Tropical Grasslands-Forrajes Tropicales (2023) Vol. 11(1):41–51
doi: 10.17138/TGFT(11)41-51

Research Paper

Effects of grazing intensity and pasture type on soil organic carbon stock in the semi-arid tropics of India

Efectos de la intensidad del pastoreo y el tipo de pastura en las reservas de carbono orgánico del suelo en los trópicos semiáridos de la India

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Abstract

Pastures may act as carbon sources and sinks depending on grazing pressure and management practices. Soil organic carbon (SOC) stock and its fractions were quantified under 3 different grazing intensities using 5, 10 and 15 sheep/ha under sown, improved and natural pastures in the semi-arid tropics of India. Results revealed that after 3 years, improved pasture had significantly higher particulate organic carbon (POC~4.5 g/kg), SOC (~0.53 %), total organic carbon (TOC~7 g/kg) and SOC stock (~15 mg/ha) as compared with sown and natural pastures. Labile carbon (LC ~185 mg/kg) and soil microbial biomass carbon (SMBC ~378 µg/g soil) were higher under natural pasture. A moderate grazing intensity of 10 sheep/ha resulted in significantly greater carbon fractions, TOC and SOC stock. SOC stock and its fractions were significantly higher in the topsoil layers as compared with the subsoil layers. These results indicate that improved pasture management practices with moderate grazing intensity can be recommended for improving SOC stock and its fractions in semi-arid tropical pastures.

Keywords: Carbon fractions, grazing pressure, improved pasture.

Resumen

Los pastos pueden actuar como fuentes y sumideros de carbono según la presión del pastoreo y las prácticas de manejo. El stock de carbono orgánico del suelo (SOC) y sus fracciones se cuantificaron bajo 3 intensidades de pastoreo diferentes utilizando 5, 10 y 15 ovejas/ha bajo pasturas sembradas, mejoradas y naturales, en los trópicos semiáridos de la India. Los resultados revelaron que después de 3 años, el suelo bajo pasturas mejoradas tenía partículas significativamente más altas de carbono orgánico (POC~4.5 g/kg), SOC (~0.53 %), carbono orgánico total (TOC~7 g/kg) y existencias de SOC (~15 mg/ha) en comparación con pasturas sembradas y pastos naturales. El carbono lábil (LC ~185 mg/kg) y el carbono de la biomasa microbiana del suelo (SMBC ~378 µg/g suelo) fueron más altos en pastos naturales. Una intensidad de pastoreo moderada de 10 ovejas/ha dio como resultado fracciones de carbono, existencias de TOC y SOC significativamente mayores. El stock de SOC y sus fracciones fueron significativamente más altos en las capas superiores del suelo en comparación con las capas del subsuelo. Estos resultados indican que se recomiendan prácticas de manejo de pasturas mejoradas con intensidad de pastoreo moderada para mejorar el stock de COS y sus fracciones en pastizales tropicales semiáridos.

Palabras clave: Fracciones de carbono, presión de pastoreo, pastura mejorada.

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Introduction

Over 40 % of the earth's land is used for grazing livestock. Grazing lands are reported to store more than 10 % of terrestrial biomass carbon and around 30 % of global soil organic carbon (SOC) stock (Scurlock and Hall 1998). Grazing lands are also known to provide ecosystem services, including regulating water flow and storage, nutrient cycling and carbon (C) storage (Schlesinger et al. 2000; Havstad et al. 2007; Morgan et al. 2016). Tropical pastures are constrained in their capacity to sequester SOC due to nitrogen (N) and phosphorus deficiencies and frequent overgrazing, which result in low biomass production and SOC losses (Saraiva et al. 2014). Recent studies suggested that adoption of improved pasture management practices increase soil C stock at a rate of 0.28 mg C/ha/yr (Conant et al. 2017). Ogle et al. (2004) conducted a meta-analysis using a global dataset and found 17 % increase in SOC stocks of improved grazing lands in tropical regions. Similarly, Maia et al. (2009) also found 19 % increase of SOC in improved grazing lands in the Amazon and Cerrado regions of Brazil. These studies indicated that overgrazing and inadequate pasture management were the main factors for SOC losses. High temperature and evapotranspiration throughout the year and low and erratic rainfall were associated with reduction in SOC stock in the semi-arid regions (Oliveira et al. 2015).

In India, grazing is practised on 40 % of the country's geographical area (National Remote Sensing Centre 2010). When total livestock, expressed as Adult Cattle Unit (ACU), and grazing pressure were calculated for the 80.54 million ha total grazing land available, India had 2.95 ACU/ha, which is much higher than carrying capacity (NITI Aayog 2018). High livestock grazing pressure resulted in grazing land deterioration and desertification, making grazing lands more susceptible to climate change and targets for restoration (Shinde and Mahanta 2020). Grazing lands in India remain a neglected natural resource with less than 1 % of Indian grasslands designated as protected areas, making them a poorly addressed and abused ecosystem. Despite the vast area of arid and semi-arid grazing lands in India, meagre information is available on the impacts of pasture and grazing management strategies on SOC stock and its fractions, which is a prerequisite for improving, as well as sustaining, soil health and biomass production. We hypothesized that higher grazing intensity would affect SOC stocks and its fractions differently in natural, improved and sown pastures. An experiment was initiated in 2015–16 with the aim to understand the impact of grazing intensity on SOC stock and its fractions in natural, improved and sown pastures in the semi-arid tropics of India. It is intended that information generated will be used for developing sustainable grazing and livestock production, while providing enhanced ecosystem services in arid and semi-arid climates, enabling policy decisions on SOC stock management strategies.

Materials and Methods

Description of the study area

A field experiment was conducted during the rainy (kharif) season (June–July) of 2015 at the Central Research Farm, ICAR-Indian Grassland and Fodder Research Institute (IGFRI), Jhansi (25º26'08" N, 78º30'21" E; 216 masl), in the semi-arid tropics of India. The region is characterized with erratic and uncertain rainfall with a long-term average annual rainfall of 908 mm, received mostly from the southwest monsoon during July to September. Drought is a recurring feature and occurs once in 4 years. The average maximum and minimum temperatures are 32.7 ºC and 25.1 ºC, respectively (Rai et al. 2018).

Pasture description and experimental design

Improved and sown pastures of 1.5 ha each were developed in June 2015 from natural pasture. Botanical composition prior to the start of the study was determined in 9 randomly selected 1 m^2 quadrats in each of the natural, improved and sown pastures in the months of September and December. Number of species present in the 1 m^2 area was counted in each of the 9 quadrats in natural, improved and sown pastures. Species were further classified into grasses, legumes and shrubs. The soil of the experimental site was sandy loam hyperthermic typic haplustepts, with acidic to slightly neutral pH (5.84-6.80). The soil was low in SOC (4.5 g/kg), available N (180 kg/ha) and medium in available P (13.5 kg/ha) and available K (170 kg/ha) in the topsoil layers before the start of the experiment.

The experiment was laid out as a 3-factor nested design to determine effects of grazing intensities on pasture types. Three different grazing intensities of 1 ACU (adult cattle unit)/ha (I_1), 2 ACU/ha (I_2) and 3 ACU/ha (I_3) were achieved by using 5, 10 and 15 adult Jalauni female sheep/ha with an average body weight of 35 kg. The 3 grazing intensities were imposed on a fenced area of 0.5 ha for each grazing intensity within the natural, improved and sown pasture areas. A total of 90 sheep were divided into 3 equal groups of 30 for each pasture and were allowed to graze following local rotational practices under different grazing intensities (I_1, I_2 and I_3) during the growing and post-growing seasons of herbage (August to February). Numbers of sheep per ACU were selected based on body weight and assigned to different grazing intensities (Table 1).

Table 1. Descriptions of design of experimental grazing of *Jalauni* sheep.

Pasture type	Grazing intensity*	Grazing paddock (ha)	Animal numbers per paddock
Natural pasture	I_1 (1 ACU/ ha)	0.5	5
	I_2 (2 ACU/ ha)	0.5	10
	I_3 (3 ACU/ ha)	0.5	15
Improved pasture	I_1 (1 ACU/ ha)	0.5	5
	I_2 (2 ACU/ ha)	0.5	10
	I_3 (3 ACU/ ha)	0.5	15
Sown pasture	I_1 (1 ACU/ ha)	0.5	5
	I_2 (2 ACU/ ha)	0.5	10
	I_3 (3 ACU/ ha)	0.5	15

*1 Adult Cattle Unit (ACU) = 10 adult Jalauni female sheep.

Biomass yield and quality

Experimental grazing using different grazing intensities was continued in the third year on the natural, improved and sown pastures to assess biomass yield and quality of pastures after grazing. Vegetation samples were taken when biomass had reached its maximum height from 9 randomly placed 1 m^2 quadrats in each pasture (3 quadrats in each grazing intensity). Weight of vegetation from each quadrat was recorded. For dry matter yield (DMY), harvested fresh biomass samples were sun dried first and then oven dried at 72 °C for 3 days to constant weight. After weighing, dry matter percentage was determined. Quadrat average dry matter percentage was converted to biomass yield in t DM/ha. Dry biomass samples were ground in a Wiley mill having a 1 mm mesh screen. Neutral detergent fibre (NDF), acid detergent fibre (ADF) and crude protein (CP) were determined following the AOAC (1995) procedure.

Soil sampling and analysis

Soil sampling was done in April 2018 after completion of the third grazing cycle. A total of 28 quadrats (0.25 m^2) per treatment (a combination of grazing intensity and pasture type) were sampled. Each grazing intensity treatment for each pasture was divided into 3 equal blocks of 40 m × 40 m and 9–10 subsamples were randomly collected from each block using quadrats at least 0.5 m from the margin of the block to avoid any edge effects. Soil samples were taken from 4 soil depths (0–20, 20–40, 40–60 and 60–80 cm) by using a soil auger (diameter 5 cm). Subsamples were combined from grazing treatments within pasture types at each depth to make 4 representative replicate soil samples. Collected soil samples were analysed for SOC stock and carbon fractions.

SOC was estimated by the wet digestion method of Walkley and Black (1934). Total SOC concentration of soils was calculated using a multiplication factor of 1.28 applied for arid and semi-arid regions of the Indo-Gangetic Plain (Bhattacharyya et al. 2015). Hot-water-soluble carbon (HWSC) was extracted by the hot extraction method of McGill et al. (1986). Particulate organic carbon (POC) was analysed by a mechanical dispersion and separation method (Cambardella and Elliott 1992). Labile carbon (LC, $KMnO_4$ extractable-C) in soil samples was analyzed using 333 mM $KMnO_4$ following the procedure of Blair et al. (1995). Soil microbial biomass carbon (SMBC) was analysed by the fumigation method (Vance et al. 1987). Soil organic carbon (SOC) stock was calculated by the following formula:

$$\text{SOC stock (mg/ha)} = \text{SOC (g/kg)} \times \text{bulk density (mg/m}^3) \times \text{soil depth (m)} \times 10$$

Statistical analysis

Impacts of pasture, grazing intensity and soil depth and their interactions on SOC stock, carbon fractions (HWSC, POC, LC, SMBC) and total organic carbon (TOC) were analysed using SAS version 9.1 mixed model procedures (SAS Institute 2011). Differences in all response parameters were evaluated by treating pasture type, grazing intensity and soil depth as fixed effects and replication as a random effect using a 3-factor nested design. Mean comparisons were made using Tukey's test ($P<0.05$). Sigmaplot (version 10; Systat Software, Inc., San Jose, California, USA) was used to make graphics.

Results

Botanical composition, biomass yield and quality

Botanical composition in each pasture type (Table 2) affected yield with maximum biomass yield reported in the sown pasture (6.57 t DM/ha), followed by improved

(5.87 t DM/ha) and natural (5.70 t DM/ha) pastures. CP content of the biomass was also higher in sown pasture (6.74 %) as compared with improved (6.41 %) and natural (6.34 %) pastures. NDF and ADF contents were relatively lower in sown pasture (Table 2).

Soil organic carbon, total organic carbon and SOC stock

Pasture type and soil depth had significant (P<0.05) effects on all the studied parameters. Interactions of grazing intensity × pasture were significant (P<0.05) for SOC, HWSC, POM, LC, SMBC, TOC and SOC stock. Interactions of pasture × soil depth were significant (P<0.05) for SOC, POC, LC, SMBC, TOC and SOC stock. Interactions of soil depth × grazing intensity (pasture) and grazing intensity × soil depth (pasture) were significant (P<0.05) only for POC, LC and SMBC (Table 3).

SOC, TOC and SOC stock were significantly (P<0.05) different by pasture type, grazing intensity and soil depth (Table 4). Among the pasture types, improved pasture resulted in a greater accumulation of SOC (15–20 %), TOC (16–39 %) and SOC stock (15–23 %) as compared with natural and sown pastures. No significant (P>0.05) differences between natural and sown pastures were recorded in the SOC, TOC and SOC stock. In different grazing intensities under studied pastures, I_2 grazing intensity in improved pasture resulted in significantly (P<0.05) higher SOC (0.59 %), TOC (7.89 g/kg) and SOC stock (16.20 mg/ha), which were at par with I_3 grazing intensity in improved pasture. In sown and natural pastures, no significant (P>0.05) changes were recorded in SOC, TOC and SOC stock under different grazing intensities. Topsoil layers (0–40 cm) had significantly (P<0.05) higher SOC, TOC and SOC stock than subsoil layers (40–80 cm), decreasing with increased soil depth in all studied pastures.

Table 2. Botanical composition, biomass yield and quality of different experimental pastures.

Pasture	Botanical composition	DMY (t DM/ha)	Quality (%)		
			CP	NDF	ADF
Natural pasture	Grasses: *Heteropogon-Dichanthium-Sehima* dominated natural grassland associated with different annual and perennial grasses, including *Chrysopogon fulvus*, *Cynodon dactylon*, *Digitaria eriantha*, *Themeda* sp., *Bothriochloa bladhii*, *Cenchrus ciliaris*, *Chloris gayana*, *Pennisetum pedicellatum*, *Paspalum notatum*, *Setaria sphacelata*. Legumes: *Cajanus scarabaeoides*, *Indigofera hirsuta*, *Clitorea ternatea* (Blue & white flowered), *Alysicarpus rugosus*, *Aeschynomene indica*, *Vigna aconitifolia*, *Tephrosia* spp. Shrub species: *Zizyphus nummularia*	5.70	6.34	75.59	54.81
Improved pasture	Grasses: *Heteropogon-Dichanthium-Sehima* natural grassland reseeded with *Cenchrus ciliaris* with *Chrysopogon fulvus*, *Cynodon dactylon*, *Paspalum notatum*, *Pennisetum pedicellatum*, *Digitaria eriantha*. Legumes: *Stylosanthes hamata*, *Cajanus scarabaeoides*, *Indigofera hirsuta*, *Clitorea ternatea*, *Tephrosia* spp. Shrub species: *Zizyphus nummularia*, *Ailanthus excelsus*, *Leuceaena leucocephala* and Thornless cactus (*Opuntia species*)	5.87	6.41	76.92	53.72
Sown pasture	Grass: *Cenchrus setigerus*. Legume: *Stylosanthes hamata*	6.57	6.74	74.84	51.71

Table 3. Analysis of variance (ANOVA) for soil organic carbon (SOC), carbon fractions (HWSC = hot-water-soluble carbon; POC = particulate organic carbon; LC = $KMnO_4$ oxidizable carbon; SMBC = soil microbial biomass carbon; TOC = total organic carbon and SOC stock) under different pasture, grazing intensities and soil depth.

Source of variation	df	SOC (%)	HWSC (mg/kg)	POC (g/kg)	LC (mg/kg)	SMBC (µg/gsoil)	TOC (mg/kg)	SOC Stock (mg/ha)
Pasture	2	0.0002	<0.0001	<0.0001	<0.0001	<0.0001	0.0002	<0.0001
Grazing intensity (Pasture)	6	0.0230	<0.0001	<0.0001	<0.0001	<0.0001	0.0210	0.0586
Soil depth	3	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Pasture×Soil depth	6	0.0137	0.9871	<0.0001	<0.0001	<0.0001	0.0132	0.0178
Grazing intensity×Soil depth (Pasture)	18	0.9212	0.9939	0.0048	<0.0001	<0.0001	0.9128	0.9638

Table 4. Influence of pasture type, grazing intensity and soil depth on soil organic carbon (SOC), total organic carbon (TOC) and SOC stock.

Treatment			SOC (%)	TOC (g/kg)	SOC stock (mg/ha)
a. Pasture	Natural pasture		0.44b	5.90b	12.07b
	Improved pasture		0.53a	7.09a	14.90a
	Sown pasture		0.46b	6.11b	12.93b
	P value		0.0002	0.0002	<0.0001
b. Grazing intensity (Pasture)	Natural pasture	I_1	0.46bc	6.15c	12.46bc
		I_2	0.45bc	6.06bc	12.24bc
		I_3	0.41c	5.47c	11.54c
	Improved pasture	I_1	0.46bc	6.07bc	12.96bc
		I_2	0.59a	7.89a	16.20a
		I_3	0.54ba	7.29ba	15.53ba
	Sown pasture	I_1	0.47bc	6.28bac	13.69bac
		I_2	0.46bc	6.16bc	12.55bc
		I_3	0.44bc	5.89bc	12.54bc
	P value		0.0230	0.0210	0.0586
c. Soil depth (cm)	0–20		0.76a	10.11a	20.49a
	20–40		0.48b	6.31b	13.09b
	40–60		0.37c	4.93c	10.59c
	60–80		0.30d	4.11d	9.03c
	P value		<0.0001	<0.0001	<0.0001
d. Pasture × Soil depth	Natural pasture	0–20	0.79a	10.60a	21.23a
		20–40	0.43dc	5.74dc	11.71dc
		40–60	0.32de	4.21de	8.84de
		60–80	0.23e	3.02e	6.53e
	Improved pasture	0–20	0.81a	10.79a	21.95a
		20–40	0.54bc	7.15bc	14.89bc
		40–60	0.43dc	5.77dc	12.50dc
		60–80	0.35de	4.63de	10.26de
	Sown pasture	0–20	0.67ba	8.92bc	18.28ba
		20–40	0.46dc	6.03dc	12.68dc
		40–60	0.36de	4.82de	10.43de
		60–80	0.35de	4.67de	10.33de
	P value		0.0137	0.0132	0.0178

Values in each column followed by different lowercase letters are significantly different according to Tukey's test ($P<0.05$). I_1, I_2 and I_3 grazing intensities were 1 ACU/ ha, 2 ACU/ha and 3 ACU/ha, respectively.

Carbon fractions

Significant ($P<0.05$) differences between pasture, grazing intensity and soil depth were recorded in HWSC. Higher HWSC (12.98 mg/kg) was found in sown pasture, which was 65.77 % and 68.35 % higher than improved and natural pastures, respectively. At 0–20 cm soil depth, HWSC was significantly ($P<0.05$) higher (11.71 mg/kg) and decreased with successive soil depths (Figure 1). I_1 grazing intensity in sown pasture had a significantly ($P<0.05$) higher HWSC (16.41 mg/kg) compared with improved (9.15 mg/kg) and natural pastures (9.86 mg/kg), in which HWSC was not influenced by grazing intensities (Figure 2).

POC, LC and SMBC contents were significantly ($P<0.05$) influenced by pasture type, grazing intensity and soil depth (Tables 5 and 6). At 0–20 cm soil depth, POC content was significantly ($P<0.05$) higher (Table 5) in

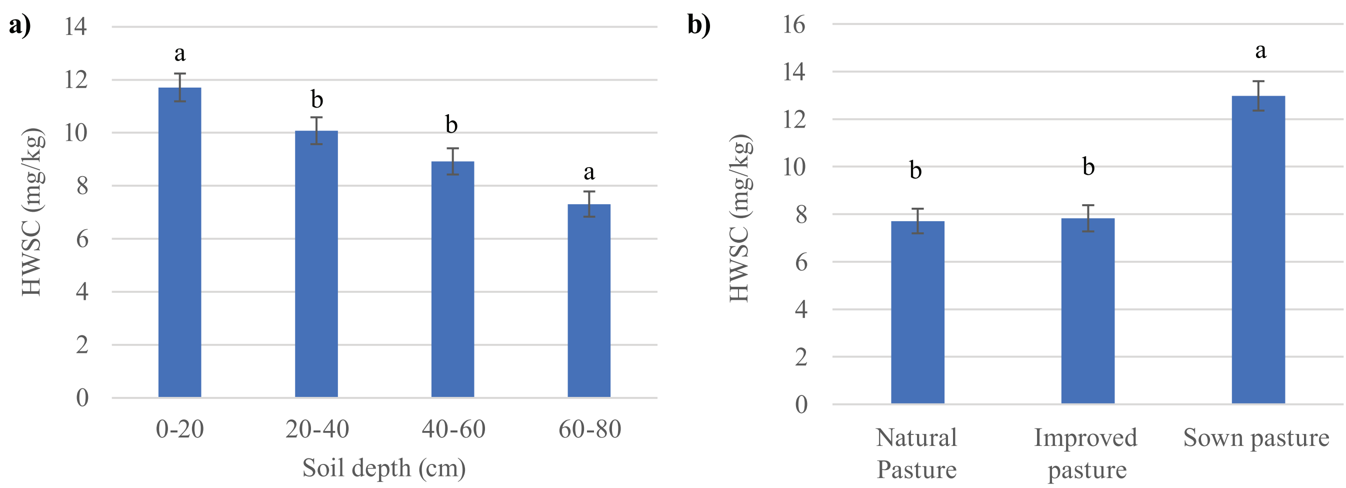

Figure 1. Hot-water-soluble carbon (HWSC mg/kg) influenced by soil depth (a) and different pastures at 0–80 cm soil depth (b). Bars with different lowercase letters indicate significant differences at $P<0.05$ level based on Tukey's test.

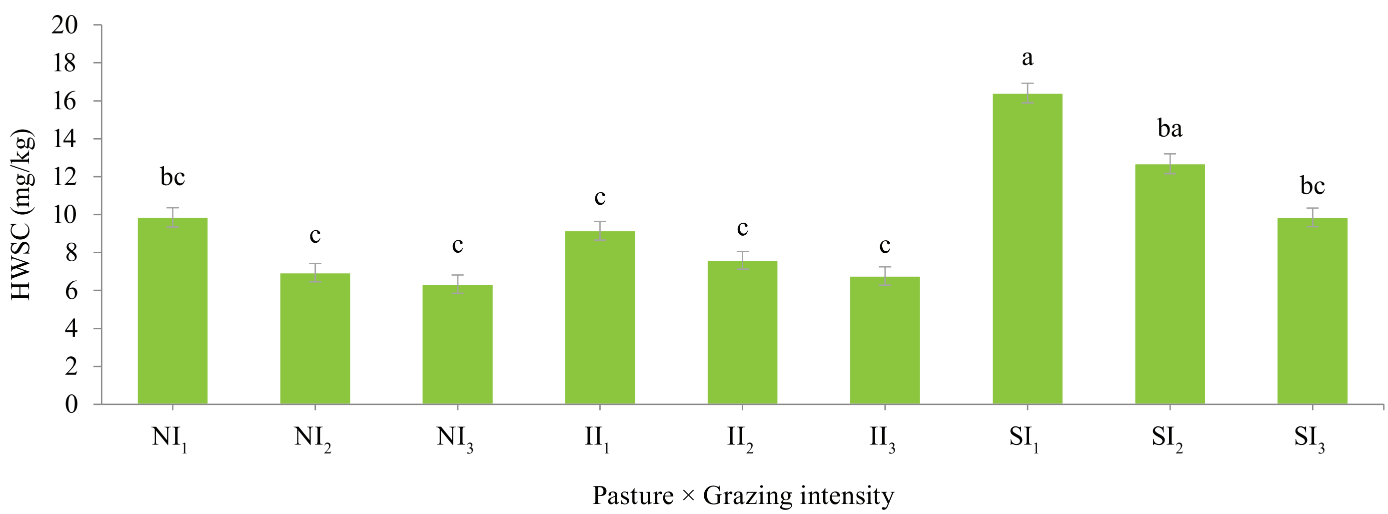

Figure 2. Hot-water-soluble carbon (HWSC mg/kg) influenced by different pastures and grazing intensities (NI_1, natural pasture I_1 grazing intensity; NI_2, natural pasture I_2 grazing intensity; NI_3, natural pasture I_3 grazing intensity; II_1, improved pasture I_1 grazing intensity; II_2, improved pasture I_2 grazing intensity; II_3, improved pasture I_3 grazing intensity; SI_1, sown pasture I_1 grazing intensity; SI_2, sown pasture I_2 grazing intensity; SI_3, sown pasture I_3 grazing intensity). Bars with different lowercase letters indicate significant differences at $P<0.05$ level based on Tukey's test.

improved pasture (6.01 g/kg) as compared with sown (5.22 g/kg) and natural pastures (1.99 g/kg) whereas, LC were higher (24.40–30.79 %) in natural pasture as compared with improved and sown pastures. The SMBC was higher (37.63 %) in natural pasture compared with improved pasture but remained at par with sown pasture (Table 6). Among the grazing intensities, I_2 grazing intensity resulted in significantly ($P<0.05$) higher POC content at 0–20 cm soil depth in improved pasture while LC and SMBC were significantly higher in natural pasture with similar depth and grazing intensity. POC, LC and SMBC content in soil were significantly ($P<0.05$) higher at 0–20 cm soil depth as compared with lower soil depths (20–80 cm) and decreased with increase in grazing intensity.

Table 5. Influence of grazing intensity (GI), pasture type and soil depth on particulate organic carbon (POC).

Treatment	GI	Soil depth (cm)	POC (g/kg)
a. Pasture × Soil depth			
Natural pasture		0–20	1.99ed
		20–40	2.22d
		40–60	2.05ed
		60–80	1.26e
Improved pasture		0–20	6.01a
		20–40	5.19b
		40–60	4.78cb
		60–80	2.63d
Sown pasture		0–20	5.22b
		20–40	4.66cb
		40–60	4.21c
		60–80	2.35d
P value			<0.0001
b. Soil depth × Grazing intensity (GI)			
Natural pasture	I_1	0–20	3.09fghijh
		20–40	4.02fgecd
		40–60	3.81fgeidh
		60–80	1.68kj
	I_2	0–20	1.72kj
		20–40	1.39k
		40–60	1.28k
		60–80	1.16k
	I_3	0–20	1.15k
		20–40	1.24k
		40–60	1.06k
		60–80	0.95k
Improved pasture	I_1	0–20	5.26bcd
		20–40	5.00bcd
		40–60	4.70becd
		60–80	2.51gkijh
	I_2	0-20	7.31a
		20-40	5.79ba
		40-60	4.84bcd
		60-80	3.15fgeijh
	I_3	0-20	5.46bc
		20-40	4.78bcd
		40-60	4.79bcd
		60-80	2.24kij
Sown pasture	I_1	0-20	5.30bcd
		20-40	4.69fbecd
		40-60	3.90fgecdh
		60-80	2.15kj
	I_2	0-20	5.26bcd
		20-40	4.85bcd
		40-60	4.50fbecd
		60-80	2.54gkijh
	I_3	0-20	5.09bcd
		20-40	4.45fbecd
		40-60	4.25fbecd
		60-80	2.35kijh
P value			0.0048

Values in each column followed by different lowercase letters are significantly different according to Tukey's test ($P<0.05$); I_1, I_2 and I_3 grazing intensities were 1 ACU/ ha, 2 ACU/ha and 3 ACU/ha, respectively.

Table 6. Influence of grazing intensity, pasture type and soil depth on labile carbon (LC) and soil microbial biomass carbon (SMBC).

Treatment	GI	Soil depth (cm)	LC (mg/kg)	SMBC (µg/g soil)
a. Pasture × Soil depth				
Natural pasture		0–20	314.42a	401.98a
		20–40	215.92c	321.63d
		40–60	116.52f	205.32h
		60–80	92.77h	179.53i
Improved pasture		0–20	252.54b	292.06f
		20–40	171.31d	312.57e
		40–60	115.56gf	256.23g
		60–80	102.63gh	248.99g
Sown pasture		0–20	240.40b	401.81a
		20–40	181.62d	377.30b
		40–60	173.94d	368.66cb
		60–80	144.44e	363.53c
P value			<0.0001	<0.0001
b. Soil depth × Grazing intensity (GI)				
Natural pasture	I_1	0–20	316.56a	397.07cb
		20–40	152.38khji	314.70hg
		40–60	109.81op	197.85m
		60–80	93.37p	175.28n
	I_2	0–20	326.44a	428.52a
		20–40	263.31c	325.39g
		40–60	122.25moln	224.80l
		60–80	95.00op	185.05nm
	I_3	0–20	300.25ba	380.35cde
		20–40	232.06de	324.80g
		40–60	117.50mopn	197.33nm
		60–80	89.94p	178.28n
Improved pasture	I_1	0–20	217.05e	288.63i
		20–40	171.69hjgi	368.19fde
		40–60	113.69opn	253.21k
		60–80	99.60op	245.76k
	I_2	0–20	274.31bc	296.98hi
		20–40	180.25hg	288.88i
		40–60	122.75moln	263.50jk
		60–80	150.06op	254.60k
	I_3	0–20	266.25c	290.56i
		20–40	162.00khjgi	280.63ji
		40–60	110.25op	251.99k
		60–80	103.19op	246.61k
Sown pasture	I_1	0–20	209.13fe	397.02cb
		20–40	175.94hgi	374.70fde
		40–60	166.00khjgi	367.86fde
		60–80	138.81kmin	365.26fde
	I_2	0–20	265.50c	403.15b
		20–40	188.44fg	382.40cd
		40–60	178.88hg	374.81fde
		60–80	150.31kjli	365.05fde
	I_3	0–20	246.56dc	405.27b
		20–40	180.50hg	374.81fde
		40–60	176.94hgi	363.33fe
		60–80	144.19kmjl	360.28f
P value			<0.0001	<0.0001

Values in each column followed by different lowercase letters are significantly different according to Tukey's test ($P<0.05$); I_1, I_2 and I_3 grazing intensities were 1 ACU/ ha, 2 ACU/ha and 3 ACU/ha, respectively.

Discussion

This study found greater accumulation of SOC, TOC and SOC stock in improved pastures compared with natural and sown pastures up to 80 cm soil depth. Topsoil layers (0–40 cm) had significantly higher SOC, TOC and SOC stock than the subsoil layers (40–80 cm) decreasing with increase in soil depths. The decreases in SOC, TOC and SOC stock were sharper in natural and sown pastures as compared with the improved pastures. It is believed that the greater TOC and SOC stock in improved pastures might be due to the addition of biomass and fine roots through perennial shrub pasture components like *Ailanthus excelsus*, *Leuceaena leucocephala* and thornless cactus (*Opunti*a species). Banegas et al. (2019) also reported that *Leucaena leucocephala* introduction increased the SOC concentration in the subsoil by 45 % after 4 years in the Chaco region of Argentina. Similar findings were also reported by Carter et al. (1998) in *Leucaena* and *Stylosanthes* pastures in northern Australia. The sharp decline in SOC, TOC and SOC stock in natural and sown pastures might be attributed to changes in plant community (Fisher et al. 1998) and deposition of C inputs in the topsoil layers (Costa et al. 2009), which makes it more susceptible to loss into the environment. Saraiva et al. (2014) also reported higher C concentration and content at shallower soil depths is directly linked to litter deposition on the soil surface and greater root biomass in the topsoil layers. Similar results were also found for SOC, TOC and SOC stock, which were greater in topsoil layers as compared with subsoil layers under studied pastures. The sharp decline in SOC, TOC and SOC stock in the subsoil layers under natural and sown pastures may also be due to sharp declines in biomass and plant cover from heavy grazing resulting in low carbon sequestration in soil (Krishna and Mohan, 2017). Xie and Wittig (2004) and Abdalla et al. (2018) also found that overgrazing leads to significant SOC loss particularly in semi-arid regions, which impairs sustainability of grazing lands. This is because heavy grazing significantly reduces carbon uptake by grasses. In addition, pressure from trampling by animals leads to compaction of topsoil layers, increased bulk density and reduced infiltration and soil aeration. This limits the proper development of the root system of plants, which ultimately reduces SOC stock (Zhang et al. 2018). The higher SOC, TOC and SOC stocks in the subsoil layer (40–80 cm) in improved pasture could be attributed to the introduced shrubs' deep root systems, since a significant proportion of fine roots (>60 %) of shrubs have been observed below 40 cm in soil compared with grasses (Radrizzani 2009). Pachas et al. (2018) also found that *Leucaena* had an abundance of roots in the deeper profile than grasses. Fine root carbon contributed significantly to the increase in subsoil layer SOC stock, particularly under high grazing pressure (Radrizzani and Nasca 2014). Results of this study clearly indicated that, in arid and semi-arid pasture lands, decline in herbaceous and shrub biomass (forage) is a key factor for pasture land deterioration. Improved pasture management practices play a vital role in grazing land sustainability, particularly under high grazing pressure in the semi-arid tropics. Many other authors also reported that shrub establishment and development offer an important safeguard against grazing land deterioration through increasing SOC, soil nutrients distribution and soil stability and by reducing soil erosion (Blaser et al. 2014; van Hall et al. 2017).

All the SOC fractions significantly decreased with successive soil depths and grazing intensities. The differences in HWSC in soils under different pasture types may be due to the difference in root exudation patterns in pasture species and the nature and amount of organic sources in soil (Campbell et al. 1999). A study conducted in Inner Mongolia, China by Cao et al. (2013) also reported that POC and LC at a depth of 0–15 cm decreased with increasing grazing intensity. The decreasing trend of POC, LC and SMBC with grazing intensity was due to over extraction of carbon for biomass and less carbon input (Li et al. 2015). Moderate grazing intensity resulting in significantly higher POC, LC and SMBC was also reported by Ma et al. (2005), where after 22 years grazing in *Leymus chinensis* steppe, LC and SMBC content at 0–10 cm soil depth decreased by 22.0 % and 27.9 %, respectively. Results of this study also indicate that POC, LC and SMBC contents in topsoil layers (0–40 cm) were significantly higher as compared with subsoil layers (40–80 cm). This was due to the fact that C contribution comes mainly from soil surface C accumulation by leaf litter, plant roots and animal excrements. The significant decline in various carbon fractions (HWSC, POC, LC and SMBC) under heavy grazing intensity (3 ACU/ha) in natural and sown pastures as compared with the improved pastures may be linked with lower input of forage biomass since the input of plant residue and vertical distribution of roots throughout the profile affect SOC stocks at depth (Jobbágy and Jackson 2000; Sampaio and Costa 2011). Carbon fractions responded more rapidly to land use and management activities and can provide a very sensitive indicator of changes in the dynamics of SOC (Su et al. 2009).

Conclusions

This study has provided valuable information on impact of different grazing intensities on SOC stock and its fractions under different pasture types in the semi-arid tropics of India. It has also highlighted the ability of different pastures to improve SOC stock for grazing land sustainability of improved pastures using improved grazing management practices. Heavy grazing intensity decreased TOC content and SOC stock of natural and sown pastures. It is proposed that inclusion of shrub species such as *Leuceaena leucocephala*, *Ailanthus excelsus*, *Zizyphus nummularia* and thornless cactus (*Opuntia* species) and moderate grazing intensity should be adopted to prevent further degradation of pasture lands and improve carbon sequestration and soil sustainability in arid and semi-arid tropical pastures.

Acknowledgments

This research was supported by ICAR-Central Research Institute for Dryland Agriculture, Hyderabad under the National Innovations on Climate Resilient Agriculture (NICRA) network project (Project Number 1006591). Authors thankfully acknowledge their financial support and technical guidance for this study.

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(Note of the editors: All hyperlinks were verified 20 January 2023).

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(Received for publication 9 April 2021; accepted 31 December 2022; published 31 January 2023)

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