



Research article

Effect of lopping shrubs and planting density on forage productivity, carbon storage, soil health and economics of three-tier silvopasture systems

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Abstract

A field experiment was conducted on eleven years old three-tier silvopasture systems under semi-arid conditions at Jhansi, India to study the effect of lopping intensity, shrub species and planting density on forage productivity, carbon storage, soil health and economic return of three-tier silvopasture systems. *Ziziphus mauritiana* recorded significantly higher top feed (3.56 and 4.48 t/ha) and fire wood yields (4.11 and 5.05 t/ha) in association with *Hardwickia binata* as compared to *Ziziphus xylopyrus* respectively during 2nd and 3rd years of study. In lopping management, lopping of shrubs and *H. binata* at 70% intensity recorded significantly higher top feed (2.81, 3.57 and 4.33 t/ha) and fire wood yields (3.80, 4.25 and 4.88 t/ha) than lopping at 50% intensity during 1st, 2nd and 3rd years respectively. Planting of *H. binata* and shrub species in alternate row at 6x6 m spacing in three-tier silvopasture system resulted in significantly higher dry forage yields of *Cenchrus ciliaris* (9.35, 9.76 and 10.03 t/ha) as compared to 6x4 m spacing and 4x4 m spacing during 1st, 2nd and 3rd years respectively. Establishment of three-tier silvopasture systems on degraded land recorded improvement in available nutrients and organic carbon in 3rd year of the experiment than initial year. Lopping of shrubs and *H. binata* in three tier silvopasture system at 70% intensity utilized by mixed herd of sheep and goats grazing at the rate of 3 ACU/ha recorded higher net return (INR 120689/ha) and benefit cost ratio (1.65) as compared to lopping at 50% intensity.

Keywords: Carbon storage, *Cenchrus ciliaris*, Forage productivity, *Hardwickia binata*, Lopping intensities, Planting density, Shrub species

Introduction

The grazing lands of arid and semiarid regions are often not capable of producing sufficient quantities of fodder for animals during abnormal weather conditions especially during drought years. It is due to continuous over-exploitation of grazing lands, lack of suitable tree, shrub and grass species, severe lopping of tree and shrub species, frequent droughts, low and erratic rainfall distribution, people negligence, etc. It is a fact that the improvement of animal husbandry is directly correlated with the improvement of degraded grazing lands. Therefore, in this context, development and management of suitable three-tier silvopasture systems comprising trees, shrubs and grasses on degraded grazing lands have great potential in increasing system productivity, enhancing fodder availability and checking soil erosion (Soni *et al.*, 2006; Soni *et al.*, 2013; Sharma, 2014; Peri *et al.*, 2024; Smith *et al.*, 2025). Establishment of suitable three-tier silvopasture systems on degraded grazing lands can serve the important role of bridging the gap in fodder

supply during the lean period of the year (Choudhary *et al.*, 2025; Mevada *et al.*, 2025). In arid and semiarid regions, establishment of suitable shrub species and trees also provides fodder in drought situations when other species have dried (Narain and Kar, 2004).

Tree and shrub species available on grazing lands are often frequently lopped by villagers to obtain green forage for livestock during lean period and small branches for firewood in arid and semiarid regions of India. During lean periods, when no other sources of green forage are available these trees and shrubs are usually heavily lopped resulting in their poor growth and productivity in subsequent years (Kumar and Tewari, 2000). Lopping of tree branches at suitable age in silvopasture systems is very important for sustainable understorey pasture production (Bhat *et al.* 1995). Goats are browsers in feeding habits prefer shrubs and tree leaves compared to grasses and pasture (Skerman 1977; Cellier *et al.*, 2022). Therefore, in this context, *Ziziphus mauritiana*, *Ziziphus xylopyrus* and *Acacia catechu* are

important browse shrub species for feeding goats and increasing their production on sustainable basis in arid and semi-arid regions of India. Optimum plant stand density is primarily a function of the growth potential of the site and the management practices. Though yield per unit area can be substantially greater at higher plant population, however, poor availability of water and nutrients may limit productivity (Shinde *et al.*, 2007). Plant density affects canopy closure, growth rates, rotation age, wood production, silvocultural and harvesting operations (Singh *et al.*, 2004).

Apart from forage production, silvopasture systems have the potential to offer many ecosystem services. The incorporation of trees or shrubs in silvopasture systems can increase the amount of carbon sequestered compared to a monoculture field of crop plants or pasture (Kirby and Potvin, 2007; Greene *et al.*, 2023). The other important role of silvopasture is reduction of pressure on natural forests for timber or non-timber forest products. Another indirect advantage of C sequestration is through the use of silvopasture technologies for forage production and soil conservation, which could enhance C storage in trees and soils (Montagnini and Nair, 2004; Stefano and Jacobson, 2017; Udawatta *et al.*, 2023). The available estimates of carbon stored in agroforestry range from 0.29 to 15.21 Mg C ha⁻¹yr⁻¹ aboveground and 30–300 Mg C ha⁻¹ up to 1 m depth in soil (Nair *et al.*, 2010). Therefore, in addition to production aspects, there is also a need to quantify the ecosystem services in terms of carbon storage potential for reducing carbon emissions for climate change mitigation. In view of this the present study was carried out to study the effect of lopping intensity, shrub species and planting density on forage productivity, carbon storage, soil health and economic return of three-tier silvopasture systems.

Materials and Methods

Experimental site: A field experiment was conducted during July 2022 to June 2025 on eleven years old three-tier silvopasture systems at Central Research Farm ([25° 27' N latitude,] 78° 34' E longitude and 275 m above mean sea level) of Indian Grassland and Fodder Research Institute, Jhansi to study the effect of lopping intensity, shrub species and planting density on forage productivity, carbon storage, soil health and economic return of three-tier silvopasture systems. The soil of the experimental field was sandy loam, low in available nitrogen, phosphorus and organic carbon and medium in available potash. The total rainfall received was 1031.0, 846.3 and 945.3 mm in 67, 37 and 43 rainy days during 2022, 2023 and 2024 respectively.

Treatment details: There were 18 treatment combinations replicated thrice in split plot design. Planting density and lopping intensities imposed in main plots and shrub species imposed in sub-plots. Plot size is 12 x 24 m. Treatment consisted three shrub species *Ziziphus xylopyrus* (Retz.) Wild, *Ziziphus mauritiana* Lam. and *Acacia catechu* (L.) Willd. established in alternate row in association with *Hardwickia binata* Roxb. and three planting density 312, 208 and 139/ha of each shrub and *H. binata* established at 4x4 m, 6x4 m and 6x6 m spacing in three-tier silvopasture systems and two lopping intensities 50% and 70% of both shrubs and *H. binata*. Lopping was carried out once every year as per treatments during winter season. A hypothesis of the study was that lopping at adequate intensity, planting at optimum density, and selection of suitable shrub species would enhance the productivity, carbon sequestration, and economic returns of the system. Forage

RI			RII			RIII		
D ₁ L ₁ AC	D ₁ L ₁ ZX	D ₁ L ₁ ZM	D ₃ L ₁ ZM	D ₃ L ₁ ZX	D ₃ L ₁ AC	D ₁ L ₂ ZX	D ₁ L ₂ AC	D ₁ L ₂ ZM
D ₁ L ₂ AC	D ₁ L ₂ ZX	D ₁ L ₂ ZM	D ₃ L ₂ ZM	D ₃ L ₂ ZX	D ₃ L ₂ AC	D ₁ L ₁ ZX	D ₁ L ₁ AC	D ₁ L ₁ ZM
D ₃ L ₁ ZX	D ₃ L ₁ ZM	D ₃ L ₁ AC	D ₂ L ₂ ZX	D ₂ L ₂ AC	D ₂ L ₂ ZM	D ₃ L ₁ ZM	D ₃ L ₁ ZX	D ₃ L ₁ AC
D ₃ L ₂ ZX	D ₃ L ₂ ZM	D ₃ L ₂ AC	D ₂ L ₁ ZX	D ₂ L ₁ AC	D ₂ L ₁ ZM	D ₃ L ₂ ZM	D ₃ L ₂ ZX	D ₃ L ₂ AC
D ₂ L ₂ ZM	D ₂ L ₂ ZX	D ₂ L ₂ AC	D ₁ L ₁ ZM	D ₁ L ₁ AC	D ₁ L ₁ ZX	D ₂ L ₁ AC	D ₂ L ₁ ZM	D ₂ L ₁ ZX
D ₂ L ₁ ZM	D ₂ L ₁ ZX	D ₂ L ₁ AC	D ₁ L ₂ ZM	D ₁ L ₂ AC	D ₁ L ₂ ZX	D ₂ L ₂ AC	D ₂ L ₂ ZM	D ₂ L ₂ ZX

Layout plan of experiment

Treatment details and symbols					
Planting densities	Symbols	Lopping	Symbols	Shrub species	Symbols
312 shrubs + 312 trees/ha (4x4 m)	D ₁	50 % lopping	L ₁	<i>Ziziphus xylopyrus</i>	ZX
208 shrubs + 208 trees/ha (6x4 m)	D ₂	70 % lopping	L ₂	<i>Ziziphus mauritiana</i>	ZM
139 shrubs + 139 trees/ha (6x6 m)	D ₃			<i>Acacia catechu</i>	AC

Note: *Acacia catechu* (L.) Willd. is now renamed as *Senegalia catechu* (L.f.) P.J.H.Hurter & Mabb.

produced from the system was uniformly utilized from all the experimental plots in grazing mode by a mixed herd of sheep and goats @3ACU/ha. In understory pasture *Cenchrus ciliaris* L. was uniformly established in association with *H. binata* and shrub species at 50 x 50 cm spacing in all the experimental plots. Interaction effects were analysed as per split plot design. Interaction effects among shrub species, planting density, and lopping intensity was found non-significant, therefore it was not given.

Sampling and methods of analysis: Growth parameters and lopped yields of shrub species and *H. binata* were recorded every year in the month of November-December. *C. ciliaris* was harvested mechanically by tractor-drawn side reaper 15 cm above the ground surface at flowering stage in each year. Growth parameters and fodder yield of *C. ciliaris* was recorded at the time of harvesting. Dry fodder yield was recorded in each plot on the basis of per square meter area and values were converted into t/ha. Dry matter yield was computed by drying 500 g plant samples of each treatment and replication in a hot-air oven at 70°C. Soil samples were collected in 1st year and 3th year of the experimentation at 0-15 cm and 15-30 cm soil layers and analysed for organic carbon, available nitrogen, phosphorus and potash adopting standard analytical methods.

The light transmission by the canopy of the *H. binata* and shrub species under different planting density and lopping intensity was measured by using a canopy analyzer. The light intensity above the canopy (I_0) and at the ground level (I) was recorded between 12:30

and 1:00 pm. Light transmission ratio was calculated by the formula given in Table 1. Measurements were conducted consequently in the month of August in each year. The light interception was measured above a canopy and beneath a canopy of grass near solar noon when the light is unobstructed by cloud cover (Board et al., 1992).

Tree, shrubs, grass, litter, soil and total carbon stock was estimated under different shrubs, planting density and lopping intensity. Carbon stock in *H. binata* trees was calculated based upon dry matter content of the tree which was calculated for various parts of *H. binata* tree using allometric equations given by Newaj et al., 2014 (Table 1). Total dry matter of *H. binata* tree was calculated by adding dry matter of tree bole, branches, leaves and roots. The total carbon stock in the tree was determined by multiplying the respective dry matter of various parts with their carbon content as given by Newaj et al.; (2014) and then adding up the carbon stock of all the parts. In shrubs, total above ground biomass was calculated by multiplying the number of stems in each category by their respective dry biomass. Above and below ground carbon stock in shrubs was calculated by multiplying above and below ground dry biomass per hectare basis with conversion factor of 0.50 (IPCC, 2006). The carbon stock was then calculated per hectare basis based on the tree and shrubs density. In grass also, above and below ground carbon stock was calculated by multiplying above and below ground dry biomass per hectare basis with conversion factor of 0.50 (IPCC, 2006). Similarly, litter carbon stock was estimated by multiplying litter dry biomass per hectare basis with conversion factor of 0.50

Table 1. Formula and allometric equations used during study

Formula and allometric equations used	Reference
$LTR (\%) = \frac{I}{I_0} \times 100$ <p>Where, I = Light intensity received at the ground level I_0 = Light intensity received at the top of grass canopy</p>	Board et al., 1992
<p>Tree components</p> <p>Bole</p> <p>Branch</p> <p>Leaves</p> <p>Root</p>	<p>Allometric equations</p> <p>0.232 (DBH)^{2.046}</p> <p>0.002 (DBH)^{3.142}</p> <p>0.0002 (DBH)^{3.514}</p> <p>0.036 (DBH)^{2.337}</p>
<p>Estimation of biomass of shrubs done by using the following formula</p>	<p>$\pi r^2 h \times \text{wood density}$</p> <p>Where,</p> <p>r = radius of bole and branches, h = height of bole and length of branches</p> <p>BGB = AGB x 0.26</p> <p>Where,</p> <p>BGB = Below ground biomass, AGB = Above ground biomass</p>
<p>Soil organic carbon stock = [Soil bulk density (g cm⁻³) x Soil depth (cm) x Carbon (%)] x100.</p>	Nelson and Sommers, 1996

Lopping management in three-tier silvopasture systems

Table 2. Effect of lopping and planting density on growth parameters of shrub species

Treatment	Shrub species											
	Height (m)			Collar diameter (cm)			Diameter at breast height (cm)			Canopy spread (m)		
	Yr 1	Yr 2	Yr 3	Yr 1	Yr 2	Yr 3	Yr 1	Yr 2	Yr 3	Yr 1	Yr 2	Yr 3
Shrub species												
<i>Z. xylopyrus</i>	4.78	3.92	4.86	10.26	11.05	12.25	8.01	8.98	10.10	5.63	3.94	4.35
<i>Z. mauritiana</i>	4.94	4.48	5.21	9.85	10.77	12.01	7.63	8.71	9.92	5.58	4.29	4.77
<i>A. catechu</i>	4.89	3.58	4.42	11.52	11.84	12.69	8.99	9.51	10.25	4.86	3.35	3.66
SEM	0.05	0.09	0.12	0.12	0.16	0.21	0.11	0.13	0.15	0.07	0.08	0.09
CD (P=0.05)	NS	0.25	0.34	0.36	0.48	NS	0.32	0.37	NS	0.21	0.22	0.25
Tree and shrubs spacing (m)												
4x4	4.69	3.70	4.40	10.24	10.74	11.51	8.02	8.73	9.55	5.13	3.67	3.99
6x4	4.85	4.03	4.86	10.58	11.24	12.36	8.24	9.09	10.11	5.38	3.88	4.28
6x6	5.08	4.26	5.22	10.80	11.67	13.08	8.38	9.37	10.60	5.56	4.04	4.52
SEM	0.09	0.15	0.20	0.20	0.28	0.35	0.18	0.21	0.26	0.12	0.11	0.15
CD (P=0.05)	0.28	NS	0.63	NS	NS	1.12	NS	NS	NS	0.36	0.32	NS
Lopping %												
50	4.93	4.13	5.09	10.71	11.51	12.79	8.35	9.27	10.42	5.47	4.01	4.45
70	4.80	3.86	4.57	10.38	10.93	11.84	8.07	8.86	9.77	5.24	3.71	4.07
SEM	0.07	0.12	0.16	0.17	0.23	0.29	0.15	0.17	0.21	0.10	0.10	0.12
CD (P=0.05)	NS	NS	0.52	NS	NS	0.91	NS	NS	NS	NS	NS	0.37

Table 3. Effect of lopping, shrub species and planting density on growth parameters of *H. binata*

Treatment	<i>H. binata</i>											
	Height (m)			Collar diameter (cm)			Diameter at breast height (cm)			Canopy spread (m)		
	Yr 1	Yr 2	Yr 3	Yr 1	Yr 2	Yr 3	Yr 1	Yr 2	Yr 3	Yr 1	Yr 2	Yr 3
Shrub species												
<i>Z. xylopyrus</i>	5.5	6.08	6.72	10.73	11.63	12.63	8.28	9.51	10.65	3.94	2.57	2.88
<i>Z. mauritiana</i>	5.58	6.32	7.06	10.94	12.04	13.16	8.42	9.8	11.02	4.03	2.67	3.02
<i>A. catechu</i>	5.78	6.17	6.85	11.3	11.78	12.84	8.67	9.61	10.78	4.18	2.61	2.93
SEM	0.08	0.08	0.11	0.18	0.17	0.20	0.13	0.15	0.17	0.07	0.04	0.06
CD (P=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Tree and shrubs spacing (m)												
4x4	5.49	5.98	6.58	10.77	11.45	12.39	8.31	9.37	10.38	3.95	2.51	2.78
6x4	5.66	6.20	6.90	11.02	11.84	12.90	8.48	9.65	10.84	4.06	2.62	2.95
6x6	5.72	6.38	7.16	11.18	12.16	13.33	8.59	9.9	11.24	4.13	2.71	3.09
SEM	0.11	0.14	0.17	0.28	0.29	0.35	0.20	0.25	0.30	0.09	0.08	0.10
CD (P=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Lopping %												
50	5.70	6.37	6.65	11.17	12.13	13.31	8.61	9.88	11.16	4.12	2.69	3.09
70	5.54	6.02	7.10	10.81	11.51	12.44	8.31	9.4	10.47	3.98	2.54	2.80
SEM	0.09	0.11	0.14	0.23	0.24	0.29	0.17	0.21	0.24	0.08	0.06	0.08
CD (P=0.05)	NS	NS	0.45	NS	NS	NS	NS	NS	NS	NS	NS	0.26

(IPCC, 2006). Total system carbon stock in *H. binata* based three-tier silvopasture was determined by adding carbon stock of tree, shrubs, grass and soil per hectare basis. Soil organic carbon stock was determined up to 30 cm depth

using an equation given by Nelson and Sommers (1996). Data obtained from all observations were statistically analysed in split plot design using the technique of analysis of variance (ANOVA). The difference between

the treatment means were tested as to their statistical significance with appropriate critical difference (CD) value at 5% level of probability.

Results and Discussion

Growth parameters of shrub species and *H. binata*:

Growth parameters of shrub species were varied significantly among different shrubs (Table 2). In 1st year of study *Z. xylopyrus* attained significantly higher canopy spread (5.63 m) as compared to *A. catechu* (4.86 m) and found at par with *Z. mauritiana* (5.58 m). However, during 2nd and 3rd years *Z. mauritiana* attained significantly higher height (4.48 m and 5.21 m) and canopy spread (4.29 m and 4.77 m) as compared to *A. catechu* (height 3.58 m and 4.42 m and canopy spread 3.35 m and 3.66 m) and *Z. xylopyrus* (height 3.92 m and 4.86 m and canopy spread 3.94 m and 4.35 m) respectively. While, collar diameter (11.52, 11.84 and 12.69 cm) and diameter at breast height (8.99, 9.51 and 10.25 cm) was maximum in *A. catechu* followed by *Z. xylopyrus* (CD 10.26, 11.05 and 12.25 cm and dbh 8.01, 8.98 and 10.10 cm) and *Z. mauritiana* (CD 9.85, 10.77 and 12.01 cm and dbh 7.63, 8.71 cm and 9.92 cm) during 1st, 2nd and 3rd years respectively. Planting of *H. binata* and shrub species in alternate row at 6x6 m spacing in three-tier silvopasture systems recorded

higher canopy spread of shrub species (5.56, 4.04 and 4.52 m) as compared to 4x4m planting spacing (5.13, 3.67 and 3.99 m) and 6x4 m (5.38, 3.88 and 4.28 m) during all three years respectively. However, growth parameters of *H. binata* did not significantly affected by different treatments (Table 3).

Growth parameters of *C. ciliaris*: Growth parameters of *C. ciliaris* did not vary significantly by establishment with different shrub species in 1st year of study (Table 4). However, during 2nd and 3rd years *A. catechu* recorded higher number of tillers/plant (111.50 and 122.64) and tussock diameter (49.73 cm and 48.05 cm) as compared to *Z. xylopyrus* (tillers/plant 101.72 and 111.27 and tussock diameter 44.05 cm and 41.65 cm) respectively. Planting of *H. binata* and shrub species in alternate row at 6x6 m spacing in three-tier silvopasture system resulted in significantly higher height (146.85 cm, 154.28 cm and 145.83 cm), number of tillers/plant (103.07, 117.23 and 129.93) and tussock diameter (50.34 cm, 52.75 cm and 51.60 cm) of *C. ciliaris* as compared to 4x4 m spacing (height 128.99 cm, 129.34 cm and 123.83 cm, tillers/plant 86.33, 94.84 and 102.66 and tussock diameter 41.83 cm, 40.33 and 37.27 cm) during 1st, 2nd and 3rd years respectively. The higher growth parameters of *C. ciliaris* at low density

Table 4. Effect of lopping, shrub species and planting density on growth parameters and dry forage yield of *C. ciliaris* in three-tier silvopasture systems

Treatment	Cenchrus ciliaris											
	Height (cm)			Tillers/plant			Tussock diameter (cm)			Pasture yield (t/ha)		
	Yr 1	Yr 2	Yr 3	Yr 1	Yr 2	Yr 3	Yr 1	Yr 2	Yr 3	Yr 1	Yr 2	Yr 3
Shrub species												
<i>Z. xylopyrus</i>	138.46	137.41	130.24	95.23	101.72	111.27	46.15	44.05	41.65	7.85	8.02	8.16
<i>Z. mauritiana</i>	135.98	140.97	134.06	92.77	105.84	116.01	44.73	46.47	44.33	7.65	8.27	8.52
<i>A. catechu</i>	141.90	148.25	141.54	97.71	111.50	122.64	48.38	49.73	48.05	8.01	8.68	9.26
SEM	2.90	3.07	3.14	2.17	2.09	2.34	1.15	1.09	1.23	0.16	0.12	0.12
CD (P=0.05)	NS	NS	NS	NS	6.10	6.83	NS	3.17	3.60	NS	0.35	0.37
Tree and shrubs spacing (m)												
4x4	128.99	129.34	123.83	86.33	94.84	102.66	41.83	40.33	37.27	6.16	6.74	7.12
6x4	140.51	143.02	136.19	96.31	106.98	117.34	47.09	47.17	45.15	8.01	8.47	8.80
6x6	146.85	154.28	145.83	103.07	117.23	129.93	50.34	52.75	51.60	9.35	9.76	10.03
SEM	3.46	3.58	3.68	2.42	2.43	3.04	1.28	1.17	1.40	0.18	0.15	0.16
CD (P=0.05)	10.91	11.28	11.58	7.62	7.64	9.57	4.04	3.70	4.41	0.56	0.48	0.49
Lopping %												
50	137.00	137.35	130.09	93.94	102.36	111.32	45.71	44.51	42.07	7.75	8.11	8.09
70	140.56	147.07	140.47	96.53	110.35	121.97	47.14	48.99	47.29	7.93	8.54	9.20
SEM	2.83	2.93	3.00	1.98	1.98	2.48	1.05	0.96	1.14	0.14	0.12	0.13
CD (P=0.05)	NS	9.21	9.45	NS	6.24	7.82	NS	3.02	3.60	NS	0.39	0.40

Table 5. Dry top feed and fire wood yields as influenced by lopping, shrub species and planting density in three-tier silvopasture systems

Treatment	Dry top feed (t/ha)			Fire wood (t/ha)														
	Yr 1	Yr 2	Yr 3	Yr 1		Yr 2		Yr 3										
Shrubs	Shrubs	H. <i>binata</i>	Total	Shrubs	H. <i>binata</i>	Total	Shrubs	H. <i>binata</i>	Total	Shrubs	H. <i>binata</i>	Total						
<i>Z. xylopyrus</i>	1.96	0.88	2.84	2.17	1.18	3.35	2.59	1.59	4.18	2.47	1.26	3.73	2.52	1.42	3.94	2.93	1.80	4.73
<i>Z. mauritiana</i>	1.67	0.84	2.51	2.35	1.21	3.56	2.84	1.64	4.48	2.15	1.22	3.37	2.65	1.46	4.11	3.21	1.84	5.05
<i>A. catechu</i>	1.20	0.81	2.01	1.32	1.19	2.51	1.55	1.57	3.12	1.66	1.21	2.86	1.74	1.43	3.17	1.69	1.78	3.47
SEM	0.02	0.03	0.02	0.04	0.01	0.04	0.05	0.03	0.05	0.04	0.02	0.04	0.04	0.02	0.05	0.06	0.03	0.06
CD (P=0.05)	0.07	NS	0.07	0.11	NS	0.11	0.15	NS	0.16	0.11	NS	0.12	0.13	NS	0.14	0.17	NS	0.19
Spacing (m)																		
4x4	1.88	0.95	2.83	2.34	1.41	3.76	2.70	1.79	4.49	2.48	1.41	3.89	2.78	1.67	4.45	3.02	2.06	5.09
6x4	1.57	0.83	2.39	1.91	1.17	3.09	2.28	1.58	3.86	2.03	1.20	3.23	2.25	1.41	3.66	2.55	1.77	4.33
6x6	1.38	0.76	2.14	1.58	0.99	2.58	2.00	1.43	3.43	1.75	1.09	2.84	1.89	1.22	3.11	2.25	1.58	3.83
SEM	0.04	0.04	0.04	0.06	0.02	0.06	0.08	0.04	0.08	0.07	0.03	0.06	0.08	0.04	0.08	0.09	0.04	0.09
CD (P=0.05)	0.13	0.12	0.11	0.20	0.07	0.20	0.26	0.13	0.26	0.21	0.09	0.19	0.24	0.12	0.24	0.29	0.13	0.27
Lopping %																		
50	1.38	0.71	2.09	1.70	1.01	2.71	2.09	1.43	3.52	1.79	1.05	2.84	1.99	1.24	3.23	2.32	1.63	3.95
70	1.84	0.98	2.81	2.19	1.37	3.57	2.56	1.77	4.33	2.39	1.41	3.80	2.62	1.63	4.25	2.90	1.99	4.88
SEM	0.03	0.03	0.03	0.05	0.02	0.05	0.07	0.04	0.07	0.05	0.02	0.05	0.06	0.03	0.06	0.08	0.04	0.07
CD (P=0.05)	0.10	0.09	0.09	0.16	0.06	0.16	0.21	0.11	0.22	0.17	0.07	0.16	0.19	0.09	0.20	0.24	0.11	0.22

planting of *H. binata* and shrub species was due to less competition for moisture, nutrients, light and space as compared to high density planting. Similar findings were also reported by Singh and Pathak (1993). Lopping of shrubs and *H. binata* at 70% intensity also resulted in higher growth parameters of *C. ciliaris* (height 147.07 cm and 140.47 cm, tillers 110.35 and 121.97 and tussock diameter 48.99 cm and 47.29 cm) than lopping at 50% intensity (height 137.35 cm and 130.09 cm, tillers 102.36 and 111.32 and tussock diameter 44.51 cm and 42.07 cm) during 2nd and 3rd years respectively. The higher growth parameters of *C. ciliaris* under 70% lopping intensity were due to less spread of canopy of shrubs and *H. binata* which facilitated adequate light to understory pasture and resulted in higher growth parameters of *C. ciliaris*.

Dry top feed and fire wood yields of shrub species and *H. binata*: *Z. xylopyrus* recorded significantly higher top feed (2.84 t/ha) and fire wood yields (3.73 t/ha) as compared to *Z. mauritiana* (2.51 and 3.37 t/ha) and *A. catechu* (2.01 and 2.86 t/ha) respectively in association with *H. binata* during 1st year. However, during 2nd and 3rd years *Z. mauritiana* recorded significantly higher top feed (3.56 and 4.48 t/ha) and fire wood yields (4.11 and 5.05 t/ha) in association with *H. binata* as compared to *Z. xylopyrus* (top feed 3.35 and 4.18 t/ha and fire wood 3.94 and 4.73 t/ha) and *A. catechu* (top feed 2.51 and 3.12 t/ha and fire wood 3.17 and 3.47 t/ha) respectively (Table 5). The higher top feed and fire wood yields obtained from *Z. mauritiana* during 2nd and 3rd years was due to their better growth after lopping as compared to *Z. xylopyrus* and *A. catechu*. Shukla et al. (1998) also found that *Z. mauritiana* is a hardy species and can be grown successfully with grasses for top feed and fruit production under semiarid rainfed condition. In planting density, high density planting 312/ha of each *H. binata* and shrub species in three-tier silvopasture significantly increased top feed (2.83, 3.76 and 4.49 t/ha) and fire wood yields (3.89, 4.45 and 5.09 t/ha) as compared to low density planting 208/ha (top feed 2.39, 3.09 and 3.86 t/ha and fire wood 3.23, 3.66 and 4.33 t/ha) and 139/ha (top feed 2.14, 2.58 and 3.43 t/ha and fire wood 2.84, 3.11 and 3.83 t/ha) during 1st, 2nd and 3rd years respectively. Jat et al. (2004) also observed a positive relation between tree density and top feed production of *H. binata*. In lopping management, lopping of shrubs and *H. binata* at 70% intensity recorded significantly higher top feed (2.81, 3.57 and 4.33 t/ha) and fire wood yields (3.80, 4.25 and 4.88 t/ha) than lopping at 50% intensity (top feed 2.09, 2.71 and 3.52 t/ha and fire wood 2.84, 3.23 and 3.95 t/ha) during 1st, 2nd and 3rd years respectively. The higher top feed and fire wood yields obtained with 70% lopping intensity was due to removal of more foliage and branches under 70% lopping intensity which resulted in higher top feed and fire wood yields. Biomass production is directly correlated with lopping intensity. Hence, severely lopped

trees tended to produce more biomass as compared to lightly lopped trees. The reason is that more foliage was removed in 70% lopping intensity which increased the lopped biomass. Similar results have also been reported by Bisht et al., (2017); Kishan and Tewari (2001) and Bhat et al. (1995). Lopping results in usage of stored reserves for its growth and production of leaves. This happened because of the exposure of lopped portions to sunlight and the dormant buds become active and sprouted into shoots with the available reserves present in the trees (Muhamad and Paudyal, 1992).

Dry forage yield of understory pasture: Dry forage yield of *C. ciliaris* was not significantly influenced by establishment with different shrub species and lopping intensity during 1st year (Table 4). However, planting of *H. binata* and shrub species in alternate row at 6x6 m spacing in three-tier silvopasture system resulted in significantly higher dry forage yields of *C. ciliaris* (9.35, 9.76 and 10.03 t/ha) as compared to 6x4 m spacing (8.01, 8.47 and 8.80 t/ha) and 4x4 m spacing (6.16, 6.74 and 7.12 t/ha) during 1st, 2nd and 3rd years respectively. The higher dry forage yield of *C. ciliaris* at wider spacing revealed that there was less competition of *H. binata* and shrubs on *C. ciliaris* at low densities planting (139/ha of each *H. binata* and shrubs). Khan et al. (2000) have also concluded that *A. tortilis* based silvopasture system recorded higher forage yield of *C. ciliaris* and *S. hamata* at wider spacing as compared to narrow spacing and Gill and Ajit (2004) reported that as the tree densities increased the relative crop yields decreased. Keshwa and Singh (2004) also reported a reverse trend in yield of *C. ciliaris* with the decrease in row spacing of *Dichrostachys cinerea*. In lopping management, lopping of shrubs and *H. binata* at 70% intensity also recorded significantly higher understory pasture (8.54 and 9.20 t/ha) than lopping at 50% intensity (8.11 and 8.09 t/ha) during 2nd and 3rd years respectively. The higher understory pasture yield under 70% lopping intensity was due to less spread of canopy of shrubs and *H. binata* which facilitated adequate light to understory pasture component and resulted in higher growth and yield of grass. Bisht et al. (2017), Bhat et al. (1995) and Singh et al. (2017) reported that forage yields of different grasses increased with the increasing intensities of lopping of different trees in silvopasture systems. Higher biomass production under lopped treatments was due the fact that lopping of trees facilitated more light to understory pasture which resulted in higher growth and yield. Light availability is the most important limiting factor for the performance of under storey pasture in silvopasture systems particularly where upper storey perennial forms a dense cover storey canopy (Miah et al., 1995).

Sustainable yield index: Sustainable yield index of *Z. xylopyrus* was maximum (0.67) followed by *Z. mauritiana* (0.63) and *A. catechu* (0.59) which indicated that *Z.*

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Table 6. Effect of lopping, shrub species and planting density on transmitted radiation, light transmission ratio (LTR), net return, benefit cost ratio and sustainability yield index of three-tier silvopasture systems

Treatment	Year 1		Year 2		Year 3		Year 3		Net return (INR/ha)	Benefit-cost ratio	Sustainability yield index	
	Transmitted radiation (Lux)		Transmitted radiation (Lux)		Transmitted radiation (Lux)		LTR (%)					
	Upper	Lower	Upper	Lower	Upper	Lower						
Shrubs												
<i>Z. xylopyrus</i>	1438.53	418.88	29.79	1411.48	465.08	32.77	1465.55	447.63	30.37	117841	1.64	0.67
<i>Z. mauritiana</i>	1453.42	457.77	31.21	1428.42	524.38	36.56	1484.77	506.68	33.99	119764	1.64	0.63
<i>A. catechu</i>	1475.68	528.8	34.90	1488.26	583.32	39.05	1544.54	568.37	36.66	110221	1.59	0.59
SEM	26.19	16.65	0.56	28.14	17.23	0.51	32.80	16.66	0.40	918	0.01	0.01
CD (P=0.05)	NS	48.62	1.64	NS	50.30	1.50	NS	48.63	1.17	2680	0.02	0.03
Spacing (m)												
4x4	1419.76	431.25	29.34	1423.97	477.11	33.30	1480.80	457.11	30.67	109467	1.58	0.62
6x4	1439.85	456.48	31.63	1440.66	515.51	35.59	1493.78	506.55	33.74	116240	1.63	0.63
6x6	1508.01	517.72	34.93	1463.53	580.16	39.49	1520.29	559.02	36.62	122119	1.66	0.64
SEM	30.38	19.59	0.73	32.18	21.20	0.70	38.69	20.58	0.54	1170	0.01	0.01
CD (P=0.05)	NS	61.69	2.31	NS	66.77	2.20	NS	64.81	1.70	3686	0.02	NS
Lopping %												
50	1448.56	463.38	31.77	1439.76	482.30	33.27	1490.84	464.43	30.94	111195	1.60	0.58
70	1463.19	473.58	32.16	1445.68	566.23	38.98	1505.73	550.69	36.41	120689	1.65	0.68
SEM	24.80	15.99	0.60	26.28	17.31	0.57	31.59	16.80	0.44	956	0.01	0.01
CD (P=0.05)	NS	NS	NS	NS	54.52	1.79	NS	52.92	1.38	3009	0.02	0.03

INR: Indian rupees; LTR: Light transmission ratio

xylopyrus was produced more stable yield over the years than *Z. mauritiana* and *A. catechu* under semiarid rainfed condition. Similarly, lopping of shrubs and *H. binata* at 70% intensity recorded higher sustainability yield index (0.68) than 50% lopping intensity (0.58) which showed that total productivity of the system obtained from 70% lopping intensity of both shrubs and *H. binata* was more stable over the years than 50% lopping intensity.

Light transmission ratio: Light interception was significantly higher in *A. catechu* (34.90, 39.05 and 36.66%) as compared to *Z. mauritiana* (31.21, 36.56 and 33.99%) and *Z. xylopyrus* (29.79, 32.77 and 30.37%) based three-tier silvipasture system during 1st, 2nd and 3rd years respectively. Similarly, light interception to the understorey pasture was also significantly higher (34.93, 39.49 and 36.62%) under wider planting spacing (6x6 m) of *H. binata* and shrub species in alternate row in three-tier silvopasture systems as compared to narrow planting spacing- 6x4m (29.34, 35.59 and 33.74%) and 4x4m (31.63, 33.39 and 30.67%) during 1st, 2nd and 3rd years respectively. This was due to more open space available for interception of light to the understorey pasture under wider spacing of planting of shrubs and *H. binata* as compared to narrow

spacing of planting. In lopping management, lopping of shrubs and *H. binata* at severe lopping intensity (70%) also resulted in significantly higher light interception (38.98 and 36.41%) to the understorey pasture than lopping at light (50%) intensity (33.27 and 30.94%) during 2nd and 3rd years respectively. The higher light interception under 70% lopping intensity was due to less spread of canopy of the shrubs and tree under 70% lopping intensity which resulted in higher penetration of light to the understorey pasture.

Carbon stock of shrubs and *H. binata*: *A. catechu* recorded significantly higher carbon stock (11.15 t/ha) as compared to *Z. mauritiana* (8.58 t/ha) and *Z. xylopyrus* (8.04 t/ha) in association with *H. binata* and *C. ciliaris* in three tier silvopasture system in 1st year of study. However, during 3rd year *Z. mauritiana* recorded maximum carbon stock (39.76t/ha) followed by *A. catechu* (27.61 t/ha) and *Z. xylopyrus* (20.54 t/ha) in association with *H. binata* and *C. ciliaris* in three tier silvopasture system. However, the carbon stock of *H. binata* was not significantly affected by different shrub species in the three tier silvopasture system in 1st and 3rd years of study. The higher carbon stock in *Z. mauritiana* was due to their better growth after

Table 7. Carbon stock (t/ha) in three-tier silvopasture systems as influenced by lopping, shrub species and planting density

Treatment	Year 1						Year 3					
	HBCS	Shrubs CS	CCCS	LCS	SCS	TCS	HBCS	Shrubs CS	CCCS	LCS	SCS	TCS
Shrubs												
<i>Z. xylopyrus</i>	2.50	8.04	5.34	1.27	18.38	34.26	4.33	20.54	5.50	1.49	19.17	49.54
<i>Z. mauritiana</i>	2.59	8.58	5.19	1.21	18.65	35.02	4.64	39.76	5.73	1.58	19.61	69.73
<i>A. catechu</i>	2.76	11.15	5.45	1.13	19.27	38.63	4.41	27.61	6.17	1.46	20.50	58.70
SEM	0.11	0.52	0.11	0.02	0.17	0.77	0.19	2.30	0.10	0.03	0.25	2.62
CD (P=0.05)	NS	1.53	NA	0.05	0.48	2.26	NS	6.71	0.29	0.07	0.74	7.65
Spacing (m)												
4x4	3.61	11.88	4.24	1.20	19.11	38.84	5.91	34.26	4.78	1.59	20.73	65.68
6x4	2.51	9.05	5.45	1.20	18.85	35.85	4.34	29.60	5.90	1.50	19.85	59.69
6x6	1.73	6.84	6.30	1.21	18.34	33.21	3.14	24.06	6.70	1.43	18.71	52.60
SEM	0.12	0.69	0.12	0.02	0.16	1.01	0.24	3.15	0.12	0.04	0.29	3.67
CD (P=0.05)	0.38	2.16	0.38	NS	0.51	3.18	0.77	NS	0.38	0.12	0.91	NS
Lopping %												
50	2.73	9.81	5.26	1.26	18.55	36.35	4.79	33.80	5.47	1.59	20.10	64.17
70	2.50	8.71	5.40	1.15	18.98	35.59	4.13	24.81	6.12	1.43	19.42	54.48
SEM	0.10	0.56	0.10	0.02	0.15	0.82	0.20	2.58	0.10	0.03	0.24	2.99
CD (P=0.05)	NS	NS	NS	0.05	NS	NS	0.63	8.11	0.31	0.10	NS	9.43

HBCS: *H. binata* carbon stock; Shrubs CS: Shrubs carbon stock; CCCS: *C. ciliaris* carbon stock; LCS: Litter carbon stock; SCS: Soil carbon stock; TCS; Total carbon stock

lopping and higher biomass yields as compared to *A. catechu* and *Z. xylopyrus*. In planting density, high density planting (312/ha of each *H. binata* and shrub species) in three tier silvopasture system significantly increased carbon stock (shrubs 11.88 and 34.26 and *H. binata* 3.61 and 5.91 t/ha) as compared to low density planting-208/ha (shrubs 9.05 and 29.60 and *H. binata* 2.51 and 4.34 t/ha) and 139/ha (shrubs 6.84 and 24.06 and *H. binata* 1.73 and 3.14 t/ha) in 1st and 3rd years respectively. Lopping intensity did not significantly affect the carbon stock of shrubs and *H. binata* in 1st year of study (Table 7). However, during 3rd year of study lopping at 50% intensity resulted in significantly higher carbon stock of shrubs 33.80 t/ha and *H. binata* 4.79 t/ha as compared to 70% lopping intensity (shrubs 24.81 t/ha and *H. binata* 4.13 t/ha). The higher carbon stock of shrubs and *H. binata* under 50% lopping intensity in 3rd year was due to increase in diameter at breast height under 50% lopping intensity as compared to 70% lopping intensity which resulted in higher biomass production and ultimately carbon stock.

Carbon stock of *Cenchrus ciliaris*: Carbon stock of *C. ciliaris* was not significantly influenced by establishment with different shrub species and lopping intensity during 1st year (Table 7). However, during 3rd year *A. catechu* recorded maximum carbon stock of *C. ciliaris* (6.17 t/ha)

followed by *Z. mauritiana* (5.73 t/ha) and *Z. xylopyrus* (5.50 t/ha) in association with *H. binata* in three tier silvopasture system. The higher carbon stock of *C. ciliaris* in association with *A. catechu* was due to their higher biomass yield as compared to *Z. mauritiana* and *Z. xylopyrus*. In planting density, low density planting (139/ha of each *H. binata* and shrub species) significantly increased carbon stock of *C. ciliaris* (6.30 and 6.70 t/ha) as compared to high density planting-208/ha (5.45 and 5.90 t/ha) and 312/ha (4.24 and 4.78 t/ha) in three tier silvopasture system during 1st and 3rd years respectively. This was due to higher biomass yield of *C. ciliaris* under low density planting of *H. binata* and shrub species as compared to high density planting in three tier silvopasture systems. In lopping management, lopping of shrubs and *H. binata* at 70% intensity recorded significantly higher carbon stock of *C. ciliaris* (6.12 t/ha) than lopping at 50% intensity (5.47 t/ha) during 3rd year of study. This was also due to higher biomass yield of *C. ciliaris* obtained under 70% lopping intensity as compared to 50% lopping intensity in three tier silvopasture systems.

Litter carbon stock: In 1st year *Z. xylopyrus* recorded significantly higher litter carbon stock (1.27 t/ha) as compared to *Z. mauritiana* (1.21 t/ha) and *A. catechu* (1.13 t/ha) in association with *H. binata* in three tier

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Table 8. Effect of of lopping, shrub species and planting density on soil health of three-tier silvopasture systems

Treatment	Year 1								Year 3									
	Available nutrients (kg/ha)								OC (%)	Available nutrients (kg/ha)								OC (%)
	N		P		K		OC (%)			N		P		K		OC (%)		
0-15	15-30	0-15	15-30	0-15	15-30	0-15	15-30	0-15	15-30	0-15	15-30	0-15	15-30	0-15	15-30			
Shrubs																		
<i>Z. xylopyrus</i>	205.18	176.50	8.69	7.73	173.07	147.17	0.48	0.40	209.65	179.39	9.10	7.86	180.21	155.46	0.50	0.42		
<i>Z. mauritiana</i>	207.97	178.68	8.80	7.81	175.40	148.99	0.49	0.41	213.49	182.81	9.19	7.94	182.27	157.83	0.51	0.43		
<i>A. catechu</i>	214.39	183.69	9.05	8.00	180.74	153.16	0.50	0.42	222.45	191.16	9.37	8.10	186.01	156.03	0.54	0.45		
SEM	2.11	1.45	0.06	0.06	1.22	1.02	0.05	0.01	3.61	3.05	0.08	0.07	2.62	2.16	0.01	0.01		
CD (P = 0.05)	6.15	4.23	0.19	0.17	3.55	2.99	0.01	0.02	NS	NS	NS	NS	NS	NS	0.02	0.02		
Spacing (m)																		
4x4	212.69	182.36	8.99	7.95	179.32	152.05	0.50	0.42	224.77	193.68	9.64	8.36	190.86	163.08	0.54	0.45		
6x4	210.03	180.29	8.88	7.87	177.11	150.32	0.49	0.41	216.15	185.32	9.27	8.02	183.60	157.17	0.52	0.43		
6x6	204.83	176.23	8.68	7.72	172.78	146.94	0.48	0.40	204.67	174.36	8.75	7.52	174.02	149.08	0.49	0.41		
SEM	2.34	1.69	0.07	0.07	1.47	1.24	0.05	0.01	3.89	3.18	0.09	0.08	2.75	2.63	0.01	0.01		
CD (P = 0.05)	7.35	5.07	0.21	0.21	4.61	3.89	0.01	0.02	12.23	10.03	0.29	0.25	8.65	8.27	0.02	0.02		
Lopping %																		
50	206.92	177.87	8.76	7.78	174.52	148.31	0.48	0.41	219.68	188.74	9.41	8.14	186.79	159.24	0.53	0.44		
70	211.44	181.39	8.94	7.91	178.28	151.24	0.50	0.42	210.71	180.17	9.03	7.79	178.88	153.64	0.51	0.42		
SEM	2.20	1.38	0.06	0.06	1.20	1.01	0.04	0.01	2.93	2.60	0.08	0.06	2.24	1.83	0.01	0.01		
CD (P = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS	8.79	8.19	0.24	0.20	7.06	5.49	NS	NS		

0-15 cm and 15-30 cm

silvopasture system. However, in 3rd year *Z. mauritiana* recorded maximum litter carbon stock (1.58 t/ha) followed by *Z. xylopyrus* (1.49 t/ha) and *A. catechu* (1.46 t/ha) in association with *H. binata* and *C. ciliaris* in three tier silvopasture system. This was due to higher litter biomass addition in soil under *Z. mauritiana* in 3rd year as compared to *Z. xylopyrus* and *A. catechu* which resulted in higher litter carbon stock. High planting density 312/ha of each *H. binata* and shrub species significantly increased litter carbon stock (1.59 t/ha) as compared to low planting density- 139/ha (1.43 t/ha) in three tier silvopasture systems during 3rd year of study. This was due to higher litter biomass addition in soil under high planting density as compared to low planting density which also resulted in higher litter carbon stock. In lopping intensity, lopping of shrubs and *H. binata* at 50% intensity recorded significantly higher litter carbon stock (1.26 and 1.59 t/ha) than lopping at 70% intensity (1.15 and 1.43 t/ha) during 1st and 3rd years respectively. This may be due higher litter biomass addition in soil under 50% lopping intensity of shrubs and *H. binata* as compared to 70% lopping intensity.

Soil carbon stock: *A. catechu* recorded maximum soil carbon stock (19.27 and 20.50 t/ha) followed by

Z. mauritiana (18.65 and 19.61 t/ha) and *Z. xylopyrus* (18.38 and 19.17 t/ha) in association with *H. binata* and *C. ciliaris* in three tier silvopasture system during 1st and 3rd years respectively. This was due to higher carbon in soil under *A. catechu* as compared to *Z. mauritiana* and *Z. xylopyrus* which also resulted in higher soil carbon stock. In planting density, high planting density (312/ha of each *H. binata* and shrub species) significantly increased soil carbon stock (19.11 and 20.73 t/ha) as compared to low planting density- 139/ha (18.34 and 18.71 t/ha) in three tier silvopasture system during 1st and 3rd years respectively. This was due to higher litter biomass addition in soil under high planting density as compared to low planting density which also resulted in higher soil carbon stock. Lopping intensity did not significantly affect the soil carbon stock in 1st and 3rd years of study (Table 7).

Total carbon stock: *A. catechu* also recorded significantly higher total carbon stock (38.63t/ha) as compared to *Z. mauritiana* (35.02 t/ha) and *Z. xylopyrus* (34.26 t/ha) in association with *H. binata* and *C. ciliaris* in three tier silvopasture system during 1st year of study. However, during 3rd year *Z. mauritiana* recorded maximum total carbon stock (69.73 t/ha) followed by *A. catechu* (58.70 t/

ha) and *Z. xylopyrus* (49.54 t/ha) in association with *H. binata* and *C. ciliaris* in three tier silvopasture system. This was due to higher biomass production and higher litter addition in soil under *Z. mauritiana* during 3rd year as compared to *A. catechu* and *Z. xylopyrus* which resulted in higher total carbon stock of the systems. High planting density (312/ha of each *H. binata* and shrub species) also recorded significantly higher total soil carbon stock of the system (38.84 and 65.68 t/ha) in three tier silvopasture system as compared to low planting density- 139/ha (33.21 and 52.60 t/ha) during 1st and 3rd years respectively. This was due to higher litter biomass addition in soil under high planting density as compared to low planting density which also resulted in higher soil carbon stock. Lopping intensity did not significantly affect the total soil carbon stock of the system in 1st year of study (Table 7). However, during 3rd year of study lopping at 50% intensity resulted in significantly higher total soil carbon stock of the system (64.17 t/ha) as compared to 70% lopping intensity (54.48 t/ha). This may be also due to higher litter biomass addition in soil under 50% lopping intensity as compared to 70% lopping intensity.

Soil health: *A. catechu* recorded higher improvement in available nutrients (N-214.39 and 183.69 kg/ha, P-9.05 and 8.00 kg/ha and K-180.74 and 153.16 kg/ha) and OC (0.50 and 0.42%) as compared to *Z. mauritiana* (N-207.97 and 178.68 kg/ha, P-8.80 and 7.81 kg/ha and K-175.40 and 148.99 kg/ha) and OC (0.49 and 0.41%) and *Z. xylopyrus* (N-205.18 and 176.50 kg/ha, P-8.69 and 7.73 kg/ha and K-173.07 and 147.17 kg/ha) and OC (0.48 and 0.40%) in 0-15 cm and 15-30 cm soil depth respectively in 1st year in three-tier silvopasture system. Similar trend was also recorded in 3rd year of study. Similarly, high density planting 312/ha of each shrubs and *H. binata* at 4x4 m spacing in three-tier silvopasture system resulted in higher improvement in available nitrogen (212.69 and 182.36 kg/ha), phosphorus (8.99 and 7.95 kg/ha), potash (179.32 and 152.05 kg/ha) and organic carbon (0.50 and 0.42%) than low density planting 208/ha at 6x4 m spacing (N-210.03 and 180.29, P-8.88 and 7.87 and K-177.11 and 150.32 kg/ha and OC-0.49 and 0.41%) and 139/ha at 6x6 m spacing (N-204.83 and 176.23, P-8.68 and 7.72 and K-172.78 and 146.94 kg/ha and OC-0.48 and 0.40%) in 0-15 cm and 15-30 cm soil layers respectively in 1st year in three-tier silvopasture system. Similar trend was also recorded in 3rd year of study. This was due to higher litter biomass addition in soil with high density planting of shrubs and *H. binata* as compared to low density planting. Lopping intensity did not significantly affect the available nutrients and organic carbon of the soil in 1st year of study (Table 8). However, during 3rd year of study lopping at 50% intensity resulted in significantly higher improvement in available nitrogen (219.68 and 118.74 kg/ha), phosphorus (9.41 and 8.14 kg/ha), potash (186.79 and 159.24 kg/ha) and organic carbon

(0.53 and 0.44%) as compared to 70% lopping intensity (N 210.71 and 180.17 kg/ha, P 9.03 and 7.79 kg/ha and K 178.88 and 153.64 kg/ha) and organic carbon (0.51 and 0.42%). This was due to higher litter biomass addition in soil under 50% lopping intensity of shrubs and *H. binata* as compared to 70% lopping intensity. Establishment of three-tier silvopasture systems on degraded land recorded improvement in available nutrients and organic carbon (N -215.20 and 184.46, P- 9.22 and 7.97 and K-182.84 and 156.44 kg/ha and OC- 0.52 and 0.43%) in 3rd year of experiment than initial year (N-209.18 and 179.63, P- 8.85 and 7.85 and K -176.40 and 149.77 kg/ha and OC- 0.49 and 0.41%.) in 0-15 cm and 15-30 cm soil layers respectively. The changes in soil organic carbon and nutrient status are as per chemical analysis of soil and reported period that is three years, so as per three years study differences in soil organic carbon and nutrient status are not small (Mohansundari et al., 2025).

Economic return: Economic estimation was carried out as per cost of input and price of output. The cost of labour was Rs 457/day, harvesting cost of pasture by tractor was Rs 850/hour, sale price of green forage was Rs. 325/quintal, sale price of dry firewood was Rs 600/ quintal, sale price of goat meat was Rs 820/kg and sale price of sheep meat was Rs 720/kg. Twenty numbers of each growing Jalauni sheep and Bundelkhandi goats at the rate of 3 ACU/ha were allowed to graze in three-tier silvopasture system during August-January. During the grazing period weight gain of edible meat in sheep (6.89 kg) and goat (7.55 kg) was taken into consideration for estimation of return. Average cost incurred on management and utilization of the system by a mixed herd of sheep and goats grazing at the rate of 3 ACU/ha was around Rs 186400/ha. *H. binata* based three-tier silvopasture system gave net returns Rupees 115942/ha and benefit cost ratio 1.63. Maximum net return (Rs 122119/ha) and benefit cost ratio (1.66) was obtained from 6x6 m planting spacing of shrubs and *H. binata* in alternate row in three-tier silvopasture system utilized by mixed herd of sheep and goats grazing at the rate of 3 ACU/ha followed by 6x4 m planting spacing (NR Rs 116240/ha and BCR 1.63) and 4x4 m planting spacing (NR Rs 109467/ha and BCR 1.58). The higher net return and benefit cost ratio obtained from 6x6 m planting spacing of shrubs and *H. binata* in alternate row in three-tier silvopasture system was mainly due to higher forage yields recorded under 6x6 m planting spacing of shrubs and *H. binata*. In lopping management, lopping of shrubs and *H. binata* in three tier silvopasture system at 70% intensity utilized by mixed herd of sheep and goats grazing at the rate of 3 ACU/ha also recorded higher net return (INR 120689/ha) and benefit cost ratio (1.65) as compared to lopping at 50% intensity (INR 111195/ha and BCR 1.60). The higher net return and benefit cost ratio obtained from 70% lopping intensity of shrubs and *H.*

binata was mainly due to higher understorey pasture, top feed and fire wood yields recorded under 70% lopping intensity. However, net return and benefit-cost ratio was not significantly affected by establishment of different shrub species in association with *H. binata* in a three-tier silvopasture system (Table 6).

Conclusion

Based on the results it can be concluded that 70% lopping intensity of branches of shrubs and *H. binata* recorded higher light interception, production from under-storey pasture and top feed components, economic return and sustainability yield index in three-tier silvopasture systems. This study also confirms that integration of perennial grass-*C. ciliaris* and shrub species- *Z. mauritiana* followed by *Z. xylopyrus* and *A. catechu* with *H. binata* in alternate row at 6x6 m spacing in three-tier silvopasture systems on degraded lands have great potential in enhancing system productivity, improving soil nutrients status and economic returns under semi-arid rainfed condition. Three-tier silvopasture systems comprising tree- *H. binata* and shrub species- *Z. mauritiana* followed by *Z. xylopyrus* and *A. catechu* and grass- *C. ciliaris* are suitable and profitable alternate land-use options for degraded lands to produce sufficient amount of understorey pasture, top feed and fire wood yields along with improvement in soil fertility status and economic returns and minimize risk due to abnormal weather conditions specially during drought years when other species have dried under semi-arid rainfed situation.

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