Potential of pastoral-based agroforestry systems in climate change mitigation in the northwestern Himalayas

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Key words: Agroforestry; pasture; biomass; carbon stock; climate change

Abstract
Silvipastoral systems, which integrate trees, forage, and grazing livestock on the same land, have gained importance because of their potential for carbon storage and for improving farmers' livelihoods. A study conducted in the subtropical region of the northwestern Himalayas along the elevation gradient (Zone I: <600 m amsl and 600-1200 m amsl). In Zone I, five agroforestry systems were identified: agrisilviculture, agrisilvihorticulture, agrisilvipastoral, pastoralsilviculture, and silvipastoral, whereas Zone II represents six agroforestry systems (agrisilviculture, agrisilvihorticulture, agrisilvipastoral, pastoralsilviculture, and silvipastoral). The pastoral-based agroforestry systems were specifically categorized as agrisilvipastoral, Pastoral silviculture, and silvipastoral. Six grass species (*Simarouba glauca, Imperata cylindrica, Cercocarpus montanus, Haemonchus contortus, Cymbopogon martini* and *Apluda mutica*) were recorded in both zones under pastoral-based systems, with tree species such as *Bauhinia variegata*, *Terminalia bellerica, Albizia chinensis, Ficus palmata, Grewia optiva, Acacia catechu, Bombax ceiba, Melia azedarach, Toona ciliata, Dalbergia sissoo, Populus deltoides, Leucaena leucocephala,* and *Morus alba*. In Zone I, the Agrisilvihorticulture system had the highest total biomass, followed by silvipastoral, agrisilviculture, agrisilvipastoral, and pastoral silviculture. In Zone II, the order was agrisilvihorticulture > silvipastoral > agrisilviculture > agrisilvipastoral > agihorticulture > pastoral silvicultureHowever, soil carbon stock was the highest in the silvipastoral system, resulting in the highest overall carbon stock in the silvipastoral system, these findings suggest that silvipastoral systems in subtropical regions have significant potential for carbon storage while meeting livestock forage demands, making them a valuable strategy for climate change mitigation in the subtropical western Himalayas

Introduction
Livestock is a key component of the agricultural system in India, and is crucial for the livelihood of rural households (Hemme and Otte 2010). Due to the rise in livestock population, increased forage demand has led to low livestock production (DAHD&F 2021). Forage production in India has always been hampered by the unavailability of sufficient arable land with irrigation facilities and changes in the land-use system. In addition, climate change has affected the productive capacity of land for high-quality forage production. Therefore, a balanced and sustainable land-use system is required to meet the forage demand, climate change mitigation, and

livelihood security of rural communities. Incorporating fodder trees with grass/other components of land use is considered a climate-change-resilient land-use system (Mbow et al., 2014). The integration of fodder trees with agricultural crops or grasses is termed agroforestry practice.

In agroforestry, the integration of fodder trees with agricultural crops or grasses is classified into different systems such as Agrisilviculture, Agrisilvihorticulture, Agrisilvipastoral, Pastoralsilviculture, and Silvipastoral systems. By integrating ecological functions with productive agricultural activities, silvopasture systems hold immense promise for confronting the challenges posed by climate change (Lawson et al., 2018; Rosenstock et al., 2019). Silvopasture/pastoralsilviculture systems represent a dynamic fusion of trees, forage, and livestock, meticulously orchestrated to optimize land productivity and ecological resilience (Jose, 2009; Peters et al., 2013). However, the synergies of tree-grass associations need to be explored and exploited by evaluating different fodder tree species with a combination of grass species under different climatic conditions. Furthermore, besides fulfilling fodder demand, agroforestry has been identified as having the greatest potential for carbon sequestration among all land uses (Nair and Garrity, 2012). The global assessment of carbon accumulation in agroforestry varied from 0.29 to 15.2 Mg C ha^{-1} $year^{-1}$ aboveground and 30–300 Mg C ha^{-1} $year^{-1}$ for soils down to 1 m depth (Nair et al. 2009). Based on the areas assessed as suitable for agroforestry interventions, a carbon storage potential of 1.1–2.2 Pg. C have been estimated globally (Albrecht and Kandji, 2003). Therefore, agroforestry is receiving increased attention in global initiatives, such as Reducing Emissions from Deforestation and Forest Degradation (REDD), because of its implication in improving and regulating climate variability (Jose and Bardhan, 2012). While previous studies have highlighted the potential of agroforestry systems for carbon sequestration, the specific contribution of silvopastoral systems in the northwestern Himalayas remains understudied, particularly across agroforestry systems. This study aims to evaluate the biomass and carbon sequestration potential of pastoral-based agroforestry systems across two elevation zones in the northwestern Himalayas, with a focus on silvopastoral systems as a climate-resilient strategy.

Methods

The study was conducted in two elevation zones, Zone I (< 600 m amsl) and Zone II (600-1200 m amsl), in the Nalagarh block of the Solan district of Himachal Pradesh, India. The stratified random sampling technique was used for the selection of the study area at two elevation zones, and then the sample plots were randomly distributed in each elevation zone. The existing agroforestry systems in the selected study area were classified into six types based on the structure (nature and arrangement) and function (role/output) of their components.

A 30 × 10 m^2 sample plot was laid in each agroforestry system. Within each sample plot, two subplots of 10 × 10 m and four subplots of size 50 × 50 cm were marked to observe respectively shrubs and herbage. To estimate agricultural crop biomass, four quadrats of size 2 × 2 m were marked for each system type. The aboveground tree biomass was estimated by a non-destructive method using volume equations developed by FSI (1996). Soil samples were collected from each plot at depths of 0-20 cm using a soil auger. Tree, herb, shrub, crop biomass, and tree carbon stock was calculated using the methods described by Singh and Kumar (2018). (2022). The collected data were statistically analyzed at a 5 percent level of critical difference using the software package "STATISTICS".

Results

Identification of pastoral-based silvopasture systems.

In zone I, the pastoralsilviculture system incorporated timber, fuel, and fodder trees, such as *Terminalia bellerica, Dalberigia sisso, Albizzia chinensis, Bauhinia variegata*, and *Ficus palmata*. Alongside these trees, various grass components, including *Seteria glauca, Imperata cylindrica, Chrysopogon montanus, Heteropogon contortus, Cymbopogan martinii*, and *Apluda mutica* were present. In the agrisilvipastoral system in Zone I, maize, brinjal, okra, rice, blackgram, and tomato were cultivated during the kharif season, whereas wheat, cauliflower, radish, barley, and onion were grown during the rabi season. Along the field bunds Various trees, such as *Cassia fistula,* *Dalbergia sissoo, Terminalia bellerica*, and *Toona ciliata*, were strategically planted in different quantities and arrangements. *Populus deltoides* trees played a significant role in this agroforestry system, being intentionally planted at various densities. Additionally, a mix of grasses, such as *Imperata cylindrica, Heteropogon contortus, Apluda mutica, Cymbopogon martini*, and *Chrysopogon montanus*, adorned the field bunds in assorted combinations.

In zone II, the pastoralsilviculture system comprised six distinct system units, incorporating a range of grasses, such as *Apluda mutica, Seteria glauca, Imperata cylindrica, Chrysopogon montanus, Heteropogon contortus*, and *Cymbopogon martinii*. Alongside these grasses, the system featured tree components, such as *Terminalia bellerica, Bauhinia variegata, Ficus palmata,* and *Albizzia chinensis*. Within the agrisilvipastoral systems in Zone II, farmers cultivate three primary cereal and vegetable crops (maize, rice, and okra) during the Kharif season and wheat, mustard, radish, and barley during the Rabi season. Along the field bunds in these systems, farmers intentionally planted trees, such as *Leucaena leucocephala, Morus alba, Albizzia chinensis, Grewia optiva, Bombax ceiba*, and *Bauhinia variegata*. Grasses such as *Digitaria stricta, Themeda anathera, Imperata cylindrica, Apluda mutica*, and *Cymbopogon martinii* were also cultivated. The pastoralsilviculture includes the trees species like *Grewia optiva, Bauhinia variegata, Ficus palmata, Morus alba, Leucaena leucocephala, Albazzia chinensis*, and *Bombax ceiba* along with *C. martinii, D. stricta, A. mutica, H. contortus, P. maximum*, and *T. anathera* as grass component.

Biomass and soil carbon density

The different types of agroforestry systems and varying elevation zones significantly influenced aboveground, belowground, and total biomass. In elevation zone I, the sequence of total aboveground biomass was highest in agrisilvihorticulture (29.57 t/ha), followed by Silvipastoral (27.97 t/ha) and Agrisilviculture (24.68/ t/ha). Similar trends were observed in Zone II, where Agrisilvihorticulture achieved 11.32 t/ha, followed by Silvipastoral (9.53 t/ha). The maximum belowground biomass in zone I was reported in Agrisilvihorticulture, Agrisilviculture, and Silvipastoral. Conversely, in elevation zone II, the maximum belowground biomass was recorded in the agrosilvihorticulture system, followed by the silvipasture system. The total biomass was found to be the highest in the Agrislivihorticulture system. The soil bulk density at elevation zone I was the highest in pastoral-silviculture, followed by silvipasture. In contrast, in elevation zone II, the highest value was recorded in the slivupasture system, followed by the pastoralsilviculture system. The soil organic carbon was found highest under Silvipastoral system (0.81 %) followed by Pastoral silviculture system (0.78 %).

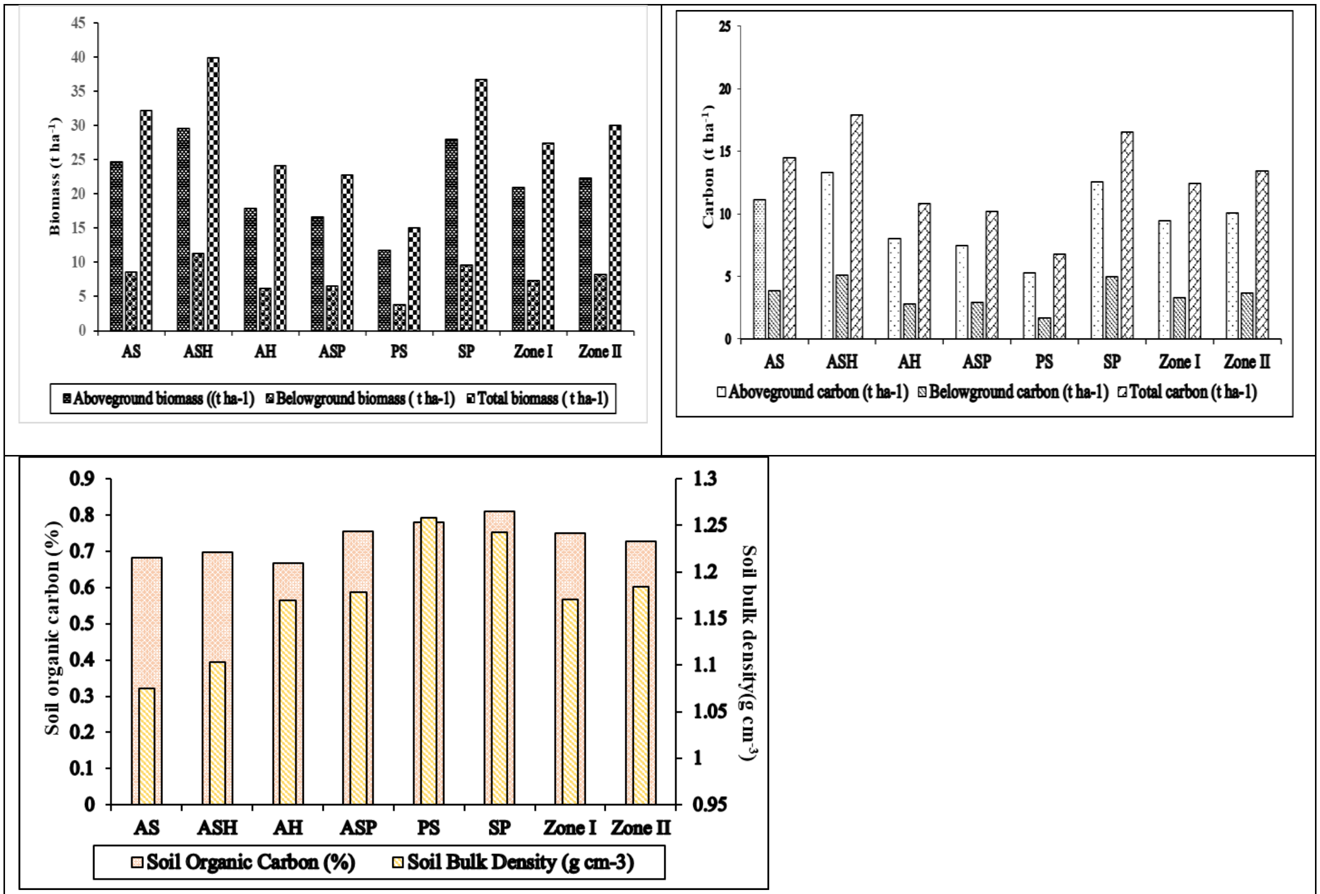

Figure 1: a) Above ground, below ground and total biomass (t ha^{-1}) of different agroforestry systems at two elevation zone; b) above ground carbon, below ground carbon and total carbon of different agroforestry systems at two elevation zone (t ha^{-1}); c) soil organic carbon (%) and soil bulk density (g cm^{-3}) of different agroforestry systems at two elevation zone. AS: agrisilviculture system; ASH: agrosilvihorticulture; AH: agrihorticulture; ASP: agrisilvipastoral; PS: pastoralsilviculture; SP: silvipastoral

Discussion

Agroforestry is a key component of climate change mitigation and livelihood security. Various agroforestry systems and their units have been studied in both the elevation zones. In this context, various researchers have recorded the same number of agroforestry systems with their respective units in the midhills of the northwestern Himalayas (Upadhyaya 1997; Goswami 2008). The multipurpose trees were recorded to exist in varied numbers on the bunds of agricultural fields, except for *P. deltoides* trees, which were regularly spaced all around the agricultural field. Trees of *D. sisoo, M. azedarach, C. fistula,* and *S. cumini* were found on bunds of agricultural fields, providing fuelwood, minor timber, and fodder for subsistence**.** Among the existing agroforestry systems, agrisilviculture, agrisilvihorticulture, and agrisilvipasture systems illustrate a greater diversity in their components.

In agroforestry, biomass accumulation and carbon sequestration are influenced by various factors, including climatic conditions, soil characteristics, phenology, and floristic diversity, which mainly occur through the absorption of atmospheric CO_2 during photosynthesis and the transfer of fixed carbon into vegetation, detritus, and soil pools for long-term storage in aboveground and belowground major segments (Baes *et al.* 1977; Nair *et al.* 2010). In the current study, the biomass and carbon stock were highest in agrisilvihorticulture, followed by the silvipasture system at elevation zone II. These findings are consistent with those of Singh (2017) and Bammanahalli (2016) in the subtropical region of Himachal Pradesh. Variations in biomass and carbon production are influenced by plant species diversity and genetic diversity interactions within dominant plant species (Crawford and Rudgers 2012). Goswami *et al.* (2014) found that agrisilvihorticulture and agrihortisilviculture systems produced higher biomass than the silvipasture system, as well as pure agriculture or grassland in the western Himalayan watershed. The higher biomass production observed at elevation zone II could be attributed to a greater number of tree species in the agroforestry systems, closer proximity to plant management practices, and variations in species composition. It is well established that incorporating trees into croplands and pastures enhances both aboveground and belowground carbon sequestration (Palm *et al.* 2004; Haile *et al.* 2008

The soil organic carbon content in the present investigation ranged from 0.66% to 0.81%, with the highest levels recorded in the silvipastoral system, followed by the pastoral silviculture system. Similar organic carbon levels have been reported by various researchers in agroforestry soils of the northwestern Himalayas (Rajput et al., 2015; Prenil, 2014; Singh, 2014; Bhutia, 2017). The higher soil carbon stock observed in silvopastoral systems may be attributed to enhanced organic matter input from tree litter and root exudates, which promote microbial activity and soil aggregation, thereby improving carbon retention. These findings highlight the significant role of agroforestry in climate change mitigation. Among various agroforestry systems, the agrisilviculture system exhibits high potential for carbon sequestration and food security, whereas the pastoral silviculture and silvipastoral systems store the highest soil organic carbon while also meeting the nation's fodder demand.

Therefore, it is concluded that in the midhills of the northwestern Himalayas, agrihortisilviculture followed by silvipastoral and pastoralsilviculture systems have a greater scope for climate change mitigation.

Table 1: Crop combination with tree components by different farmers s in terms of system units at elevation zone I and zone II.

Agroforestry systems	Agriculture/grass component		Tree components
	Kharif	Rabi	
Zone I			
Agrisilviculture	Zea mays (Maize), Capsicum annuum (Chilli), Abelmoschus esculentus (Okra), Solanum lycopersicon (Tomato) Solanum melogena (Brinjal), Oryza stavia (rice), Vigna mungo (Blackgram), Curcuma longa (Turmeric)	Triticum aestivum (Wheat), Hordeum vulgare (Barley), Brassica juncea (Mustard), Allium. cepa (Onion), Brassica oleracea (cauliflower), R. raphanistrum & Brassica juncea	Dalbergia sisso, Bahunia variegata, Bambax ceiba, Toona ciliata, Ficus palmata, Populus deltiodes, Grevia optiva, Morus alba, Melia azedarach,
Agrisilvihorticulture	Zea mays, Capsicum annuum, Abelmoschus esculentus, Solanum Lycopersicon, Solanum melogena, Oryza stavia, Curcuma longa & Vigna mungo	Triticum aestivum, Brassica juncea, Allium Cepa, Brassica oleracea oleracea, R. raphanistrum, Hordeum vulgare	Morus alba, Grewia optiva, Citrus limon, Mangifera indica, Psidium guajava, Melia azedarach & Cassia fistula

Pastoralsilviculture	**Grasses:** Simarounba glauca, Imperata cylindrica, Cercocarpus montanus, Haemonchus contortus, Cymbopogon martini, Apluda mutica, C. martini		Terminalia bellerica, Dalbergia sisoo, Albizia chinensis, Bahunia variegata, Ficus palmata, Grevia optiva, Acacia catechu & Bombax ceiba
Agrisilvipastoral	Zea. mays, Oryza stavia, Abelmoschus esculentus, Solanum melogena, Solanum Lycopersicon, Vigna mungo	Triticum aestivum, Brassica oleracea, R. raphanistrum, Hordeum vulgare, Allium cepa, Brassica juncea	Populus deltoides, Cassia fistula, Dalbergia sissoo, Terminalia bellerica, Toona ciliata, Grevia optiva, Albizia chinensis, Bombax ceiba
	Grasses: Imperata cylindrica, Haemonchus contortus, Apluda mutica, Cercocarpus montanus, Simarounba glauca, Cymbopogon martini		
Silvipastoral	**Grasses:** Cercocarpus montanus, Haemonchus contortus, Imperata cylindrica, Apluda mutica, Simarounba glauca, Cymbopogon martini		Melia azedarach, Terminalia bellerica, Toona ciliata, Bombax ceiba, Dalbergia sissoo, Bahunia variegata, Albizia chinensis
Zone II			
Agrisilviculture	Z. mays, C. annuum, A. esculentus, S. melogena, V. mungo, C. longa, S. lycopersicon C. annuum, A. esculentus	T. aestivum, R. raphanistrum, H. vulgare, B. juncea, A. sativum, H. vulgare, B. oleracea and A. cepa	G. optiva, A. chinensis, L. leucocephala, T. bellerica, M. alba, F. palmata, B. variegata, L. leucocephala, B. ceiba, Z. mauritiana & A. chinensis
Agrisilvihorticulture	Z. mays, C. annuum, A. esculentus, O. sativa, C. longa & S. lycopersicon,	T. aestivum, B. juncea, R. raphanistrum, H. vulgare, A. cepa	G. optiva, A. chinensis, L. leucocephala, C. limon, T. bellerica, M. alba, F. palmata, B. variegata
Agrisilvipastoral	Z. mays, A. esculentus, O. sativa,	T. aestivum, R. raphanistrum, B. nigra, B. oleracea, H. vulgare & B. juncea	L. leucocephala, M. alba, A. chinensis, B. ceiba, G. optiva, B. variegata M. indica, B. variegata + C. limon, F. palmata, T. belerica & Z. mauritiana
	Grasses: T. anathera, A. mutica, C. martinii, I. cylindrica P. maximum, D. stricta, C. longa, S. Lycopersicon, C. annuum, V. mungo, S. melogena, C. montanus, H. contortus & I. cylindrica		
Pastoralsilviculture	C. martinii, T. anathera, H. contortus, D. strica, A. mutica, P. maximum, I. cylindrica & C. montanus,		M. alba, B. ceiba, F. palmata, G. optiva, A. catechu, L. leucocephala, B. variegate, Z. mauritiana, T. belerica, A. chinensis, T. bellerica, A. catechu
Silvipastoral	A. mutica, H. contortus, I. cylindrica, P. maximum, C. martini, D. stricta, & C. montanus		G. optiva, M. alba, B. variegata, L. leucocephala, Z. mauritiana, T. belerica, B. ceiba, F. palmata, A. catechu, A. chinensis & F. palmata

Acknowledgements
The authors would like to thank all the farmers who kindly provided data from their farms. We also thank Professor and Head of the Department of Silviculture and Agroforestry for providing all the necessary resources for the data analysis.

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