Range Management and Agroforestry 45 (2) : 189-196, 2024
ISSN 0971-2070 (Print); 2249-5231 (Online)
https://doi.org/10.59515/rma.2024.v45.i2.01

Research article

Enhancing fodder biomass and mitigating climate change in Central India's semi-arid zones through silvipastures

R. V. Kumar, Kamini Gautam*, Sunil Kumar, A. K. Singh, Avijit Ghosh and A. K. Roy

ICAR-Indian Grassland and Fodder Research Institute, Jhansi-284003, India
*Corresponding author email: kaminigautam1989@gmail.com

Received: 12th January, 2024 Accepted: 08th October, 2024

Abstract

Fodder production, biomass carbon storage and the oxygen release potentials of the silvipasture system consisting of *Acacia nilotica*, *Ficus infectoria*, *Morus alba* and *Leucaena leucocephala* integrated with grass species *Megathyrsus maximus* and *Chrysopogon fulvus* along with fodder legume *Stylosanthes seabrana* were evaluated. Among trees/shrubs, at the age of 12 years, *F. infectoria* yielded (Mg ha^{-1}) highest green fodder (5.72) followed by *L. leucocephala* (5.01), *A. nilotica* (3.93) and *M. alba* (2.87). Among pasture species, *M. maximus* yielded (Mg ha^{-1}) the highest green fodder (31.13), followed by *C. fulvus* (22.10) and legume *S. seabrana* (4.75). The system stored 7.51 to 20.80 Mg C ha^{-1} in its biomass, amounting to 27.56 to 76.34 Mg ha^{-1}of carbon dioxide equivalent (CO$_2$e) and besides this, the system also released 20.05 to 55.54 Mg ha^{-1} of oxygen under various tree/shrub+ grass/legume combinations. Thus, silvipasture systems with *F. infectoria* + *M. maximus* (fodder: 36.85 Mg/ha; carbon stock: 13.61 Mg C ha^{-1}; oxygen released: 36.34 Mg ha^{-1}); *A. nilotica* + *M. maximus* (fodder: 35.06 Mg ha^{-1}; carbon stock: 18.66 Mg C ha^{-1}; oxygen released:49.82 Mg ha^{-1}); *F. infectoria* + *C. fulvus* (fodder: 27.82 Mg ha^{-1}; carbon stock: 13.78 Mg C ha^{-1}; oxygen released:36.79 Mg ha^{-1}) and *A. nilotica* + *C. fulvus* (fodder: 26.03 Mg ha^{-1}; carbon stock: 20.80 Mg C ha^{-1}; oxygen released: 55.54 Mg ha^{-1}) are ideal system for fodder as well as environmental security in degraded lands of semi-arid India.

Keywords: Carbon sequestration, Degraded landscapes, Fodder security, Oxygen release, Semi-arid India, Silvipastures

Introduction

Semi-arid zones of India are facing challenges of land degradation, drought, erratic rainfall, high temperature, poor agriculture as well as livestock productivity coupled with the presence of low vegetation cover, which makes the region more vulnerable to climate vagaries (Kumar *et al*., 2019; Gautam *et al*., 2021; Dev *et al*., 2022; Kumar *et al*., 2022). Under such conditions, livestock as an integral part of agriculture, act as an assured means of livelihood security of people in the region, especially resource-poor small and marginal farmers. Such farmers are completely dependent on livestock for their nutrition and derive more than 96% of their total income from agriculture and livestock rearing (Rathod and Dixit, 2020; Gautam *et al*., 2021). The high dependency of people on livestock in the region is also reflected in the prevalence of a high human to livestock ratio (1:1.5–1:3) in the region as compared to other regions of the country (1:0.5) (Rathod and Dixit, 2020; Gautam *et al*., 2021). However, the productivity of livestock in the region is poor as compared to the rest of the parts of the country (Rathod and Dixit, 2020; Kamini *et al*., 2020). Grazing and feeding on poor feed/fodder/vegetation by various categories of livestock owing to lack of accessibility to round-the-year quality fodder and especially green fodder during lean period accounts for 50% loss in livestock productivity in this region (Ajith *et al*. 2012; Kamini *et al*., 2020; Gautam *et al*., 2021). The fodder scarcity, especially in lean period, has led many farmers of these regions to sometimes leave their cattle free to graze (popularly known as 'Anna Pratha'), causing 25 to 35% loss in agricultural crops of the kharif season (Rathod and Dixit, 2020). Since meeting out demand for round-the-year quality fodder for sustaining livestock productivity in the region is very crucial to supporting local livelihoods, the silvipasture system can act as a boon in the region.

Silvipasture systems combining fodder trees, shrubs, grasses and legumes are ideal for year-round quality fodder supply and can be established on degraded lands/wastelands and community lands. Further, silvipastures have been proven to mitigate climate change by sequestering huge amounts of atmospheric carbon dioxide in its above and below-ground carbon pools and releasing oxygen into the atmosphere (Shukla *et al*., 2019; Aryal *et al*., 2022; Gautam *et al*., 2022). Thus, establishing silvipastures can also play a significant role in offsetting the methane emissions from the livestock sector. The silvipasture is win-win land use system in a way that, beyond assuring fodder security and climate resilience, this system provides added benefits of ensuring livelihood security to local farmers in the long run (Kumar *et al*., 2019; Dev *et al*., 2022; Kumar *et al*., 2022; Ghosh *et al*., 2023; Rather *et al*., 2023). Furthermore, the carbon sequestered in these systems can be leveraged for trading to create opportunities for additional financial gains (Pinnschmidt *et al.,* 2023). The emission of oxygen from silvipasture systems can also play a crucial role in mitigating oxygen shortages attributed to the increasing levels of air pollution in the country. Thus, silvipasture has the potential to be a crucial contributor in India's pursuit of achieving carbon neutrality by 2070. Considering the overall context, a study was conducted on a 10-year-old silvipasture system established in semi-arid central India on degraded land for a period of 3 years. This system incorporated a mix of fodder trees, shrubs, grasses, and fodder legumes. The aim of the study was to generate scientific insights into the system's potential for fodder production and to quantify the carbon storage in both above-ground and below-ground biomass, as well as to evaluate the oxygen release potential of the system, as these dimensions were previously unexplored.

Materials and Methods

Study site: The study was carried out at the semi-arid Bundelkhand region of India in the Jhansi district, located at an altitude of 216 m above mean sea level, between 25º26'08" N latitude and 78º30'21" E longitude. The study site is characterized by the presence of erratic rainfall (average rainfall: 867 mm); drought, very high temperature during summer (maximum: 47.4°C in June); a minimum temperature of 4.1°C in December and about 60% mean annual relative humidity (Dev *et al*., 2020). The soil of the experimental site was typically inceptisol, characterized by shallow depth, poor fertility, dark brown to yellowish-red color, poor water holding capacity, low organic matter percentage (0.3–0.5) and pH ranging between 6.2 to 7.8.

Silvipasture system: The silvipasture systems consisted of three indigenous high-value fodder trees of semi-arid zone *viz*., *Ficus infectoria*, *Morus alba*, *Acacia nilotica*, and a shrub *Leucaena leucocephala* planted during the rainy season of the year 2010 (July month). Trees were planted at the spacing of 5 × 5 m and shrubs at 5 m (row to row) × 2 m (plant to plant) in 60 cm^3 pits. For the establishment of silvipasture, two perennial grass species *Megathyrsus maximus* and *Chrysopogon fulvus,* along with a perennial fodder legume *Stylosanthes seabrana,* having good quality fodder biomass production potential, were sown under these 10-year-old trees and shrubs. Grasses and legumes were separately seeded at the spacing of 50 × 50 cm in rows between two tree rows during the rainy season in the month of July, 2020. The system was maintained under rain-fed conditions. Plot size was kept as 60 × 60 m and each treatment was replicated thrice under a randomized complete block design. Data was recorded for three consecutive years 2020, 2021 and 2022.

Tree growth and fodder yield: *Above*-ground growth parameters *viz*., tree height, diameter at breast height (DBH) and canopy spread of trees, were measured. Tree height was measured using a Ravi multimeter, DBH using a digital tree caliper and canopy spread using measuring tape. Green biomass yield of grasses and legumes was measured by harvesting 1 × 1 m area at six random places in each plot (60 × 60 m), and then it was calculated per hectare basis and expressed as Mg ha^{-1}. For tree species, canopies were imposed to 30% pruning and, shrubs were pollarded at 1 m height during the winter season and green pruned fodder biomass (leaves and soft twigs) per tree/shrub was recorded. Thereafter, the fresh biomass was calculated per hectare basis based on the number of stems per hectare and was expressed as Mg ha^{-1}.

Carbon stock, carbon dioxide mitigation and oxygen release potential: For trees, grasses and legume species under silvipasture system, above-ground biomass carbon stock was calculated based on their per hectare dry above-ground biomass (AGB) content. For tree and shrub species, total dry AGB was calculated by adding dry biomass of their stem, branches and foliage. Stem dry biomass in *F. infectoria* was calculated by multiplying tree stem volume with specific gravity (Brown, 1997) and foliage as well as branch dry biomass using Forest Survey of India biomass equations (https://fsi.nic.in/carbon_stock/annexure-I.pdf). In *L. leucocephala* stem dry biomass was calculated by multiplying tree stem volume with specific gravity (Brown, 1997) and foliage as well as branch dry biomass by harvesting them, followed by calculating their dry biomass per tree basis. In *A. nilotica*, total dry AGB was calculated by multiplying stem dry biomass (tree stem volume × specific gravity) with the biomass expansion factor (2.55) (Newaj *et al*., 2014). In the case of *M. alba*, total dry AGB was calculated using the tree biomass equation for dry region given by Brown *et al*. (1989). Thereafter, the total dry AGB was calculated per hectare basis based on the number of stems of trees/shrubs per hectare. For grasses and legumes, dry AGB was calculated by harvesting them in 1 × 1 m area at six random places in each plot and determining dry biomass per hectare on a moisture content basis. Finally, above-ground biomass carbon (AGBC) contents in trees, shrub, grasses and legumes was determined by multiplying respective dry AGB with a conversion factor of 0.50 and was expressed as Mg C ha^{-1} (IPCC, 2006).

For trees, grasses and legume species under silvipasture system, below-ground biomass carbon stock was calculated based on their per hectare dry below-ground biomass (BGB) content. Total dry BGB of trees/shrubs was calculated by multiplying dry AGB with 0.26 (IPCC default value (IPCC, 2006). The total dry BGB of grasses and legumes was determined from their root: shoot ratio (Dry biomass of roots/above-ground dry biomass). Below-ground biomass carbon (BGBC) content in trees, shrubs, grasses and legumes was determined by multiplying respective dry BGB with a conversion factor of 0.50 (IPCC, 2006) and was expressed as Mg C ha^{-1}. Total carbon stock in trees, shrub, grasses, and legumes was determined by adding their respective AGBC and BGBC on per hectare basis.

Finally total biomass carbon stock under each silvipasture system was calculated by adding the total biomass carbon stock of the respective trees/shrubs with the total biomass carbon stock of grasses/legumes under each combination. This total carbon stock potential was converted to carbon dioxide mitigation potential or carbon dioxide equivalent storage (CO_2e) (carbon stock × 3.67) as per IPCC 2006. Total oxygen release in the system was calculated as Mg ha^{-1} using the formula (total oxygen release = total carbon stock (Mg ha^{-1}) × 32/12) described earlier (Nowak *et al.*, 2007; Keerthika and Chavan, 2022).

Statistical analysis: Statistical analysis was carried out using ANOVA as per Gomez and Gomez (1984). Data were analyzed using one and two-factor analyses in online OPSTAT software, a statistical software package for agricultural research workers (Sheoran *et al.*, 1998). The mean values were compared at 5% level of significance.

Results and Discussion

Growth performance of trees: Species-level variation in growth performance like DBH, canopy spread and height was observed in 12 years old trees. *A. nilotica* showed maximum growth in height (6.27 m) followed by *F. infectoria* (6.08 m) and *M. alba* (5.01 m; Fig 1). However, *F. infectoria* (18.21 cm; 5.79 m) outperformed *A. nilotica* (15.22 cm; 5.47m) and *M. alba* (11.19 cm; 4.81m) for DBH and canopy spread growth, respectively (Fig 1). Variation in tree performance for growth parameters under silvipasture was also reported earlier (Kumar *et al.*, 2017; 2022; Castillo *et al.*, 2020). The variation in the performance of tree species was attributed to variation in their ability to utilize above and below-ground resources efficiently on degraded lands (Rai *et al.*, 2001; Castillo *et al.*, 2020; Kumar *et al.*, 2022). Higher canopy spread and diameter growth performance in case of *F. infectoria* was also reflected with higher fodder yield in comparison to other species (Table 1).

Fodder production potential of trees/shrub: Selecting the right tree/shrub species having quality top feed potential is essential for the successful establishment of a silvipasture system, which requires a comprehensive examination of different tree/shrub species. In the current study, variability among different tree and shrub species was recorded for their fodder biomass production potential and it maintained a consistent trend over the course of three years (Table 1). At the age of 12 years, *F. infectoria* recorded the highest green fodder yield (5.72 Mg ha^{-1}) followed by *L. leucocephala* (5.01Mg ha^{-1}), *A. nilotica* (3.93 Mg ha^{-1}) and *M. alba* (2.87 Mg ha^{-1}). Variation in fodder production potential of tree/shrub species under silvipasture on degraded lands was also observed by several researchers (Kumar *et al.*, 2015; Kumar *et al.*, 2017; Dagar, 2017; Patidar and Mathur, 2017; Raj *et al.*, 2016; Kumar *et al.*, 2022). The increased fodder yield from the *F. infectoria* tree could be attributed to its higher canopy growth, dense canopy, and thicker leaves in comparison to other species. Conversely, the

Table 1. Green fodder yield (Mg ha^{-1}) from fodder trees/shrub

Tree/Shrub	2020	2021	2022
Ficus infectoria	5.02	5.36	5.72
Morus alba	2.45	2.79	2.87
Acacia nilotica	3.48	3.66	3.93
Leucaena leucocephala	4.35	4.78	5.01
CD	0.67	1.37	0.79
CV (%)	12.63	44.57	21.59

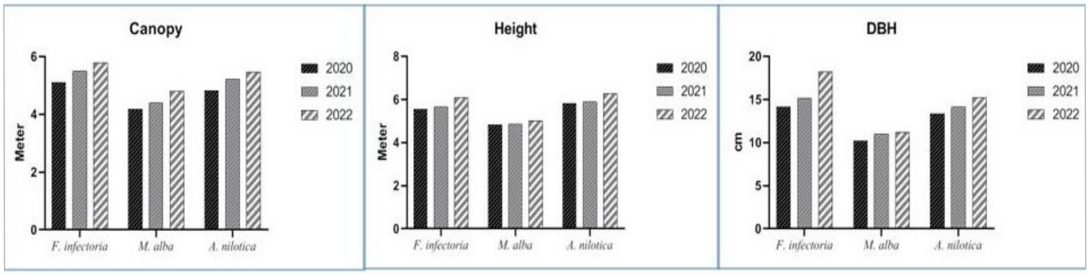

Fig 1. Tree growth performances under silvipasture systems

Table 2. Green fodder yield (Mg ha^{-1}) from grasses and legume under various trees/shrub combinations

Grasses/legume Tree/shrub	*M. maximus*	*C. fulvus*	Mean	*M. maximus*	*C. fulvus*	*S. seabrana*	Mean	*M. maximus*	*C. fulvus*	*S. seabrana*	Mean
Year	2020			2021				2022			
F. infectoria	2.63	1.94	2.29	12.92	9.83	2.90	8.55	25.10	20.98	5.05	17.04
M. alba	3.51	2.01	2.76	10.83	15.17	3.08	9.69	29.30	20.43	6.03	18.59
A. nilotica	2.76	1.91	2.34	16.33	18.83	4.15	13.11	30.03	22.52	3.75	18.77
L. leucocephala	2.40	2.11	2.26	18.33	9.33	1.60	9.76	40.08	24.48	4.15	22.91
Mean	2.83	1.99		14.60	13.29	2.93		31.13	22.10	4.75	
	CD	SEM			CD	SEM			CD	SEM	
Tree	NS	0.10		Tree	NS	1.19		Tree	3.02	1.0	
Grasses	0.21	0.10		Grasses	2.63	0.92		Grasses	2.32	0.60	
Tree × Grasses	0.54	0.20		Tree × Grasses	NS	2.06		Tree × Grasses	5.7	1.70	

lower fodder yield observed in *A. nilotica* was linked to the presence of compound leaves with small leaflets, as well as the production of more woody biomass and in *M. alba* to the presence of a sparse canopy (Kumar *et al.*, 2015; Dagar, 2017; Kumar *et al.*, 2017, 2022). Additionally, the higher biomass production from shrub *L. leucocephala,* when compared to tree species, was due to the adoption of pollarding practices on the shrub and the presence of a higher stem density (1000 ha^{-1}) compared to tree species (400 trees ha^{-1}).

Fodder production potential of grasses and legumes: Choosing the most suitable pasture species is crucial for establishing a successful silvipasture which necessitates a comparative assessment of understory forage production potential study of various pasture species. Under the current study, the potential for fodder biomass production exhibited variation among different grass and legume species and it followed a consistent trend over a three-year period (Table 2). In the initial year, *S. seabrana* exhibited poor seed germination and failed to establish in the field. Subsequently, it was replanted during the second year, which resulted in a successful establishment. Among pasture species, *M. maximus* produced higher green fodder yield (31.13 Mg ha^{-1}) as compared to *C. fulvus* (22.10 Mg ha^{-1}) and *S. seabrana* (4.75 Mg ha^{-1}). Variation in fodder production potential of grass/legume species under silvipasture on degraded lands was previously reported (Kumar *et al.*, 2017; 2022; Ram *et al.*, 2023), which could be attributed to several factors such as genetic composition of the grasses, growth characteristics, rooting patterns, and their enhanced ability to withstand competition (Bantihun *et al.*, 2022). Higher fodder yield from *M. maximus* compared to other suitable perennial grasses was previously reported under semi-arid degraded lands by researchers (Kumar *et al.*, 2017; Raj *et al.*, 2016; Ram *et al.*, 2019; Kumar *et al.*, 2022; Ram *et al.*, 2023). Silvipasture system with *F. infectoria* + grass/legume recorded higher green fodder yield (10.47 to 36.85 Mg ha^{-1}) than *L. leucocephala* + grass/legume (9.76 to 36.14 Mg ha^{-1}); *A. nilotica* + grass/legume (8.68 to 35.06 Mg ha^{-1}) and *M. alba* + grass/legume (7.62 to 34 Mg ha^{-1}) during third year of growth after establishment of pasture. Thus trees and shrubs grown under silvipasture could ensure a consistent supply of green fodder during the lean months of December to June and grasses from July to December months. Further, fodder biomass produced by silvipasture could maintain 4-5 adult cattle units (ACU) ha^{-1} year^{-1}, ensuring year-round fodder security for livestock in the region.

Carbon stock, carbon dioxide mitigation and oxygen release potentials: The quantification of ecosystem services in silvipasture ranging from carbon sequestration to oxygen release potential holds a paramount importance in economic valuation and comprehensive understanding of environmental and economic impacts of silvipasture systems. This quantification not only facilitates evidence-based decision-making and informed policy development but also aids in promoting the adoption of resilient landscapes like silvipasture in the long run. Thus, we quantified the carbon storage and oxygen release potential of the silvipasture system during the studies.

Three years data was pooled to find out carbon stock potential of trees/shrubs and pasture species under silvipasture system. Trees/shrubs stored total AGC and BGC in their biomass ranging from 4.72 to 12.46 Mg C ha^{-1} and 1.23 to 3.24 Mg C ha$^{-1,}$ respectively under different grasses and legume combinations (Table 3). The total (AGC + BGC) stored carbon in tree/shrub biomass ranged from 5.95 to 15.71 Mg C ha^{-1}; (Table 3). Among tree/shrub species, *A. nilotica* stored maximum and *L. leucocephala* stored the minimum amount of carbon in their biomass. The grasses/legumes stored total AGC and BGC (Table 4)

Table 3. Tree biomass carbon stock (Mg C ha^{-1}) under silvipasture system

Grass/legume Tree/shrub	*M. maximus*	*C. fulvus*	*S. seabrana*	**Mean**	*M. maximus*	*C. fulvus*	*S. seabrana*	**Mean**	*M. maximus*	*C. fulvus*	*S. seabrana*	**Mean**
	Above ground carbon stock				**Below ground carbon stock**				**Total carbon stock**			
F. infectoria	7.87	7.94	8.80	8.20	2.05	2.07	2.29	2.13	9.92	10.01	11.09	10.34
M. alba	5.05	4.87	5.27	5.06	1.31	1.27	1.37	1.32	6.36	6.14	6.64	6.38
A. nilotica	11.32	12.46	12.19	11.99	2.94	3.24	3.17	3.12	14.26	15.71	15.36	15.11
L. Leucocephala	4.77	4.72	5.21	4.90	1.24	1.23	1.35	1.27	6.01	5.95	6.56	6.17
Mean	7.25	7.50	7.87		1.89	1.95	2.05		9.14	9.45	9.91	
	CD	SEM			CD	SEM			CD	SEM		
Tree	1.13	0.38			0.59	0.20			0.40	0.18		
Grasses	NS	0.33			NS	0.17			NS	0.09		
Tree × Grasses	NS	0.66			NS	0.35			NS	0.01		

Table 4. Grass biomass carbon stock (Mg C ha^{-1}) under silvipasture system

Grass/legume Tree/shrub	*M. maximus*	*C. fulvus*	*S. seabrana*	**Mean**	*M. maximus*	*C. fulvus*	*S. seabrana*	**Mean**	*M. maximus*	*C. fulvus*	*S. seabrana*	**Mean**
	Above ground carbon stock				**Below ground carbon stock**				**Total carbon stock**			
F. infectoria	2.44	2.37	0.91	1.91	1.25	1.40	0.40	1.01	3.69	3.77	1.30	2.92
M. alba	2.52	2.64	1.08	2.08	1.29	1.55	0.47	1.10	3.81	4.19	1.55	3.18
A. nilotica	2.92	3.20	0.91	2.34	1.49	1.89	0.40	1.26	4.40	5.09	1.31	3.60
L. Leucocephala	3.75	2.58	0.67	2.33	1.91	1.52	0.29	1.24	5.66	4.10	0.96	3.57
Mean	2.91	2.70	0.89		1.48	1.59	0.39		4.39	4.29	1.28	
	CD	SEM			CD	SEM			CD	SEM		
Tree	NS	0.38			NS	0.32			NS	0.24		
Grasses	0.97	0.33			0.84	0.28			0.63	0.10		
Tree × Grasses	NS	0.66			NS	0.56			NS	0.38		

Table 5. Total biomass carbon stock, CO$_2$e storage and oxygen release potential of silvipasture system

Grass/legume Tree/shrub	*M. maximus*	*C. fulvus*	*S. seabrana*	**Mean**	*M. maximus*	*C. fulvus*	*S. seabrana*	**Mean**	*M. maximus*	*C. fulvus*	*S. seabrana*	**Mean**
	Total carbon stock (Mg C ha^{-1})				Co$_2$e (Mg ha^{-1})				O$_2$ released (Mg ha^{-1})			
F. infectoria	13.61	13.78	12.39	13.26	49.95	50.57	45.47	48.66	36.34	36.79	33.08	35.40
M. alba	10.18	10.32	8.19	9.56	37.36	37.87	30.06	35.09	27.18	27.55	21.87	25.53
A. nilotica	18.66	20.80	16.67	18.71	68.48	76.34	61.18	68.67	49.82	55.54	44.51	49.96
L. Leucocephala	11.67	10.05	7.51	9.74	42.83	36.88	27.56	35.75	31.16	26.83	20.05	26.01
Mean	13.53	13.74	11.19		49.66	50.43	41.07		36.13	36.69	29.88	
	CD	SEM			CD	SEM			CD	SEM		
Tree	2.56	0.8			9.38	3.10			6.81	2.30		
Grasses	2.21	0.7			8.12	2.75			5.91	2.00		
Tree × Grasses	NS	1.21			NS	5.50			NS	4.01		

in their biomass ranging from 0.67 to 3.75 Mg C ha^{-1} and 0.29 to 1.91 Mg C ha^{-1}, respectively, under different trees and shrub combinations. The total (AGC + BGC) stored carbon in grasses/legumes ranged from 0.96 to 5.66 Mg C ha^{-1}, respectively (Table 4). Among pasture species, *M. maximus* stored the maximum and *S. seabrana* stored the minimum amount of carbon in their biomass.

Three years data was pooled to find out carbon stock, CO$_2$e storage and oxygen release potentials of silvipasture systems. The system stored a total of 7.51 to 20.80 Mg C ha^{-1} under different trees/shrub + grasses and legume combinations with maximum storage under *A. nilotica* + *C. fulvus* combination (20.80 Mg C ha^{-1}) (Table 5). Higher biomass carbon stock potential of silvipasture ranging between 16 to 41 Mg C ha^{-1} was also reported earlier across the globe (Tanwar *et al.*, 2019; Fernandez *et al.*, 2020; Singh *et al.*, 2022; Kumar *et al.*, 2022; Torres *et al.*, 2022; Ram *et al.*, 2023). The carbon storage in biomass under the current study has amounted to 27.56 to 76.34 Mg ha^{-1} of CO$_2$e of storage in its biomass and the system also released 20.05 to 55.54 Mg ha^{-1} of oxygen (Table 5). Executing a carbon finance mechanism in conjunction with CO$_2$e storage, this silvipasture system has the potential to generate additional financial returns ranging from approximately INR 7720 to 21382 ≈ USD 92 to 255 (market value of one CO$_2$e = 3.34 USD (Asia) as per forest trends' ecosystem marketplace report, 2021). As of now, the prices of carbon offsets are relatively low and exhibit variation across different continents. Specifically, prices range from 2.96 USD in Europe to 32.93 USD in Oceania (Forest Trends' Ecosystem Marketplace, 2021). However, there is an anticipated increase in carbon credit prices to the range of USD 20-50 Mg^{-1} CO$_2$e by 2030. This expectation stems from a growing need for increased investment in projects that effectively sequester substantial amounts of atmospheric carbon dioxide, aiming to address long-term climate change (Sciencedaily, 2021). As a result, the implementation of silvipasture system holds the potential to secure additional sustainable monetary gains for individuals. Furthermore, these silvipasture systems, by virtue of storing carbon in these systems, can act as a crucial contributor to India's pursuit of achieving carbon neutrality by 2070.

Conclusion

The findings of the current study suggest that in degraded semi-arid lands of India, a silvipasture system integrating *F. infectoria* + *M. maximus* (fodder: 36.85 Mg/ha; carbon stock: 13.61 Mg C ha^{-1}; oxygen released: 36.34 Mg ha^{-1}); *A. nilotica* + *M. maximus* (fodder: 35.06 Mg ha^{-1}; carbon stock: 18.66 Mg C ha^{-1}; oxygen released: 49.82 Mg ha^{-1}); *F. infectoria* + *C. fulvus* (fodder: 27.82 Mg ha^{-1}; carbon stock: 13.78 Mg C ha^{-1}; oxygen released: 36.79 Mg ha^{-1}) and *A. nilotica* + *C. fulvus* (fodder: 26.03 Mg ha^{-1}; carbon stock: 20.80 Mg C ha^{-1}; oxygen released: 55.54 Mg ha^{-1}) could be an ideal nature-based solution for providing year-round, high-quality fodder and sequestering significant amounts of atmospheric carbon dioxide. Although the yield of the legume, *S. seabrana* was less than grasses to ensure nutritious understory pasture composition, S. seabrana could be mixed with grasses under silvipasture system. Moreover, these silvipasture systems enhance the capacity to address oxygen shortages resulting from escalating air pollution, serving as a measure to both mitigate and adapt to climate change on degraded landscapes. Such silvipasture systems could be crucial to address the persisting demand for high-quality livestock fodder, supporting rural economies, and promoting environmental sustainability.

Acknowledgment

The authors are highly thankful to ICAR-Indian Grassland and Fodder Research Institute, Jhansi, India for the research support.

References

Ajith, K.S., A.K. Kumar and M.T. Dipu. 2012. How to improve the livestock sector in Kerala: some nutritional thoughts. *Journal Indian Veterinary Association Kerala* 10: 66-68.

Aryal, D.R., D.E. Morales-Ruiz, S. Lopez-Cruz, C.N. Tondopo-Marroquin, A. Lara-Nucamendi, J.A. Jimenez-Trujillo, E. Perez-Sanchez, J.E. Betanzos-Simon, F. Casasola-Coto, A. Martinez-Salinas and C.J. Sepulveda-Lopez. 2022. Silvopastoral systems and remnant forests enhance carbon storage in livestock-dominated landscapes in Mexico. *Scientific Reports* 12: 16769.https://doi.org/10.1038/s41598-022-21089-4.

Bantihun, A., B. Asmare and Y. Mekuriaw. 2022. Comparative evaluation of selected grass species for agronomic performance, forage yield, and chemical composition in the highlands of Ethiopia. *Advances in Agriculture* 22: 6974681. https://doi.org/10.1155/2022/6974681.

Brown, S. 1997. *Estimating Biomass and Biomass Change of Tropical Forests: A Primer*. Food and Agriculture Organization, Rome, Italy.

Brown, S., A.J.R. Gillespie and A.E. Lugo. 1989. Biomass estimation methods for tropical forests with applications to forest inventory data. *Forest Science* 35: 881-902.

Castillo, M.S., F. Tiezzi and A.J. Franzluebbers. 2020. Tree species effects on understory forage productivity and microclimate in a silvopasture of the south-eastern USA. *Agriculture, Ecosystems and Environment* 295: 106917. https://doi.org/10.1016/j.agee.2020.106917.

Dagar, J.C. 2017. Potentials for fodder production in degraded lands. In: P.K. Ghosh, S.K. Mahanta, J.B. Singh, D. Vijay, R.V. Kumar, V.K. Yadav and S. Kumar (eds). *Approaches Towards Fodder Security in India*. Studera Press, New Delhi. pp. 333-364.

Dev, I., A. Ram, S. P. Ahlawat, D.R. Palsaniya, R. Singh, S. K. Dhyani, N. Kumar, R.K. Tewari, M. Singh, K. B. Shridhar, R. Newaj, R. P. Dwivedi, R.V. Kumar, R.S. Yadav, L. Chand, D. Kumar and J. Prasad. 2020. Bamboo-based agroforestry system (*Dendrocalamus strictus* + sesame + chickpea) for enhancing productivity in semi-arid tropics of central India. *Agroforestry Systems* 8: 1167-1175.

Dev, I., R. Singh, K. K. Garg, A. Ram, D. Singh, N. Kumar, S.K. Dhyani, A. Singh, K.H. Anantha, V. Akuraju and S. Dixit. 2022. Transforming livestock productivity through watershed interventions: a case study of Parasai-Sindh watershed in Bundelkhand region of central India. *Agricultural Systems* 196: 103346. https://doi.org/10.1016/j.agsy.2021.103346.

Fernandez, P. D., Y. L. P. de Waroux, E. G. Jobbagy, D. E. Loto and N.L. Gasparri. 2020. A hard-to-keep promise: vegetation use and above-ground carbon storage in silvopastures of the dry Chaco. *Agriculture, Ecosystems and Environment* 303: 107117. https://doi.org/10.1016/j.agee.2020.107117.

Forest Trends' Ecosystem Marketplace. 2021. Voluntary carbon and the post-pandemic recovery. State of Voluntary Carbon Markets Report, Special Climate Week NYC.

Gautam, K., S. Kumar, A.K. Singh, A. Ghosh and R. V. Kumar. 2021. A guava-based hortipasture system for mitigating climate change and sustaining fodder and fruit supply in semi-arid regions of India. In: *Proceedings of XXIV International Grassland Congress/ XI International Rangeland Congress on Sustainable Use of Grassland and Rangeland Resources for Improved Livelihoods*, Kenya Agricultural and Livestock Research Organization. pp.1-3.

Gautam, K., S. Thakur, Vipasha and S. S. Bhat. 2022. Forests and tree-based land use systems: mitigation and adaptation option to combat climate change. *In:* A. M. Dervash and A. A. Wani (eds). *Climate Change Alleviation for Sustainable Progression*. CRC Press. pp. 219-255.

Ghosh, A., A. K. Singh, B. Das, K. Modak, R.V. Kumar, S. Kumar, K. Gautam, D. R. Biswas and A. K. Roy. 2023. Resiliencies of soil phosphorus fractions after natural summer fire are governed by microbial activity and cation availability in a semi-arid Inceptisol. *Environmental Research* 216: 114583. doi: 10.1016/j.envres.2022.114583.

Gomez, K.A. and A. A. Gomez. 1984. *Statistical Procedures for Agricultural Research*. 2nd edn. John Wiley and Sons, New York. pp. 1-680.

IPCC. 2006. Guidelines for national greenhouse gas inventories. Institute for Global Environmental Strategies, Hayama, Kanagawa, Japan.

Kamini, S. N. Ram and S. S. Manjanagouda. 2020. *Hardwickia binata*: A valuable fodder tree species of semi-arid region. E-Bulletin. ICAR-Indian Grassland and Fodder Research Institute, Jhansi, India. pp. 1-32.

Keerthika, A. and S. B. Chavan. 2022. Oxygen production potential of trees in India. *Current Science* 122: 850-853.

Kumar, R. V., A. K. Roy, S. Kumar, K. Gautam, A. K. Singh, A. Ghosh, H. V. Singh, and P. Koli. 2022. Silvopasture systems for restoration of degraded lands in a semi-arid region of India. *Land Degradation and Development* 33: 2843-2854.

Kumar, R.V., H. V. Singh, S. Kumar, A. K. Roy and P. K. Ghosh. 2015. Forage from trees and grasses of silvipasture system in degraded land of semi-arid India. XXIII International Grassland Congress (November 20-24, 2015), paper ID: 759, New Delhi.

Kumar, R.V., H. V. Singh, S. Kumar, A. K. Roy and K. A. Singh. 2017. Growth and biomass production of fodder trees and grasses in a silvipasture system on non-arable land of semi-arid India. *Range Management and Agroforestry* 38: 43-47.

Kumar, S., A. K. Singh, R. Singh, A. Ghosh, M. Chaudhary, A. K. Shukla, S. Kumar, H.V. Singh, A. Ahmed and R.V. Kumar. 2019. Degraded land restoration: ecological way through horti-pasture systems and soil moisture conservation to sustain productive economic viability. *Land Degradation and Development* 30: 1516-1529.

Newaj, R., S. K. Dhyani, S.B. Chavan, R.H. Rizvi, R. Prasad, Ajit, B. Alam and A. K. Handa. 2014. Methodologies for assessing biomass, carbon stock and carbon sequestration in agroforestry systems. National Research Centre for Agroforestry, Jhansi. pp. 1-62.

Nowak, D. J., R. Hoehn and D. E. Crane. 2007. Oxygen production by urban trees in the United States. *Arboriculture and Urban Forestry* 33: 220-226.

Patidar, M. and B. K. Mathur. 2017. Enhancing forage production through a silvi-pastoral system in an arid environment. *Agroforestry Systems* 91: 713-727.

Pinnschmidt, A., R. Yousefpour, A. Nolte and M. Hanewinkel. 2023. Tropical mixed-species plantations can outperform monocultures in terms of carbon sequestration and economic return. *Ecological Economics* 211: 107885. https://doi.org/10.1016/j.ecolecon.2023.107885.

Rai, P., R. S. Yadav, K.R. Solanki, G. R. Rao and R. Singh. 2001. Growth and pruned production of multipurpose tree species in silvo-pastoral systems on degraded lands in semi-arid region of Uttar Pradesh, India. *Forests, Trees and Livelihoods* 11: 347-364.

Raj, A.K., T.K. Kunhamu, V. Jamaludheen and S. Kiroshima. 2016. Forage yield and nutritive value of intensive silvopasture systems under cut and carry scheme in humid tropics of Kerala, India. *Indian Journal of Agroforestry* 18: 47-52.

Ram, S. N., Kamini and S. S. Manjanagouda. 2023. Forage productivity and carbon storage from *Hardwickia binata* based silvopasture systems in semi-arid rainfed conditions. *Range Management and Agroforestry* 44: 233-240.

Ram, S. N., R V Kumar and A. K. Shukla. 2019. Influence of shrubs and tree densities on three-tier silvopasture components in semi-arid rainfed conditions. *Range Management and Agroforestry* 40: 104-108.

Ram, S. N., M. M. Das and A. Ahmed. 2023. Performance of anjan tree (*Hardwickia binata*)-based silvopasture systems under moisture-conservation practices in semi-arid conditions. *Indian Journal of Agronomy* 68: 83-88.

Rather, T.A., A. Singh and B. Ayoob. 2023. Impact of different silvipastoral systems on understorey vegetation and soil properties. *Range Management and Agroforestry* 44: 385-390.

Rathod, P. and S. Dixit. 2020. Dairying in Bundelkhand region of Uttar Pradesh: constraints to realizing the potential. *Indian Journal of Animal Sciences* 90: 3-11.

Sciencedaily. 2021. Ten-fold increase in carbon offset cost predicted-Sciencedaily. https://www.sciencedaily.com/releases/2021/06/210604122439.htm (accessed on Oct. 17, 2023).

Sheoran, O.P., D. S. Tonk and L. S. Kaushik.1998. OPSTAT. In: Statistical Software Package. Agricultural Research Work. CCS HAU. http://www.202.141.47.5/opstat/index.asp (accessed on Oct. 17, 2023).

Shukla, P.R., J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.O. Portner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. Van Diemen and M. Ferrat. 2019. Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. IPCC-2019.

Singh, N. R., D. Kumar, A. K. Handa, N. Ram, M. Prasad, Kamini, N. Kumar, A. Ram, I. Dev, B. P. Bhatt, O.P. Chaturvedi, A. Arunachalam and L. N. Singh. 2022. Land use effect on soil organic carbon stocks, microbial biomass and basal respiration in Bundelkhand region of central India. *Agricultural Research* 11: 1-11.

Tanwar, S.P. S., P. Kumar, A. Verma, R. K. Bhatt, A. Singh, K. Lal, M. Patidar and B. K. Mathur. 2019. Carbon sequestration potential of agroforestry systems in the Indian arid zone. *Current Science* 117: 2014-2022.

Torres, B., B. Carlos, A. Torres, C. Tipan-Torres, J.C. Vargas, R. J. Herrera-Feijoo, M. R. Heredia, C. Barba and A. Garcia. 2022. Carbon stock assessment in silvopastoral systems along an elevational gradient: a study from cattle producers in the sumaco biosphere reserve, Ecuadorian Amazon. *Sustainability* 15: 449. https://doi.org/10.3390/su15010449.