	555.46^{ab}
T4	558.16^{d}	558.16^{a}	558.16^{a}	558.16^{c}	558.16^{c}	543.64^{b}
T5	842.69^{a}	558.16^{a}	233.62^{e}	233.62^{f}	233.62^{f}	556.71^{ab}
T6	612.40^{c}	558.16^{a}	558.16^{a}	920.26^{a}	920.26^{a}	573.98^{a}
T7	497.25^{e}	497.25^{b}	456.66^{c}	497^{d}	497^{d}	484.67^{c}
F value	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

* Significant at 0.05 level; values with the same superscripts do not differ significantly

Table 26. Available nitrogen content in soil at various depths in silvopasture and monoculture systems.

Treatments	Available nitrogen (kg ha^{-1})					
	0-20 cm	20-40 cm	40-60 cm	60-80 cm	80-100 cm	Mean
T1	264.11^{c}	245.05^{c}	231.53^{c}	169.29^{c}	202.96^{bc}	222.59^{c}
T2	299.95^{b}	293.93^{b}	273.58^{b}	191.10^{b}	215.16^{b}	254.75^{b}
T3	228.26^{de}	196.16^{d}	189.48^{de}	147.48^{d}	190.76^{cd}	190.43^{de}
T4	212.30^{e}	194.48^{d}	175.28^{e}	147.06^{d}	179.23^{d}	181.67^{e}
T5	431.43^{a}	443.11^{a}	421.04^{a}	257.15^{a}	269.06^{a}	364.36^{a}
T6	252.19^{cd}	198.68^{d}	210.78^{cd}	148.11^{d}	208.06^{b}	203.56^{cd}
T7	236.10^{cde}	234.52^{c}	214.02^{c}	157.93^{cd}	180.19^{d}	204.55^{cd}
F value	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

* Significant at 0.05 level; values with the same superscripts do not differ significantly

Table 27. Total phosphorus content in soil at various depths in silvopasture and monoculture systems.

Treatments	Total phosphorus (kg ha^{-1})					
	0-20 cm	20-40 cm	40-60 cm	60-80 cm	80-100 cm	Mean
T1	635.33^{c}	893.20^{c}	966.13^{b}	747.06^{c}	1002.1^{ab}	848.77^{c}
T2	532.80^{d}	826.93^{c}	880.13^{c}	622.66^{d}	935.62^{b}	759.63^{d}
T3	737.86^{b}	959.46^{b}	1052.1^{ab}	871.46^{b}	1068.66^{a}	937.92^{b}
T4	517.33^{d}	886.66^{c}	1068.66^{a}	740.00^{c}	1068.66^{a}	856.26^{c}
T5	556.00^{d}	737.33^{d}	597.33^{d}	446.66^{e}	736.05^{c}	614.67^{e}
T6	1068.66^{a}	1068.66^{a}	1027.3^{ab}	1068.66^{a}	1068.66^{a}	1060.40^{a}
T7	1068.66^{a}	546.00^{e}	1068.66^{a}	599.00^{d}	740.000^{c}	804.46^{cd}
F value	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

* Significant at 0.05 level; values with the same superscripts do not differ significantly

Table 28. Available phosphorus in soil at various depths from silvopasture and monoculture systems.

Treatments	Available phosphorus (kg ha^{-1})					
	0-20 cm	20-40 cm	40-60 cm	60-80 cm	80-100 cm	Mean
T1	7.86^{c}	19.23^{a}	15.63^{b}	2.13^{b}	1.71^{b}	9.31^{b}
T2	1.61^{d}	19.24^{a}	15.83^{b}	2.13^{b}	1.71^{b}	8.10^{c}
T3	14.11^{b}	19.21^{a}	15.44^{b}	2.13^{b}	1.71^{b}	10.52^{a}
T4	1.07^{d}	1.07^{c}	24.33^{a}	2.14^{b}	2.14^{a}	6.15^{d}
T5	2.43^{d}	2.18^{b}	3.08^{c}	2.11^{b}	1.07^{c}	2.17^{e}
T6	33.66^{a}	2.11^{b}	2.11^{c}	2.11^{b}	1.07^{c}	8.21^{c}
T7	1.07^{d}	2.11^{b}	1.07^{c}	1.07^{a}	1.08^{c}	1.28^{e}
F value	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

* Significant at 0.05 level; values with the same superscripts do not differ significantly

Table 29. Total potassium in soil at various depths from silvopasture and monoculture systems.

Treatments	Total potassium in soil (kg ha^{-1})					
	0-20 cm	20-40 cm	40-60 cm	60-80 cm	80-100 cm	Mean
T1	559.45^{bc}	307.81^{c}	816.6^{cd}	445.42^{e}	753.98^{c}	576.67^{cd}
T2	539.58^{c}	312.86^{c}	796.45^{d}	411.07^{f}	740.39^{c}	560.07^{d}
T3	579.32^{bc}	302.76^{e}	836.92^{c}	479.78^{d}	767.58^{c}	593.27^{c}
T4	572.44^{bc}	101.63^{d}	922.25^{a}	336.96^{g}	727.89^{c}	532.23^{e}
T5	490.30^{d}	629.71^{a}	607.76^{f}	522.23^{c}	759.14^{c}	601.83^{c}
T6	589.65^{b}	604.46^{b}	708.93^{e}	694.00^{b}	827.11^{b}	684.83^{b}
T7	662.81^{a}	604.76^{b}	872.19^{b}	828.80^{a}	1026.75^{a}	799.06^{a}
F value	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

* Significant at 0.05 level; values with the same superscripts do not differ significantly

Table 30. Available potassium in soil at various depths from silvopasture and monoculture systems.

Treatments	Available potassium (kg ha^{-1})					
	0-20 cm	20-40 cm	40-60 cm	60-80 cm	80-100 cm	Mean
T1	101.02^{bc}	99.03^{d}	110.99^{d}	158.40^{c}	207.16^{c}	135.32^{c}
T2	109.78^{bc}	121.91^{c}	140.33^{b}	206.19^{b}	316.81^{b}	179.00^{b}
T3	92.26^{c}	76.15^{e}	81.65^{f}	110.62^{e}	97.52^{f}	91.64^{e}
T4	87.41^{c}	59.29^{f}	70.85^{g}	101.42^{e}	92.24^{f}	82.24^{e}
T5	143.33^{a}	215.86^{a}	244.56^{a}	363.33^{a}	653.66^{a}	324.14^{a}
T6	99.52^{bc}	101.45^{d}	97.85^{e}	124.41^{d}	105.43^{e}	105.73^{d}
T7	129.92^{ab}	171.36^{b}	130.24^{c}	150.51^{c}	154.26^{d}	147.26^{c}
F value	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

* Significant at 0.05 level; values with the same superscripts do not differ significantly

DISCUSSION

CHAPTER 5

DISCUSSION

Carbon storage potential and soil fertility status of various intensive silvopasture and fodder monoculture systems were explored and the observations are discussed hereunder.

5.1 Harvested biomass

Fig. 3 depicts the harvested fresh and dry fodder biomass from various fodder production systems. In both the years, hybrid napier monoculture recorded the maximum harvested fresh fodder yield with total of 384.11 Mg ha^{-1}(fig. 4) and was significantly superior to silvopasture and other monoculture systems. Owing to clear superiority in green yields, overall dry matter yield was also significantly higher from HN monoculture plots (51.20 Mg ha^{-1}) (fig. 5 and 6). The rapid establishment of HN within a period of 75 days, vigorous growth and tillering, shorter cutting interval of 35 days and 6 to 8 annual prunings resulted in significantly higher annual fresh fodder yields and dry matter production from grass monoculture plots. Among various fodder groups hybrid napier CO 4 had the highest yield potential, and productivity can be maintained throughout the year with good fertilization and irrigation and is an ideal fodder for intensive cultivation as cut and carry forage for all stall feeder systems. Its popularity owing to high yield and palatability as also adaptability to varying soil and climatic conditions has already been confirmed and is widely cultivated across India, Africa, Srilanka, and South East Asian countries (Vijayakumar *et al.,* 2009). Several authors reported that hybrid napier grass has been the most promising and high yielding fodder giving dry matter yields that surpasses most tropical grasses (Anindo and Potter, 1994; Humphreys, 1994; Skerman and Riveros, 1990).

The second best system with respect to fresh (290.41 Mg ha^{-1}) and dry fodder yield (48 Mg ha^{-1}) was 2-tier system (HN+Mulberry). An important point to be noted is that eventhough, HN monoculture system recorded an increment of 32% fresh fodder over grass- mulberry 2-tier systems, the dry fodder increment was found to be only 6% which could be attributed to the higher dry matter content in mulberry as compared to HN as depicted in fig. 6. Hence inclusion of tree fodders has a definite advantage in enhancing the dry matter content of forage which is positively related to fodder quality and milk production.

Data also revealed that 2-tier HN+ mulberry was significantly superior to 3-tier silvopasture systems with grass+ trees + legume, which could be attributed to the lower yield of herbaceous/shrub legume fodder than grasses and trees. The data on fractional yield obtained from different fodder groups showed the trends of fresh fodder yield in the order HN> Mulberry> Stylosanthus. The yield of stylosanthus was only half that of mulberry. The growth pattern of various crops over two year period revealed that trees required care during the establishment phase and once it is established the yield increase over the passage of time. When compared to fodder trees, herbaceous/shrub legumes require more care and frequent weeding during the establishment phase and after each harvest increasing the production cost. However, herbaceous legumes require more careful tending throughout the crop growing period and yield decline for subsequent cutting over years. Moreover, legumes were easily dominated by companion weeds. Hence, trees have good establishment, persistence and sustainable production which resulted in higher yield in grass-trees system as compared to 3-tier systems. Hence this study had shown that tree species like mulberry, had greater potential to produce good quality forage for livestock than herbaceous species in humid tropical regions of Kerala and supported the findings of Adjolohoun *et al.*, (2008) and Jones and Jones (1982) in subtropical coastal Queensland. All other systems produced relatively lower yields with the lowest producton from stylosanthus monoculture.

5.1.1 Carbon content in harvested biomass

Following the yield trends, the carbon stock was also significantly higher (48.13 Mg ha^{-1}) in hybrid napier monoculture followed by 2-tier HN+mulberry system (45 Mg ha^{-1}) (fig. 8). This was due to higher harvested fresh fodder and dry matter yield coupled with high carbon content in HN (94 per cent dry basis) and mulberry (average 93 per cent, dry basis) (fig. 10). All other systems recorded relatively lower carbon stocks owing to the lower fresh and dry matter yields. Lowest carbon capture was found in stylosanthus monoculture (fig. 9) owing to lower biomass production. Hybrid napier sequestered carbon higher than hedge lucerne, fodder cowpea and fodder maize (Meenakshi *et al.*, 2012).

5.2 Standing biomass

In contrast to the harvested fodder yield trends, the maximum standing biomass was obtained from the mulberry monoculture (fresh biomass-51 Mg ha^{-1} and dry biomass-22 Mg ha^{-1}) (Fig. 11 and12). Mulberry was planted at a higher tree density of 11111 trees per hectare and maintained as hedge by leaving a stubble height of 1m, whereas all other crops were harvested close to the ground at height of 15 cm leaving only less standing biomass. Moreover, mulberry stubble constituted of woody biomass with more production per unit area as compared to the herbaceous stem of HN and stylosanthus. All these resulted in higher standing biomass in mulberry. Kadin and Kreil (1990) reported high biomass yield from mulberry at higher cutting height.

The next best treatment was 2-tier HN and mulberry system (fresh biomass, 40.20 Mg ha^{-1} ; dry biomass, 15 Mg ha^{-1}) and was significantly superior to 3-tier silvopasture systems with grass+ trees + legume, which could be attributed to the lower yield of herbaceous/shrub legume fodder than grasses and trees. The lowest standing biomass was recorded in open plot. The treeless open plot contained natural grass vegetation which had a lower standing biomass.

Due to woody stem, dry matter content was also higher in mulberry and it further enhanced the dry standing biomass of mulberry. Dry matter content of standing biomass in various fodder crops ranged from 30-43 per cent with the maximum dry matter in mulberry and was significantly higher than that of HN (31 %) and stylosanthus (fig. 13).

5.2.1 Carbon content in standing biomass

It was revealed from the fig. 14 that the carbon stocks in standing biomass was significantly higher for mulberry monoculture (21 Mg ha^{-1}) followed by 2-tier system (HN+Mulberry) with 14.019 Mg ha^{-1} of carbon. This was due to higher standing biomass production with high dry matter and carbon content in mulberry stem (fig 15). Carbon content of various fodder crops varied from 92-96 per cent with the maximum in mulberry. Research indicates that by adding trees in grassland or pasture systems the soil organic carbon (SOC) content can be increased considerably (Reyes-Reyes *et al.*, 2002; Yelenik *et al.*, 2004, Haile *et al.*, 2008). Tree-based land-use systems have greater potential of soil carbon sequestration than agronomic crops (Post and Mann, 1990). All other systems recorded comparatively lower carbon stocks in standing biomass with the least value from open plot (1.48 Mg ha^{-1}).

5.3 Root biomass

Similar to standing biomass trends, the maximum fresh (68 Mg ha^{-1}) and dry (28 Mg ha^{-1}) root biomass were recorded in mulberry monoculture (fig. 16 and 17). It was observed that on completion of two years, mulberry had well developed and extensive woody root system that penetrated to the depth of beyond 1.2 m. Moreover the dry matter content in mulberry roots was also significantly higher as compared to other fodder groups (fig. 18). Thus the deep woody root of mulberry produced higher root biomass in mulberry monoculture systems, followed by 2-tier hybrid napier + mulberry system (fresh biomass, 30.09 Mg ha^{-1}; dry biomass, 12.072 Mg ha^{-1}) and 3-tier system with mulberry. More biomass results in increased production of aboveground litter and belowground root activity and these make trees an important factor for SOC sequestration (Lemma *et al.*, 2007).

Contrary to the above, HN and stylosanthus monoculture and 2-tier systems produced very low root biomass. As noticed in our study, HN had weak fibrous root system that confined mainly to the top soil to the maximum depth of 40 cm, whereas in the case of stylosanthus most of the original plants died after two years due to frequent pruning and the current vegetation mainly composed of new regenerated seedlings from the seeds of the original plant which resulted in a feeble root system that extended to less than 60 cm. However, the dry matter content was found to be higher in stylosanthus roots as compared to HN. The lowest root biomass was recorded in open plot.

5.3.1 Carbon content in root biomass

Fig. 19 reveals that the carbon stock in root biomass was also significantly higher (26 Mg ha^{-1}) in mulberry monoculture followed by 2-tier HN and mulberry system (11.32 Mg ha^{-1}). This was due to higher fresh and dry root biomass along with high carbon content in mulberry roots (fig. 20). Roots make a significant contribution to SOC (Strand *et al.,* 2008). The lowest carbon stocks were recorded in open plot and HN monoculture.

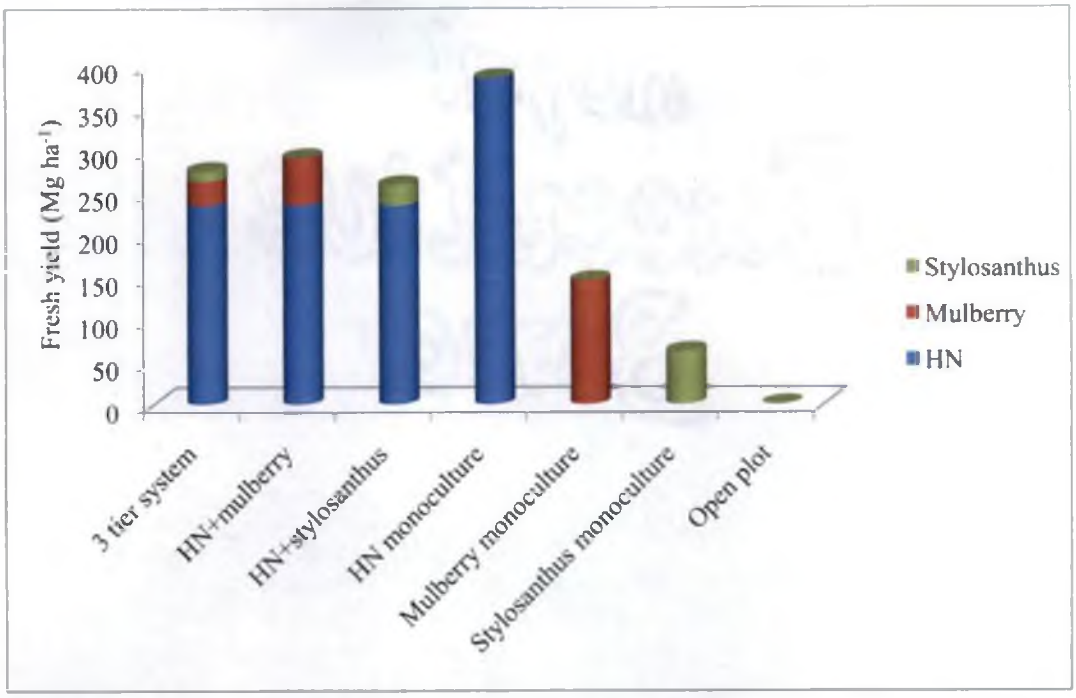

Fig. 3. Fractional fresh fodder yield over two year period from silvopasture and monoculture systems

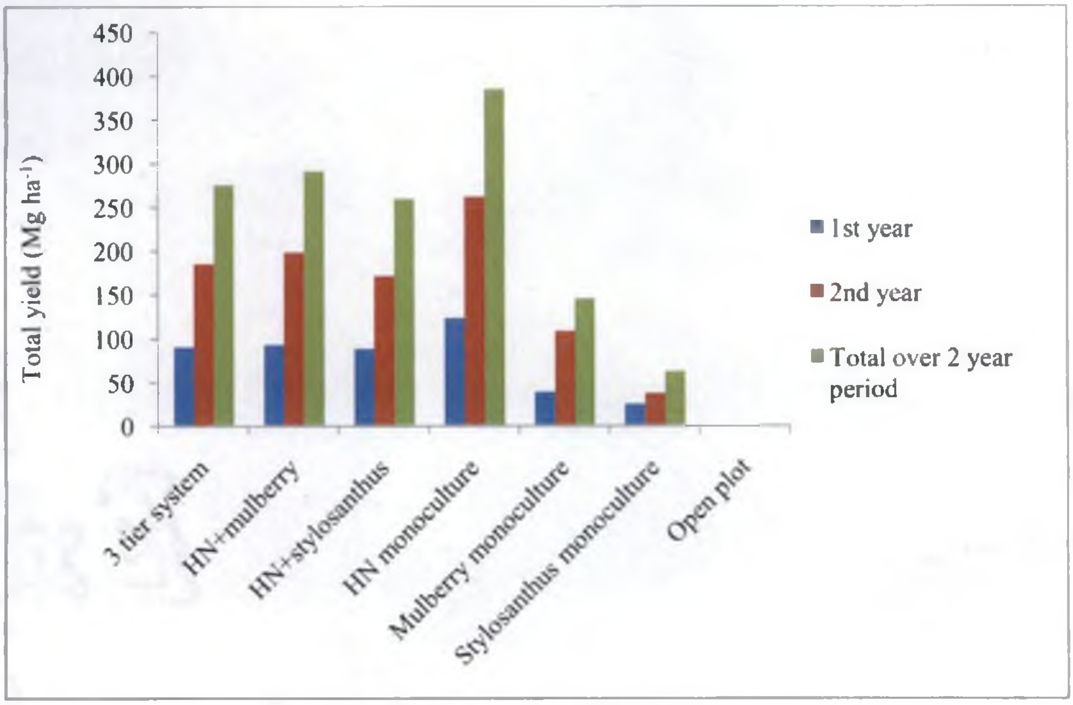

Fig. 4. Total harvested fresh fodder yield over two year period from silvopasture and monoculture systems

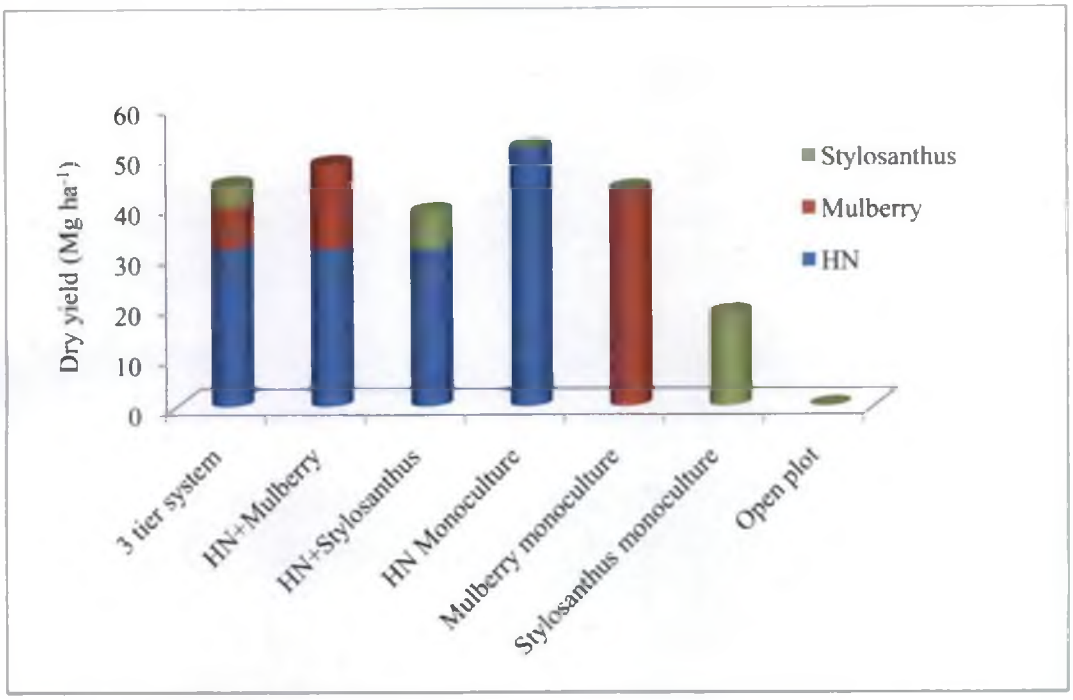

Fig. 5. Fractional dry fodder yield over two year period in silvopasture and monoculture systems

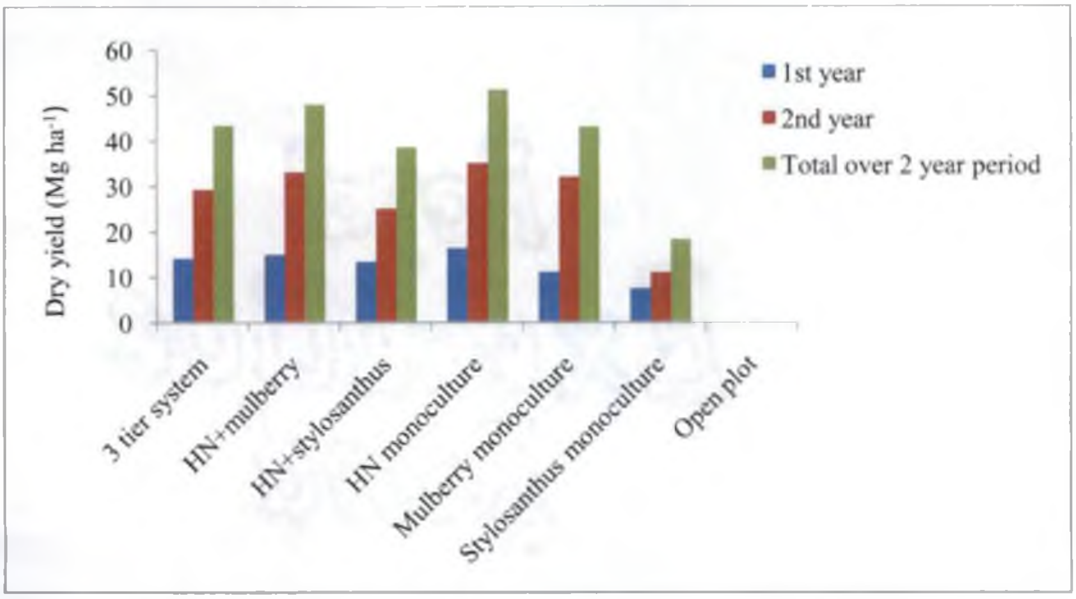

Fig. 6. Total dry fodder yield from various systems over two year period

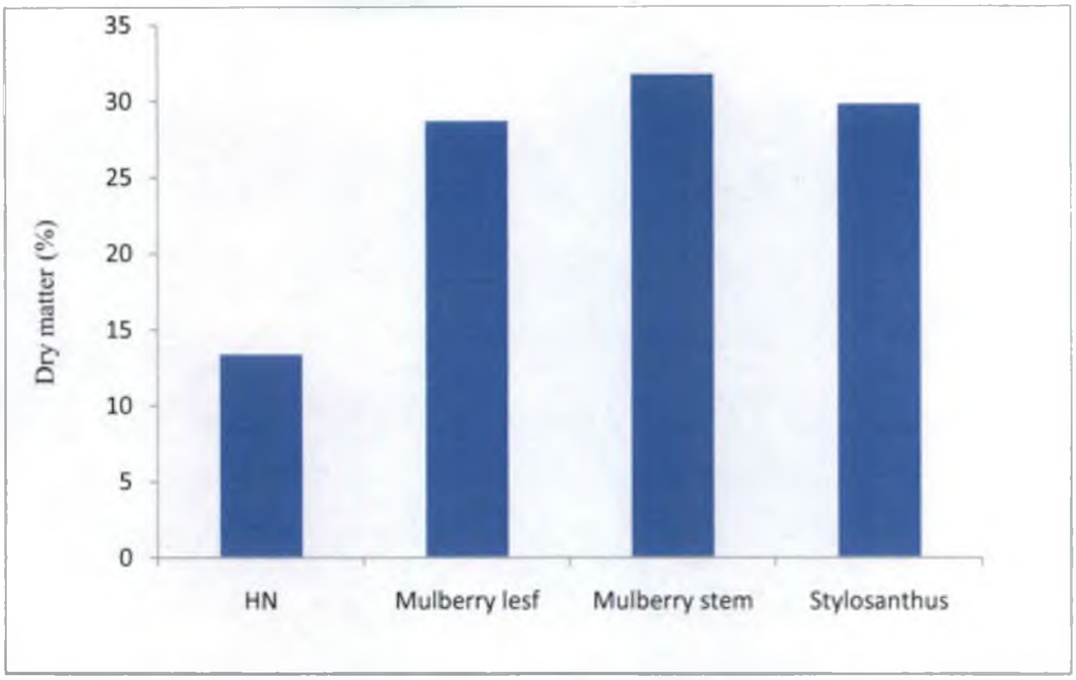

Fig. 7. Dry matter content in various fodder crops

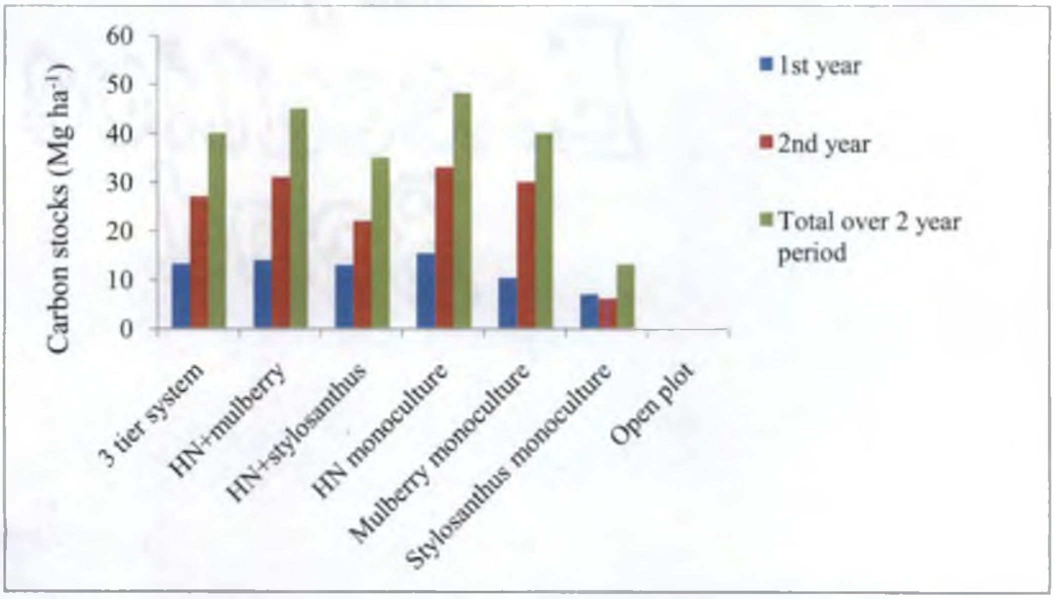

Fig. 8. Total carbon stocks in harvested biomass over two year period in silvopasture and monoculture systems

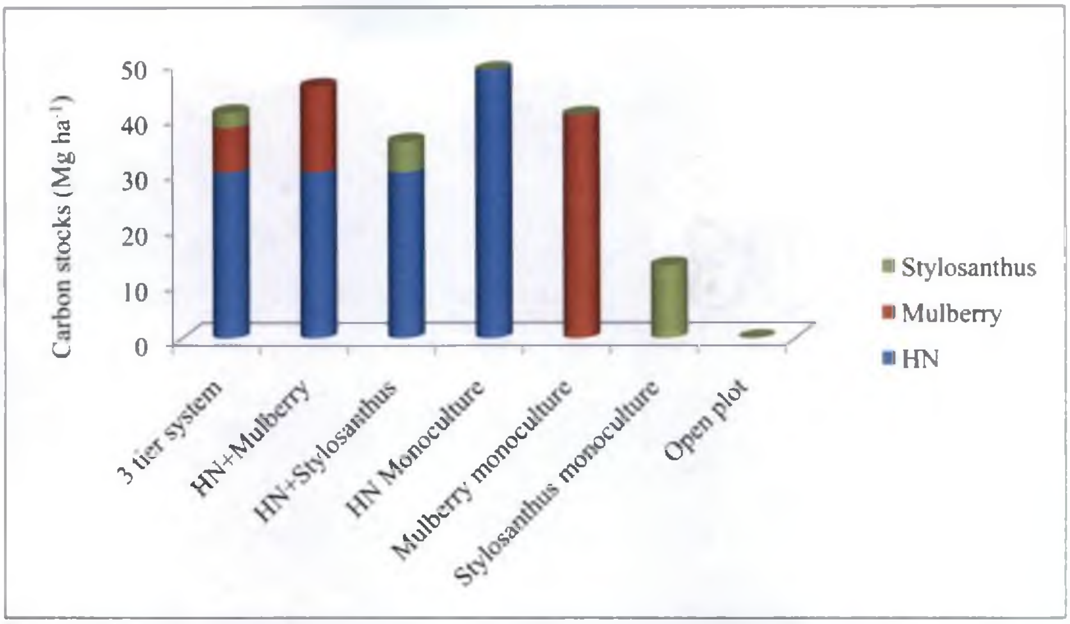

Fig. 9. Fractional carbon stocks over two year period in silvopasture and monoculture systems

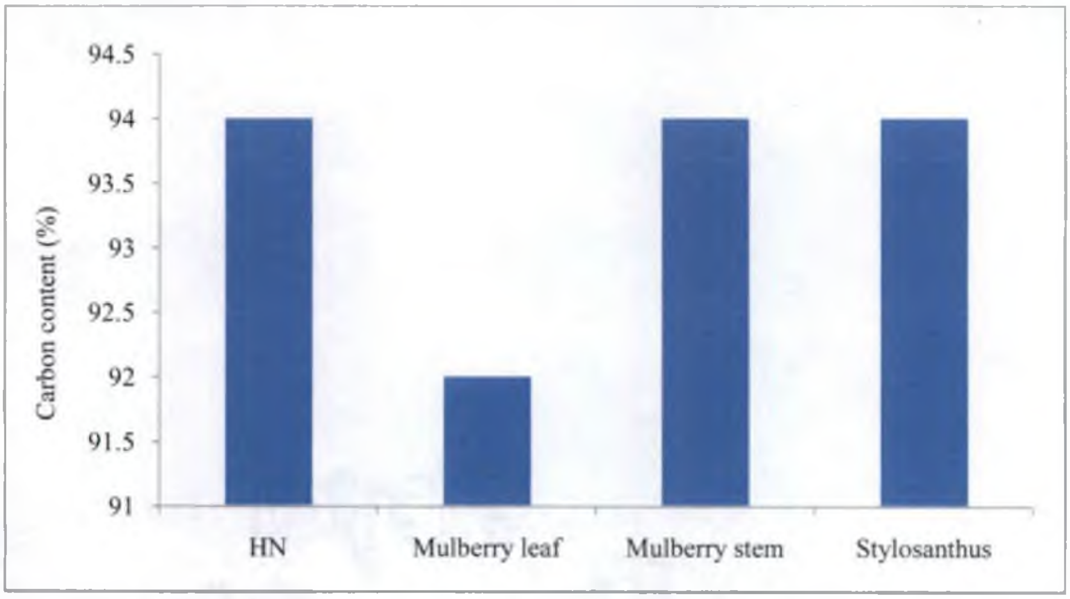

Fig. 10. Carbon content in above ground portion of various fodder crops

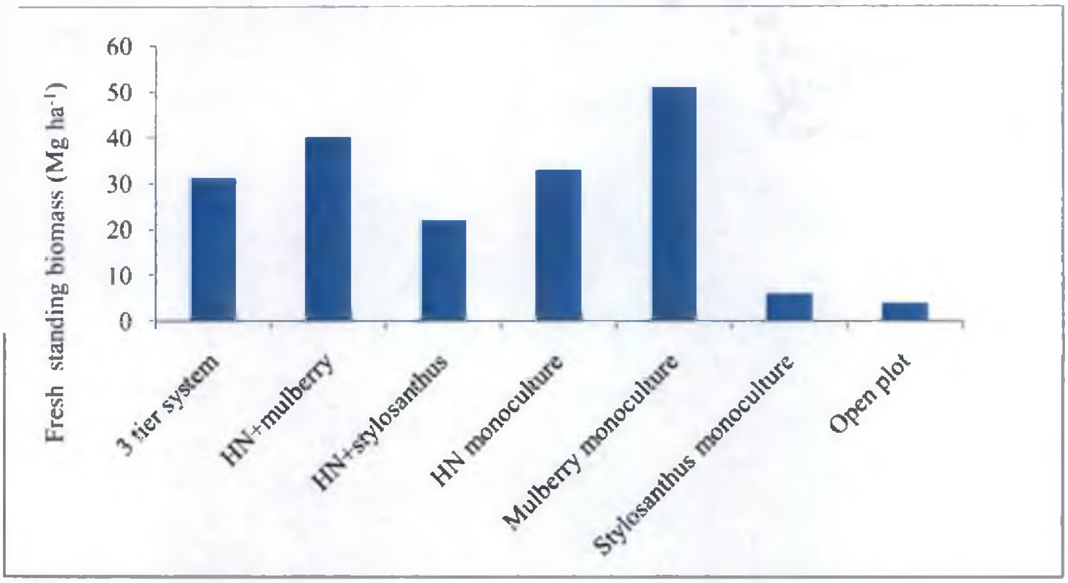

Fig.11. Total fresh standing biomass in silvopasture and monoculture systems

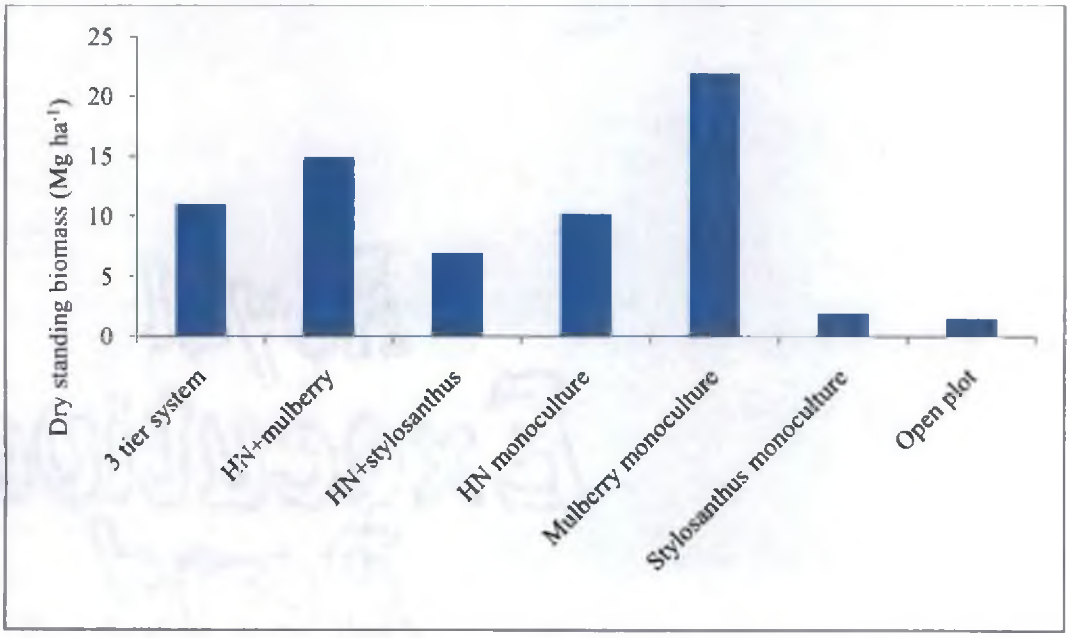

Fig. 12. Total dry standing biomass in silvopasture and monoculture systems

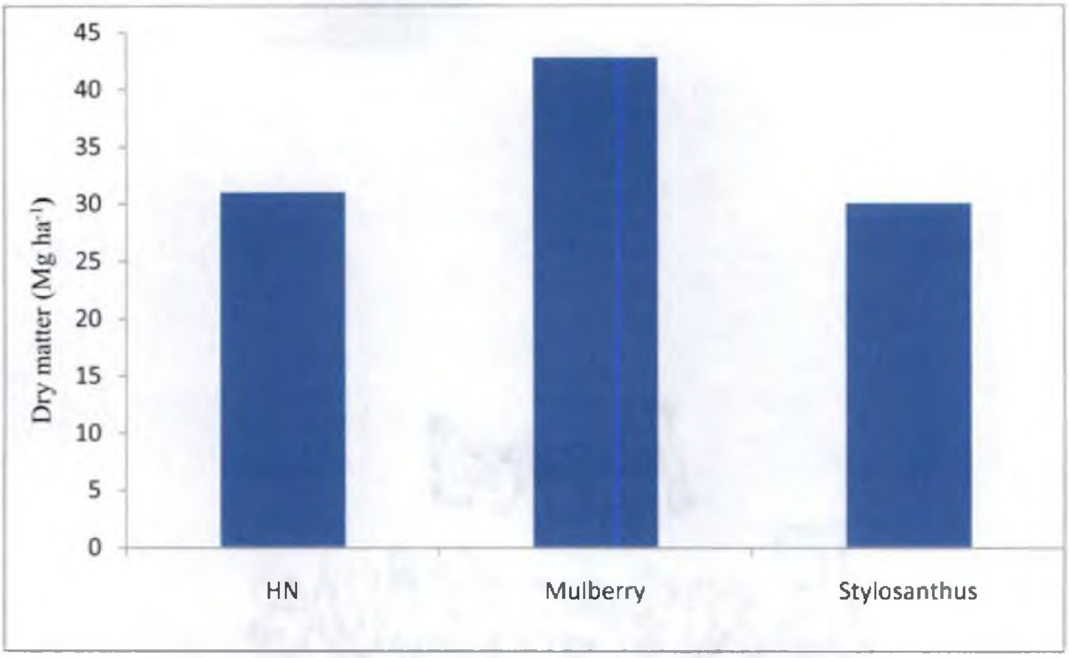

Fig. 13. Dry matter content in standing biomass of various fodder crops

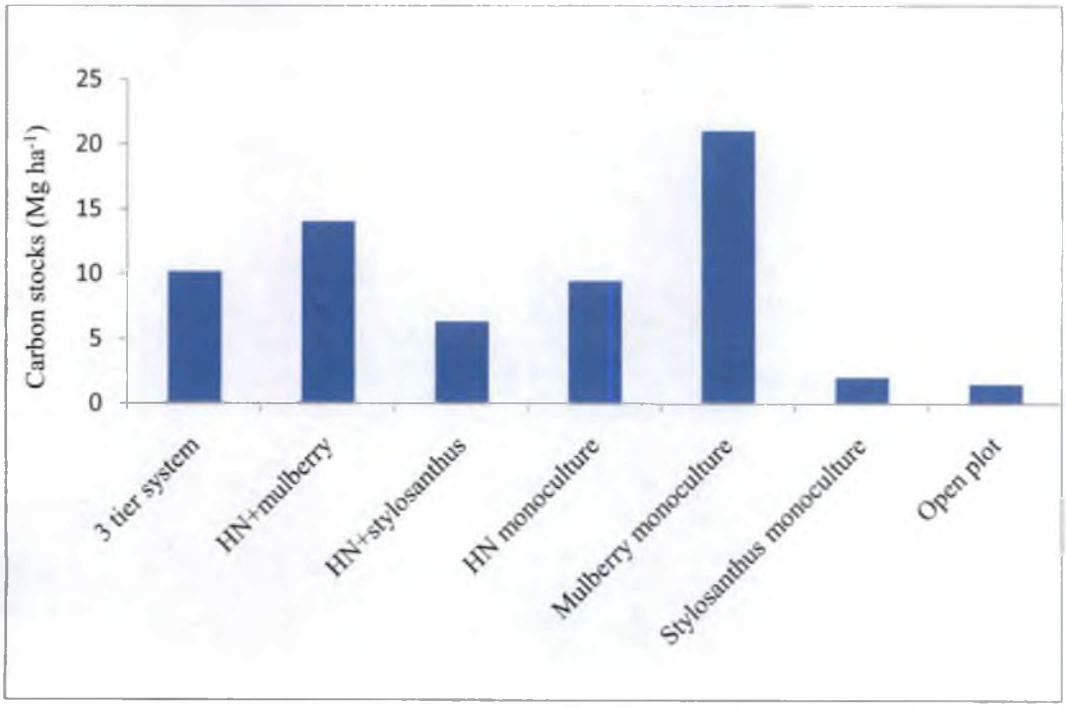

Fig. 14. Carbon stocks in dry standing biomass of silvopasture and monoculture systems

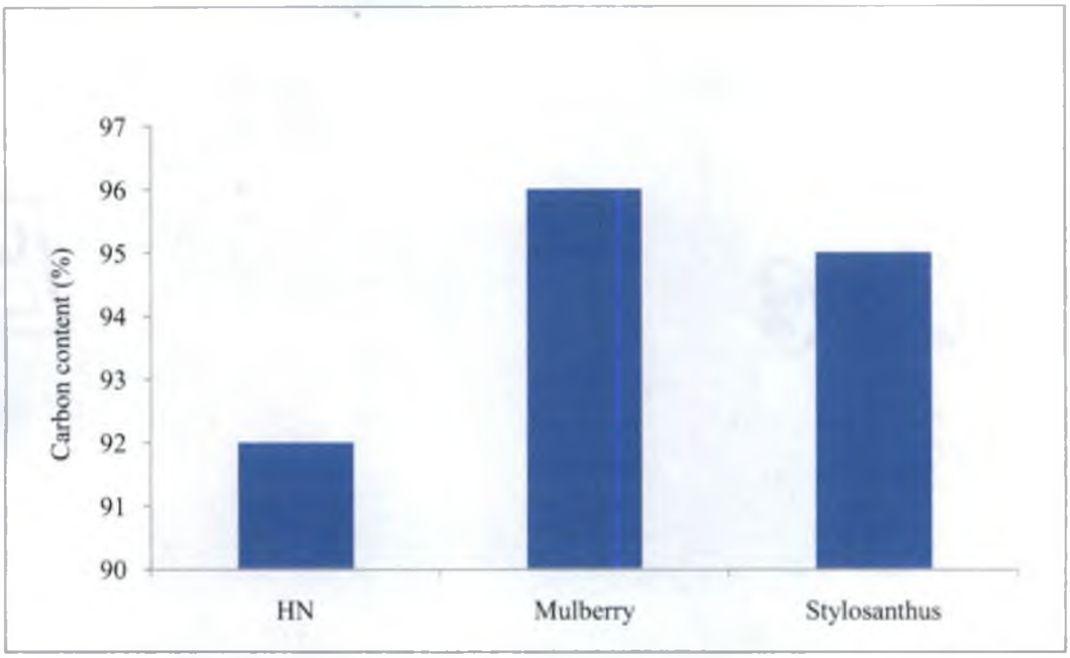

Fig. 15. Carbon content in dry standing biomass of fodder crops

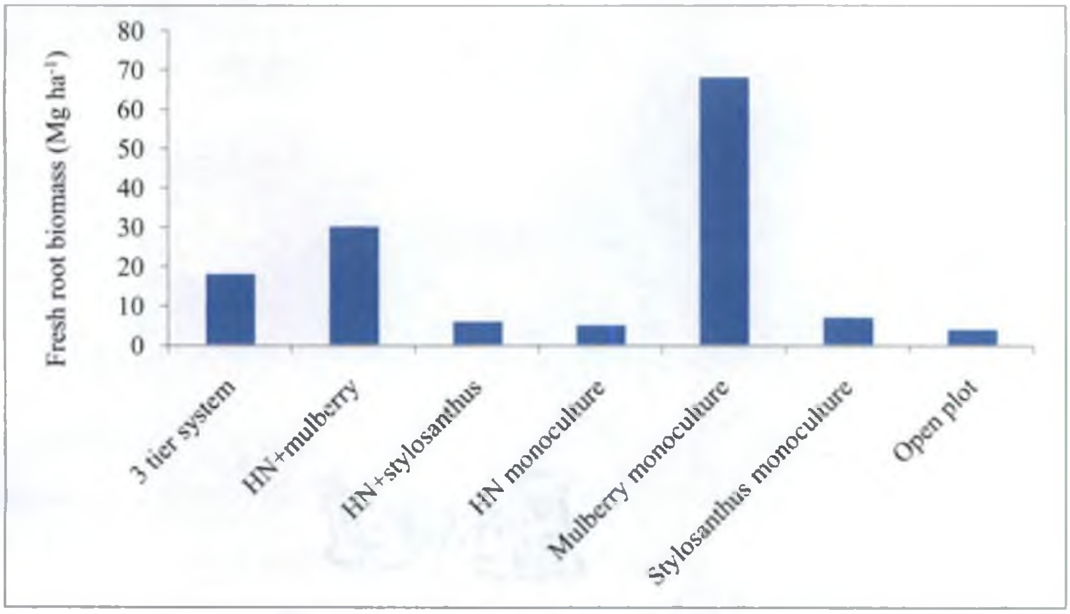

Fig. 16. Total fresh root biomass in silvopasture and monoculture systems

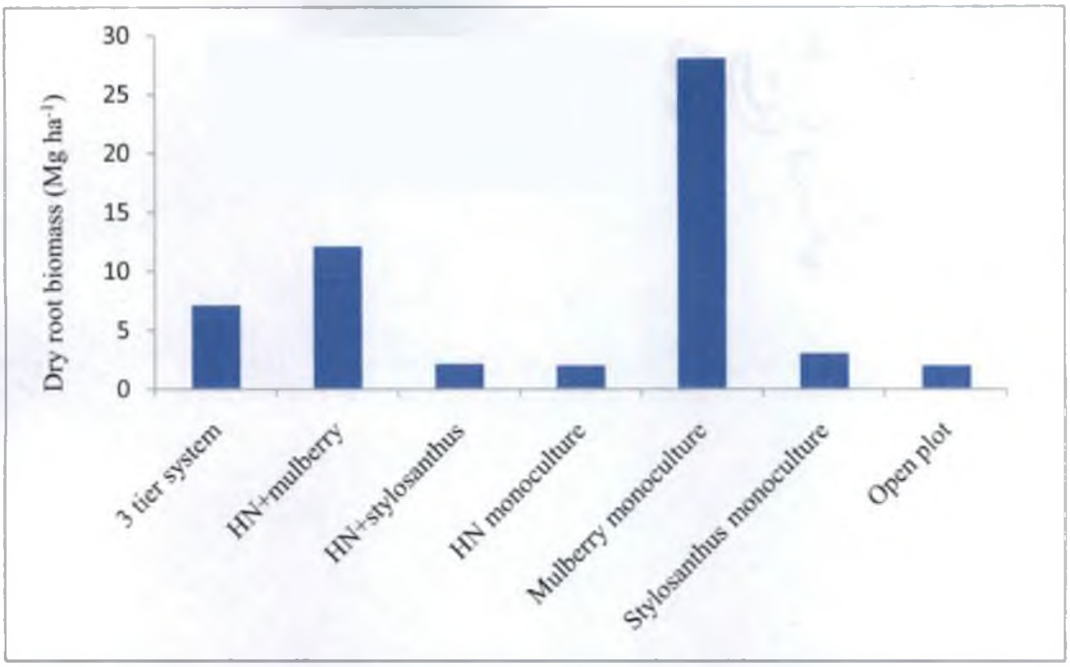

Fig. 17. Total dry root biomass in silvopasture and monoculture systems

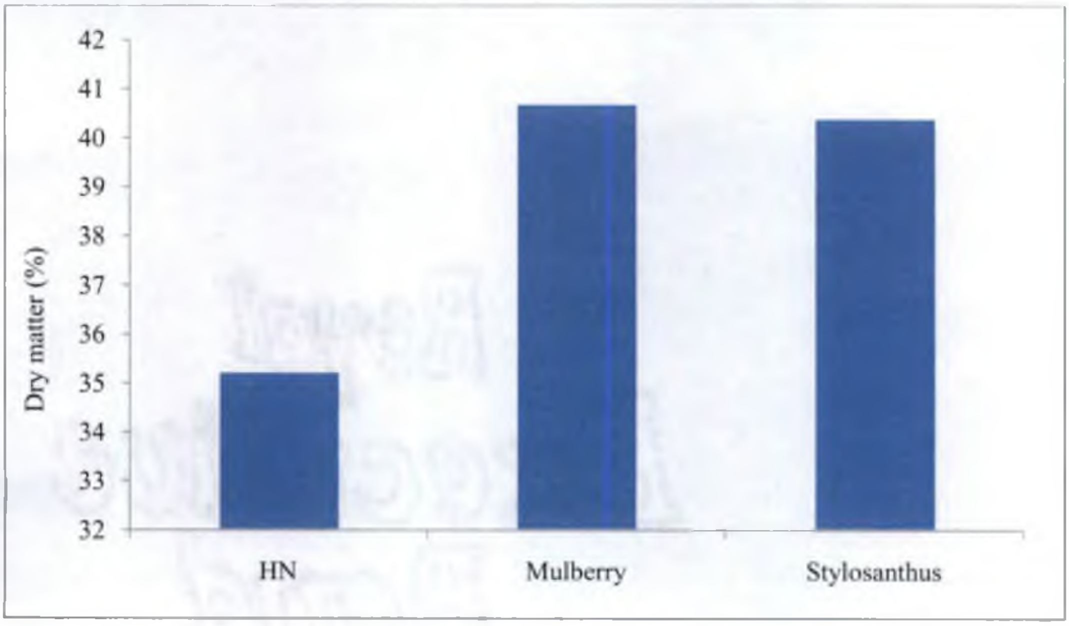

Fig. 18. Root dry matter in different fodder crops

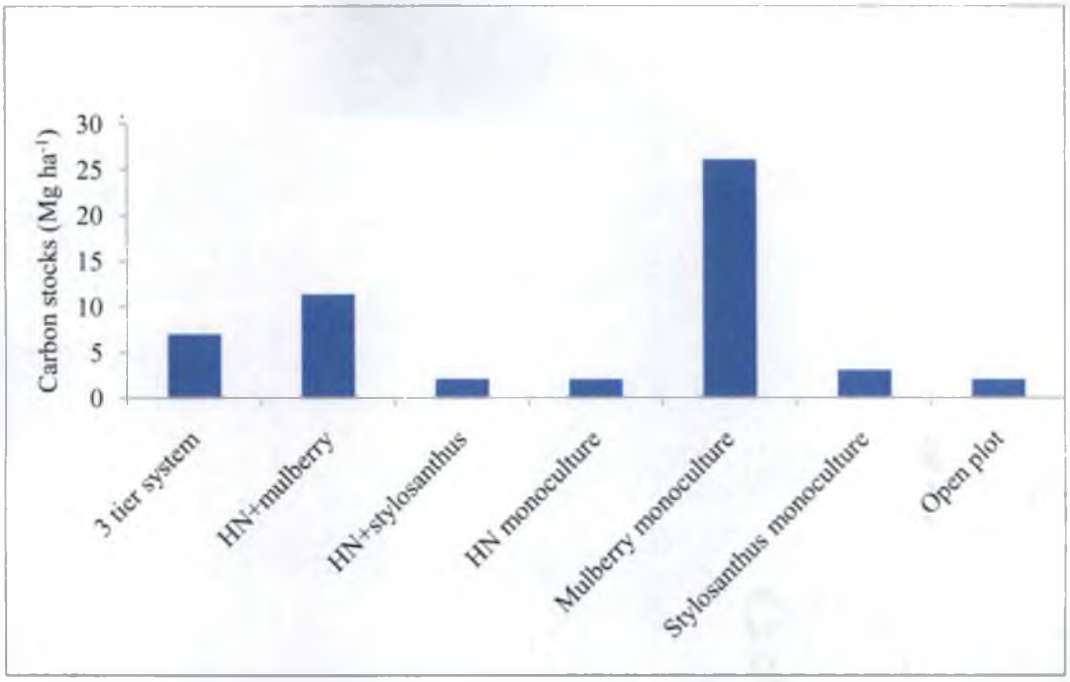

Fig. 19. Carbon stocks in dry root biomass in silvopasture and monoculture Systems

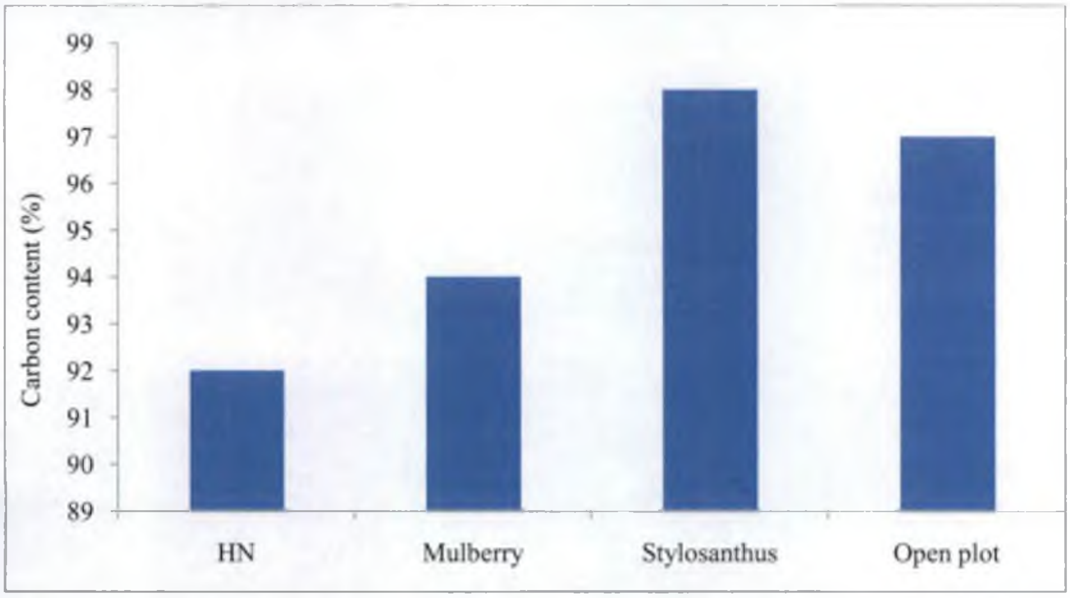

Fig. 20. Root carbon content in different fodder crops

5.4 Soil carbon

5.4.1 Soil carbon content

Soil organic carbon content under various systems and in different profile depths are given in fig. 21. It was observed that for both silvopasture and monoculture systems, the top 20 cm depth of the field were found to have comparatively higher C content than lower depths. This could be due to the recycling of organic matter and higher root concentration and activity in top soil. Soils under mulberry monoculture sequestered the maximum carbon throughout the entire profile depth with a mean value of 0.84 per cent and were significantly superior to all other systems. Accumulation of SOC occurs primarily through the return of plant-fixed C to the soil mainly through leaves and roots (Lal and Kimble 2000; Oelbermann *et al.,* 2006). Litter fall, exerts a profound influence on belowground C sequestration (Jamaludheen and Kumar, 1999). Mulberry was pruned leaving a stubble height of 1m. The litter fall from this portion might have enriched the surface soil carbon content, whereas HN and stylosanthus was cut close to the ground preventing the recycling of leaf litter. Yet another important pathway of enriching the soil C pool is the fine root dynamics. It is well known that trees allocate a large proportion of gross primary production belowground for the production and maintenance of roots and mycorrhizae (Giardina and Ryan, 2002). It was observed that the root biomass from mulberry was substantially higher than that of HN and stylosanthus . Thus the extensive and well developed deep root system of mulberry might have contributed more C throughout the entire profile depth.

The Second best treatment was the 2-tier system (hybrid napier+mulberry) with 0.739 per cent mean SOC. This could be attributed to the presence of mulberry trees which contributed more carbon through litter fall and root dynamics. The control open system registered comparatively lower SOC than mulberry monoculture and HN +mulberry 2-tier systems, whereas it was comparatively superior to 3-tier and other treeless systems. The open system was under natural grass vegetation over a long period of time, resulting in accumulation of C in soil and as the soil was never disturbed, the accumulated carbon remained conserved without decomposition resulting in higher SOC. However in other treeless systems, the carbon content depleted owing to soil manipulation, intensive cultivation, frequent harvest and poor organic matter recycling. The lowest mean soil carbon was recorded in stylosanthus monoculture (0.60%).

5.4.2 Soil carbon stocks

Fig. 22 shows the soil carbon stocks under various systems. Among various systems, mulberry monoculture recorded the highest carbon stocks at different depths. The total carbon stock (124.59 Mg ha^{-1}) was also highest in mulberry monoculture but was on par with that of controlled open system (124.16 Mg ha^{-1}) under natural vegetation. Even though the mulberry monoculture and 2-tier HN+ mulberry systems had significantly higher SOC content than open system, owing to the higher soil bulk density in open systems, the overall carbon stocks in open system was comparable to mulberry monoculture and superior to the 2-tier systems. Tree-based land-use systems have greater soil carbon sequestration potential (CSP) than agronomic crops (Post and Mann, 1990). Trees have the potential of producing larger quantities of aboveground and belowground biomass compared to shrubs or herbs. More biomass results in increased production of aboveground litter and belowground root activity and these make trees an important factor for SOC sequestration (Lemma *et al.*, 2007). The second best system was HN+ mulberry 2-tier system which sequestered 107 Mg ha^{-1} of carbon in soil. Lowest carbon stocks were recorded in stylosanthus monoculture (90.72 Mg ha^{-1}).

Comparing the C stocks in various soil layers, the top 20 cm soil layer sequestered the maximum carbon and the content decreased with increase in depth in general, except for stylosanthus monoculture. In stylosanthus, organic matter recycling to surface soil was negligible due to continuous harvest. Root zone as well as root nodule activity in stylosanthus was concentrated at a depth of 40-60 cm resulting in higher organic carbon content in that zone compared to other layers.

5.5 Carbon storage potential of various systems

Fig. 23 reveals the total carbon stocks in various systems. Mulberry monoculture captured the maximum (211.23 Mg ha^{-1}) quantity of carbon as compared to other systems. Out of the total carbon stocks, 39.85 Mg ha^{-1}(18.86 %) of carbon was captured by harvested biomass, which accounted for the labile carbon and 171.38 Mg ha^{-1} (81.13 %) of carbon was stored in above ground standing biomass, root biomass and in soil which accounted for the permanently stored carbon. Several authors reported that the inclusion of trees in a treeless system changes some functional mechanisms such as total productivity, rooting depth and distribution, and litter quantity and quality (Gill and Burke, 1999; Jackson *et al.,* 2000; Jobbagy and Jackson, 2000). Loreau *et al.* (2002) reported that high tree diversity should reduce temporal instabilities caused by climate change and other disturbances. Production of larger quantities of aboveground and belowground biomass compared to shrubs or herbs makes trees more efficient in promoting soil C sequestration (Brady and Weil, 2007). More biomass results in increased production of aboveground litter and belowground root activity. By adding trees in agricultural systems agroforestry can increase the C storage capacity of the system (Kursten, 2000). Agroforestry is also important in enhancing farmers' adaptive capacity in reducing the vulnerability of agricultural systems to climate change or climate variability (Boye and Albrecht,2005).

The next best treatment was 2-tier system of HN and mulberry which captured 177.14 Mg ha^{-1} of carbon, out of this 132.33 Mg ha^{-1} (74.70 %) was permanent and the rest of 44.79 Mg ha^{-1} (25.28 %) was labile. The lowest carbon stocks were found in open plot (127.27 Mg ha^{-1}), out of which 99.99% was sequestered in soil. The 3-tier system recorded 156.79 Mg ha^{-1} of carbon, in that 39.83 Mg ha^{-1} (25.40 %) of carbon was labile and 116.95 Mg ha^{-1} (74.59 %) was permanent. Eventhough mulberry monoculture captured the maximum carbon (211.23 Mg ha^{-1}), the fodder yields were significantly lower (43 Mg ha^{-1}, dry basis) than 2-tier HN+mulberry system (48 Mg ha^{-1}), which was the second best system with respect to carbon capture (177.14 Mg ha^{-1}). Hybrid napier monoculture out yielded all other systems in fodder production (51.20 Mg ha^{-1}), but carbon storage was comparatively poor (154.47 Mg ha^{-1}) with a large portion as labile carbon. All other systems were inferior in both fodder yields and carbon stocks. Hence, considering the fodder production efficiency and carbon storage capacity, 2-tier HN+mulberry system was found to be the most promising for meeting both farmer needs and environmental services. Moreover, higher protein content in mulberry adds to the quality of the forage, which is an important factor in economic milk production.

5.6 Soil fertility status

Prominent soil parameters like bulk density, pH, total and available nitrogen, total and available phosphorus,total and available potassium and organic carbon of various systems were analysed and compared with that of treeless control plots for evaluating soil fertility changes associated with various systems.

5.6.1 Soil physical properties

5.6.1.1 Bulk density

The various systems as well as soil depths significantly influenced the soil bulk density (fig. 24). In general, bulk density (BD) increased with increase in soil depth. Many reports suggest such increase in bulk density with soil depth (Lemma *et al.,* 2006; Jangra *et al.,* 2010; Singh *et al.,* 2010 and Tumwebaze *et al.,* 2012). The top soil in tropical areas is usually low in bulk density owing to the highly weathered soil, rich in litter and organic matter which turns harder with increasing soil depth. Comparing the mean BD values of the entire profile depth of various systems, the least bulk density (1.45 g cm^{-3}) was recorded in both 2-tier system (hybrid napier+mulberry) and hybrid napier monoculture. The open plot showed higher bulk density of mean value 1.75 g cm^{-3}. Pandey and Pathak (1975) stressed on higher compaction and deflocculation of soil particles (which considerably restricts the capillary pores) to be an important reason for higher values of bulk density in the treeless control site. In the top 0-20 cm depth, the bulk density was lower in HN monoculture plots which could be attributed to the heavy fibrous root system of grass in the top soil which increased the porosity causing a reduction in BD. In 20-40 cm depth, almost all systems recorded comparable and lower bulk densities than open system. However in 40-100cm depth the lowest BD was found in plots with mulberry monoculture and HN+mulberry plots, which could be attributed to the deep rooting pattern of mulberry which improved the porosity and lowered BD at higher depths.

5.6.1.2 Soil pH

Soil pH at different profile depths of various systems are given in fig. 25. In general, pH was comparatively higher at 20-40 cm depth than top and bottom layers. In top soil pH was comparatively higher for stylosanthus monoculture (6.07), whereas all other systems had slightly acidic surface soils with the highest acidity for open plots. In various silvopasture and monoculture systems, mulberry monoculture recorded the highest mean pH value (7.28) followed by 2-tier system (hybrid napier+mulberry) of mean value 6.36. Lowest mean value (5.79) was recorded in open plot. In humid tropical soils, the pH is usually slightly acidic in reaction.

5.6.1.3 Soil moisture

Fig. 26 reveals the soil moisture at different depths. It could be seen that the higher moisture was retained in open plot in all depths except 0-20 cm. This could be due to the reduced transpirational loss of water from the treeless open plot. At 0-20 cm depth maximum soil moisture recorded in stylosanthus monoculture (18.940 %) which was on par with 2-tier system (hybrid napier+stylosanthus) of 18.57 per cent followed by hybrid napier monoculture (18.32%). In stylosanthus plots, the soil was completely covered by the crop which minimized the moisture loss. Similarly, HN grass also completely covered the ground conserving the soil moisture. Stylosanthus species are being grown as an intercrop with food and fodder crops to improve the soil fertility and soil conservation and to provide additional forage (Ramesh *et al.,* 1997). The minimum soil moisture was recorded in mulberry monoculture in all depths except at 60-80 cm which could be attributed to the exposure of surface layers of soil promoting evaporation and moisture loss. The higher evapotranspiration capacity associated with plantation forest and shrub vegetation results in a lower soil moisture content (Chenet *et al.*, 2010).

5.6.1.4 Water holding capacity

The maximum water holding capacity was recorded in mulberry monoculture except at 0-20 cm (fig. 27), which could be due to the better porosity as indicated by the lower bulk density in mulberry plots. At 0-20 cm depth stylosanthus monoculture recorded highest water holding capacity (47.34 %) which was on par with hybrid napier monoculture (47.20%), 2-tier systems, and 3-tier system (hybrid napier+ mulberry+ stylosanthus). The lowest water holding capacity was recorded in open plot (45.92 %). The second best treatment of water holding capacity was recorded in 2-tier hybrid napier+mulberry system (49.30 %). Research has demonstrated that inclusion of trees within agricultural systems can improve water quality (Lowrance, 1992). Water quality benefits of maintaining trees and other vegetation on farms and ranches are realized by reducing runoff, maintaining long-term water cycle, and recharging ground water aquifers (Wu *et al.*, 2001; Stednick, 1996).

5.6.1.5 Soil temperature

Fig. 28 reveals the soil temperature at different soil depths. The significant difference was observed at depths of 20-40 cm, 80-100 cm and overall mean values. The maximum mean temperature was observed in mulberry monoculture (32.93 ^{0}C) which was on par with three tier system, 2-tier system (hybrid napier+ mulberry), open plot and stylosanthus monoculture. Higher temperature in mulberry based systems could be due to the exposure of surface soils to heat and light as the soil was not completely covered .The minimum soil temperature was recorded in 2-tier system (hybrid napier+stylosanthus) and hybrid napier monoculture and they were on par. In HN and stylosanthus as well as open plot,the soil was completely covered and protected from direct heating thereby reducing soil temperature.

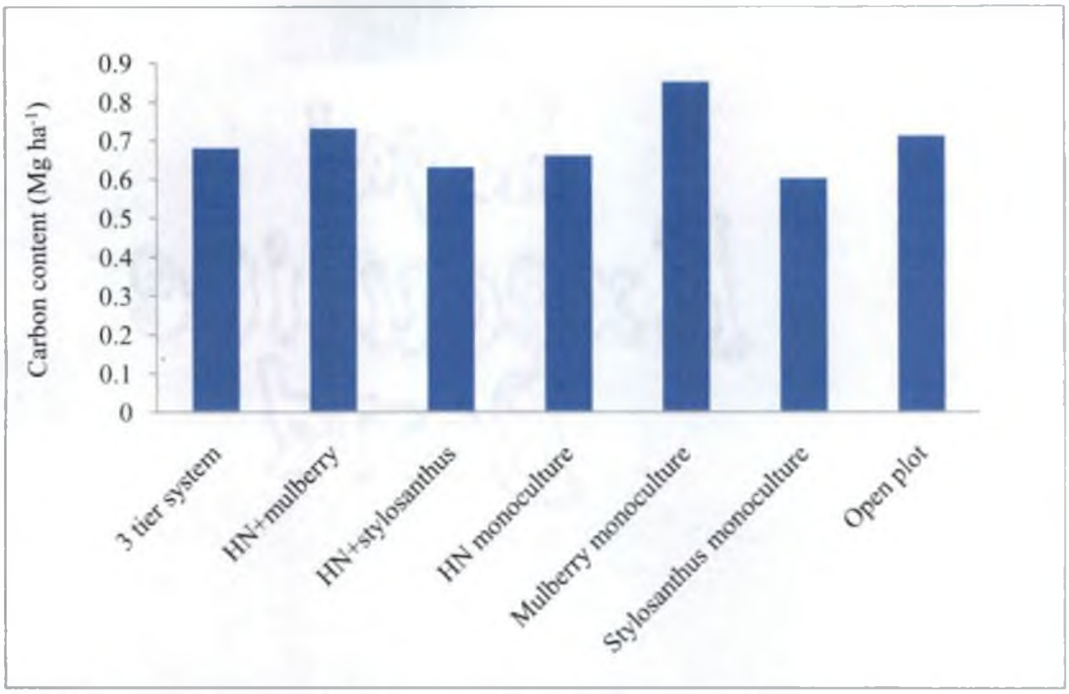

Fig. 21. Soil organic carbon content in silvopasture and monoculture systems

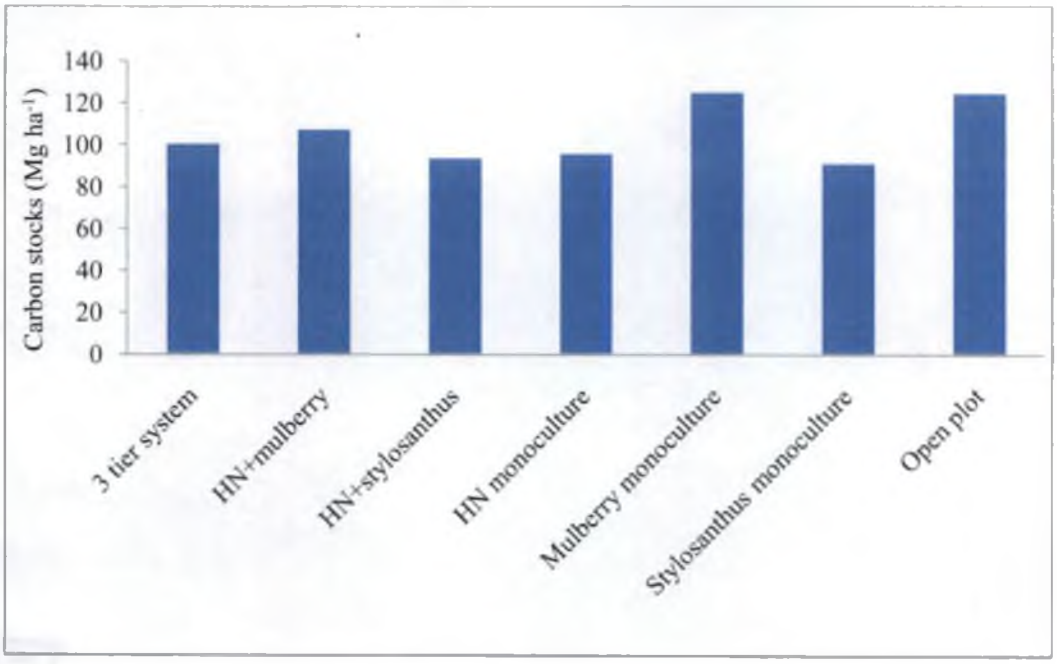

Fig. 22. Soil carbon stocks in silvopasture and monoculture systems

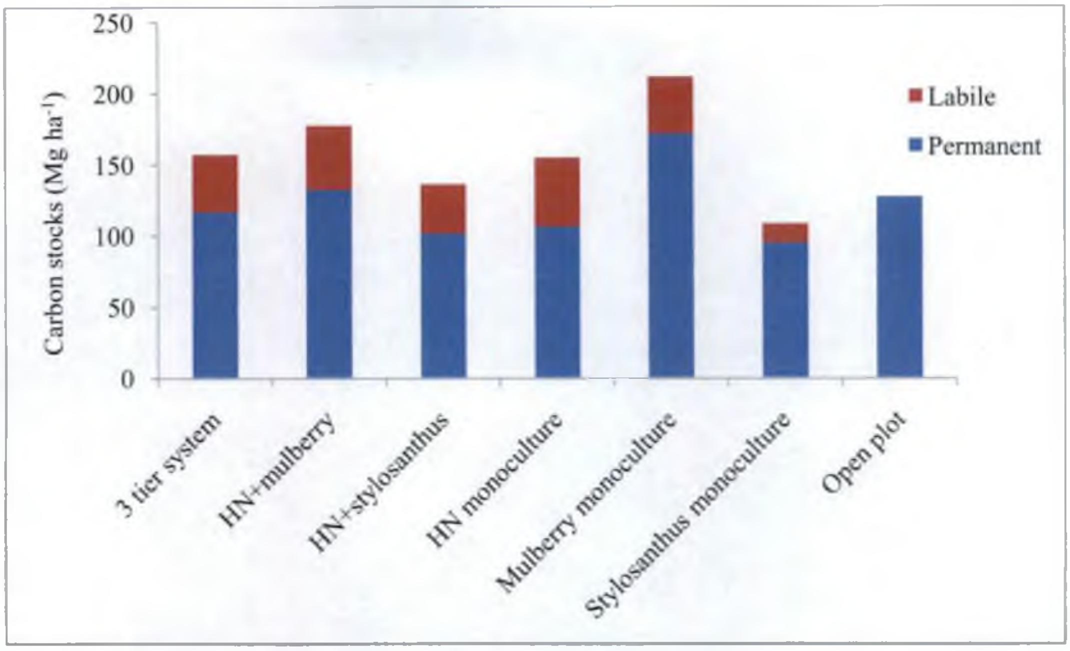

Fig. 23. Labile and permanent carbon stocks from silvopasture and monoculture systems

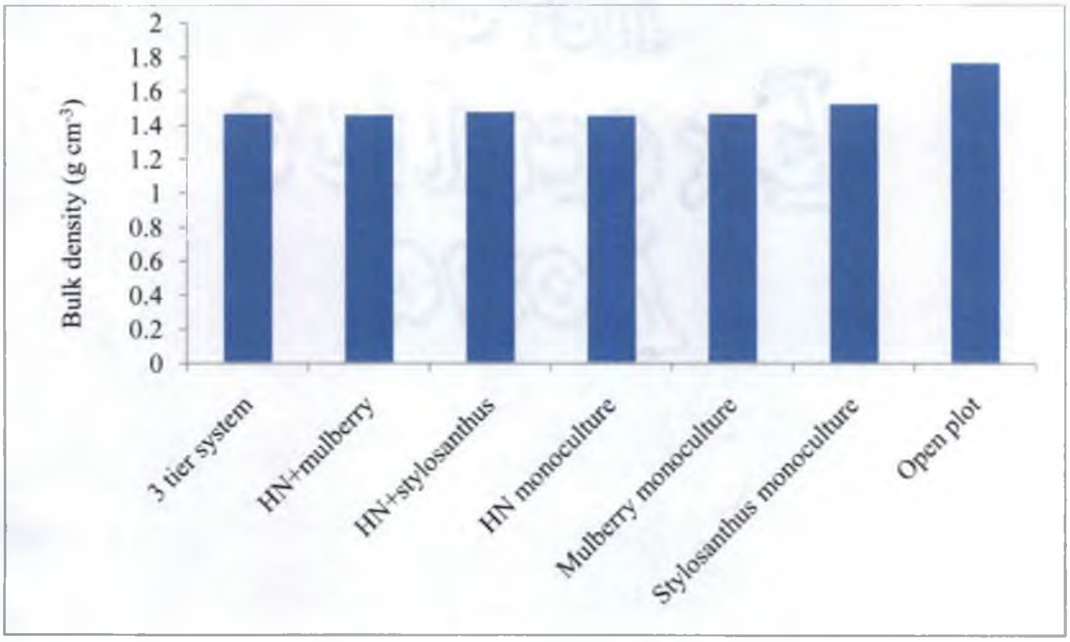

Fig. 24. Average soil bulk density in silvopasture and monoculture systems

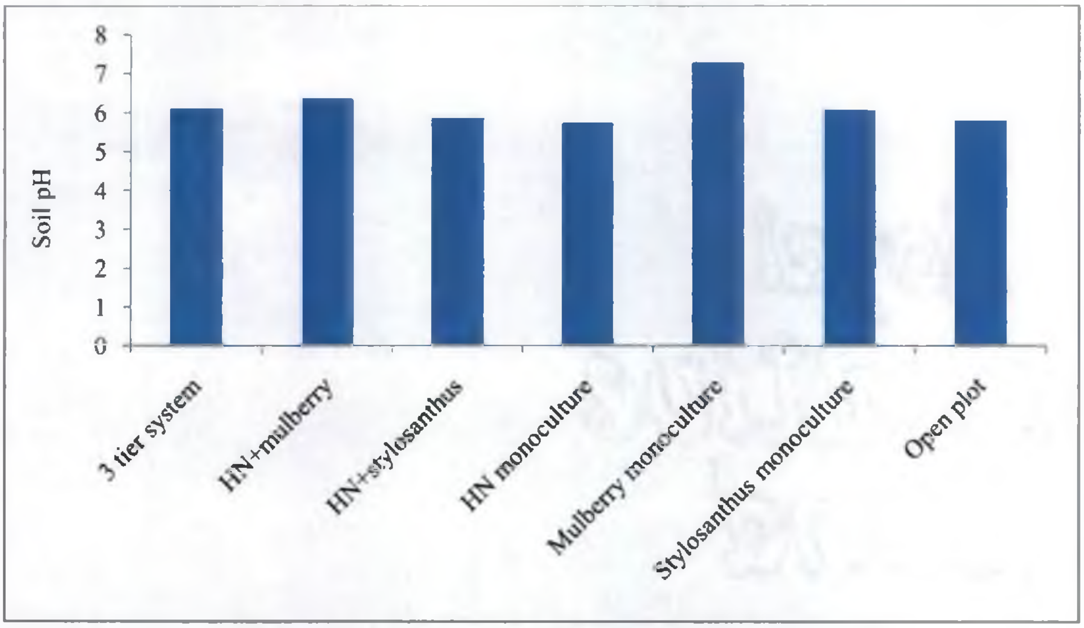

Fig. 25. Soil pH in silvopasture and monoculture systems

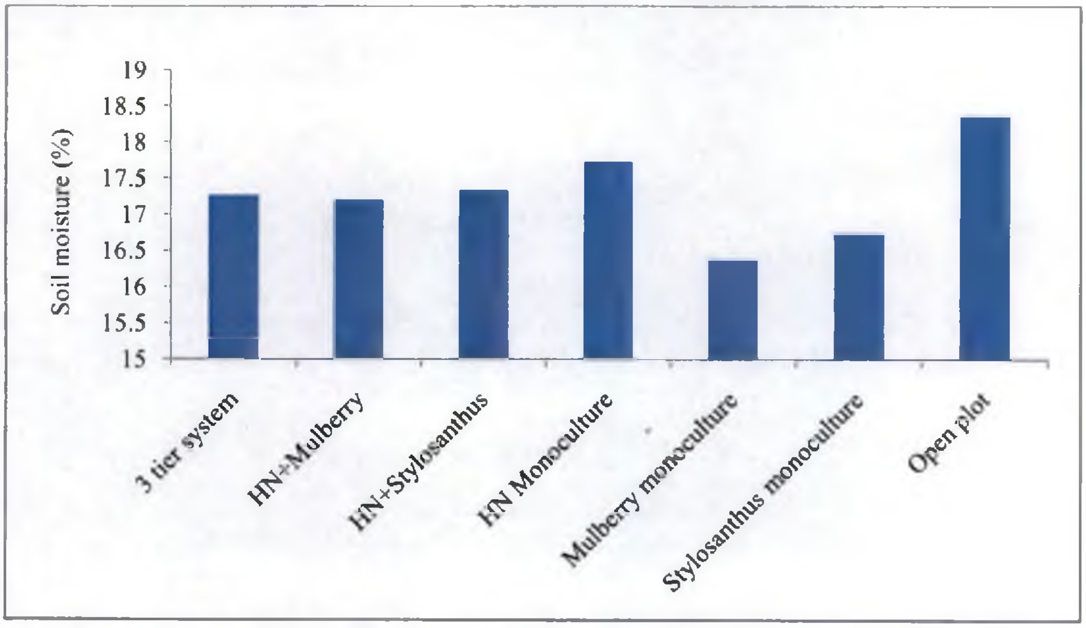

Fig. 26. Soil moisture content of silvopasture and monoculture systems

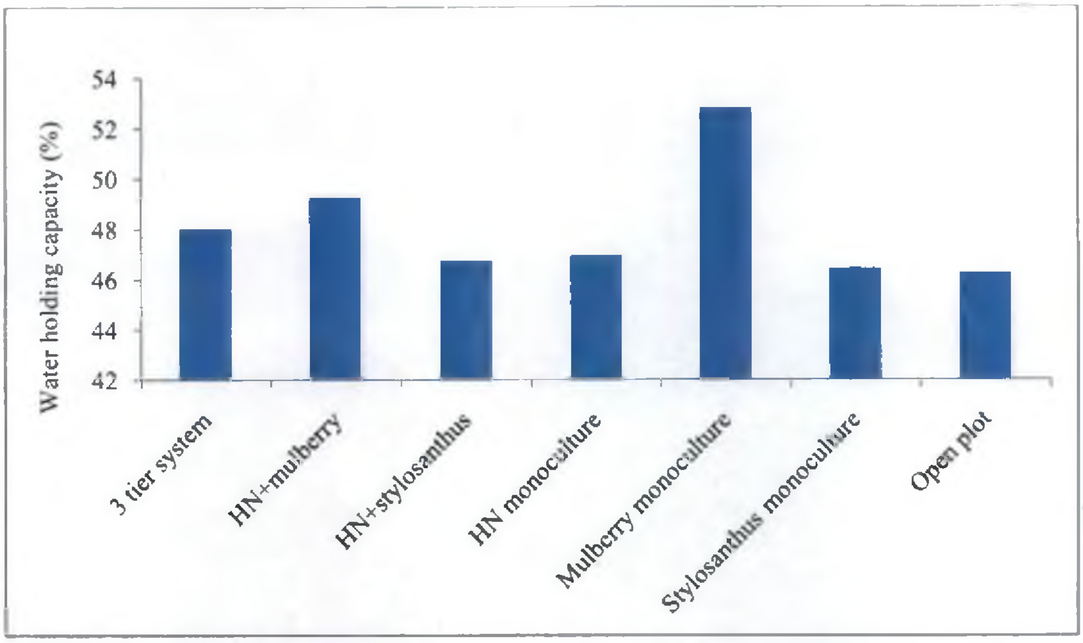

Fig. 27. Soil water holding capacity of silvopasture and monoculture systems

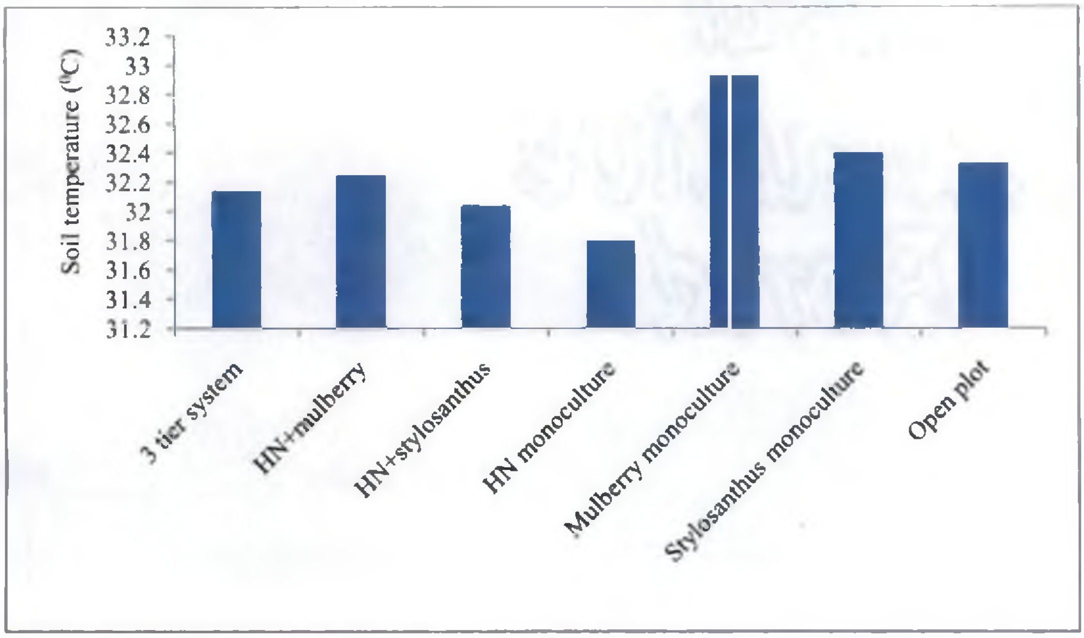

Fig. 28. Soil temperature in silvopasture and monoculture systems

5.6.2 Soil nutrient status

5.6.2.1 Total and available nitrogen content in soil

The various treatments as well as soil depths significantly influenced the total nitrogen (fig. 29). At 20-40 cm depth, all silvopasture and monoculture systems were found to be significantly superior to open system. Among various depths, except 0-20 cm, stylosanthus monoculture recorded the highest mean total nitrogen (573.98 kg ha^{-1}) .This could be due to nitrogen fixing property of stylosanthus which added nitrogen at lower layers through root nodule nitrogen fixation. Leguminous crops (herbs, shrubs, or trees) play a critical role in natural ecosystems, agriculture, and agro-forestry, where their ability to fix nitrogen in symbiosis makes them excellent colonizers of low- N environments hence an economic and environmentally friendly species (Rejili *et al.*, 2012) .However in top 0-20 cm layer total nitrogen content was maximum in mulberry monoculture plots followed by 2-tier sysrem (HN+mulberry). This could be attributed to the nitrogen replenishment in the top layers by leaf fall from mulberry, whereas in other crops, nitrogen absorption was higher from surface layers with no nitrogen addition, resulting in lower nitrogen content in top soil. Comparing various systems the stylosanthus monoculture recorded the maximum total nitrogen content and was on par with all other systems except HN monoculture and open plot, and lowest total nitrogen was recorded in open plot (484.67 kg ha^{-1}).

Available nitrogen decreases with increase in depths except at 80-100cm depth (fig. 30). Among all treatments, mulberry monoculture recorded the highest mean available nitrogen (364.36 kg ha^{-1}) in all depths followed by 2-tier HN+mulberry system (254.75 kg ha^{-1}). The yield of mulberry was influenced more by the amount of nitrogenous fertilizer than phosphorus and potassium (Pain, 1965; Kasiviswanathan *et al.,* 1979; Islam *et al.,* 1982 and1985), while the hybrid napier monoculture showed the lowest available nitrogen content (181.675 kg ha^{-1}). HN is an exhaustive crop and voracious consumer of nutrients; moreover it is harvested frequently resulting in nitrogen depletion in the system. Available nitrogen also showed a decreasing trend with depth except at 80-100 cm. This is due to the leaching of available nitrogen from surface to deeper layers and its accumulation at 1m depth due to interrupted mobility by the laterite hard pan.

5.6.2.2 Total and available phosphorus content in soil

In all treatments, except mulberry monoculture,stylosanthus monoculture and open plot a gradual increase in concentration was noted for 0-60 cm depth then it declined (fig. 31). Among all treatments, the stylosanthus monoculture recorded the highest total phosphorus content in all depths (1060.40 kg ha^{-1}) followed by 2-tier HN+stylosanthus system (937.92 kg ha^{-1}). Comparing the mean values, the least and comparable total phosphorus was recorded in mulberry monoculture (614.67 kg ha^{-1}).

Fig. 32 shows the available phosphorus in soil. A gradual increase in concentration was noted for the initial 2 depths and then declined drastically. At 60-80 cm all silvopasture and monoculture systems had significantly lower available P as compared to the open system. The mean available phosphorus was higher in 2-tier system (hybrid napier+stylosanthus) with10.52 kg ha^{-1}. About 80 kg of phosphorus was applied to stylosanthus annually; however absorption of phosphorus might be less due to lower biomass production which resulted in accumulation of phosphorus in soil. The second best system was 3-tier system, while the least was observed in mulberry monoculture and open plot of about 2.17 and 1.28 kg ha^{-1} respectively. Prasad *et al.*, (1992) reported that application of phosphate significantly influenced the N and P uptake of mulberry.

5.6.2.3 Total and available potassium content in soil

In all depths except 20-40 cm, open plot recorded the highest total potassium compared to other treatments (fig. 33). Due to absence of harvest in open plot whatever potassium is there it remains in the soil itself. In 20-40 cm, depth mulberry monoculture recorded the maximum value (629.71 kg ha^{-1}). The lowest value at 20-40 cm depth was hybrid napier monoculture (101.63 kg ha^{-1}).

This was due to the intensive growth and frequent harvest of HN which extracted almost all the potassium. At 40-60 cm depth, hybrid napier monoculture recorded the maximum value (922.25 kg ha^{-1}), and the lowest value was recorded in stylosanthus monoculture (708.93 kg ha^{-1}). In HN about 90% of roots were confined to the top soil upto 40 cm which extracted potassium from that zone leaving behind the potassium in lower layers, whereas in stylosanthus, the nutrient absorption zone of tap rooted stylosanthus was concentrated in 40-60 cm, thereby depleting the nutrients at that zone. The lowest mean total potassium of 532.23 kg ha^{-1} was recorded in hybrid napier monoculture.

Among all treatments, mulberry monoculture recorded the highest mean available potassium (324.14 kg ha^{-1}), followed by stylosanthus monoculture (fig. 34). In trees like mulberry, nutrient pumping takes place by absorbtion of nutrient from deeper layers and deposition on the surface through litter fall thereby replenishing the nutrients on the top layers. The mulberry litter decomposes very fast releasing the available nutrient which might have resulted in increasing the available potassium content in soil under mulberry monoculture. Potassium is essential for normal growth and development of mulberry plants. Due to its high requirement by plants and the important role in physiology, it has been termed as 'master cation' in plants (Yadav, 1983). Shortage of potassium results in soft branches and poor quality leaves in mulberry (Anonymous, 1988).

In stylosanthus, the biomass production was relatively less resulting in lower potassium extraction and left more potassium in soil. The lowest value of mean available potassium was recorded in 2-tier HN+stylosanthus system (91.64 kg ha^{-1}) and hybrid napier monoculture (82.248 kg ha^{-1}) and they were on par.

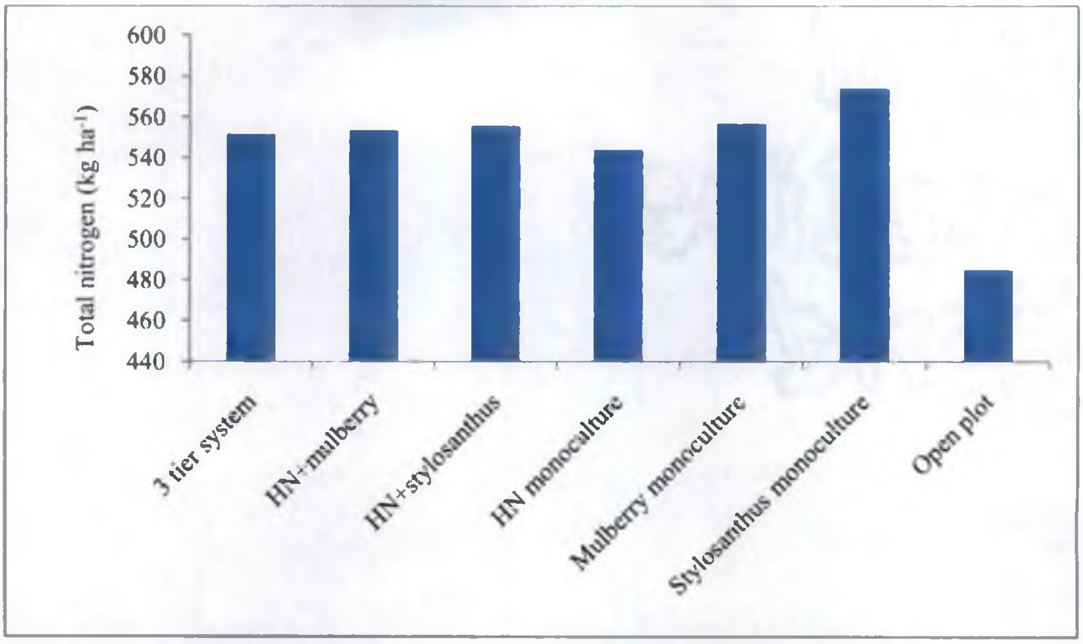

Fig. 29. Total soil nitrogen in silvopasture and monoculture systems

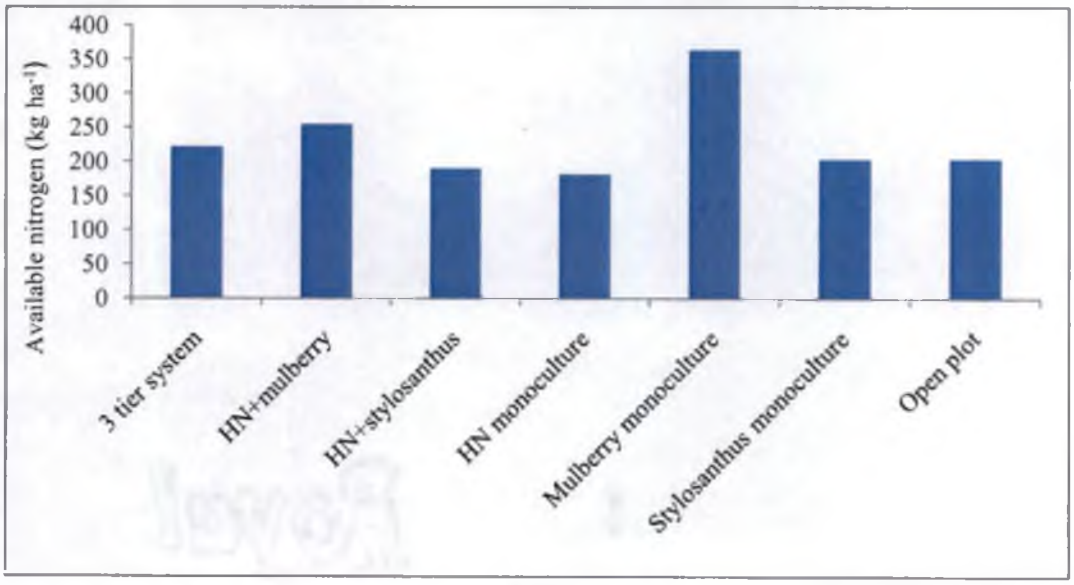

Fig. 30. Available soil nitrogen in silvopasture and monoculture systems

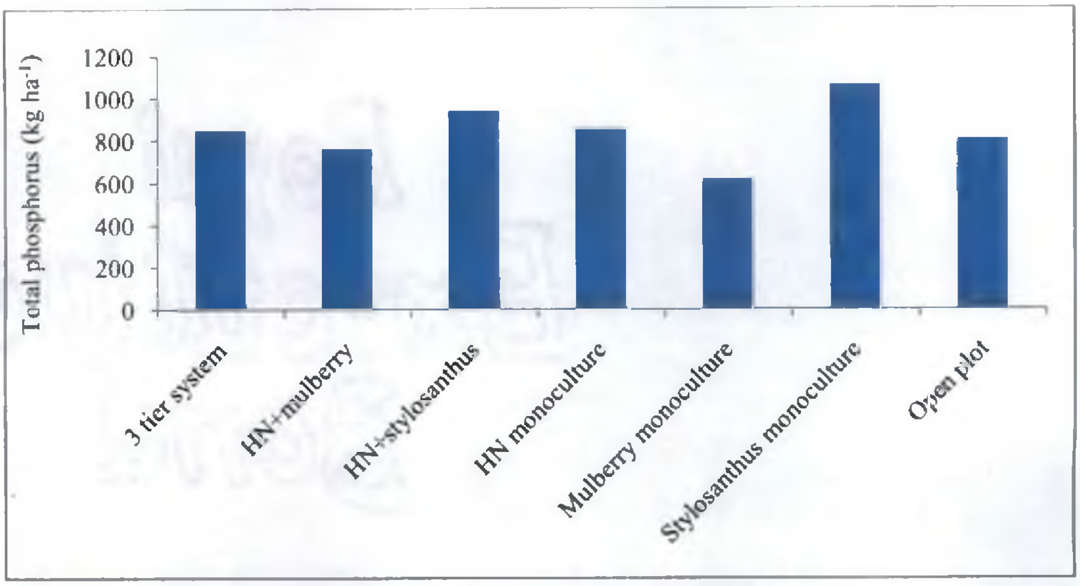

Fig. 31. Total soil phosphorus in silvopasture and monoculture systems

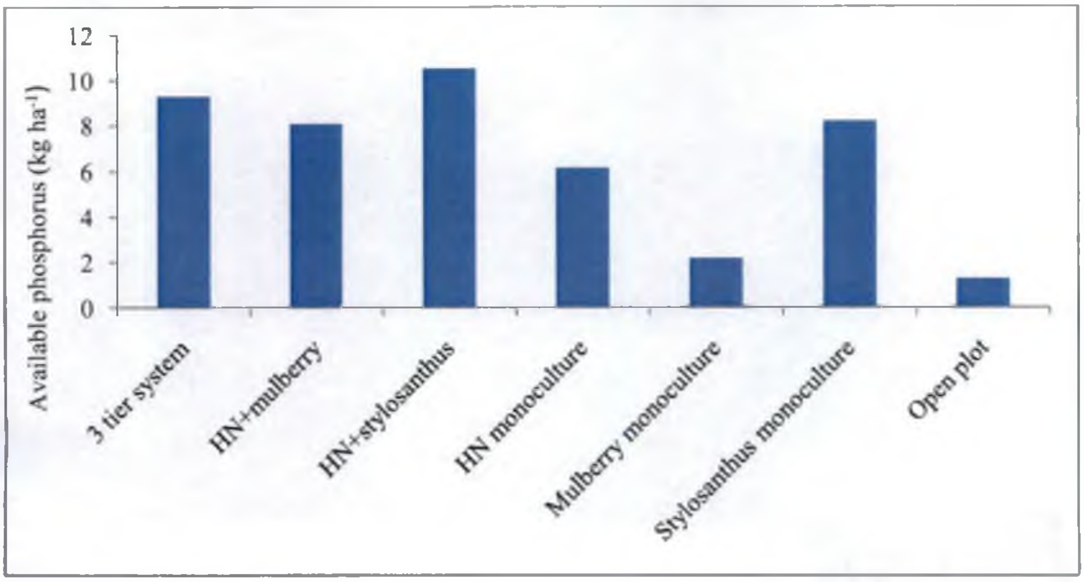

Fig. 32. Available soil phosphorus in silvopasture and monoculture systems

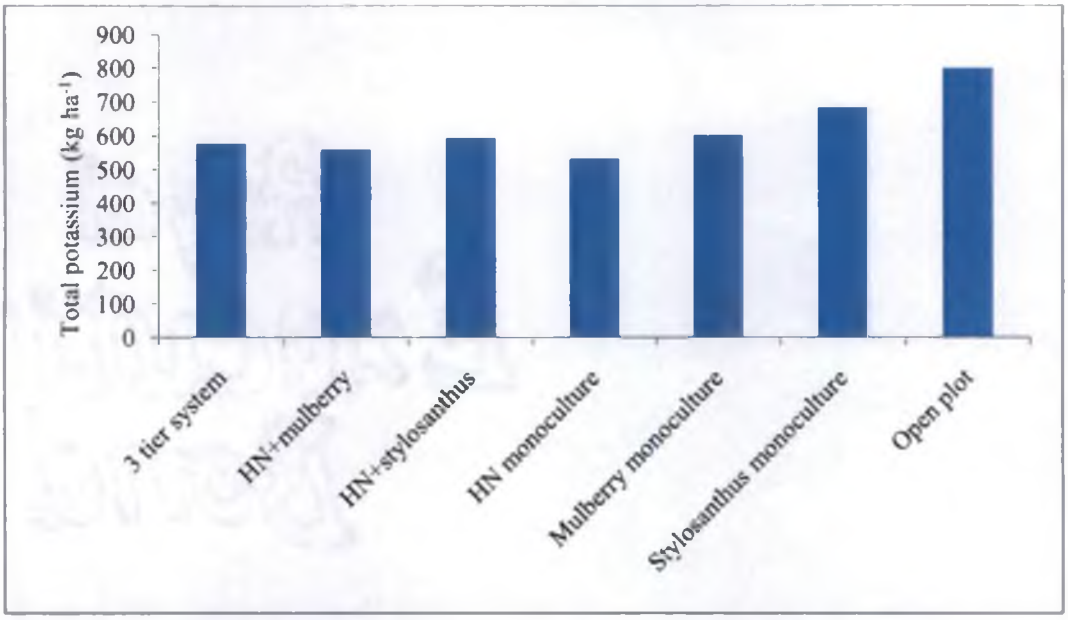

Fig. 33. Total soil potassium in silvopasture and monoculture systems

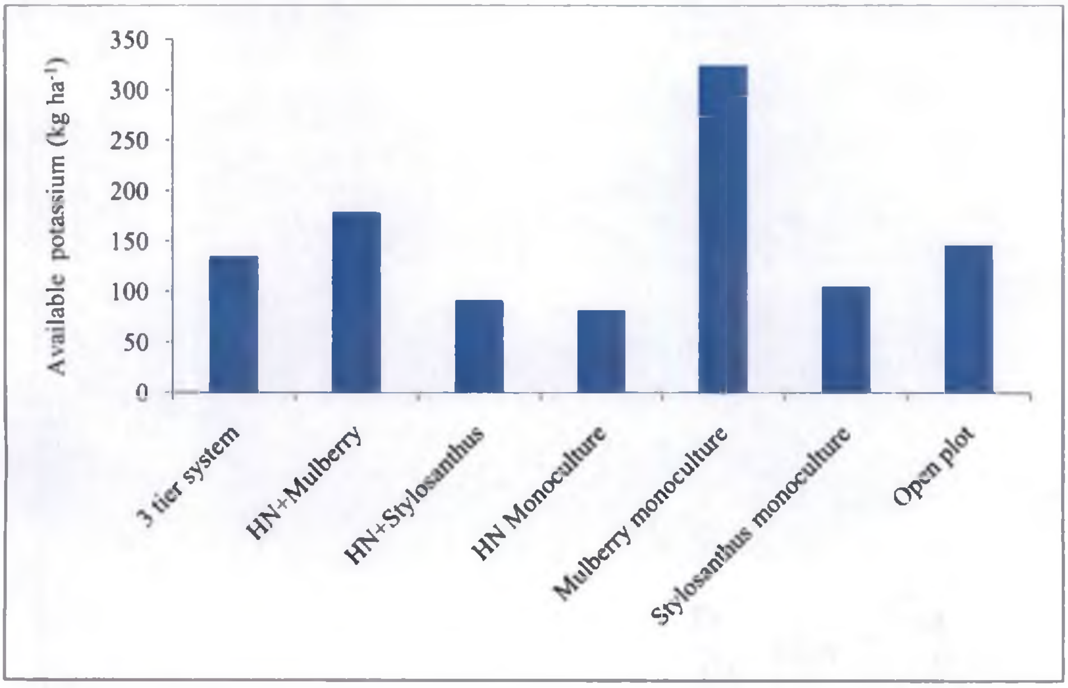

Fig. 34. Available soil potassium in silvopasture and monoculture systems

SUMMARY & CONCLUSIONS

CHAPTER 6

SUMMARY AND CONCLUSIONS

A field experiment entitled "Carbon storage potential of intensive silvopasture systems in humid tropics of Kerala" was carried out at Instructional farm, College of Horticulture Vellanikkara during the year 2013-2015. The main objective of the study was to assess the carbon storage potential of silvopasture systems in comparison with monoculture system and also investigate the soil fertility changes associated with different systems.

Salient results are summarized as follows:

1. Among various systems, hybrid napier (HN) grass monoculture produced the maximum harvested fodder biomass, followed by 2-tier HN+ mulberry system and 3-tier HN+ mulberry+ stylosanthus system. The lowest harvested biomass was found in stylosanthus monoculture.
2. The highest standing biomass and root biomass was obtained from mulberry monoculture system, followed by 2-tier HN+ mulberry system. The 3-tier systems recorded intermediate values, whereas all other treeless systems produced very low standing and root biomass.
3. Carbon stocks in harvested biomass were highest for HN monoculture, followed by 2-tier HN+mulberry systems, whereas the carbon stocks in standing and root biomass was maximum for mulberry monoculture followed by HN+ mulberry system. The 3-tier system registered intermediate values whereas all other systems were inferior. The overall carbon stocks from above and below ground plant biomass followed the trend mulberry monoculture > 2-tier HN+mulberry > HN monoculture > 3-tier system. All other fodder production systems captured very less carbon and were almost negligible in control open system with natural grass vegetation.

4. Significant variation was observed in soil carbon stocks for various systems and at different soil depths. In general, soil carbon stocks were found to be higher for tree based systems than other treeless fodder production systems. Soils under mulberry monoculture captured the maximum carbon (124.59 Mg ha^{-1}), followed by 2-tier HN+ mulberry system and 3-tier system. However, the soil carbon stock under control open system under natural grass vegetation was found to be substantially higher and equivalent to that of mulberry monoculture.

5. Comparing carbon stocks at various soil depths, the top 20 cm soil layer sequestered the maximum carbon, whereas carbon content declined with depth for all systems except stylosanthus monoculture. Soils under control open system had higher carbon stocks up to 40 cm depth whereas, mulberry monoculture sequestered more carbon in deeper soil layers.

6. Comparing the overall carbon storage potential of various systems, mulberry monoculture captured the maximum carbon (211.23 Mg ha^{-1}); 81% of which form permanent carbon stored in standing, root biomass and soil and 19% as labile carbon in harvested biomass. The second best system was 2-tier HN + mulberry (177.14 Mg ha^{-1}) followed by 3-tier system (156.79 Mg ha^{-1}), with three-fourth carbon stored in permanent form. In general, overall carbon capture and storage was higher in tree based systems.

7. Despite the higher carbon storage potential of mulberry monoculture, the fodder yields were significantly lower than 2-tier HN+mulberry system which was the second best system with respect to carbon capture. HN monoculture out yielded all other systems in fodder production, but carbon storage was comparatively poor with a large portion as labile carbon. Hence, considering the fodder production efficiency and carbon storage capacity, 2-tier intensive silvopasture HN+mulberry system was found to be the most promising system for meeting both farmer needs and

environmental services. Moreover, higher protein content in mulberry adds to the quality of the forage, which is an important factor in economic milk production.

8. Even though inferior to 2-tier systems, the 3-tier HN+ mulberry+ stylosanthus systems had higher carbon storage potential and produced quality forage than HN monoculture systems due to the inclusion of protein rich leguminous stylosanthus.

9. Various fodder production systems significantly influenced soil properties and nutrient levels. The least and comparable bulk density was recorded in 2-tier HN+mulberry system (1.456 g cm^{-3}) and HN monoculture (1.451 g cm^{-3}). The open plot recorded the highest bulk density (1.75 g cm^{-3}). The bulk density in upper 20 cm soil horizon was lower.

10. General trends showed a favourable improvement in soil pH in tree based systems, with the highest value in mulberry monoculture (7.283) followed by 2-tier HN+ mulberry system (6.362).The 3-tier system recorded the intermediate pH value of 6.119. Lowest mean value (5.791) was recorded in open plot indicating higher acidity.

11. The soil moisture content was significantly higher in control open plot (18.37 %), followed by all silvopasture systems, whereas the lowest value was found in mulberry monoculture. Comparing moisture content at different depths stylosanthus based systems retained more moisture in surface layers, whereas higher moisture was found in sub surface soil in open control plot followed by silvopasture systems.

12. The overall soil water holding capacity (WHC) was highest in mulberry monoculture (52.82%), followed by 2-tier hybrid napier+ mulberry system. Mulberry monoculture systems had higher WHC in sub surface layers, whereas in surface layer, WHC was higher for stylosanthus, hybrid

napier monoculture and 3-tier systems. The least WHC was observed in control open plot.

13. The maximum mean soil temperature was observed in mulberry monoculture (32.933 ^{0}C) which was on par with 3- tier system, 2-tier system (hybrid napier+ mulberry), open plot and stylosanthus monoculture. The minimum soil temperature was recorded in 2-tier (hybrid napier+ stylosanthus) and hybrid napier monoculture system and they were on par.

14. In general, soil physical properties were favourably influenced by tree based systems as compared to others.

15. Significant variation was observed in total and available soil nutrient contents for silvopasture and monoculture systems as well as at different soil depths.

16. The stylosanthus monoculture system recorded the highest total nitrogen content (573.98 kg ha^{-1}) in soil and was comparable with all other systems except HN monoculture, whereas the available N content was highest in mulberry monoculture (364.36 kg ha^{-1}), followed by 2-tier HN + mulberry system. Soils under HN monoculture (181.67 kg ha^{-1}) and control open plots (484.67 kg ha^{-}1) had the least available and total nitrogen content respectively. Comparing various soil depths, total nitrogen declined with depth for all systems except those with stylosanthus, where in higher nitrogen accumulation was observed in subsurface layers. Available nitrogen also showed a decreasing trend with depth upto 80 cm beyond which the content increased. Mulberry monoculture recorded the maximum available N content throughout the soil profile, followed by that of 2-tier HN+ mulberry system. In general, tree based systems favourably influenced the available nitrogen content in soil, whereas leguminous stylosanthus had a marked effect on total nitrogen pool.

17. The total phosphorus content at various depth as well as the overall mean was also highest for stylosanthus monoculture(1060.40 kg ha^{-1}), followed by 2-tier HN+ stylosanthus system, whereas the available P was highest for HN+stylosanthus system (10.52 kg ha^{-1}), followed by 3-tier system. The total and available P was comparatively lower in mulberry monoculture and open plot respectively. Hybrid napier grass monoculture systems had higher total P but available P content was low. In general total and available P content increased upto 40-60 cm depth and thereafter declined. On overall basis, only a very small portion of total P became available in soils; however P availability was substantially improved in various intensive cropping systems as compared to open plot.

18. Total potassium content was significantly higher in control open plot (799.06 kg ha^{-1}), followed by stylosanthus monoculture, whereas the available potassium content was greatest in mulberry monoculture(324.14 kg ha^{-1}) plots, followed by 2-tier HN+ mulberry and 3-tier systems. Total as well as available potassium was significantly lower in HN monoculture and 2-tier HN+ stylosanthus system. Potassium content varied at different depths and no specific trend was observed in variation.

19. In general the total N, P, K and available P content was higher in stylosanthus based systems, whereas the available N and K content excelled in mulberry based systems. Mulberry based systems significantly improved the available nutrient status in soil, owing to litter recycling and nutrient pumping from deeper layers, but could not contribute much to total nutrient pool owing to the non leguminous and exhaustive feeding nature.

20. Eventhough HN+ mulberry system proved superior in terms of fodder yield, carbon storage potential, soil physical properties and nutrient availability, it could not enrich soil fertility owing to the non leguminous and exhaustive feeding behaviour of mulberry as well as HN, whereas, 3-

tier HN+ mulberry+ stylosanthus had favourable impact on soil nutrient pool due to the leguminous nature of stylosanthus. However, 3-tier systems were much inferior in fodder yields as well as in carbon dynamics owing to the poor biomass yields from stylosanthus. Hence, substituting it with a suitable leguminous fodder tree can take care of both the forage yields as well as the soil fertility aspects.

21. Mulberry based systems significantly improved the available nutrient status in soil, owing to litter recycling and nutrient pumping from deeper layers, but could not contribute much to total nutrient pool owing to the non leguminous and exhaustive feeding nature, whereas systems involving stylosanthus enriched the soil fertility status to a considerable extent but could not influence nutrient availability. Hence with respect to the soil fertility aspects 3-tier HN+mulberry+stylosanthus system seemed more favourable for replenishing soil fertility as well as nutrient availability. However, stylosanthus being a poor fodder yielder, substituting it with a suitable leguminous fodder tree can take care of both the forage yields as well as the soil fertility aspects.

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APPENDICES

Appendix I

Mean weather parameters during the experimental period (May 2013-May 2015) recorded by the Department of Agricultural Meterology, College of Horticulture, Vellanikkara, Kerala

	2013		
months	Maximum temperature	Minimum temperature	Rainfall
May	33.6	25.2	99.1
Jun	28.5	22.7	1031.8
July	28.4	22.7	932.3
Aug	29.9	22.9	305.9
Sept	30	22.2	344.9
Oct	30.8	22.6	369.8
Nov	32.6	23.9	82
Dec	31.9	22.3	0.5

	2014		
months	Maximum temperature	Minimum temperature	Rainfall
Jan	33	23	0
Feb	34	24	0
Mar	36.7	24.2	0
Apr	35.3	25.7	61
May	33.2	24.2	323.6
Jun	30.9	24.4	46.9
July	29.5	23.1	768.0
Aug	29.5	23.2	599.8
Sept	31.3	23.3	215.1
Oct	31.9	23.7	224.6
Nov	31.9	23.2	85.3
Dec	24.9	22.5	9.6

	2015		
Jan	32.5	22.1	0
Feb	34.3	23	0
Mar	35.8	24.9	72
Apr	36	25	62
May	35	24	0

CARBON STORAGE POTENTIAL OF INTENSIVE SILVOPASTURE SYSTEMS IN HUMID TROPICS OF KERALA

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ABSTRACT OF THE THESIS

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ABSTRACT

The research project entitled "Carbon storage potential of intensive silvopasture systems in humid tropics of Kerala" was carried out at Instructional Farm, College of Horticulture, Vellanikkara during 2013-2015, in existing 2 year old intensive fodder production systems, to assess their carbon storage potential and associated soil fertility changes.

Comparative carbon storage efficiency of six different fodder production systems viz; 3-tier hybrid napier. (HN)+ mulberry+ stylosanthus system, 2-tier HN+ mulberry/ stylosanthus systems and HN/ mulberry/ stylosanthus monoculture systems and one open plot with natural grass vegetation as absolute control was assessed in randomized block design replicated thrice. The 3- tier silvopastoral system consisted of grass, trees and herbaceous legumes in 3:1:1 ratio, 2- tier systems contained grass + tree/ legume in 3: 2 ratios on area basis, whereas the entire area contained either grass or legume or tree for monoculture treatments. Trees were planted at a high density (11111 trees ha^{-1}) at 60 cm x 60 cm spacing and maintained as hedges of 1m height by harvesting at 3 months interval. All other crops were planted and harvested as per state recommendation. Fodder yields from various systems and carbon storage in plant biomass and soil was assessed for two years.

Among various systems, mulberry monoculture captured the maximum carbon (211.23 Mg ha^{-1}); 81% of which form permanent carbon stored in standing, root biomass and soil and 19% as labile carbon in harvested biomass. The second best system was 2-tier HN + mulberry (177.14 Mg ha^{-1}), which captured 13 % more carbon than 3-tier silvopasture and HN monoculture systems. However, despite the higher carbon storage potential of mulberry monoculture, the fodder yields were significantly lower than HN+mulberry system. HN monoculture outyielded all other systems in fodder production, but carbon storage was comparatively poor. Hence, considering the fodder production efficiency and

carbon storage capacity, 2-tier HN+mulberry system was found to be the most promising system for meeting both farmer needs and environmental services. Moreover, higher protein content in mulberry adds to the quality of the forage, which is an important factor in economic milk production.

Variations in soil physical properties and nutrient status were assessed after two years. In general, soil physical properties were favourably influenced by tree based systems as compared to others.The least and comparable bulk density (1.45 g cm^{-3}) was recorded in HN+mulberry and HN monoculture system. Soil pH and water holding capacity considerably improved in mulberry monoculture (7.283) followed by 2-tier HN+mulberry system (6.36). Soil temperature was also higher in tree based systems. The 3-tier systems were found to be superior to monoculture systems but inferior to 2-tier HN+mulberry system with respect to soil physical properties.Comparing the soil nutrient status, the total N, P, K and available P content was higher in stylosanthus based systems, whereas the available N and K content excelled in mulberry based systems. Hence, 3-tier HN+mulberry+stylosanthus system seemed more favourable for replenishing soil fertility as well as nutrient availability. However, stylosanthus being a poor fodder yielder, substituting it with a suitable high yielding leguminous fodder tree can take care of both the forage yields as well as the soil fertility aspects.

To conclude,the current research brings out the suitability of intensive silvopasture systems with high yielding grass species (HN) and densely planted fodder tree hedges (mulberry @ 11111 trees ha^{-1}), for maximizing quality fodder production and carbon sequestration and favourably influencing soil physical properties in humid tropics of Kerala. However, the above system could not contribute much to soil fertility owing to the non leguminous and exhaustive feeding behaviour of mulberry and HN. Hence, inclusion of a leguminous fodder tree along with mulberry and HN can take care of both the forage yields as well as the soil fertility improvement.