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Soil Nutrient Dynamics under Silviculture, Silvipasture and Hortipasture as Alternate Land-Use Systems in Semi-Arid Environment

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Abstract: In order to support livelihoods, enhance food security, restore ecosystem services, and reduce pressure on forests, degraded land can be restored by utilising alternative land-use systems (ALUS), such as silviculture, silvipasture, and hortipasture techniques. ALUS significantly modify the dynamics of soil nutrients in both the surface and subsurface layers. Soils from the 0–15, 15–30, and 30–45 cm layers of *Leucaena leucocephala* (S)-, *Hardwickia binata* (H)-, *Emblica officinalis* (A)-, and *Azadiracta indica* (N)-based silviculture systems, *Acacia nilotica*-based silvipasture systems (SPS), natural grassland (NT), and fallow land (F) were sampled in order to better understand the nutrient dynamics of ALUS. Soils under S, H, and SPS had ~203%, 195%, and 129% higher organic carbon (SOC), respectively, than fallow land in the 0–15 cm soil layer. In the subsequent soil layer, those land-use systems had ~199%, 82%, and 110% higher SOC, respectively, than fallow land. Similarly, in the deeper layer, those land uses had ~232%, 23%, and 105% higher SOC, respectively, than fallow land. SPS and NT also improved the SOC concentration significantly over fallow land. Plots under S, H, and SPS had ~198%, 190%, and 125% higher available N, respectively, than fallow land in 0–15 cm soil layer. In the 15–30 cm soil layer, those land-use systems had ~19%9, 82%, and 110% higher available N, respectively, than fallow land. These systems also improved the P and K contents in subsurface soil. Micronutrient concentrations were also improved in soils under S, H, and SPS. Hence, ALUS' adoption in degraded areas with trees provides a chance for C storage and improves the nutrient dynamics on degraded land.

Keywords: land-use system; silviculture; hortipasture; soil organic carbon; nutrient dynamics

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1. Introduction

In general, agricultural production serves as the foundation of the economy in the majority of developing nations [1]. Alternate land-use systems (ALUS) including silviculture, silvipasture, and hortipasture techniques can be used to repair degraded land in order to sustain livelihoods, increase food security, restore ecosystem services, and reduce pressure on forests [2]. However, obtaining these benefits is not simple [3,4]. By utilising both concrete and intangible advantages, silviculture plays a considerable role in the Indian economy. In reality, it allows for the simultaneous achievement of three important objectives, namely, safeguarding and stabilising ecosystems, producing an excess level of financial commodities, and increasing income and access to essentials for rural people. Additionally, silviculture plays a key role in maintaining the resource base and generally increasing basic production in rainfed regions and particularly in arid and semi-arid regions.

In the near future, silviculture will play a crucial role in environmental services such as carbon sequestration for local weather-change mitigation, phytoremediation for watershed safety, and biodiversity preservation. Now that woody elements such as trees, shrubs, bamboos, canes, and pasture/animals are being simultaneously or sequentially introduced and/or retained on the same unit of land to meet both the ecological and socioeconomic needs of people, silviculture is being recognised as a science that involves planning and developing integrated self-sustainable land management structures [5]. Silviculture is essential for lowering vulnerability, boosting agricultural structural resilience, and shielding households from weather-related threats. Additionally, it offers natural benefits including access to water, healthy soil, and biodiversity [6].

Agroforestry also provides nutritional protection due to numerous manufacturing systems that include food plants grown by farmers as well as oilseed crops, fruits, vegetables, legumes, and aromatic medicinal plants. Silviculture structures allow farmers to diversify their income sources and increase farm output. In silviculture, enhanced productivity is most likely caused by the size of more growth factors, such as light or water, or by increased soil fertility. A huge degraded area (96 m ha), remarkable natural habitat degradation, and extreme weather events are all leading Indian environmental concerns [7]. Silviculture structures have been effective in preventing droughts, reclaiming waterlogged places, controlling floods, reclaiming wastelands, reclaiming ravines, stopping sea erosion, managing desertification, reclaiming mine scrap, and treating saline and alkaline lands. ALUS have been identified as an economically effective solution for degraded soil to address these problems [8].

Prior research has mostly concentrated on ALUS' potential for productivity [9] or carbon sequestration [10], and little effort has been made to understand the nutrient cycles and dynamics associated with ALUS. The main goal of this particular experiment was to assess the nutrient dynamics in order to determine how various silvopasture and silvicultural systems affected such dynamics of the nutrients in the topsoil and subsurface soil layers. However, based on the suitability of land-use systems in this particular climatic condition, a *Leucaena leucocephala*-, *Hardwickia binata*-, *Emblica officinalis*-, *Azadiracta indica*-, and *Acacia nilotica*-based land-use system and natural grassland (NT) were tested for their efficiency.

2. Materials and Methods

2.1. Study Site Description

Our research was conducted in the Jhansi District of Indian state of Uttar Pradesh. The area is part of the Bundelkhand region geologically. The experiment site's soil type is sandy loamy and of the inceptisol order (Table 1). Physical appearance of the soil was dark brown to reddish red, shallow, and well-drained. Six ALUS were chosen for the study, including silviculture based on *Leucaena leucocephala* (Lam), also known as subabul (S), *Hardwickia binata* (Roxb.) *Emblica officinalis* (Gaertn.), also known as aonla, and *Azadiractha indica* (A.Juss), also known as neem; silvipasture systems (SPS) based on *Acacia nilotica* (L.); and natural grassland (NT). Location, area covered, grazing frequency, and establishment year are mentioned in Table 1. The values were compared with fallow land because these systems were built throughout a variety of time periods. In 2000, a 3.0 ha subabul-based system was established, and grass species such as *Heteropogon contortus*, *Brachiaria decumbens*, *Panicum maximum*, and *Cenchrus ciliaris* dominated it. In 1980, the *Hardwickia*-based system was established, and *Syda acuta*, *Syda cordifoilia*, *Achyranthes aspera*, and *Alternanthera sessilis* dominated it. *Chrysopogon fulvus* and *Panicum maximum* are two common grass species found in the Acacia-based SPS established in 2010. *Panicum maximum*, *Cenchrus ciliaris*, *Cenchrus setigerus*, *Pennisetum pedicellatum*, and *Brachiaria decumbens* dominated the 1.2-hectare aonla-based HPS. *Celosia argentea*, *Cenchrus ciliaris*, *Acanthospermum hispidum*, *Hyptis suaveolens*, and *Eragrostis cilianensis* dominated the natural grassland region. *Cenchrus ciliaris*, *Cynodondactylon*, and *Alternanthera sessilis* were dominant in neem-based SPS. The ALUS were developed for restoration purposes. The seedlings were native in nature and planted manually by hand, after digging hole in soil. The systems were not close to one another. They were established in different areas of the farm. The ALUS were developed on degraded land. Geologically, the area belongs to the part of the Bundelkhand region, which is characterised by devastating drought, barren soil, and extreme climate. The altitude of the site is ~326 msl. Rocks such as gneisses and granites with highly ferruginous beds and basic igneous intrusions are observed in this tract. The major drivers for land degradation are wind erosion and poor soil fertility. The soil of the experimental site belongs to the hypothermic family of Typic *Haplustepts* with sandy loam texture. They are shallow and dark brown to yellowish red. The soil is low in SOC (0.35%), mineral N (183 kg ha^{-1}), and plant-available P (9 kg ha^{-1}) and K (250 kg ha^{-1}). The water-holding capacity and nutrient-retention capacity of these soils are medium. Saturation water-holding capacity of soil was 32.5% (v/v). During May to July, the mean wind velocity is >8 km hr^{-1}, causing soil erosion ranging between 37 and 53 t ha^{-1} $year^{-1}$. Hence, cultivation of commercial crops, such as, rice, wheat, maize, and pulses is not possible in this region. To support livelihoods of common people, tree-based alternate land-use systems were chosen.

Table 1. The details of experimental site.

Land-Use Systems	Area (ha)	Soil Type	Grazing Type
Leucaena leucocephala (S)	3	Sandy Loam	Occasional grazing
Hardwickia binata (H)	2	Sandy Loam	Occasional grazing
Acacia nilotica (SPS)	1.1	Sandy Loam	Occasional grazing
Emblica officinalis (A)	1.2	Sandy Loam	Occasional grazing
Natural grassland (NT)	2	Sandy Loam	Frequent grazing
Azadiracta indica (N)	2	Sandy Loam	Occasional grazing
Fallow (F)	2	Sandy Loam	

The normal environment in our study location includes dry air, hot summer, and a cold, foggy winter (late November to middle of March). The district receives 840 mm of precipitation on average every year, with 90% of that coming during the southwest monsoon and the other 10% falling throughout the rest of the year. In the Bundelkhand region, the pattern of rainfall is frequently irregular, leading to periodic droughts. In January (the coldest month), the average daily high and low temperatures were 21.34 °C and 6.84 °C, respectively. The hottest month from 2015 to 2020 was May, with a mean daily maximum temperature of 41.48 °C. The hottest temperature occasionally exceeded 48 °C in May and June. June had the highest mean daily evaporation (12.80 mm d^{-1}).

2.2. Soil Sampling and Processing

Soil samples were collected from three layers (i.e., 0–15, 15–30, and 30–45 cm depths) of all ALUS in October 2020. In three replicates, dual units of clean samples (500 g) were randomly selected from all ALUS. Thus, a total of 21 soil samples from all soil depths were collected in each batch. In a nutshell, a core sampler comprises a galvanised iron cylinder of 5.5 cm diameter and 15 cm top used to press into the soil. Soil samples were accumulated from 3 factors in every plot. Thereafter, they were merged to create a unified sample for one plot. For measuring soil bulk density, one set was utilised. Once, there were two sub-samples taken from the other set. One sub-sample set was air dried, ground in a wooden pestle and mortar, and then sieved to skip via a 2.0 mm sieve (bulk soils). A <2.0 mm sieve was also employed to separate combinations from the second sub-sample. Soil chemical analysis was determined using processed soil samples.

2.3. Soil Analysis

With a pH meter, deionised water was used to measure the pH of the soil (1:2.5 soil:water). The salinity of the soil was assessed with a conductivity meter using the electrical conductivity of an aqueous soil extract in deionised water. Soil bulk density was measured using a soil core sampler method. Nitrogen, phosphorous, and potassium were expected to be accessible to plants [10,11]. They were estimated by extracting soil with potassium chloride, sodium bicarbonate, and ammonium acetate, respectively. Nitogen was estimated using Kjeldahl method. Phosphorus was measured colourimetrically. Potassium was quantified using a flame photometer. The Walkley–Black technique was used to calculate SOC [12]. Soil micronutrients were determined through the use of DTPA (Diethylen triamine Penta acetic acid) extract (1:2 Soil:DTPA). Fe, Mn, Zn, and Cu were determined per the method outlined by Lindsay and Norvell using an atomic absorption spectrophotometer [13].

2.4. Statistical Analysis

The generated data were dealt with for evaluation of variance (ANOVA)—as applicable to one-way ANOVA—to check differences among the land-use systems as described by [14]. Tukey's honest significant difference test was used as mean separation test ($p < 0.05$).

3. Results

3.1. Impact of Alternate Land-Use Systems on Soil pH and EC

The pHs of the soil appraised at the surface soil layers in all land-use systems were acidic in reaction (Table 2). Significant differences in pH were observed between the systems of different LUS. Overall, pH values in were significantly higher in S, A, NT, and F than H, SPS, and N systems. This finding is in line with that of Muche et al. [15]: the pH of cultivated land was more acidic than the pH of other land-use types.

Table 2. The pH and electrical conductivity (EC) in surface (0–15 cm) soil layer, as influenced by different LUS in semi-arid environment. Means with similar lowercase letters within a column are not significantly different at $p < 0.05$ according to LSD test. See Materials and Methods for detailed information on LUS.

LUS	**pH (H_2O)**	**EC**
	0–15 cm	**0–15 cm**
S	6.5a	0.031
H	5.5a	0.026
SPS	6.0a	0.034
A	6.5a	0.033
NT	6.5a	0.029
N	6.0a	0.027
F	6.5a	0.019
SE (m)	0.39	

The electrical conductivity (EC) of soil was estimated at surface soil layers in all LUS. Significant differences in EC were observed between the systems of different LUS (Table 2). Overall, the maximum EC value was observed in the SPS system at 0.034 dSm^{-1}, and the minimum EC value was observed in fallow land at 0.019 dSm^{-1}. The EC values were significantly greater in S, H, SPS, A, NT, and N compared to fallow land (Table 2).

3.2. Impact of Alternate Land-Use Systems on Bulk Density (BD)

The soils under S, H, and SPS had ~9%, 8%, and 4% less BD, respectively, than fallow land in the 0–15 cm soil layer. In the 15–30 cm soil layer, these land-use systems had ~6%, 6%, and 3% decreased BD than fallow land (Figure 1). Similar to this, in the deeper soil layer, i.e., 30–45 cm, these land uses had ~11%, 9%, and 7% less BD, respectively, than fallow land and a significantly higher bulk density in S than H and SPS, respectively. The *Acacia*-based ALUS had ~4%, 3%, and 3% less BD, respectively, than fallow land, a higher BD than S and H, and a significantly similar concentration to SPS and NT; they had a similar BD to NT in the 30–45 cm soil layer. Interestingly, neem-based ALUS and fallow land had significantly less BD in all soil layers (Figure 1).

3.3. Impact of Alternate Land-Use Systems on Total Organic Carbon in Soil (TOC)

Under the 0–15 cm soil depth, S, H, and SPS had ~204%, 195%, and 129% greater TOC, respectively, than fallow land. These land-use systems showed TOC values that were ~199%, 83%, and 110% greater than fallow land, respectively, in the 15–30 cm soil layer (Table 3). Similarly, in the deeper soil layer i.e., 30–45 cm, those land uses had ~232%, 24%, and 105% higher TOC, respectively, than fallow land. *Acacia*-based ALUS and NT also improved the TOC concentration significantly over fallow land. Nevertheless, they had less TOC content than S, H, and SPS. Interestingly, neem-based LUS and fallow land had a similar TOC in all soil layers (Table 3).

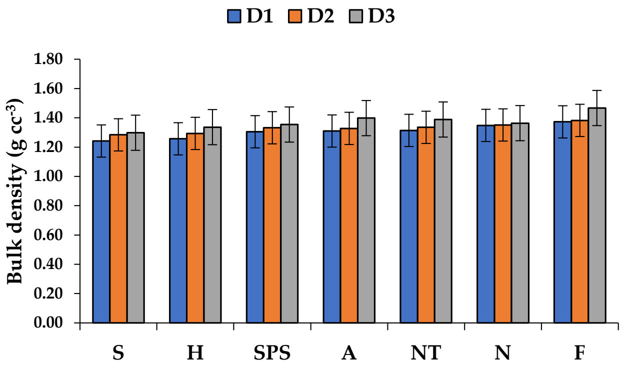

Figure 1. Bulk density (g cc^{-3}) in surface (0–15 cm) and subsurface (15–30 cm and 30–45 cm) soil layers, as influenced by different LUS in semi-arid environment. Error bars indicate LSD at $p < 0.05$. See Materials and Methods for detailed information on LUS. D1: 0–15 cm, D2: 15–30 cm, and D3: 30–45 cm soil layers.

Table 3. Total soil organic carbon (SOC; g kg^{-1}), available nitrogen (N; g kg^{-1}), phosphorus (P; kg ha^{-1}), and potassium (K; kg ha^{-1}) in surface (0–15 cm) and subsurface (15–30 cm and 30–45 cm) soil layers, as influenced by different LUS in semi-arid environment. Means with similar lowercase letters within a column are not significantly different at $p < 0.05$ according to LSD test. See Materials and Methods for detailed information on LUS.

	SOC		
	0–15 cm	**15–30 cm**	**30–45 cm**
S	1.46a	1.44a	1.36a
H	1.42a	0.88c	0.51d
SPS	1.10b	1.01b	0.84bc
A	0.99c	1.01b	0.89b
NT	0.83d	0.86c	0.79c
N	0.54e	0.40d	0.38e
F	0.48e	0.48d	0.41e
SE (m)	0.39	0.35	0.35
	N		
	0–15 cm	**15–30 cm**	**30–45 cm**
S	1.82a	1.80a	1.70a
H	1.77a	1.10c	0.63d
SPS	1.38b	1.26b	1.05bc
A	1.24b	1.26b	1.12b
NT	1.04c	1.08d	0.99c
N	0.67d	0.50f	0.48e
F	0.61d	0.60e	0.51de
SE (m)	0.48	0.44	0.43
	P		
	0–15 cm	**15–30 cm**	**30–45 cm**
S	38.53a	32.38a	31.97a
H	31.97b	27.46b	28.28b
SPS	27.87c	27.05b	24.19c
A	27.05c	22.96c	22.55de
NT	25.01d	22.96c	21.32d
N	20.50e	19.27d	24.60c
F	18.04e	15.58e	20.91d
SE (m)	6.89	5.58	4.01
	K		
	0–15 cm	**15–30 cm**	**30–45 cm**
S	268.8b	262.08a	257.60b
H	239.68c	257.60ab	230.72c
SPS	238.56c	256.48ab	196.00d
A	286.72a	264.32a	294.56a
NT	228.48c	240.80bc	189.28d
N	202.72d	229.60c	228.48c
F	252bc	244.16bc	259.84b
SE (m)	27.34	12.79	37.26

3.4. Impact of Alternate Land-Use Systems on Available Nitrogen (N)

In the 0–15 cm soil layer, plots under S, H, and SPS had ~198%, 190%, and 125% higher available N, respectively, than fallow land. In the case of the 15–30 cm soil layer, those land-use systems had ~200%, 110%, and 210% higher available N, respectively, than fallow land. Similar to this, for the deeper soil layer, i.e., 30–45 cm, those land uses had ~233%, 39%, and 205% greater available N, respectively, than fallow land (Table 3). The *Acacia*-based plot had ~103% greater available N than fallow land and a significantly lower concentration than S, H, and SPS. NT-based ALUS had 70%, 180%, and 194% higher concentrations in the 0–15, 15–30 and 30–45 cm depths of soil, respectively, in comparison to fallow land. Neem-based LUS and fallow land had similar available N content in the 0–15 cm and 30–45 cm depths of soil, but in the case of the 15–30 cm soil depth, there was an 83% higher concentration in comparison to fallow land (Table 3).

3.5. Impact of Alternate Land-Use Systems on Available Phosphorus (P)

In the 0–15 cm soil layer, the soils under S, H, and SPS had ~113%, 77%, and 54% more available phosphorus, respectively, than fallow land. The available phosphorus in those land-use systems was ~107%, 76%, and 73% higher, respectively, than it was in fallow land in the 15–30 cm soil layer (Table 3). Similar to this, those areas of land usage had approximately 52%, 35%, and 15% more available phosphorus in the deeper soil layer, i.e., 30–45 cm, respectively, than fallow land. Compared to fallow land, *Acacia*-based ALUS significantly increased the available phosphorus level. However, compared to S, H, and NT, they had a lower available phosphorus amount, and they had a similar concentration to SPS in the surface soil, with a similar concentration to NT in the 15–30 cm depth, a higher concentration than NT, and a lower concentration than S, H, and SPS. In neem-based ALUS, the available phosphorus concentration had ~23% and 17% rise in the deeper soil layer (Table 3).

3.6. Impact of Alternate Land-Use Systems on Available Potassium (K)

The soil under *Acacia* had ~14%, 8%, and 13% greater concentrations of K in all three layers, respectively; however, soil under H, SPS, NT, and N had ~4%, 5%, 9%, and 19% lower concentrations of K, respectively, in comparison to fallow land at the 0–15 cm soil depth. In the case of the lower soil depth, i.e., 15–30 cm, S, H, and SPS had ~7%, 5%, and 5% greater concentrations for available potassium, respectively, than fallow land. Soil under NT and N had ~1% and 5% lower concentrations of K, respectively, than fallow land. Likewise, in the deeper soil depth, i.e., 30–45 cm, soil under H, SPS, NT, and N had ~11%, 24%, 27%, and 12% lower concentrations of available potassium, respectively, than fallow land. Interestingly, only *Acacia* had a higher concentration of available potassium (Table 3).

3.7. Impact of Alternate Land-Use Systems on Iron (Fe)

In the 0–15 cm soil layer, soils under S, H, and SPS had ~172%, 66%, and 33% higher iron, respectively, than fallow land. In the 15–30 cm soil layer, those land-use systems had ~66%, 46%, and 26% higher iron, respectively, than fallow land. Likewise, in the deeper soil layer, i.e., 30–45 cm, those land uses had ~53%, 41%, and 35% higher iron, respectively, than fallow land (Table 4). *Acacia*-based ALUS also had ~27%, 26%, and 23% improved iron concentrations, respectively, above fallow land; however, they had lower iron concentrations than S, H, and SPS. The NT-based system had ~22%, 6%, and 17% improved iron concentration in the three soil layers, respectively. Neem-based LUS had ~5% improved iron concentration in the 0–15 and 30–45 cm soil depths, in comparison to fallow land (Table 4).

3.8. Impact of Alternate Land-Use Systems on Manganese (Mn)

Soils beneath S, H, and SPS had ~80%, 61%, and 53% greater manganese, respectively, than fallow land in the 0–15 cm soil layer. Under the 15–30 cm depth, these land-use systems had ~52%, 45%, and 45% greater manganese, respectively, than fallow land. Similar to this, in the deeper soil layer, i.e., 30–45 cm, these land uses had ~96%, 84%, and 56% greater manganese, respectively, than fallow land (Table 4). *Acacia*-based ALUS accelerated manganese concentration by ~33%, 41%, and 32% for the three years, respectively, all considerably more than fallow land. A similar trend was also observed in the NT-based system. Neem-based LUS had a relatively lower level of increase, ~20%, 7%, and 13% than fallow land for the three layers, respectively (Table 4).

Table 4. Iron (Fe; ppm), manganese (Mn; ppm), copper (Cu; ppm), and zinc (Zn; ppm) in surface (0–15 cm) and subsurface (15–30 cm and 30–45 cm) soil layers, as influenced by different LUS in semi-arid environment. Means with similar lowercase letters within a column are not significantly different at $p < 0.05$ according to LSD test. See Materials and Methods for detailed information on LUS.

	Fe (ppm)		
	0–15 cm	**15–30 cm**	**30–45 cm**
S	17.59a	8.97a	9.33a
H	10.77b	7.90b	8.62b
SPS	8.62c	6.82c	8.26b
A	8.26c	6.82c	7.54c
NT	7.90d	5.74d	7.18d
N	6.82e	5.38e	6.46e
F	6.46f	5.38e	6.10f
SE (m)	3.84	1.35	1.17
	Mn (ppm)		
	0–15 cm	**15–30 cm**	**30–45 cm**
S	51.32a	43.96a	49.24a
H	46.04b	41.88ab	46.22a
SPS	43.66b	41.82ab	39.16b
A	37.96c	40.70b	32.04c
NT	37.56c	38.50b	31.80c
N	34.40d	30.96c	28.48d
F	28.48e	28.84c	25.04d
SE (m)	7.66	5.86	9.13
	Cu (ppm)		
	0–15 cm	**15–30 cm**	**30–45 cm**
S	2.17a	2.01a	2.25a
H	2.01b	1.97a	1.93b
SPS	1.97b	1.74b	1.74c
A	1.78c	1.62b	1.74c
NT	1.74cd	1.46c	1.70c
N	1.62d	1.39c	1.62cd
F	1.50d	1.35c	1.54d
SE (m)	0.24	0.27	0.24
	Zn (ppm)		
	0–15 cm	**15–30 cm**	**30–45 cm**
S	4.78a	1.35a	3.77a
H	4.75a	1.14ab	1.30b
SPS	2.07b	1.09b	1.16c
A	1.28c	0.99c	1.07cd
NT	1.09c	0.99c	1.02d
N	0.97d	0.93cd	1.00d
F	0.96d	0.86d	0.78e
SE (m)	1.74	0.16	1.04

3.9. Impact of Alternate Land-Use Systems on Copper (Cu)

The soils in the 0–15 cm soil layer underneath S, H, and SPS had ~44%, 34%, and 31% greater copper, respectively, than fallow land. Their land-use systems comprised 49%, 46%, and 28% more copper, respectively, than fallow land in the 15–30 cm layer of soil (Table 4). Additionally, these land uses had copper concentrations that were 46%, 25%, and 12% greater, respectively, than fallow land in the deeper soil layer, i.e., 30–45 cm (Table 4). *Acacia*-based LUS had ~8%, 20%, and 12% copper concentrations, respectively, than fallow land; however, they had a much lower Cu concentration than S, H, and SPS in all three soil layers. The NT-based ALUS had ~16%, 8%, and 10% increased copper concentrations than fallow land. Interestingly, neem-based ALUS and the fallow system had similar copper concentrations in all three soil layers (Table 4).

3.10. Impact of Alternate Land-Use Systems on Zinc (Zn)

The S, H, and SPS soils in the 0–15 cm layer of soil had 397%, 394%, and 115% more zinc, respectively, than fallow land. Under the 15–30 cm soil depth, their land-use systems had ~57%, 33%, and 27% higher copper concentrations, respectively, than fallow land (Table 4). Likewise, in the deeper soil layer, i.e., 30–45 cm, these land uses had ~383%, 67%, and 49% higher zinc concentrations, respectively, than fallow land (Table 4). *Acacia*-based ALUS had ~33%, 15%, and 37% higher copper concentrations than fallow land; however, they had much lower concentrations than S, H, and SPS in all soil layers. The NT-based ALUS had ~14%, 15%, and 30% increased Zn concentrations, respectively, than fallow land. Interestingly, neem-based ALUS and the fallow system had similar Zn concentrations at both depths (0–15 and 15–30 cm) (Table 4).

4. Discussion

It is estimated that at different spatial scales, soil properties are controlled mainly by land use, soil type, land management, and vegetation type [16–21]. The available nitrogen, phosphorous, and potassium significantly ($p < 0.001$) varied along soil depths for all land uses. Further, the interaction between the soil depth and land use for the available nutrients was significant ($p < 0.05$).

The greater amount of micronutrient availability in S-, H-, and SPS-based ALUS is probably due to higher decomposition and nutrient mineralisation. Available Zn and Mn (DTPA-extracted) were highly significant ($p < 0.001$) for land use and soil depth. In addition, DTPA-extractable Cu was significant ($p < 0.001$) for all land uses and soil depth. Leaf litters and their decomposition under perennial vegetation of S, H, and SPS favour nutrient enrichment compared to regular crop removal. For all land uses, the amount of available N, P, and K varied considerably ($p < 0.001$) with the soil depth. Additionally, the interaction between soil depth and land use for the available micronutrients was significant ($p < 0.05$). The increased breakdown and nutrient mineralisation in S, H, and SPS are likely the causes of the larger micronutrient availability.

Along with NPK, calcium (Ca), magnesium (Mg), and sulphur (S) are considered as essential macronutrients. Micronutrients such as copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn) are also considered essential for plant nutrition. These micronutrients act as a co-factor for the various enzymes associated with the metabolism of various organic molecules such as carbohydrates, nucleic acids, proteins, and lipids. Micronutrients' deficiency became a restriction for the productivity, stability, and sustainability of soils. Hence, studying their availability is extremely important [22].

The relationship between soil depth and available Zn (DTPA-extracted) was significant ($p < 0.001$). The relationship between soil depth and DTPA-extractable Mn was highly significant ($p < 0.001$). This indicates that upon using tree leaves as fodder, animal products will be rich in micronutrients, thus avoiding nutrient deficiency in the local people. In addition, for all land uses and soil depths, DTPA-extractable Cu was significant ($p < 0.001$). In comparison to routine crop removal, the decomposition of leaf litters under perennial S, H, and SPS plants favours nitrogen enrichment. The concentration of accessible micronutrients may rise as a result of increased decomposition due to litter accumulation and favourable environmental conditions [23]. Additionally, as organic matter breaks down, it creates organic molecules that turn into chelates of micronutrients, increasing the availability of those nutrients in soils.

Although no nutrients were applied externally, soil-nutrient availability increased in all systems (possibly by foliage litter fall, remineralisation, reduced leaching, etc.), compared to the initial status. N, P, and K availability increased by at least ~14%, 6%, and 9.5%, respectively, over the initial status. In silvopasture systems, the method of litter decomposition and mineralisation provides an abundant nutrient stock, which increases crop yield. While litter decomposition is the primary source of nutrients, it might be augmented by nutrient deposition from leaves and rainfall. The observed increase might be due to a decline in the nutrient loss out of the systems, owing to restricted leaching in tree rows due to a sheltering effect [24,25]. Hence, deep-rooted trees in silvopasture systems could improve the nutrient status of degraded soil by redistributing nutrients from the deeper soil layer to the upper layer.

In some ecosystems, the litter layer is essential for retaining nutrients, and litter fall is a significant factor in the transfer of nutrients from plants to soil. The amount of available N, P, and K generally decreased with the soil depth across all land uses. The soil's top layer (0–15 cm) offered more N, P, and K than at other depths. Increased uptake, scavenging from deeper soil layers, and return to the soil top through litter fall were ascribed for the notable rise in the concentrations of these nutrients in the surface layer.

The level of organic matter has a clear correlation with the sharp rise in accessible N, P, and K concentrations. This was further supported by the association between SOC and the available N, P, and K ($r = 0.71$ **, 0.84 **, and 0.73 *, $p < 0.01$), respectively. The rise in the concentration of K that is readily available could be the result of K being released from K-bearing minerals. Additionally, by lowering the metal ions that bind phosphates through chelation and by competing for exchange sites, the organic acids released during the breakdown of residues and organic debris increased P release [26].

However, different land-use strategies result in different nutrient releases during decomposition. In contrast, the current study's findings showed that soil depth decreased across all land uses. Positive factors, such as high temperatures and soil wetness, that hasten the breakdown of sugarcane garbage and litter, may be to blame for the rise in these nutrients under S, H, and SPS. Additionally, organic molecules increase the availability of micronutrients in soils by forming chelates of their cations. Authors such as [27,28] point out that tree-based land uses offer more sustainable alternatives to practices such as cattle ranching and shifting cultivation, in which nutrient cycles are completely disrupted. Further studies need to be conducted on the deterioration rate of soil chemical properties, soil microbial activity, and plant nutrition, in relation to sustainable land management. In addition, further study is necessary before determining if soil nutrient contents are really more protected under tree-based land uses.

Aside from assessing soils' capacities and current conditions in terms of various functions, one of the most pressing issues in soil science today is determining the consistency and durability of soil functions as well as how they adjust in reaction to external forces (e.g., through agriculture or climate change). Soil functions, such as nutrient cycling, carbon dynamics, productivity, decomposition, etc., are closely linked to the ecosystem services (like erosion control, soil fertility, nutrient retention, carbon sequestration, and nutrient dynamics) provided by soil. Degraded soils have lower diversity, and their soil functions deteriorate, affecting the delivery of ecosystem offerings. Hence, ALUS adoption in degraded areas with trees provides a chance for improving ecosystem functioning.

5. Conclusions

Given that the effects of widespread land-use change on nutrient contents and cycles in soil and vegetation are not well understood, adopting ALUS in regions with trees that are degraded offers nutritional and fodder security, as well as C storage in the soil and vegetation. According to this paper, ALUS are essential for restoring nutrients to damaged areas. Trees have an impact on how well rehabilitation techniques work. Additionally, ALUS enhance the capability for nutrient supply and carbon buildup. Thus, compared to other systems and fallow, legume tree-based ALUS such as S, H, and SPS significantly enhance soil physicochemical characteristics and biological quality. Greater micronutrient availability in soils under ALUS assures the supply of micronutrients to humans through animal products. ALUS could also support livelihoods, enhance food security, restore ecosystem services, and reduce pressure on forests. After all, revived ALUS will help with the prompt execution of helpful strategies to fulfil the promises of the Paris Agreement. Under the Paris Agreement, India had committed to creating a cumulative carbon sink of 2.5–3 billion tonnes of carbon dioxide equivalent by 2030. Currently, India's forest and tree cover is about 24% of its geographical area, according to the India State of Forest Report 2017, and India has repeatedly highlighted that it wants to bring at least 33% of its total area under green cover, to achieve the national goal for ecological security. Therefore, India is in the process of making significant contributions to REDD-plus (reducing emissions from deforestation and forest degradation in developing countries), through its ecological restoration projects and sustainable forest managements. Thus, the annual ecosystem C sink in eco-restored lands could offset India's annual emissions. Notably, most of the expansion of ecorestored land shows significant potential to contribute to C sequestration. Additionally, the storage of massive amounts of C in mature trees will also contribute to the global C balance, although the C sink may gradually decrease and reach a C saturation state as the trees grow. However, this considerable C sequestration potential could also be regarded as an approach for gaining C credits. Finally, our study indicates that the implementation of ecological restoration strategies could be a quantitatively important component of national climate change mitigation strategies in India and, thus, should be continually paid great attention.

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