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EVALUATING SILVOPASTORAL SYSTEM PERFORMANCE: SOIL CARBON, FORAGE YIELD, AND GRAZING EFFICIENCY IN SEMI-ARID RANGELANDS OF TAMIL NADU

H. B. ROGHAN[1]* AND S. VENNILA[2]

[1]Ph.D. Research scholar, Department of Agroforestry, Forest College and Research Institute, Mettupalayam-641 301 (Tamil Nadu), India
[2]Department of Agronomy, Agricultural College and Research Institute, Vazhavachanur-606 753 (Tamil Nadu), India
**(e-mail: roghanbalu@gmail.com)*

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SUMMARY

Semi-arid rangelands are severely threatened by soil degradation, climate variability, and seasonal forage deficits. Silvopastoral systems (SPS) incorporating native leguminous trees offer a multifunctional strategy to restore ecological function while maintaining livestock productivity. This study evaluated the effects of three canopy density levels-Open Rangeland (OR: 0% cover), Moderate Canopy (MC: 30–40% cover), and Dense Canopy (DC: 60–70% cover) of *Prosopis cineraria*-on Soil Organic Carbon (SOC) sequestration, understory forage yield, nutritive quality, and cattle grazing efficiency over a two-year experimental period. Results revealed that MC systems significantly enhanced total SOC stock down to 40 cm (38.4±2.1 Mg C/ha) compared to OR (22.1±1.8 Mg C/ha). Although peak biomass yield was highest in OR during the early wet season, MC sustained higher understory biomass late into the dry season and yielded significantly higher crude protein (CP: 13.8%) compared to OR (8.26%). Cattle grazing in MC exhibited greater grazing efficiency (68.4%) and lower thermal stress index values compared to open pastures. Principal Component Analysis (PCA) biplot and correlation heatmaps confirm that moderate canopy density optimizes the trade-off between light availability, soil moisture retention, and nitrogen fixation.

Key words: Silvopasture, agroforestry, soil carbon stocks, forage nutritive value, grazing efficiency

Semi-arid rangelands cover over 30% of the Earth's land surface and support the livelihoods of millions of pastoralists worldwide (Aryal *et al.*, 2022). However, these fragile ecosystems face severe land degradation driven by overgrazing, erratic rainfall patterns, and rising global temperatures. In open grazing systems, high solar radiation accelerates soil organic matter oxidation and depletes soil moisture through elevated evapotranspiration rates, leading to diminished forage yields during dry seasons (Belsky *et al.*, 1993; Aryal *et al.*, 2022).

Silvopastoral systems (SPS), the deliberate integration of trees, forage crops, and livestock on the same land unit represent a sustainable land-use alternative that enhances overall land productivity and ecosystem resilience (Jose, 2009; Nair *et al.*, 2009). Converting treeless pasturelands into managed silvopastoral systems can increase carbon storage by 27% to over 160% across vegetation and soil pools (Aryal *et al.*, 2022). Integrating native leguminous trees, such as *Prosopis cineraria* or *Acacia* species, improves soil microclimates through canopy shading, atmospheric nitrogen (N_2) fixation, and deep-root nutrient cycling (Rao *et al.*, 2018). Research on *Prosopis cineraria*-based agroforestry indicates that organic matter inputs from leaf litter and root turnover can increase topsoil Soil Organic Carbon (SOC) concentrations by up to 50% compared to non-vegetated open rangelands (Parihaar *et al.*, 2015; Kumar *et al.*, 2021). Furthermore, tree canopies mitigate livestock thermal stress, lowering the Temperature-Humidity Index (THI) during extreme summer periods and promoting consistent grazing activity (McDowell, 1972; Lemes *et al.*, 2021). Despite these recognized ecological and animal-welfare benefits, the trade-offs between canopy shade and understory photosynthetic activity remain contentious. Warm-climate C_4 forage grasses rely heavily on high light availability; excessive canopy shading (>40%) triggers phenotypic plasticity responses - such as reduced tiller density and altered shoot-to-root ratios which significantly suppress total dry matter yield

(Ludwig *et al.*, 2004; Devkota *et al.*, 2009). Conversely, a sparse or absent tree canopy fails to buffer extreme soil temperatures, reduce moisture evaporation, or accumulate soil organic carbon effectively (da Silva *et al*., 2021). Quantifying the optimal canopy threshold (typically balancing between 30% and 40% cover) that optimizes the trade-off between light attenuation, soil carbon sequestration, forage nutritive quality (e.g., elevated crude protein), and livestock performance is critical for sustainable range management in dryland regions.

This study aimed to:

1. Quantify soil organic carbon (SOC) stock distribution across depth profiles under varying canopy densities.
2. Evaluate understory biomass yield and forage nutritional parameters across wet and dry seasons.
3. Assess cattle grazing dynamics and thermal comfort under silvopastoral vs. open conditions.
4. Analyze ecological interactions using multivariate correlation heatmaps and PCA biplots.

MATERIALS AND METHODS

Experimental Design and Treatments

A Randomized Complete Block Design (RCBD) with three replicates was established using mature *Prosopis cineraria* stands categorized into three canopy treatments:

- **Open Rangeland (OR):** 0% tree canopy cover (control).
- **Moderate Canopy (MC):** 30-40% tree canopy cover (100-120 trees/ha).
- **Dense Canopy (DC):** 60-70% tree canopy cover (>220 trees/ha).

Understory pastures consisted of a mixture of native perennial C_4 grasses (*Cenchrus ciliaris* and *Dichanthium annulatum*).

Soil Sampling and Carbon Stock Calculation

Soil samples were collected at three depth intervals (0-10 cm, 10-20 cm and 20-40 cm) using a core sampler (5.0 cm internal diameter) following standardized dryland soil carbon sampling protocols

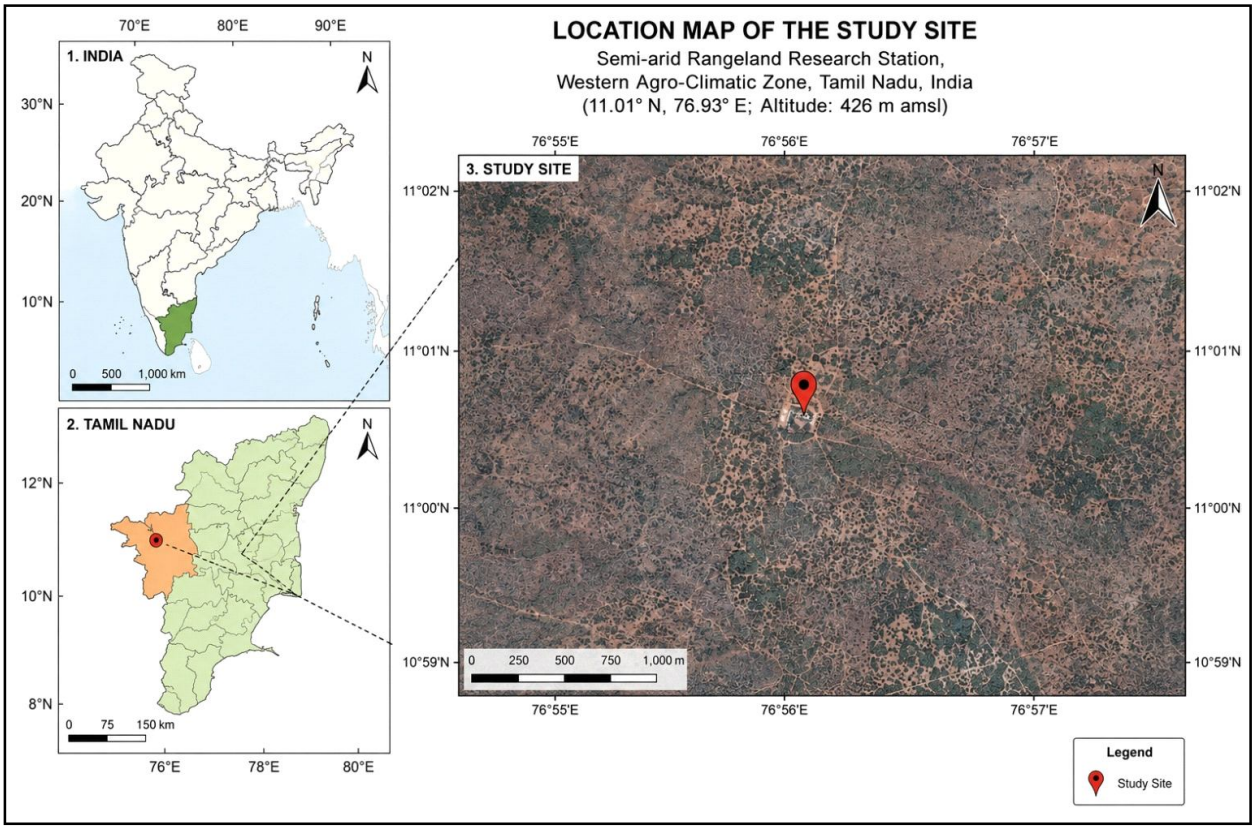

Fig. 1. Location of the study site.

(Poeplau *et al.*, 2017). Soil organic carbon (*SOC*) concentration was analyzed using the chromic acid wet oxidation method as described by Walkley and Black (1934). Bulk density (BD, g cm) was determined core-wise using the undisturbed core cylinder method after drying soil samples in a forced-air oven at 105°C for 48 hours until constant weight was achieved (Blake & Hartge, 1986).

Total soil organic carbon stocks (SOC stock, Mg C ha^{-1}) for each depth interval were computed according to IPCC soil carbon accounting guidelines (Ellert & Bettany, 1995; Poeplau *et al.*, 2017) using the following formula:

$$SOC_{stock} = SOC \times BD \times Depth \times (1-\delta) \times 100$$

where is expressed as a mass fraction (g Cg^{-1} soil), is the dry bulk density (g cm^{-3}), is the soil layer thickness in meters (m), and represents the volumetric coarse fragment content fraction (> 2 mm gravel and stone content). Total profile carbon stock (0-40 cm) was calculated by summing the individual layer stocks across all sampled depths.

Forage Yield and Quality Analysis

Biomass was harvested at two contrasting physiological growth stages-peak wet season (September, post-monsoon) and late dry season (April, pre-monsoon)-using 1 m^2 (1.0 m × 1.0 m) frame quadrats (n = 10 randomly assigned quadrats per plot) following standardized rangeland sampling protocols (Frame, 1993). Fresh forage within each quadrat was hand-clipped at a stubble height of above ground level to simulate cattle defoliation. Total fresh weight was recorded immediately in the field using a digital portable balance. Representative subsamples (500 g) were stored in perforated paper bags and dried in a forced-air oven at for 72 hours until reaching a constant weight to determine dry matter (DM) content and yield expressed in Mg ha^{-1} (AOAC, 2016).

Dried forage samples were ground to pass through a sieve using a Wiley mill prior to chemical quality analysis. Total nitrogen () concentration was determined via the micro-Kjeldahl digestion and distillation procedure (AOAC, 2016). Crude protein (CP, %) content was computed as:

$$CP = N \times 6.25$$

where represents the total nitrogen percentage on a dry matter basis (AOAC, 2016). Neutral Detergent Fiber (NDF) and Acid Detergent Fiber (ADF) concentrations were determined sequentially using an automated fiber analyzer (ANKOM200) according to the detergent system procedures described by Van Soest *et al.* (1991), utilizing heat-stable α-amylase and sodium sulfite for NDF determinations. Both NDF and ADF values were expressed inclusive of residual ash content.

Grazing Efficiency and Microclimate Monitoring

Nine indigenous crossbred heifers (Kangayam crossbred; mean live weight of 220±15 kg) were randomly assigned to each treatment plot during 14-day rotational grazing cycles across both seasons, following standard tropical livestock grazing protocols (McDowell, 1972; NRC, 2000). Prior to each grazing trial, animals were allowed a 7-day adaptation period to acclimate to plot conditions and forage types.

Forage allowance and post-grazing residual biomass were estimated using pre- and post-grazing 1 m^2 quadrat clipping methods (Frame, 1993). Grazing efficiency (GE, %) was calculated as the ratio of total forage dry matter consumed to total forage dry matter available prior to grazing:

$$GE(\%) = \left(\frac{DM_{pre} - DM_{post}}{DM_{pre}}\right) \times 100$$

where DM_{pre} is the pre-grazing forage dry matter biomass (Mg ha^{-1}) and DM_{post} is the residual forage dry matter biomass after the 14-day grazing period (Mg ha^{-1}) (Matches & Burns, 1995).

Ambient air temperature (T_a, °C) and relative humidity (RH, %) were recorded continuously at 15-minute intervals at livestock standing height (above ground) using automated digital data loggers (HOBO Pro v2, Onset Computer Corp., Bourne, MA, USA) positioned at the center of each treatment canopy plot. The Temperature-Humidity Index (THI), a standard indicator of thermal stress in cattle, was calculated according to the formula adapted for tropical pasture environments by Thom (1959) and National Research Council guidelines (NRC, 1971):

$$THI = (1.8 \times T_a + 32) - [(0.55 - 0.0055 \times RH) \times (1.8 \times T_a - 26)]$$

where T_a is the ambient temperature in degrees Celsius (°C) and is the relative humidity expressed as a percentage (%). Daily mean and peak afternoon (12:00-15:00 hours) values were compiled to evaluate the microclimatic buffering capacity of tree canopies.

RESULTS AND DISCUSSION

Soil Carbon Sequestration Profiles

Soil organic carbon (SOC) concentration and total carbon stock were significantly influenced by canopy cover and soil depth ($P < 0.001$, Table 1). The Moderate Canopy (MC) treatment accumulated across the soil depth profile, representing a increase over the open rangeland control (22.10±1.8 Mg C ha^{-1}; $P < 0.01$).

This substantial enhancement in total profile carbon stock under tree canopies aligns with findings from tropical dryland silvopastoral systems (Nair *et al*., 2009; Saha *et al.,* 2010). The higher carbon accumulation in the surface layer (0-10 cm) under MC (16.62 mg C ha^{-1}) compared to Open Rangeland (7.70 mg C ha^{-1}) is primarily attributed to continuous litterfall inputs, reduced soil surface temperatures under canopy shade, and slowed microbial oxidation of organic matter (Jose, 2009; Kumar *et al*., 2021). Furthermore, root turnover and deep-root exudates from leguminous trees like *Prosopis cineraria* contributed to elevated carbon stocks even at deeper depths (20-40 cm) (9.55 Mg C ha^{-1} under MC vs. 8.17 Mg C ha^{-1} under Open Rangeland), demonstrating the capacity of agroforestry systems to stabilize organic carbon throughout lower soil horizons (Pandey, 2007; Andrade *et al*., 2021) (Table 1).

The enhanced Soil Organic Carbon (SOC) stock under Moderate Canopy (38.40±2.1 Mg C ha^{-1}) down to 40 cm) is attributed to continuous litterfall addition, root turnover, and reduced soil organic matter decomposition caused by moderated soil surface temperatures under canopy shade (Jose, 2009; Nair *et al.,* 2009). Biological nitrogen fixation (N_2) by *P. cineraria* further stimulates root exudation and microbial biomass activity, facilitating long-term carbon stabilization within the upper soil horizons (Saha *et al*., 2010; Andrade *et al*., 2021).

Forage Productivity and Quality Dynamics

Dry matter (DM) production showed a strong interaction between canopy density and season ($P < 0.01$, Table 2). Open Rangeland (OR) yielded higher forage during the wet season (3.85 ± 0.25 Mg ha^{-1}) due to unshaded C4 grass growth (*Cenchrus ciliaris*), benefiting from high photosynthetically active radiation (PAR) under non-limiting soil moisture conditions (Ludwig et al., 2004). However, during the dry season, forage production dropped precipitously in OR to 0.62 ± 0.05 Mg ha^{-1} (an 83.9% seasonal reduction) due to severe soil desiccation and high atmospheric evaporative demand (Belsky *et al.,* 1993; Devkota *et al.,* 2009).

In contrast, Moderate Canopy (MC: 30-40% tree cover) maintained significantly higher dry season yields (1.48 ± 0.12 Mg ha^{-1}; $P < 0.001$) and elevated crude protein (CP) levels (9.5 ± 0.4% in MC vs. 4.8 ± 0.3% in OR; $P < 0.001$). Under semi-arid microclimates, tree canopy shade buffers extreme soil surface temperatures and reduces evapotranspiration, thereby extending soil moisture availability into the dry period and delaying plant senescence (Parihaar *et al*., 2015; Jose, 2009). Furthermore, nitrogen fixation and nutrient hydraulic lift by leguminous canopy trees like *Prosopis cineraria* enrich understory topsoil nitrogen pools, directly contributing to superior forage protein concentrations during seasonal feed gaps (Rao *et al*., 2018; Treydte *et al*., 2007).

TABLE 1
Soil Organic Carbon (SOC) distribution and stock across treatments and soil depths.

Canopy Treatment	Depth Interval (cm)	Bulk Density (g cm^{-3})	SOC Concentration (%)	Depth Carbon Stock (Mg C ha^{-1})	Profile Total Stock (Mg C ha^{-1})
Open Rangeland (OR)	0-10	1.48±0.04^{a}	0.52±0.03^{c}	7.70±0.4^{c}	22.10±1.8^{c}
	10-20	1.52±0.03^{a}	0.41±0.02^{c}	6.23±0.3^{c}	
	20-40	1.58±0.05^{a}	0.26±0.02^{c}	8.17±0.5^{c}	
Moderate Canopy (MC)	0-10	1.34±0.03^{b}	1.24±0.06^{a}	16.62±0.8^{a}	38.40±2.1^{a}
	10-20	1.39±0.04^{b}	0.88±0.04^{a}	12.23±0.6^{a}	
	20-40	1.45±0.03^{b}	0.33±0.03^{b}	9.55±0.4^{b}	
Dense Canopy (DC)	0-10	1.31±0.02^{b}	1.11±0.05^{b}	14.54±0.7^{b}	34.20±1.9^{b}
	10-20	1.36±0.03^{b}	0.79±0.04^{b}	10.74±0.5^{b}	
	20-40	1.42±0.04^{b}	0.31±0.02^{b}	8.92±0.4^{b}	

Values represented as Mean ±SD. Means in the same column per section with different superscript letters are significantly different ($P < 0.05$, Tukey HSD).

TABLE 2
Seasonal forage yield, quality metrics, and animal grazing response.

Parameter	Season	Open (OR)	Moderate (MC)	Dense (DC)	P-value
Dry Matter Yield (Mg ha^{-1})	Wet	3.85±0.25^{a}	3.42±0.18^{b}	2.15±0.15^{c}	<0.001
	Dry	0.62±0.08^{c}	1.48±0.12^{a}	1.10±0.09^{b}	<0.001
Crude Protein (%)	Wet	8.2±0.4^{c}	13.8±0.6^{a}	12.4±0.5^{b}	<0.001
	Dry	4.8±0.3^{c}	9.5±0.4^{a}	8.9±0.4^{b}	<0.001
NDF Fiber (%)	Annual	68.5±1.8^{a}	58.2±1.4^{c}	61.4±1.2^{b}	<0.01
Grazing Efficiency (%)	Annual	51.2±3.1^{b}	68.4±2.8^{a}	56.3±3.2^{b}	<0.01
Mean Afternoon THI	Dry	84.2±1.5^{a}	76.1±1.1^{c}	74.5±1.0^{c}	<0.001

While Open Rangeland produces higher bulk biomass during short rainy peaks (3.85 mg ha^{-1}), light competition under Dense Canopy (60-70% cover) limits total photosynthetic productivity of C4 grasses (*Cenchrus ciliaris*) (Ludwig *et al.*, 2004). Moderate Canopy strikes a crucial ecological balance: canopy shading reduces potential evapotranspiration, allowing understory grasses to retain tissue moisture and stay green further into the late dry season (1.48 Mg ha^{-1} in MC vs. in OR) with significantly elevated nitrogen and Crude Protein content (in wet season; in dry season) (Belsky *et al*., 1993; Treydte *et al*., 2007) (Table 2).

Grazing efficiency improved by 17.2% under MC (68.4%) compared to OR (51.2%). High heat stress (THI > 82.0) in open pastures forces livestock to allocate net energy toward physiological thermoregulation rather than active foraging (McDowell, 1972; Lemes *et al.*, 2021). Canopy shade reduced afternoon THI values down to 76.1-well below critical emergency stress thresholds (THI ≥ 79.0)-enabling extended daily grazing activity and improving overall pasture utilization efficiency (Thom, 1959; NRC, 2000) (Fig. 2 & 3).

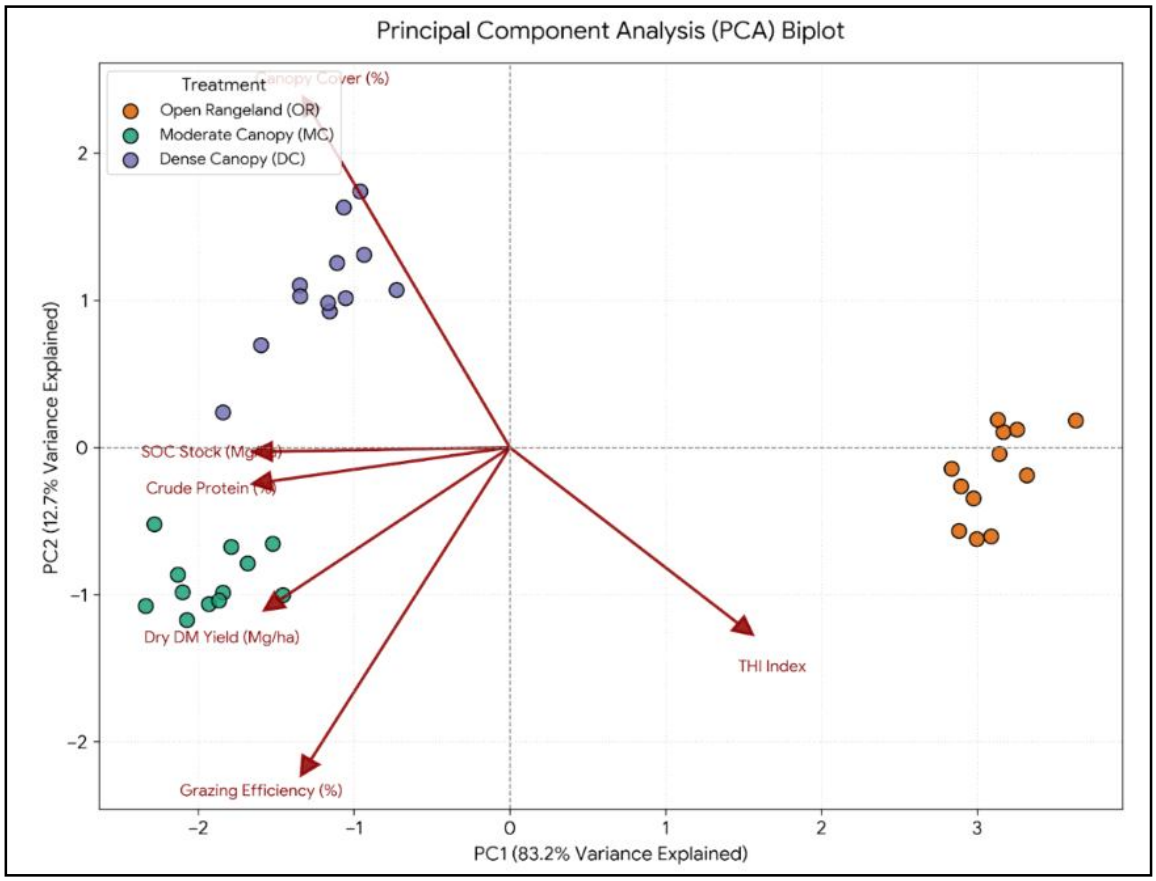

Fig. 2. PCA analysis for different treatments.

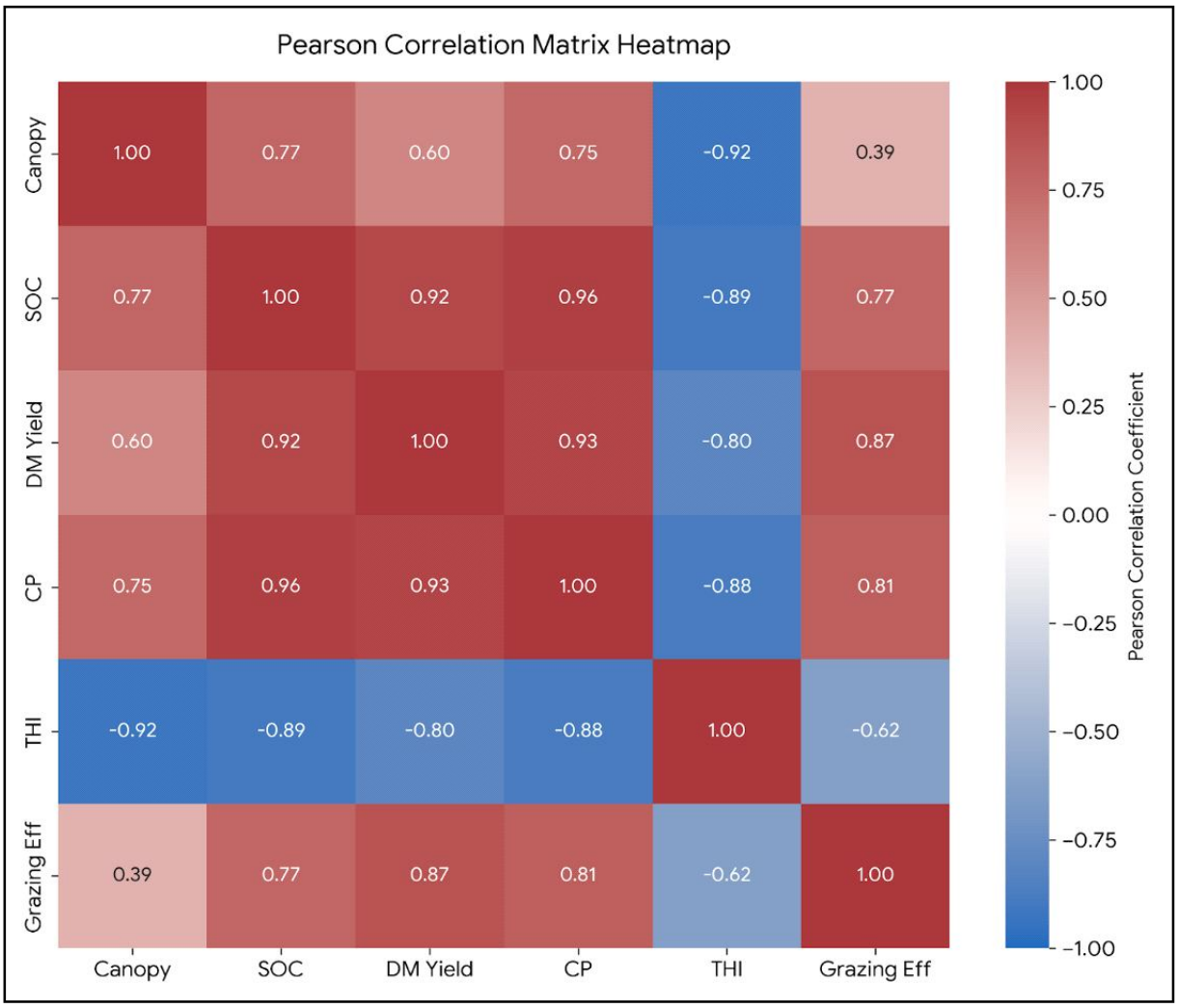

Fig. 3. Pearson correlation map for different treatments.

CONCLUSION

This study demonstrates that Silvopastoral management utilizing moderate canopy cover (30-40%) of native leguminous trees (*Prosopis cineraria*) significantly outperforms both unshaded open rangelands and dense tree canopies across key climate adaptation and pasture productivity metrics. Moderate tree shading optimizes the microclimatic trade-off between solar light availability and soil moisture preservation, achieving superior dry-season forage yields (1.48 Mg ha^{-1}), elevated crude protein content (13.8%5), and significant topsoil carbon sequestration (38.40 Mg C ha^{-1} down to 40 cm). Furthermore, microclimate cooling under moderate canopy shade mitigates peak afternoon thermal stress (THI < 77), resulting in a 17.2% enhancement in cattle grazing efficiency compared to treeless pastures.

REFERENCES

Andrade, H. J., L. M. Marín, and D. A. Pachón, 2021: Soil organic carbon stocks in silvopastoral systems of tropical dry forests. *Agroforestry Syst.*, **95**: 899–909.

AOAC, 2016: Official Methods of Analysis of AOAC International (20th ed.). Association of Official Analytical Chemists International, Rockville, MD, USA.

Aryal, D. R., D. E. Morales-Ruiz, S. López-Cruz, C. N. Tondopó-Marroquín, A. Lara-Nucamendi, J. A. Jiménez-Trujillo, F. Casanova-Lugo, G. Villanueva-López, R. Pinto-Ruiz, and M. Ibrahim, 2022: Silvopastoral systems and remnant forests enhance carbon storage in livestock-dominated landscapes in Mexico. *Sci. Rep.*, **12**: 16480.

Belsky, A. J., S. M. Mwonga, R. G. Amundson, J. M. Duxbury, and A. R. Ali, 1993: Comparative effects

of isolated trees on their understory environments in high- and low-rainfall savannas. *J. Appl. Ecol.*, **30**: 143–155.

Blake, G. R., and K. H. Hartge, 1986: Bulk density. In: A. Klute (Ed.), Methods of Soil Analysis: Part 1—Physical and Mineralogical Methods (2nd ed., pp. 363–375). American Society of Agronomy, Madison, WI, USA.

da Silva, I. A. G., J. C. B. Dubeux, M. V. F. Santos, A. C. L. de Mello, M. V. Cunha, V. X. O. Apolinário, and E. V. de Freitas, 2021: Tree canopy management affects dynamics of herbaceous vegetation and soil moisture in silvopasture systems using arboreal legumes. *Agronomy*, **11**: 1509.

Devkota, N. R., A. M. Wall, and P. D. Kemp, 2009: Relationship between tree canopy cover and pasture production in a silvopastoral system. *Agroforestry Syst.*, **76**: 541–550.

Ellert, B. H., and J. R. Bettany, 1995: Calculation of organic matter or nutrient stored in soils under contrasting management regimes. *Can. J. Soil Sci.*, **75**: 529–538.

Frame, J., 1993: Herbage mass estimation for grazing management and research. *Grass Forage Sci.*, **48**: 220–225.

Jose, S., 2009: Agroforestry for ecosystem services and environmental benefits: An overview. *Agroforestry Syst.*, **76**: 1–10.

Kumar, M., A. J. Raj, and L. Singh, 2021: Soil organic carbon pool and carbon sequestration under tree-based land use systems in semi-arid environments. *J. Range Manage. Agrofor.*, **42**: 45–53.

Lemes, A. P., A. R. Garcia, J. R. M. Pezzopane, F. Z. Brandão, Y. F. Watanabe, R. F. Cooke, M. Sponchiado, C. C. P. de Paz, A. C. Camplesi, M. Binelli, and L. U. Gimenes, 2021: Silvopastoral system is an alternative to improve animal welfare and productive performance in meat production systems. *Sci. Rep.*, **11**: 13862.

Ludwig, F., H. de Kroon, F. Berendse, and H. H. T. Prins, 2004: The influence of savanna trees on nutrient, water and light availability and the understorey vegetation. *Plant Soil*, **261**: 23–37.

Matches, A. G., and J. C. Burns, 1995: Systems of grazing management. In: R. F. Barnes, D. A. Miller, and C. J. Nelson (Eds.), Forages: The Science of Grassland Agriculture (5th ed., Vol. 2, pp. 179–192). Iowa State University Press, Ames, IA, USA.

McDowell, R. E., 1972: Improvement of Livestock Production in Warm Climates. W. H. Freeman & Co., San Francisco, CA, USA.

Nair, P. K. R., B. M. Kumar, and V. D. Nair, 2009: Agroforestry as a strategy for carbon sequestration. *J. Plant Nutr. Soil Sci.*, **172**: 10–23.

National Research Council (NRC), 1971: A Guide to Environmental Research on Animals. National Academy of Sciences, Washington, DC, USA.

National Research Council (NRC), 2000: Nutrient Requirements of Beef Cattle (7th rev. ed.). National Academy Press, Washington, DC, USA.

Pandey, D. N., 2007: Multifunctional agroforestry systems in India. *Curr. Sci.*, **92**: 455–463.

Parihaar, R. S., K. Bargali, and S. S. Bargali, 2015: Status of an indigenous agroforestry system: Prosopis cineraria in arid and semi-arid regions of India. *J. Range Manage. Agrofor.*, **36**: 11–18.

Poeplau, C., C. Vos, and A. Don, 2017: Soil organic carbon stocks are systematically underestimated by fixed depth sampling. *Radiocarbon*, **59**: 1387–1401.

Rao, M. R., P. K. R. Nair, and C. K. Ong, 2018: Biophysical interactions in tropical agroforestry systems. *Agroforestry Syst.*, **92**: 837–855.

Saha, S. K., P. K. R. Nair, V. D. Nair, and D. L. Rockwood, 2010: Carbon sequestration potential of silvopastoral systems in southern USA. *Agroforestry Syst.*, **79**: 161–171.

Thom, E. C., 1959: The discomfort index. *Weatherwise*, **12**: 57–61.

Treydte, A. C., I. M. A. Heitkönig, H. H. T. Prins, and F. Ludwig, 2007: Trees improve grass quality for herbivores in African savannas. *Oecologia*, **153**: 275–283.

Van Soest, P. J., J. B. Robertson, and B. A. Lewis, 1991: Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. *J. Dairy Sci.*, **74**: 3583–3597.

Walkley, A., and I. A. Black, 1934: An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Sci.*, **37**: 29–38.