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Agroforestry Systems in North-Western Himalayas, India: An Overview

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Abstract

The Agroforestry systems practiced traditionally in Himalayan region are witnessed by the trees retained by farmers on their farmland. This traditional sustainable land use may be driven by topographical features, socio-economic conditions, cultural and aesthetic values in the region. For the development of any location-specific agroforestry technology, understanding the basis as well as goals towards which it is to be directed plays an important role. With the time human population has increased, rapid urbanization and industrialization increasing demand an alternate land use system tending to cope with the developmental activities in a sustainable manner. Agroforestry technology acts as a cushion against the ecological hazards associated with the developmental activities. The present article is an overview of the various agroforestry practices prevalent and their structural composition in different agro-ecological zones, along with their potential bio-economic productivity, in Himachal Pradesh of North-Western Himalayan region. Agri-silviculture, agri-horticulture, agri-silvi-horticulture, agri-horti-silviculture, horti-silviculture, silvi-pasture, pastoral-silviculture, agri-silvi-pasture, pastoral-silvi-horticulture, etc. are among different agroforestry systems in the region with structural composition varying as per needs and preferences of the farmers and suiting ecological conditions. The production potential in terms of biological productivity ranged between 5.13ton ha^{-1} and 198.20 ton ha^{-1}. Economically, the benefit and cost ratio of the systems varied from 1.23 to 5.77 depending on the nature of the components associated, expenses incurred, and the returns obtained from the systems. Further, being economically viable the important advantage associated with the agroforestry is the carbon storage potential helping in mitigation and adaptation to the changing climatic conditions. The carbon stock potential among different agroforestry systems varied from 29.72 ton ha^{-1} to109.93 ton ha^{-1}.

Keywords

Carbon; Himalayas; Land use; Productivity; Sustainability

1. Introduction

The Western Himalayas are more or less agroecosystems with 90 per cent of the inhabitants living in villages where agriculture, horticulture and animal husbandry are the primary sources of income (Atul, Punam and Khosla, 1994). On the bunds of agriculture fields, various fodder, fruit, fuelwood and timber trees are intentionally kept, and species composition varies according to land holdings and necessities of farmers (Toky, Kumar and Khosla, 1989). Planting trees on farms helps farmers satisfy their timber needs, and planting leads to an increase in tree cover and thereby reducing the burden on existing natural forests. This deliberate integration as well as retention of the trees in the farmland gives rise to a more or less sustainable land use system known as 'Agroforestry'. Agroforestry systems can meet the needs of farmers under almost any set of environmental conditions. Farmers' investments are far less risky because they diversify their crop range and source of income, which reduces economic and social risks (Lefroy, 2009). In India, agroforestry is traditionally practiced in a variety of ways (Sharma, 1996; Solanki, 1998) and are based on the population's socio-economic, cultural, demographic factors, as well as farmers' experiences and other related factors. It has promoted an alternative land-use system to address various issues related to land use sustainability and environmental improvement, though scientific evidence is needed to determine its true potential. Agroforestry systems in India have diverse variations in their components both structurally and functionally, depending upon the temperature, elevation, soil structure and rainfall pattern (Combe, 1982; Nair and Dagar, 1991). Different agroforestry systems have been developed in various agro-climatic regions of the country, all of which have proven to be highly productive and environment-friendly. As they can include any of the crops, animals and tree species used in agriculture and forestry, agroforestry systems can take almost unlimited number of different forms. In order to support such efforts on a scientific basis, several activities have been undertaken in India, and, thus, India has become one of the leaders in agroforestry research (ISFR, 2013). The area under agroforestry is expected to increase from 25.32 million ha to 53 million ha in the next forty years; therefore, agroforestry will be contributing substantially to meet the requirements of the society through increased production and providing environmental benefits (Dhyani, Handa and Uma, 2013). In Himachal Pradesh and other Himalayan states, agroforestry has been practiced historically from time immemorial and it plays an important role in attaining sustainability in the hill farming systems. The diversity of agroforestry systems, their floristics, biomass production, carbon sequestration potential, soil amelioration, etc. in Himachal Pradesh have been described by Toky, Kumar and Khosla (1989) and Thakur, Gupta and Gupta (2004). Hill farming systems are dominated by small-scale, subsistence or near-subsistence agricultural groups. In comparison to larger and more financially oriented farms, these farmers have distinct land management goals and limits. Minimizing risk in food production, a lack of cash for farm inputs and necessities such as small timber and fuelwood, a lack of labour for intensive farming, and the gradual loss of community rights and resources are some of the constraints faced by typical small and intermediate land users in Himachal Pradesh hill farming systems.

With rapid urbanization and economic growth taking place in the country, there are several unprecedented opportunities for farming communities to supply farming products beyond subsistence level (ICAR, 2020). In Himachal Pradesh also, there is paradigm shift in hill farming systems shifting towards high value cash crops. For making such shifts, proper planning of the farming system beneficial to the stakeholders is necessary based on physical and environmental conditions for which the state of Himachal Pradesh is categorized into four agro-ecological zones as shown table 1. Agroforestry provides end-to-end link between sustainability and profitability along with greater opportunities for the sustained productivity. The adoption of agroforestry technologies depends on the edaphic-climatic, socioeconomic status, and needs of the farmers, and the management is influenced by physical, demographic and institutional factors (Bayard, Jolly and Shannon, 2007). However, in recent years, changes in the climatic conditions, increase in human population and decrease in the size of agricultural landholdings have generated interest among farmers to adopt agroforestry systems. Climate change poses a great threat to agriculture and food security. The increasing land-use conflicts call for the development of land use systems that reconcile agricultural production with the provisioning of multiple ecosystem services, including climate change mitigation. To overcome the uncertainty of the monsoon and frequent natural calamities and to maintain food security, the farmers adopt a sustainable land-use system having diversified outputs, sustained agriculture productivity and diverse incomes. Agroforestry has been suggested as a global solution to increase land-use efficiency while reducing environmental impacts and economic risks for farmers (Paul, Weber and Knoke, 2017). Usually, lack of scientific knowledge, institutional approach and negative attributes of tree component (*viz.* long rotation, shade effect, allelopathy and large canopy) compel farmers to avoid adopting tree components in their fields. Agroforestry practices are more substantial, efficient and feasible for small and marginal farmers in Himachal Pradesh. The possibility of adopting agroforestry practices in Himachal Pradesh is very high as the farmers of Himachal Pradesh are now well educated and equipped with modern technology.

Table 1: Area under different agro-ecological zones in Himachal Pradesh, India (DoA, 2009)

S. No.	*Zone*	*Elevation range (m)*	*Area (km^2)*	*Per cent*	*Districts within zone*
1.	Sub- Montane & Low hills sub-tropical zone (Zone-I)	240-1,000	10,260	18.44	Kangra, Una, Hamirpur, Bilaspur, Solan, Chamba, Mandi, Sirmaur
2.	Mid-hills sub-humid zone (Zone-II)	1,000-1,500	4,664	8.38	Chamba, Kangra, Mandi, Shimla, Solan, Sirmaur, Kullu, Kinnaur, Hamirpur, Bilaspur
3.	High hills wet temperate zone (Zone-III)	1,500-2,500	9,217	16.56	Shimla, Mandi, Chamba, Kangra, Kullu, Solan, Sirmaur, Kinnaur, Lahaul & Spiti
4.	High hills dry temperate zone (Zone-IV)	>2,500	31,509	56.62	Kangra, Lahaul & Spiti, Kinnaur, Chamba, Mandi, Sirmaur, Shimla

2. Prevalent Agroforestry Systems in Himachal Pradesh

Himachal Pradesh is characterized by the diverse agroecosystems as state varies in altitudinal ranges from 350 to 6,975 m above mean sea level that increases from West to East and from South to North (Gupta, Sarvade and Singh, 2017). With the altitudinal variation in the state, climatic conditions significantly vary affecting the farming practices. The farming practices, along with their composition, that are need based and comparatively more adaptive as well as productive in a particular region are commonly practiced by majority of the people. Various studies have been carried out in the Himachal Pradesh (Bammanahalli, 2016; Chisanga, Bhardwaj and Sharma, 2013; Goswami, Verma and Kaushal, 2014; Gupta, Sarvade and Singh, 2017; Jhanju, 2021; Kaler, Gupta and Negi, 2017; Kumar *et al.* 2018a, 2018b; Kumari, Sehgal and Kumar, 2008; Rajput, Bhardwaj and Pala, 2017; Salve and Bhardwaj, 2020; Thakur, 2020;

Tiwari, Pant and Singh, 2018; Toky, Kumar and Khosla, 1989) regarding the identification of the prevalent agroforestry practices in the state. Table 2 shows the various prevalent agroforestry systems present in the state and their composition of agricultural crops, forest trees, fruit trees and grasses at each agro-ecological zone. Mazumdar (1991) identified five farming systems at Nauni *viz*., agricultural system, horti-agriculture, horti-silvi-pastoral, grasslands and wastelands. Among the different systems, agri-horticulture system was the dominating system in the study area. Diagnostic survey of agroforestry systems in the sub-temperate and sub-humid regions of Himachal Pradesh by Kachru (1997) reported eight agroforestry system types *viz.*, agri-silviculture, agri-horticulture, agri-silvi-horticulture, pastoral-silviculture, pastoral-horti-silviculture and pasture in the area. Sood (2006) identified traditional agroforestry practices in Mandi district of Himachal Pradesh and reported agri-silvicultural, agri-silvi-horticultural, silvi-pastoral, agri-horti-silvicultural, horti-agricultural and horti-silvicultural systems in the study area. In arid districts of Himachal Pradesh, Kumari, Sehgal and Kumar (2008) reported agri-horticulture (pea + potato + apple), agri-silviculture (pea + potato + kidney bean + *Salix*), agri-silvi-pastoral (pea + *Salix* + grasses), pastoral-silviculture (grasses + *Salix*) and pastoral-horticulture (grasses + apple) as the five major agroforestry systems in the Lahaul area. Agroforestry systems and their components were similar in Kinnaur district, except for lack of an agri-silvi-pastoral system which was found absent in Kinnaur. In this region, major tree species were willow, poplar and apple, first two being the source of fuel and fodder, whereas the third has now been introduced in the region as a horticulture cash crop. Goswami (2009) identified five agroforestry systems in the Kwaalkhad watershed in district Solan, namely agri-silvi-horticulture (maize, wheat, blackgram, *Grewia*, *Ficus* and pear), agri-horti-silviculture (wheat, kidney bean, tomato, pomegranate and *Grewia*), agri-silviculture (maize, barley, *Ficus* and *Grewia*), agri-horticulture (maize, *Capsicum*, tomato, plum and pear) and silvi-pasture (*Pinus, Acacia* and grasses). Singh (2014) reported agri-silviculture, silvi-pastoral, agri-horticulture, and agri-horti-silviculture systems in subtropical areas of district Sirmaur, Solan and Kangra of Himachal Pradesh. In Bilaspur and Hamirpur districts of Himachal Pradesh, Bammanahalli (2016) reported that the predominant systems in Bilaspur district were pastoral-silviculture (PS), agri-silvi-horticulture (ASH) and agri-silviculture (AS); whereas, in Hamirpur district, the predominant agroforestry systems were pastoral-silviculture (PS) followed by pastoral-silvi-horticulture (PSH) and agri-silviculture (AS). Kumar (2016) reported six different types of agroforestry systems *viz*. agri-silviculture, agri-silvi-pastoral, agri-silvi-horticulture, agri-horti-silviculture, horti-pastoral and silvi-pastoral in sub-temperate region of Solan district in Himachal Pradesh. Kumar *et al*. (2018b) identified the agroforestry systems in Kandaghat block of Solan district that included agri-silviculture, agri-silvi-pastoral, agri-silvi-horticulture, agri-horti-silviculture, horti-pastoral and silvi-pastoral systems. In Sirmaur district, Tiwari, Pant and Singh (2018) identified different land use systems *viz.,* agri-silviculture, agri-horticulture, agri-silvi-horticulture, agri-silvi-pastoral, pastoral-silviculture, silvi-pastoral and pastoral-silvi-horticulture. In Shimla district, Singh (2019) reported that agri-silviculture, agri-horticulture, horti-agriculture, horti-pastoral, pastoral-horti-silviculture, pastoral-silviculture and silvi-pastoral were the major agroforestry systems. In altitudinal zone-I and Zone-II, the most predominant agroforestry system was agri-silviculture (AS), followed by agri-horticulture (AH) and silvi-pastoral (SP), whereas, in altitudinal zones-III, IV and V, the most predominant agroforestry system was agri-horticulture (AH) followed by horti-agriculture (HA) and horti-pastoral (HP). In Chuhar valley of district Mandi, Thakur (2020) identified six types of agroforestry systems *viz.,* agri-silviculture (AS), agri-horti-silviculture (AHS), agri-silvi-horticulture (ASH), horti-pastoral (HP), pastoral-silviculture (PS) and pastoral-silvi-horticulture (PSH). In the northern region, the most predominant agroforestry system was agri-horti-silviculture (AHS), followed by pastoral-silviculture (PS), whereas, in the southern region, the most predominant agroforestry system was pastoral-silviculture (PS) followed by agri-silviculture (AS). In Seraj valley of district Mandi, Jhanju (2021) identified seven different types of agroforestry systems where the horti-agriculture system was the predominant agroforestry system followed by agri-horticulture and agri-horti-silviculture. In the study area, pastoral-silviculture was the least used agroforestry system, which might be due to the lack of land for further diversification of existing land use systems, as pastoral-silviculture was not present in the marginal category of farmers. The prevalence of these systems in these districts may be attributed to local ecological conditions, to meet out the fodder demands of livestock, which are mainly reared to meet their daily needs.

3. Biological Productivity Potential of Agroforestry

Land is one of the fundamental resources required for agricultural and non-agricultural use with an irony that it is a fixed resource and can't be expanded at will. To fulfil the ever-increasing needs of the people from the limited land resources available, it is important to increase the productivity of the available land resources by incorporating the plants having higher production potential per unit area. Plant productivity is a function of the net photosynthesis rate which is dependent on the gross photosynthesis and the respiration losses from the plant. However, the selection of tree species for agroforestry system is not only based on cultural, economic and environmental basis, but also on certain photosynthetic principles (Nair, 1993). It may be useful in selecting tree species for agroforestry that will increase the overall productivity in terms of biomass and economic returns from the system. The biomass production potential of the prevalent agroforestry systems in different agro-ecological zones present in the Himachal Pradesh has been worked out by several researchers (Bammanahalli, 2016; Gupta, Sarvade and Singh, 2017; Sharma *et al.,* 2021; Kaler, Gupta and Negi, 2017; Singh, 2019; Toky , Kumar and Khosla, 1989; Goswami, Verma and Kaushal, 2014; Singh *et al.,* 2015; Rajput, Bhardwaj and Pala, 2017; Chisanga *et al.,* 2018; Singh *et al.,* 2020; Thakur, 2020) as summarized in the table 3. Mazumdar (1991) carried out the research on biomass production pattern in traditional agroforestry systems in western Himalayas and reported that horti-silvi-pastoral system gave the highest standing biomass (355.5 quintal ha^{-1}) compared to horti-agricultural system (301.5 quintal ha^{-1}) and grassland (63.2 quintal ha^{-1}). Horticultural trees in horti-agricultural system produced the maximum biomass of 55.8 quintal ha^{-1} yr^{-1}at the highest rate of 18.5 per cent. Fruit trees also put the major portion of the annual biomass by 53.5 per cent to horti-silvi-pastoral system followed by fodder trees (26.0%) and timber/fuelwood trees (20.7%). In grassland system, timber/fuelwood species contributed the maximum share by 51.1 per cent to system productivity. Kumar (1996) conducted bio-economic appraisal of agroforestry systems in Himachal Pradesh and found that biomass productivity in different agroforestry systems followed the order "agri-silviculture>agri-horti-silviculture>agri-horticulture>sole cropping". As different system yielded 1.10, 1.23 and1.31 times higher biomass in maize and lentil cropping pattern and 1.09, 1.22 and 1.29 times in the soybean and wheat cropping pattern than agri-horti-silviculture system, agri-horticulture system and sole cropping, respectively. Rajput (2010) reported the trend forest> silvi-pasture> agri-horticulture> horticulture> agriculture for biological productivity of the different land use systems in Kullu district of Himachal Pradesh. Kumar (2016) conducted a study for the evaluation of existing agroforestry systems for biological productivity in the sub-temperate region of Solan district of Himachal Pradesh. The biological yield was found to be maximum (24.88ton $ha^{-1}yr^{-1}$) under silvi-pastoral among all the agroforestry systems attributed to preponderance of mature trees at the site, while minimum (12.16ton $ha^{-1}yr^{-1}$) was found under agri-horti-silviculture. Goswami *et al.* (2014) studied the biomass production potential of traditional agroforestry systems in Giri river watershed in Himachal Pradesh and found that, among all the systems, the agri-silvi-horticulture was having highest accumulated biomass averaging 222.63 quintal followed by agri-horti-silviculture (191.60 quintal), silvi-pasture (122.63 quintal), agri-horticulture (118.20 quintal) and agri-silviculture (108.56 quintal). Singh *et al.* (2019) conducted an experiment to identify variation in biomass production potential of eight land use systems *viz.* agriculture, horticulture, agri-silvicultural, silvi-pastoral agri-horticulture, agri-horti-silvicultural, forest and grassland at two altitudinal ranges (365-635 m amsl, 636-914 m amsl) of Himachal Pradesh. They found that the maximum value of aboveground biomass (184.75 ton ha^{-1}), belowground biomass (47.84 ton ha^{-1}) and total biomass (232.59 ton ha^{-1}) was in forest land use system with minimum aboveground biomass (2.43 ton ha^{-1}), below ground biomass (1.09 ton ha^{-1}) and total biomass (3.52 ton ha^{-1}) under pasture land use system. Among the agroforestry systems maximum aboveground (66.46 ton ha^{-1}), belowground (20.84 ton ha^{-1}) and total biomass (86.48 ton ha^{-1}) was accumulated in agri-horti-silviculture system with minimum aboveground biomass (34.49 ton ha^{-1}), belowground biomass (9.01 ton ha^{-1}) and total biomass (43.51 ton ha^{-1}) under silvi-pastoral system. The biomass production potential of different land use systems showed declining trend with increase in altitude. Sharma *et al.* (2021) assessed the biological productivity of the agroforestry system in the sub-tropical low hill zone of Himachal Pradesh and reported highest biological productivity in silvi-pastoral (31.02 ton $ha^{-1}yr^{-1}$) system having higher mature tree density, while minimum (16.60 ton $ha^{-1}yr^{-1}$) biological productivity was recorded for agri-horticulture system.

4. Economic Potential of Agroforestry in Himachal Pradesh

Besides various ecological benefits associated with agroforestry system, it has potential to meet the subsistence needs of the low-income households (Shukla, Pandey and Kumar, 2018). Integration of trees with agricultural crops ensures higher benefits depending upon the components associated in the system. Various studies highlight the economic potential of agroforestry in Himachal Pradesh ranging from Rs. 11,451 – Rs. 2,633,000 ha^{-1} $year^{-1}$ yielding a benefit cost ratio 1.23- 5.77 (Table 4). However, the economic benefits of the system are mainly attributed to the components of prime importance integrated in the system. Besides the monetary benefits, agroforestry also has a great potential for employment generation, thereby, ensuring and improving livelihood of the agriculture dependent communities. Agroforestry in the Indian Himalayan region has a potential of employment generation to a tune of 5.76 million mandays per year (Arunachalam *et al.,* 2020). Agroforestry, thus, can be a suitable tool for the reduction of unemployment target of state government from 10.6% to 6% (GoHP, 2021). Further, growing of two or more components, simultaneously, on the same land unit minimizes the risk associated with the production from sole cropping. If one crop failure takes place, there is other component that can still produce and can help in the minimization of the losses from complete crop failure. Moreover, integrating livestock in agroforestry systems acts as a cushion and provides regular income to the households besides meeting out the nutritional demands. Sharma *et al.* (2008) evaluated the economics of a mandarin (kinnow) based agroforestry system in Himachal Pradesh with wheat and cauliflower - mustard. Average yields of wheat (18.68 quintal ha^{-1}) and cauliflower – mustard (10.34 quintal ha^{-1}) were reported beneath mandarin plants, which were lower than those of wheat (22.34 quintal ha^{-1}) and cauliflower – mustard (12.00 quintal ha^{-1}) grown in open fields. However, the overall return from the agri-horticulture system was higher than that of sole crops. Cauliflower – mustard cultivation with mandarin was shown to be more lucrative than wheat cultivation. The mandarin - cauliflower – mustard combination had the highest returns per hectare (Rs. 56,407.55). The bio-economic appraisal of different land use systems in temperate north-western Himalayas was studied by Rajput (2010) in the Kullu district of Himachal Pradesh and revealed that the orchard + vegetable-vegetable land use system situated at 1,600-1,900 m amsl gave net profit of Rs. 1,023,430 $ha^{-1}yr^{-1}$ in valley ecosystem, whereas, in the mountainous ecosystem, agri-horticulture land use system situated at 1,700-2,000 m amsl resulted in the net profit of Rs. 969,194 $ha^{-1}yr^{-1}$. Total benefits (net profit + carbon credits) in the valley ecosystem were highest for orchard + vegetable-based cropping system at all the four altitudinal gradients. Similarly, in the mountainous ecosystem also, fruit based agri-horticulture system showed maximum total benefits at all the altitudinal gradients. Chisanga, Bhardwaj and Sharma (2013) assessed the bio-economics of several land-use systems in the dry temperate north-western Himalayas and found that the agri-horticulture system produced the highest net profit (Rs. 1,310,000) followed by horticulture (Rs. 1,165,852); whereas, other land-use systems, such as agriculture, agri-horti-silviculture, silvi-pasture and barren land, had lower net returns than fruit-based land use systems. Thakur (2020) studied the economic productivity of different agroforestry system in northern and southern regions of Chuhar valley in Mandi District of HP and revealed that in northern region the economic productivity of agroforestry systems were in the order of Agri-horti-silviculture (Rs. 168,554 ha^{-1} yr^{-1}) > Agri-silvi-horticulture (Rs.127,086 ha^{-1} yr^{-1}) > Horti-pastoral (Rs. 104,779 ha^{-1} yr^{-1}) > Pastoral-silvi-horticulture (Rs.15,873 ha^{-1} yr^{-1}) > Pastoral-silviculture (Rs. 8,074 ha^{-1} yr^{-1}), whereas, in southern region of the valley net returns followed the order Agri-silviculture (Rs.185,404 ha^{-1} yr^{-1}) > Agri-horti-silviculture (Rs.176,660 ha^{-1} yr^{-1}) > Agri-silvi-horticulture (Rs.165,117 ha^{-1} yr^{-1}) > Horti-pastoral (Rs.132,836 ha^{-1} yr^{-1}) > Pastoral-silvi-horticulture (Rs.13,113ha^{-1} yr^{-1}) > Pastoral-silviculture (Rs.8,695 ha^{-1} yr^{-1}). In Seraj valley of district Mandi, Jhanju (2021) found horti-agriculture system to be the most profitable with net returns of Rs. 206,830.44 $ha^{-1}yr^{-1}$, while pastoral-silviculture with net returns of Rs. 15,634.63 $ha^{-1}yr^{-1}$ was found to be less profitable in terms of net returns.

Table 2: Agroforestry systems practiced and their major components in different agro-ecological zones in Himachal Pradesh, India

Agro-climatic zones	*Agroforestry systems*	*Major agricultural crops*	*Major forest trees*	*Major fruit trees*	*Major grasses*	*References*
Zone-I	Agrisilviculture, Agrihorticulture, Agrisilvihorticulture, Agrihortisilviculture, Hortisilviculture, Silvipasture, Pastoralsilviculture, Agrisilvipasture	Maize, Rice, Blackgram, Tomato, Okra, Soybean, Wheat, Barley, Mustard, Gram, Pea, Cabbage, Cauliflower, Potato, Garlic, Onion	*Grewia optiva, Celtis australis, Dalbergia sissoo, Toona ciliata, Morus alba, Bauhinia variegata, Melia, Albizia, Acacia, Pinus roxburghii, Sapindus, Emblica officinalis, Shorea, Eucalypts, Melia, Anogeissus latifolia*	Mango, Citrus, Plum, Litchi, Guava, Papaya, Aonla	*Apluda mutica, Imperata cylindrica, Chrysopogon montanus, Seteria glauca, Cymbopogon martinii, Heteropogon contortus*	Bammanahalli (2016); Gupta, Sarvade and Singh (2017); Kumar *et al.* (2018a) Tiwari, Pant and Singh (2018); Toky, Kumar and Khosla (1989)
Zone-II	Agrisilviculture, Agrisilvihorticulture, Agrihortisilviculture Agrisilvipastoral, Agrihorticulture, Hortisilviculture, Silvipastoral, Pastoralsilviculture	Maize, Blackgram, Tomato, Soybean, Colocasia, Kidney bean, Zinger, Capsicum, Wheat, Barley, Mustard, Gram, Pea, Cabbage, Cauliflower, Garlic, Onion, Turmeric	*Grewia optiva, Celtis australis, Toona ciliata, Morus alba, Robinia, Bauhinia, Salix, Melia, Albizia, Acacia catechu, Pinus roxburghii, Quercus* spp., *Ficus* spp., *Bombax ceiba, Leucaena, Myrica esculenta*	Peach Pear, Plum, Apricot, Apple, Walnut, Wild pomegranate	*Dicanthium annulatum, Themeda anathera, Chrysopogon montanus, Heteropogon contortus, Cymbopogon martini, Paspalum notatum*	Goswami, Verma and Kaushal (2014); Gupta, Sarvade and Singh (2017); Kumar *et al.* (2018b); Rajput, Bhardwaj and Pala (2017); Singh (2014); Tiwari, Pant and Singh *(*2018); Toky, Kumar and Khosla (1989)
Zone-III	Agrisilviculture, Agrihorticulture, Hortiagriculture, Agrisilvihorticulture, Agrihortisilviculture, Pastoralsilviculture, Hortipastoral, Silvipastoral	Maize, Blackgram, Tomato, Soybean, Colocasia, Kidney bean, Capsicum, Amaranthus, Millets, Wheat, Barley, Mustard, Buckwheat, Gram, Pea, Cabbage, Cauliflower, Potato, Garlic, Zinger, Turmeric	*Grewia optiva, Celtis australis, Toona ciliata, Morus alba, Robinia, Ulmus, Bahunia variegata, Salix* spp., *Pinus wallichiana, Quercus* spp., *Cedrus deodara, Fir* spp., *Spruce, Bombax ceiba, Rhododendron, Horse chestnut, Alnus* spp.	Apple, Peach, Pear, Plum, Apricot, Persimon, Wild pomegranate, Walnut, Almond, Pistachio nut	*Cymbopogon martinii, Themeda anathera, Cynodon dactylon, Apluda mutica, Andropogon nardus, Pennisetum clandestinum, Dactylis gloemerata*	Chisanga, Bhardwaj and Sharma (2013); Goswami, Verma and Kaushal (2014); Gupta, Sarvade and Singh (2017); Jhanju (2021); Kumari, Sehgal and Kumar (2008); Kumar *et al.* (2018a); Rajput, Bhardwaj and Pala (2017); Salve and Bhardwaj

Agro-climatic zones	*Agroforestry systems*	*Major agricultural crops*	*Major forest trees*	*Major fruit trees*	*Major grasses*	*References*
						(2020); Thakur (2020); Tiwari, Pant and Singh (2018)
Zone-IV	Agrisilviculture, Agrihorticulture, Agrisilvihorticulture, Agrihortisilviculture, Pastoralhorticulture, Silvipasture, Pastoralsilviculture	Maize, Potato, Amaranthus, Millets, Peas, Wheat, Barley, Oat, Millets	*Populus ciliata, Salix* spp., *Robinia* spp., *Cedrus deodara, Pinus wallichiana, Pinus gerardiana, Sea buckthorn*	Apple, Apricot, Grapes, Walnut, Almond, Pistachio nut	*Arundinella nepalensis Agrostis* spp., *Poa annua, Trifolium repens, Dactylis golemerata, Agrotis canina, P. alpinum, Poa pratensis*	Chisanga, Bhardwaj and Sharma (2013); Gupta, Sarvade and Singh (2017); Kaler, Gupta and Negi (2017); Kumari, Sehgal and Kumar (2008); Kumar *et al.* (2018a); Salve and Bhardwaj (2020)

Table 3: Biomass production potential of most prevalent agroforestry systems in Himachal Pradesh, India

Agro-climatic zones	*Agroforestry System*	*Biomass production*			*References*
		Above ground biomass (ton ha^{-1})	*Below ground biomass (ton ha^{-1})*	*Total biomass (ton ha^{-1})*	
Zone-I	Agrisilviculture	12.66-53.29	4.15- 13.47	17.24-66.76	Bammanahalli (2016); Gupta, Sarvade and Singh (2017); Kaler, Gupta and Negi (2017); Sharma *et al.* (2021); Singh (2019)
	Agrihorticulture	10.69-60.58	3.53 - 13.51	14.45-74.10	Bammanahalli (2016); Gupta, Sarvade and Singh (2017); Kaler, Gupta and Negi (2017); Sharma *et al.* (2021); Singh (2019); Singh *et al.* (2020)
	Agrisilvihorticulture	16.65 - 31.75	4.57 - 5.92	21.36 - 37.67	Bammanahalli (2016); Kaler, Gupta and Negi (2017)
	Agrihortisilviculture	16.93-70.91	3.38 – 21.21	20.31 - 92.12	Bammanahalli (2016); Gupta, Sarvade and Singh (2017); Sharma *et al.* (2021)
	Silvipastoral	4.58 - 45.04	1.33 - 11.30	5.92 - 56.35	Gupta, Sarvade and Singh (2017); Sharma *et al.* (2021); Singh (2019)
	Pastoralsilviculture	6.89-9.76	0.59 – 2.61	7.48 - 10.94	Bammanahalli (2016); Singh (2019)
Zone-II	Agrisilviculture	10.31 - 48.63	3.06 -14.50	13.47 - 63.13	Goswami, Verma and Kaushal (2014); Gupta, Sarvade and Singh (2017); Singh *et al.* (2015); Singh (2019); Toky, Kumar and Khosla (1989)
	Agrihorticulture	9.61 – 47.8	2.68 – 13.73	12.29 - 93.84	Goswami, Verma and Kaushal (2014); Gupta, Sarvade and Singh (2017); Rajput, Bhardwaj and Pala (2017); Singh *et al.* (2015); Singh *et al.* (2020); Singh (2019); Toky, Kumar and Khosla (1989)
	Agrisilvihorticulture	57.45-63.13	16.92 - 18.86	32.85 - 81.98	Goswami, Verma and Kaushal (2014); Gupta, Sarvade and Singh (2017); Singh *et al.* (2015)
	Agrihortisilviculture	47.2 – 60.95	17.60 - 18.02	32.01 - 78.98	Goswami, Verma and Kaushal (2014); Gupta, Sarvade and Singh (2017); Singh *et al.* (2015); Toky, Kumar and Khosla (1989)

Agro-climatic zones	*Agroforestry System*	*Biomass production*			*References*
		Above ground biomass (ton ha^{-1})	*Below ground biomass (ton ha^{-1})*	*Total biomass (ton ha^{-1})*	
	Silvipastoral	13.89 - 70.63	3.70 - 18.61	7.48 - 102.10	Goswami, Verma and Kaushal (2014); Gupta, Sarvade and Singh (2017); Rajput, Bhardwaj and Pala (2017); Singh *et al.* (2015); Singh (2019)
	Pastoralsilviculture	3.77 - 3.98	1.28- 1.36	5.13- 5.26	Singh (2019)
Zone-III	Agrisilviculture	13.93-56.87	3.98- 16.72	18.05 - 73.59	Goswami, Verma and Kaushal (2014); Gupta, Sarvade and Singh (2017); Thakur (2020)
	Agrihorticulture	9.58 - 52.12	3.25 – 15.29	12.83 – 103.2	Chisanga *et al.* (2018); Goswami, Verma and Kaushal (2014); Gupta, Sarvade and Singh (2017); Rajput, Bhardwaj and Pala (2017); Singh *et al.* (2020); Singh (2019)
	Hortiagriculture	14.17 - 26.42	3.99 -7.10	19.26 - 33.26	Jhanju (2021); Singh *et al.* (2020)
	Agrisilvihorticulture	15.15-67.97	4.30- 20.20	16.31 - 88.17	Goswami, Verma and Kaushal (2014); Gupta, Sarvade and Singh (2017); Thakur (2020)
	Agrihortisilviculture	13.26 – 85.49	4.08 - 23.08	18.40 - 108.60	Chisanga *et al.* (2018); Goswami, Verma and Kaushal (2014); Gupta, Sarvade and Singh (2017); Jhanju (2021); Thakur (2020)
	Silvipastoral	17.66 - 77.63	6.87 - 21.17	7.48 - 143.29	Chisanga *et al.* (2018); Goswami, Verma and Kaushal (2014); Gupta, Sarvade and Singh (2017); Rajput, Bhardwaj and Pala (2017); Singh (2019)
	Hortipastoral	11.24 - 22.51	3.23 - 5.76	14.47 - 28.27	Jhanju (2021); Singh *et al.* (2020); Thakur (2019)
	Pastoralsilvicultural	5.07-10.58	1.58- 3.27	6.66- 13.85	Jhanju (2021); Singh (2019); Thakur (2019)
Zone-IV	Agrisilviculture	89.59	24.58	105.9	Gupta, Sarvade and Singh (2017)
	Agrihorticulture	10 – 69.70	3.35 – 21.90	13.35 - 91.60	Chisanga *et al.* (2018); Gupta, Sarvade and Singh (2017); Singh *et al.* (2020)
	Hortiagriculture	15.45 - 25.29	4.34 - 6.56	19.79 - 31.85	Singh *et al.* (2020)
	Agrihortisilviculture	36.18	10.04	46.21	Chisanga *et al.* (2018); Gupta, Sarvade and Singh (2017)
	Silvipastoral	162.80 - 118.8	24.44- 35.7	143.29 – 198.20	Chisanga *et al.* (2018); Gupta, Sarvade and Singh (2017)
	Hortipastoral	19.19 - 24.97	4.93 - 6.33	24.11 - 31.30	Singh *et al.* (2020)

Table 4: Economic benefits of prevalent agroforestry systems in Himachal Pradesh

Agro-climatic zones	*Agroforestry System*	*Total Expenses (Rs. ha^{-1} yr^{-1})*	*Gross Returns (Rs. ha^{-1} yr^{-1})*	*Benefit Cost Ratio*	*References*
Zone-I	Agrisilviculture	59,046 – 243,667	126,446 – 484,401	1.23 – 2.92	Bammanahalli (2016); Kaler, Gupta and Negi (2017); Sharma *et al.* (2021); Singh (2014); Singh (2019)
	Agrihorticulture	22,781 – 219,029	49,489 – 506,333	1.86 – 2.74	Bammanahalli (2016); Kaler, Gupta and Negi (2017); Sharma *et al.* (2021); Singh (2014); Singh (2019)
	Agrisilvihorticulture	63,461 – 234,494	120,071 – 462,631	1.86 - 2.00	Bammanahalli (2016); Kaler, Gupta and Negi (2017); Sharma *et al.* (2021)

Agro-climatic zones	*Agroforestry System*	*Total Expenses (Rs. ha^{-1} yr^{-1})*	*Gross Returns (Rs. ha^{-1} yr^{-1})*	*Benefit Cost Ratio*	*References*
	Agrihortisilviculture	82,470 – 160,469	143,120-552,613	1.85- 4.97	Bammanahalli (2016); Sharma *et al.* (2021); Singh (2014)
	Silvipastoral	8,349 – 14,540	14,342 – 52,156	1.78 – 5.77	Sharma *et al.* (2021); Singh (2014); Singh (2019)
	Pastoralsilviculture	14,796 – 20,729	30,276-39,922	1.92- 2.05	Bammanahalli (2016); Singh (2019)
Zone-II	Agrisilviculture	29,141 – 180,802	64,632-380,814	2.05 – 2.24	Singh *et al.* (2015); Singh (2019)
	Agrihorticulture	28,882 – 171,935	65,166 – 293,563	1.52- 2.33	Singh *et al.* (2015); Singh (2019)
	Agrisilvihorticulture	128,660 – 139,837	190,292 – 285,825	1.93 – 2.40	Singh *et al.* (2015)
	Agrihortisilviculture	99,173-130,361	246,941 – 334,672	1.93- 2.16	Singh *et al.* (2015)
	Silvipastoral	6,467 – 20,236	20,532 – 35,214	1.74-3.45	Singh *et al.* (2015); Singh (2019)
	Pastoralsilviculture	18,828-19,437	37,891	1.95- 2.02	Singh (2019)
Zone-III	Agrisilviculture	148,889-194,802	299,133-399,915	1.97	Singh *et al.* (2015); Thakur (2020)
	Agrihorticulture	33,940 – 447,100	75,417 – 1,616,000	2.19- 2.40	Chisanga, Bhardwaj and Sharma (2013); Singh *et al.* (2015); Singh (2019)
	Hortiagriculture	42,054-87,772	100,983-207,463	2.25- 2.44	Singh (2019)
	Agrisilvihorticulture	112,511-173,297	231,687-405,282	2.83	Singh *et al.* (2015); Thakur (2020)
	Agrihortisilviculture	143,893-345,500	305,864 – 631,600	2.43	Chisanga, Bhardwaj and Sharma (2013); Singh *et al.* (2015); Thakur (2020)
	Silvipastoral	6,467 – 97,200	21,908-647,000	1.96- 3.38	Chisanga, Bhardwaj and Sharma (2013); Singh *et al.* (2015); Singh 2019
	Pastoralsilviculture	4,358-16,149	11,451-16,027	1.99	Singh (2019); Thakur (2020)
	Hortipastoral	48,850-79,493	146,020-199,320	2.12- 2.18	Singh (2019); Thakur (2020)
Zone-IV	Agrihorticulture	44,503-697,800	91,960-2,633,000	2.05- 3.78	Chisanga, Bhardwaj and Sharma (2013); Singh (2019)
	Hortiagriculture	48,692-86,637	112,966-206,592	2.32- 2.39	Singh (2019)
	Agrihortisilviculture	575,700	1,396,000	2.44	Chisanga, Bhardwaj and Sharma (2013)
	Silvipastoral	99,100	523,400	5.28	Chisanga, Bhardwaj and Sharma (2013)
	Hortipastoral	56,436-71,919	124,000-163,490	2.20- 2.29	Singh (2019)

Table 5: Carbon storage potential of different agroforestry systems in Himachal Pradesh

Agro-climatic zones	*Agroforestry System*	*Carbon stock potential (ton ha⁻¹)*					*References*
		Above ground carbon stock (ton ha⁻¹)	*Below ground carbon stock (ton ha⁻¹)*	*Total vegetation carbon stock (ton ha⁻¹)*	*Soil organic carbon stock (ton ha⁻¹)*	*Total carbon stock (ton ha⁻¹)*	
Zone-I	Agrisilviculture	5.86 – 26.65	2.16- 6.73	8.44-33.38	9.37-32.26	35.11-42.75	Bammanahalli (2016); Gupta, Sarvade and Singh (2017); Singh *et al.* (2019)
	Agrihorticulture	6.33-30.29	2.30- 6.76	8.64-37.05	17.05-31.51	36.58-58.39	Bammanahalli (2016); Gupta, Sarvade and Singh (2017); Singh *et al.* (2019)
	Agrisilvihorticulture	8.73-13.01	2.44-2.80	11.17-15.81	19.80-35.63	49.97-52.31	Bammanahalli (2016)
	Agrihortisilviculture	9.41-35.45	2.19- 10.60	12.10-46.06	12.40-27.29	32.12-58.46	Bammanahalli (2016); Gupta, Sarvade and Singh (2017); Singh *et al.* (2019)
	Silvipastoral	11.97-22.52	3.36- 5.65	15.34-28.17	17.96	46.13	Gupta, Sarvade and Singh (2017); Singh *et al.*, 2019
	Pastoralsilviculture	1.01-2.10	0.17-0.54	1.19-4.94	20.18-32.62	29.72-38.32	Bammanahalli (2016)
Zone-II	Agrisilviculture	22.26-24.32	6.69-7.25	28.95-31.57	49.43-50.01	78.38-81.58	Gupta, Sarvade and Singh (2017); Singh *et al.* (2015)
	Agrihorticulture	22.11-23.43	6.47-6.87	28.58-45.89	40.49-51.88	78.58-86.38	Gupta, Sarvade and Singh (2017); Rajput, Bhardwaj and Pala (2017); Singh *et al.* (2015)
	Agrisilvihorticulture	28.72-31.57	8.46-9.43	37.18-40.99	50.5-51.18	87.68-92.17	Gupta, Sarvade and Singh (2017); Singh *et al.* (2015)
	Agrihortisilviculture	29.37-30.48	8.80-9.01	38.17-39.49	49.74-52.57	87.91-92.06	Gupta, Sarvade and Singh (2017); Singh *et al.* (2015)
	Silvipastoral	33.57-35.32	8.66-9.31	42.23-51.06	36.25-49.76	87.31-94.38	Gupta, Sarvade and Singh (2017); Rajput, Bhardwaj and Pala (2017); Singh *et al.* (2015)
Zone-III	Agrisilviculture	28.44	8.36	36.80	51.19	87.99	Gupta, Sarvade and Singh (2017)
	Agrihorticulture	26.06	7.65	33.71-51.65	41.19-55.64	88.29-96.67	Gupta, Sarvade and Singh (2017); Rajput, Bhardwaj and Pala (2017)
	Agrisilvihorticulture	33.98	10.10	44.08	56.70	100.78	Gupta, Sarvade and Singh (2017)
	Agrihortisilviculture	35.96	10.69	46.65	54.06	100.71	Gupta, Sarvade and Singh (2017)
	Silvipastoral	38.81	10.59	49.40-71.61	37.41-53.12	100.28-109.93	Gupta, Sarvade and Singh (2017); Rajput, Bhardwaj and Pala (2017)

Agro-climatic zones	*Agroforestry System*	*Carbon stock potential (ton ha^{-1})*					*References*
		Above ground carbon stock (ton ha^{-1})	*Below ground carbon stock (ton ha^{-1})*	*Total vegetation carbon stock (ton ha^{-1})*	*Soil organic carbon stock (ton ha^{-1})*	*Total carbon stock (ton ha^{-1})*	
Zone-IV	Agrisilviculture	40.29	12.29	52.95	-	52.95	Gupta, Sarvade and Singh (2017)
	Agrihorticulture	33.43	10.95	46.04	21.03	67.07	Gupta, Sarvade and Singh (2017)
	Silvipastoral	59.4	12.23	71.61	17.91	89.54	Gupta, Sarvade and Singh (2017)

5. Carbon Stock Potential of Agroforestry

Agroforestry is a sustainable land use system that synergies the climate change mitigation as well as adaptation strategies. Various advantages associated with agroforestry land use are food security, prevention of degradation of soil resources, increase along with stabilization of farm income through diversification, enhancement in employment opportunities, sequestration of carbon, etc. (Chavan *et al.*, 2015; Sharma *et al.*, 2020). The CO_2 concentration in Earth's atmosphere is 413.20 + 0.2 ppm (WMO, 2021), which represents only a fraction of the CO_2 emitted as about 55% of it is removed by oceans and terrestrial vegetation. Forests being the lungs of the Earth have higher carbon sequestration potential than any other land use. Agroforestry has a high potential to sequester carbon from the atmosphere as compared to agricultural mono-cropping, thereby, helps in the mitigation and adaptation to climate change. The carbon storage potential of different agroforestry systems in Himachal Pradesh, as shown in table 5, depicts that agroforestry can store carbon ranging from 1.19- 71.61 ton ha^{-1} in vegetation and 9.37- 56.70 ton ha^{-1} as soil carbon with total carbon storage potential ranging from 29.72-109.93 ton ha^{-1}. Sequestering carbon through agroforestry land use also offers an additional economic opportunity through carbon trading in international market, thereby, mitigating climate change as well as meeting the societal needs through multiple products (Goswami, Verma and Kaushal, 2014). Further, it can be a way forward towards reduction of emissions by 10 per cent of 2012 emission levels upto 2022 as targeted by state government (GoHP, 2021).

6. Conclusion

From the above discussion, it can be concluded that, agroforestry being a sustainable land use system, certainly it is the need of the hour. Agroforestry technology at any area is ecologically driven for its structural arrangement as well as compositional difference. Through agroforestry farmers, especially in mountainous region facing multiple constraints can push productivity in desired direction guided by the need-based approach and can harness biological and economic benefits. Marginal and small farmers can reap higher economic benefits from small land units by adopting horticulture-based systems. Fodder tree-based farming systems can solve the dual objectives of fodder scarcity as well as uplifting livelihood status of farming families. Further, having higher carbon storage potential agroforestry land use can be used as the productive as well as protective tool to mitigate and adapt to changing climatic scenarios.

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Author' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

Contribution	Author 1	Author 2	Author 3	Author 4	Author 5
Conceived and designed the research or analysis	Yes	Yes	Yes	Yes	No
Collected the data	Yes	Yes	Yes	Yes	Yes
Contributed to data analysis & interpretation	Yes	Yes	Yes	Yes	Yes
Wrote the article/ paper	Yes	Yes	Yes	Yes	Yes
Critical revision of the article/paper	Yes	Yes	Yes	Yes	Yes
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