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Chapter

Strategic Management of Grazing Grassland Systems to Maintain and Increase Organic Carbon in Soils

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Abstract

Understanding management-induced C sequestration potential in soils under agriculture, forestry, and other land use systems and their quantification to offset increasing greenhouse gases are of global concern. This chapter reviews management-induced changes in C storage in soils of grazing grassland systems, their impacts on ecosystem functions, and their adaptability and needs of protection across socio-economic and cultural settings. In general, improved management of grassland/pasture such as manuring/slurry application, liming and rotational grazing, and low to medium livestock units could sequester C more than under high intensity grazing conditions. Converting cultivated land to pasture, restoration of degraded land, and maximizing pasture phases in mixed-cropping, pasture with mixed-livestock, integrated forestry-pasturage of livestock (silvopastoral) and crop-forestry-pasturage of livestock (agro-silvopastoral) systems could also maintain and enhance soil organic C density (SOCρ). In areas receiving low precipitation and having high erodibility, grazing exclusion might restore degraded grasslands and increase SOCρ. Yet, optimizing C sequestration rates, sowing of more productive grass varieties, judicial inorganic and organic fertilization, rotational grazing, and other climate-resilient approaches could improve overall farm productivity and profitability and attain sustainability in livestock farming systems.

Keywords: carbon sequestration, grazing grassland, silvopastoralism, integrated land uses, livestock farming

1. Introduction

Soil stores 2–3 times more carbon (C) than the atmosphere. Soil organic carbon (SOC) pools under contrasting long-term management systems provide insights into the potential for sequestering C, sustaining soil productivity and maintaining functions in the biosphere-atmosphere interface. The broadest division of grassland, both natural and anthropogenic, is between temperate and tropical grasslands. Globally, grasslands (pasture, silage and hay) dominate major agricultural areas and contribute 20–30% to the SOC pool by sequestering atmospheric CO_2, thus mitigating climate change [1, 2]. Livestock graze mostly on pasture and meadows, and the production systems are highly diverse, ranging from low-input grasslands in arid and semiarid regions to highly intensive pasture in more mesic environments, integrating livestock-crop-forage systems. Grazing is one of the most important factors that could change the soil C density in grassland systems. Understanding the impacts of grazing intensity and livestock types under different management systems on SOC sequestration is a key to providing the most effective soil C management strategies.

Soil C storage depends on the C input mainly through the root biomass, added C, and its release mediated by soil processes. Belowground processes may respond differently from aboveground vegetation to grazing whereas change of plant community structure induced by grazing does not necessarily lead to decreased soil C storage [3]. Although grazing in some cases decreases vegetation growth, good management can improve its growth on many degraded lands [4]. In addition to biogeochemical processes and environmental factors, SOC storage under grasslands and the associated land uses is regulated importantly by biotic factors, e.g., livestock type, grazing intensity, grass species, and their heterogeneity [1]. Some recent studies show that intensification of livestock management could enhance C losses in association with emissions of GHGs [5]. Others show that intense grazing pressure and large additions of manure over short periods (e.g., rotational grazing) increase soil C and water infiltration and retention, and eventually enhance plant production [4]. Soil C sequestration in grasslands varies between 0.03 and 1 t C ha^{-1} $year^{-1}$, depending on land type, land use, climatic factors, and treatments [6].

Grazing intensity and management may modify soil physical structure, function, and SOC storage capacity that could reduce or increase nutrient retention, water storage, pollutant attenuation, soil fertility, plant productivity, and species composition [7]. For sustainable management of pastures and rehabilitation of degraded lands, tailoring flexible and site-specific grazing management, depending on climate conditions and the availability of local resources, and avoidance of the extreme process of land degradation that may deteriorate further with climate change are in need. Carbon balance is controlled by the nature, frequency, and intensity of disturbances in grassland ecosystems [8]. However, the relationship between grazing intensity and SOC is generally nonlinear [9]. Previous studies have found mixed results [10], with some showing increases [11], no effect [12], or decreases [13] in SOCρ. Other recent reviews [10] state that high grazing intensity significantly decreases belowground C and N pools, and those effects depend on livestock type and climatic conditions. However, some mechanisms are not well understood, and mixed results are common. Animal manure and other offsite organic applications have significant potential for sequestering C in soils, but the proportion stabilized may depend on local climatic and edaphic conditions and the decomposability/degradability of the materials added [14]. Grazing also accelerates N cycling and promotes N losses through NH_3 from urine and dung patches [15] which, in nutrient limited systems, may constrain C inputs and humification rates.

Globally, most soils are responsive to management changes to increase SOCρ. The greatest response comes from retirement and restoration of degraded agricultural lands, manure/bio-solid applications [10], improvements of pasture lands, adaptive grazing management systems, inclusion of woody species into the pasture system, and conversion from cropland to pasture [6]. This chapter advances evidence-based C sequestration potential in soils of pasture and associated lands under various livestock systems (**Figure 1**). The main aims are to (a) improve the knowledge base and understanding of

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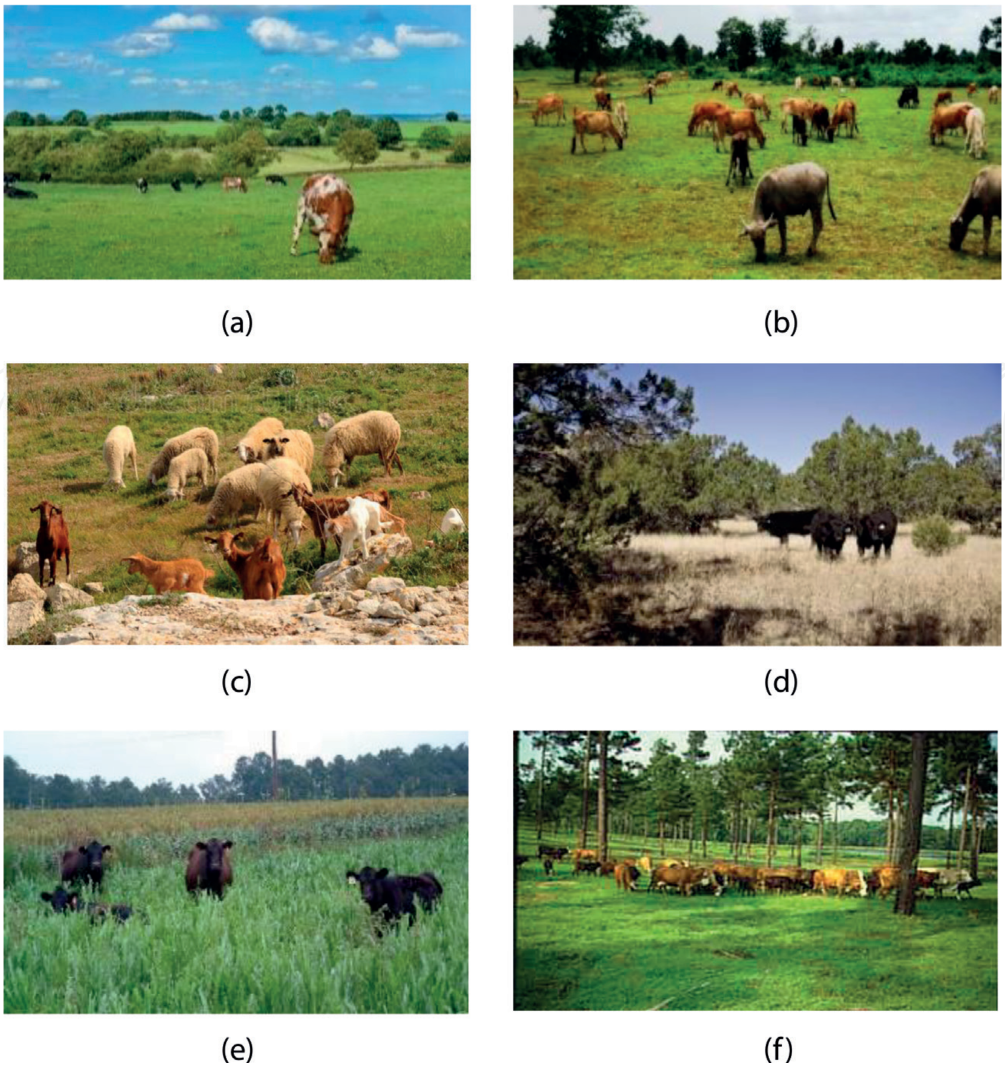

Figure 1.
Livestock grazing in grassland and other related land uses. (a) Grazing grassland in Temperate regions (Source: ARC 2020), (b) Grazing grassland in Tropical regions (Source: SLU), (c) Grazing grassland in Mediterranean regions (Source: Dreamstime), (d) Grazing grassland in Arid regions (Source: NMSU), (e) Integrated crop-livestock system (Source: People Food & Nature) and (f) Integrated silvo-pastural system (Source: Aftaweb).

management practices and technologies to increase and maintain SOC while reducing climate change footprint and achieving productivity and environmental benefits; (b) identify region/biome-specific management practices to enhance/maintain SOC and combat environmental degradation without sacrificing food security; and (c) outline economic, ecological, social, and policy options for storing additional SOC.

2. Carbon sequestration potential in soils under livestock-associated pasture management practices

2.1 Grazing grassland/pasture management

Adjustment of grazing/management intensity to climate and soil type could increase SOC. Positive and negative impacts of grazing on SOC storage compared to unharvested rangeland have been reported for semi-arid regions of the USA [5], Western Canada [16], the Netherlands [17] and the United Kingdom [18]. In many cases, grazing favors C sequestration via animal returns and heterogeneity of vegetation with the exception of very intensive systems. This can be considered as a mosaic of patches of variable vegetation height, with or without the presence of urine and dung. In contrast, very intense grazing, or short periods between successive grazing can lead to a trade-off between biomass production and C inputs to soil (i.e., root production and litter), and subsequent C sequestration [8].

Even so, managed grasslands have the potential to act as C sinks, sequestrating on average 0.7 ± 0.16 t C ha^{-1} $year^{-1}$ [19]. However, there is a large variability in soil C accrual due to differences in climate, soil, and vegetation conditions as well as due to varying biomass removal. Under low biomass removal [~30% of present biomass], soil C sequestration of European grasslands may reach up to 1.27 ± 0.40 t C ha^{-1} $year^{-1}$, while at medium biomass removal (30–70%) to high (>70%) values are lower, depending on fertilization level and climate (**Table 1**). Indeed, high biomass removal (>70%) may lead to SOC losses. In North Dakota, USA, a long-term study in three mixed prairie sites (mainly Blue grama: *Bouteloua gracilis*) found that the moderately grazed pasture (2.6 ha $steer^{-1}$) contained 17% less SOC than the exclosure treatment, but heavy grazing (0.9 ha $steer^{-1}$) did not reduce it further (**Table 1**) [5, 18]. For 12 years, the annual rate of change in SOC (0–90 cm) followed the order: low grazing pressure (1.17 t C ha^{-1} $year^{-1}$) > unharvested (0.64) = high grazing pressure (0.51) > hayed (0.22). Moreover, grazed (cattle) tall fescue-common bermudagrass pasture (20 years old) had greater SOC (31%) at a depth of 0–20 cm than adjacent 24-year old conservation-tillage cropland [19]. Improved C sequestration for extensive grazing, showing a sink of C (0.86 ± 0.74 t C ha^{-1} $year^{-1}$), vs. mown systems was also confirmed for Hungarian sandy grasslands, during which the mowing management (cut once per year) became a source of C (−1.22 ± 0.35 t C ha^{-1} $year^{-1}$) [20]. These C losses were attributed to a higher herbage use intensity of the mowed grassland compared to the grazed one. In addition to intensive biomass removal, soil erosion can contribute to reducing SOC in pastures heavily grazed by cattle.

Even so, under some conditions, high biomass removal may improve C sequestration. Such as the semi-arid grasslands in Colorado (shortgrass steppe), where changes in SOC were higher with heavy grazing (60–75% utilization; 2.27 t C ha^{-1} $year^{-1}$) compared to light grazing (20–35% utilization; 0.55 t C ha^{-1} $year^{-1}$) (**Table 1**) [21]. Significantly higher soil C (0–30 cm) was measured in grazed pastures (1.06 ± 0.03 t C ha^{-1} $year^{-1}$) compared to nongrazed exclosures (0.20 ± 0.14). In fact, heavy stocking rates in shortgrass steppe resulted in a plant community dominated by the C4 grass, blue grama, while exclusion of livestock grazing increased the production of C3 grasses and prickly pear cactus (*Opuntia polyacantha*) [22]. In addition to plant community changes, grazing exclusion leads to an immobilization of C in excessive aboveground plant litter of forbs and grasses and lack of dense fibrous rooting systems conducive to SOM formation and accumulation. Accordingly, outcomes indicate that stimulation of annual shoot turnover and redistribution of C within the plant-soil system contributes to an increase in SOC. Furthermore, the higher SOC in heavily grazed grassland may be attributable to higher inorganic C (SIC), than the nongrazed treatment, and long-term grazing could decrease the readily mineralizable fraction of SOM. These effects emphasize the importance of inorganic C in assessing the mass and distribution of plant-soil C, and in evaluating the impacts of grazing management on C sequestration particularly in semiarid and arid ecosystems.

C sequestration, of course, should not be the only priority when making decision of pasture-based livestock farming systems located in less productive areas, (e.g., southern Europe and mountainous regions), which are highly relevant in both environmental and social terms. Although, C sequestration should be promoted to mitigate climate change and improve soil quality (water holding capacity and nutrient turnover). Solutions such as adaptive multi-paddock grazing or rotational grazing systems may increase carrying capacity and restore soil C. In other systems

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Biomes/regions	Livestock category	Livestock density (LSU: L, M, and H) * and management practices	Fertilization (N, P) and liming (kg ha^{-1})	SOCρ changes (t C ha^{-1} year^{-1})
The EU and France (managed grassland) [23]	Cattle	L = LSU <0.6; HUI <0.3	Zero and ≥100 N	1.27 ± 0.40*
		M = LSU 0.6–1.3, HUI 0.3–0.7	Zero and ≥100 N	1.12 ± 0.32*
		H = HUI 0.7–1	Zero	−0.57 ± nd
			>100 kg N	0.74 ± 0.30
Australia (perennial and annual pasture) [24–28]	Mixed (cattle/ sheep)	M	—	0.50 ± nd
			Liming ± nutrients	0.40 ± 0.06*
			Liming ± phosphate	0.35 ± nd*
		Density = 0%, L to H = 50–200%	—	0.10 ± 0.10 −0.45 ± 0.53*
Rotational grazing [29]		M	—	0.35 ± nd
Hungary (extensive grazing) (Grazing +1 cut) [20]	Cattle (mowed)	L = 0.64 NLSU, HUE: 0.4	—	0.86 ± 0.74
		L = HUE 0.6	—	−1.23 ± 0.35
Hungary [30]	Mixed	L (Cattle, sheep, goat, and horses)	—	0.0013 ± nd
Mediterranean, Spain (extensive grazing)		L = 0.7–2.5 ewe eq ha^{-1} (cattle, sheep, pigs, and goats)	—	0.05–0.10
USA (mixed prairie) [5] (Grazed Bermuda grass) [31, 32] -Mixed prairie - Short-grass steppe [21, 22]	Steers	H + M	Inorg. (N: 200–270), inorg-org. (73.6), and broiler litter	0.03 ± 0.00
	Cattle Angus Steers	L H	—	1.17 ± nd 0.51 ± nd
		M	—	0.65 ± nd
	Sheep	L H	—	0.20 ± nd* 1.51 ± nd*
		L = YH (20–35% utilization) H = YH (60–75% utilization)	Long-term grazing Heavy grazing	0.55 ± nd 2.27 ± nd

*LSU = Livestock density unit (ha^{-1} year^{-1}); L = Low; M = Medium; H = High; nd = Not determined; YH = Yearling heifers; SOCρ = SOC density; * = Pooled/Averaged.*

Table 1.
Annual SOC density changes (t C ha^{-1} year^{-1}) in grazing grassland/pasture and the associated management practices.

such as marginal grasslands, introducing perennial grasses can increase pasture productivity [33] and build SOC storage, while minimizing surface erosion. Perennial grasses, compared to annuals, generally allocate a greater fraction of productivity to the maintenance of a deeper and more extensive root system [24, 25], resulting in an average increase of 0.15–0.50 t C ha^{-1} $year^{-1}$. Also, the introduction of more productive species [34], improved grazing regimes, fertilization practices, and irrigation management has been proposed for intensively managed pastures in North America for further potential C gains of 0.2 t C ha^{-1} $year^{-1}$.

Practices, including liming, gypsum amendment (e.g., 125 kg ha^{-1}), and nutrient managements, could increase SOC within a range of 0.29–0.55 t C ha^{-1} $year^{-1}$ (e.g., Australia). These gains are primarily attributed to increased plant production. In general, mineral phosphate fertilizers are applied to pastures on granite-derived soil, while gypsum is applied to address inherent deficiencies on basalt-derived soil. The application of P either alone or coupled with lime sequestrated C in soils at 0.41 and 0.29 t C ha^{-1} $year^{-1}$. However, for land occupied by low to medium intensity grazing (~90% of Australia's agricultural land), soil and climate conditions are not suitable for other more intensive agricultural practices. Given the large area occupied by these lands, a small gain in SOC per hectare would translate to a high total sequestration [26].

2.2 Integrated farming with grazing

Adoption of sustainable practices is needed to maintain soil fertility and subsequent productivity, and to avoid soil degradation and SOC depletion. Integrated farming systems often provide a combination of good management practices. The success of integrated system in promoting SOC accumulation largely depends on successful maintenance of good management practices over time. Besides, C accumulation and the capacity of the soil to maintain its levels depend on a variety of factors such as clay soils contribute to higher SOCρ and its maintenance [35, 36] and above-ground species diversity such as co-existence of shallow and deep-rooting species [37] influence below-ground diversity [38] and provide a constant soil cover and biomass inputs to combat erosion and maintain nutrient inputs balance at various soil depths through.

Incorporating legumes into grazed grasslands and woodlands/savannas can address the N deficiency as common in mature, unfertilized rangeland soils. This practice has been used in tropical/subtropical regions of northeastern Australia [39] and in areas of Western Australia with a temperate climate. Here, growing *Leucaena leucocephala* in rows in C4 grassland in subtropical regions increased SOC by 17–30% over 40 years (sequestration rate of 0.28 t ha^{-1} $year^{-1}$, **Table 2**). Also, improved management practices (fertilization, liming, irrigation, seeding legumes, planting more productive grasses, and using appropriate grazing regimes) have been reported to increase C sequestration (0.72 t C ha^{-1} $year^{-1}$) in 22 municipalities of the Brazilian states of Rondônia and Mato Grosso [40].

A number of integrated farming systems (IS) such as crop-livestock (agropastoral system, ICL), crop-forestry (silvoarable system, ICF), forestry-pasturage of livestock (silvopastoral system, ILF), and crop-forestry-pasturage of livestock (agro-silvopastoral system, ICLF) are reported to improve C sequestration. For IS in Southern Amazon and Cerrado (neo-tropical savanna) of Brazil, C sequestration rates of 0.60 and 1.30 t C ha^{-1} $year^{-1}$ were reported for 0–30 and 0–100 cm soil depth, respectively (**Table 2**) [37]. In the Mediterranean area of Italy with Dystric Cambisols, the conversion of cork oak forests to grasslands (i.e., silvopastoral ecosystems) showed that the C sequestration rate in topsoil (20 cm depth) was 0.71 ± 0.13 under frequent crop rotation (with 5 years of cereals or legumes, oats, Italian ryegrass, and annual clovers or vetch followed by spontaneous herbaceous vegetation in the sixth year), and 1.20 ± 0.07 t C ha^{-1} $year^{-1}$, under temporary pasture (5 years of spontaneous herbaceous vegetation and 1 year of hay crop), respectively (**Table 2**) [41].

In agrosilvopastoral system of the Iberian Peninsula (Mediterranean woodlands, Dehesas or Montados in Spain and Portugal, respectively), the improvement of C sequestration was mainly attributed to permanent pastures with mixed livestock raising at low stocking densities without external fodder inputs, exploitation of holm and/or cork oaks and arable systems with long rotations, and closed nutrient cycles. This was in opposite to soil tillage required in many Mediterranean soil/climate conditions to allow production of arable crops likely to reduce C sequestration.

Biomes/regions	Livestock category	Livestock density and/or No. LSU*	Fertilization (N and P) and liming (kg ha^{-1})	SOCρ changes (t C ha^{-1} $year^{-1}$)
Queensland, Australia (grassland and planted tree legumes mixed) [39]	Cattle	L to M = 0.45 AE ha^{-1}; 1 AE = 400 kg steer	P = 22 S = 28	0.28 ± 0.00
Southern Amazon, Brazil (integrated crop-livestock-forestry) [37]	Cattle	H = 21.27 AU ha^{-1}	370 NPK; 318 SP; 105 KCl; 324; NPK; 86 urea +10 KCl; 400 SP + 69 KCl; Pasture: 30 SP	0.60 ± 0.12 1.30 ± 0.23
Amazon, Brazil (nominal)	Beef cattle	M	—	−0.03 to 0.72 ± nd
Improved with legume and productive varieties [40]			Fertilization, lime, and irrigation	0.61 ± nd
Mediterranean, Italy (silvopasture) [41]	Sheep	L = 3–4 sheep ha^{-1}	50–39 (N-P)	0.71 ± 0.13
		L = 6 sheep ha^{-1}	50–39 (N-P)	1.20 ± 0.07
Inner Mongolia (semi-arid steppe) [9]	Cattle/sheep grazing exclusion	L	Season long grazing	0.10 ± 0.00
China (degraded grassland) [42]		M	0–30 cm 0–100 cm	0.23 ± 0.03 0.19 ± 0.04
Northern China (semi-arid, grassland) [43]		M	—	0.10 ± 0.00
China (desert steppe) [44]		H	—	1.43 ± 0.00

LSU = Livestock density unit (ha^{-1} $year^{-1}$); L = Low; M = Medium and H = High; SOCρ = SOC density change; nd: Not determined.

Table 2.
Annual SOC density changes (t C ha^{-1} $year^{-1}$) in integrated farming with grazing grassland, shrublands, and the associated management practices.

2.3 Grazing shrublands and exclusions

Overgrazing is one of the main causes of desertification in semiarid grasslands, and grazing exclusion (GE) is an effective management practice globally, to restore degraded grasslands and improve SOCρ significantly via plant biomass and soil microbial biomass compared to grazing management [44]. The C dynamics in grassland ecosystems with GE showed a positive impact of GE on vegetation and SOCρ at most sites [42]. The mean values for SOCρ change were 0.23 ± 0.03 and 0.19 ± 0.04 t C ha^{-1} $year^{-1}$ in 0–30 and 0–100 cm, respectively. Changes in SOCρ rates showed an exponential decay trend since GE and reached steady state at a later stage. Also, reduction in grazing pressure was reported (medium grazing, cattle/sheep) to result in a considerable increase of SOC and that the rate due to GE (10 years) was 0.10 t C ha^{-1} $year^{-1}$ (**Table 2**), suggesting that degradation of the grassland is being reversed [43].

For instance, the Alexa desert steppe has been strongly degraded by overgrazing, contributing around 22% of the total springtime dust originating from Asia. The effects of 7 years of GE on C dynamics showed lower SOC and higher SIC pools in areas with GE [44]. The total C pool in the GE plant-soil system was 10% greater than that in the area grazed over that time period (primarily due to 21% greater SIC), with a sequestration of 1.43 t C ha^{-1} $year^{-1}$ (**Table 2**). In semiarid steppes, recovery of heavily declined SOC caused by overgrazing is difficult and influences of long-term grazing on depression of nutrient cycling could be observed. For instance, in the semiarid steppes typical of Inner Mongolia, SOCρ was found comparable between grazed sites (average of 3 locations with sheep) and nongrazed GE sites at 0.1 t C ha^{-1} $year^{-1}$ (**Table 2**) [9]. Soil organic C levels in *Artemisia frigida* grassland was about 70% of that in *Leymus chinensis*, and in *A. frigida* grassland, it was significantly lower in grazing compared to nongrazing sites.

However, contrasting effects of overgrazing have also been reported [43, 45]. Soil IC pools could markedly contribute to the total C pool following GE, possibly due to the enhanced formation of pedogenic carbonates, higher soil water content, or increased carbonate capture in dust by recovering vegetation. On the other hand, the pool of SOC can be decreased by 11.5% in exclosure soils compared with the grazed site [46], linked mainly to the decrease in surface soil bulk density. These findings are potentially important because the Inner Mongolia grassland is the largest in the world and its degradation under heavy grazing is a source of dust storms that have major regional and global impacts. The positive impact of GE on vegetation and SOCρ [42] could improve enzyme activities and basal soil respiration in degraded sandy grassland, suggesting that degradation of the grassland is being reversed [13, 43]. A viable option for sandy grassland management could be to adopt proper exclosure in a rotation grazing system in the initial stage of degradation.

In Mediterranean regions, livestock take advantage of shrubs and grass during grazing while producing and dispersing manure. This represents the acceleration of transformation of plant OM into SOM, leading to an increase in SOCρ and makes them more resilient to future scenarios of global change [14]. Revegetation is very important especially to stop desertification processes and thereby increase SOC storage and improve soil health. Grazing management and cultivation of fodder have a high level of structural diversity both on a within and between habitat scale [47]. Greater SOCρ directly underneath the tree canopy suggests that maintaining or increasing tree cover may increase long term storage of soil C in Mediterranean silvopastoral systems.

2.4 Land use change from pasture to cropland and vice-versa

Multiple factors such as soil properties, land management, vegetation types, LUC, and climatic conditions influence soil C sequestration. Overall, the conversion of pasture into arable land leads to SOC loses with a balance up to 50 Pg [6] and up to 59% [48]. In the humid temperate zone of Europe, conversion of permanent grassland/pasture to arable land by plowing is associated with high SOC losses, especially in the first year after conversion (**Table 4**) [49].

Carbon loss after grassland conversion to cropland are often rapid (−36 ± 5%; on average estimated 1.81 t ha^{-1} year^{-1}) with a new SOC equilibrium being reached after 17 years [50]. Conversely, grassland establishment on cropland can be a long-lasting C sink with a relative density change of 128 ± 23% with no new equilibrium reached within 120 years (**Table 3**). Comparing sites, SOC increased with temperature and precipitation but decreased with depth and clay content. Regarding depth, top and subsoil SOC changes follow the same trend, but changes are often smaller in subsoil (25 ± 5% of the total SOC changes). Results of a meta-analysis from 74 publications indicate that overall, SOCρ declines after land use change from pasture to crop (−59%; −19 ± 7 t ha^{-1}) and increases when converting crop to pasture (+19%; 18 ± 11 t ha^{-1}; on average 0.56 t ha^{-1} of 32 years; **Table 4**) [48, 50], while mean SOC changes mostly occurred in the upper 30 cm.

Biomes/regions	Livestock category	Livestock density (LSU*)	Fertilization (N and P); liming (kg ha^{-1}) and slurry (t C ha^{-1} year^{-1})	SOCρ changes (t C ha^{-1} year^{-1})
Germany (grassland to cropland) [49]	Cattle	M = 2.2, 0–1 cut	~46 N, ~7 P (7 yrs); Slurry: ~0.1–0.2 t C ha^{-1} year^{-1}	−2.77 ± 1.79[a]
		M = 1.9; 2–3 cuts	~64 N (1 year); Slurry: ~0.2–0.4	−27.2 ± 11.70[b]
Ireland [51]	—	—	87–316 N (mineral and organic fertilizers)	−12.88[c]
Temperate zone [50]	—	—	—	−1.81 ± 0.55[d]
Europe [52]	—	—	—	−19.00 ± 7.00
Europe (cropland to pasture) [50–53]	—	—	—	1.99 ± 0.55[e]
				0.56 ± 0.34[f]
				0.22 ± nd
Australia (cropland to pasture) [2, 37, 54]	—	—	—	0.33–0.70 ± nd

LSU = Livestock density unit (ha^{-1} year^{-1}); L = Low; M = Medium and H = High; SOCρ = SOC density change; nd: Not determined.
[a]7-year average.
[b]1-year average.
[c]2.5-year average.
[d]20-year average.
[e]20-year average but reaching an equilibrium may take >100 years.
[f]32-year average, yet to reach equilibrium.

Table 3.
Annual SOC density changes (t C ha^{-1} year^{-1}) in land uses change from grazing grassland/pasture to cropland, from cropland to grazing grassland/pasture, and the associated management practices.

2.5 Degraded and other grassland areas

Soil carbon can be lost from grassland areas due to degradation, sometimes in association with management for grazing. For example, evaluation of the effects of management on SOCρ in grasslands compared to native vegetation in 22 municipalities of the Brazilian states of Rondônia and Mato Grosso showed that in degraded grassland, SOCρ declined by about 0.27–0.28 t C ha^{-1} $year^{-1}$ [39]. This indicates that degraded unmanaged grasslands in tropical regions lose C from the system (**Table 4**). Similar losses were found in temperate regions. In a shortgrass steppe, 28% less SOC was measured at locations with little or no plant input for about 45 years [55].

To assess the impact of animal trampling on soil properties, a study was conducted at a sub-alpine pasture in the Canton of Fribourg, Switzerland that had been used for summer grazing for over 150 years with a livestock density of about 4 cattle ha^{-1} (**Table 4**) [56]. The SOCρ in the 0–25 cm depth for areas of intensive trampling ("Bare steps") was 60 t C ha^{-1}, vegetated shoulder between trampled areas 74 t C ha^{-1}, and unaffected slope 76 t C ha^{-1}. The loss of SOC by trampling accounted for about 15 t C ha^{-1}, 20% of the total stock in this layer, or 30% on an equivalent soil mass basis (16 t C ha^{-1} over 150 years = 0.11 t C ha^{-1} $year^{-1}$). In the bare steps, physical protection and aggregate stability are reduced, exposing soils to the eroding power of raindrops, making them susceptible to overland waterflow, and depletion of organic C and N. Decrease in SOCρ is most probably the result of three different processes, (i) erosion of the unprotected bare soils, (ii) reduced C input due to the lack of vegetation, and (iii) soil aggregate disruption through trampling.

Sequestration estimates for more marginal and less-managed rangelands generally fall below 0.5 t C ha^{-1} $year^{-1}$ [7]. With recommended management, it was assessed that rangelands could sequester SOC at a rate of 0.1 t C ha^{-1} $year^{-1}$ with an additional 0.2–0.3 t C ha^{-1} $year^{-1}$ mitigation through avoided emissions [57]. In addition to a general increase in sequestration rates, planting of permanent vegetation in degraded and marginal lands could act as larger C sinks with sequestration rates in soils from nil to 1.1 t C ha^{-1} $year^{-1}$ depending on the use of manure/bio-solid applications [7, 15]. In summary, sequestration potential for numerous management practices could be 0.44 ± 0.20 t C ha^{-1} $year^{-1}$ [15]. While most studies have shown increased sequestration rates with improved grassland management, nil or negative effects on C sequestration in soils have been reported, possibly associated with poor experimental design or climate and soil limitations [2].

Biomes/regions	**Livestock category**	**Livestock density (LSU*) and management practices**	**SOCρ changes (t C ha^{-1} $year^{-1}$)**
Switzerland (summer grazing pasture) [56]	Cattle	L = Bare steps = 4 cattle ha^{-1} L = Vegetated shoulder = 4 cattle ha^{-1} L = Unaffected slope = 4 cattle ha^{-1}	−0.10 ± nd 0.09 ± nd 0.11 ± nd
Brazil (Amazon) [40]	Beef cattle	—	−0.28 ± nd

LSU = Livestock density unit (ha^{-1} $year^{-1}$); L = Low; nd: Not determined.

Table 4.
Examples of SOC density changes (t C ha^{-1} $year^{-1}$) in degraded and other land areas and the associated management practices.

3. Challenges and opportunities to improve SOC storage in pasture management systems

3.1 Livestock management impacts on soil carbon sequestration potential

Anthropogenic land use decreases soil C storage worldwide and often contributes to soil degradation and erosion. Loss of SOC occurs due to reduced organic matter inputs, deforestation, plowing, and sealing and animal impacts such as trampling. Globally, grazing lands comprise the largest and most diverse single land resource and represent an important component of terrestrial C cycling and sequestration [1]. Trade-offs among productivity, GHG emissions and SOC sequestration should be considered for the management of livestock farming to ensure sustainable production and climate mitigation. Climatic variables, particularly rainfall and temperature, and soil characteristics are major factors in determining potential storage of C in soils under managed livestock systems [58]. The data available suggest that C content varies widely among different grassland types as well as livestock management practices.

The effects of grazing management on the ecosystem processes that control C cycling and distribution have not been sufficiently evaluated in native grassland ecosystems. Current literature suggests no clear general relationships between grazing management and C sequestration. Some studies have reported no effect of grazing on SOC [43] while several others reported increases [13, 59] and a few reported decreases [42] as a result of grazing. Land use change is a major factor in determining SOC density in agricultural systems [52]. Conversion of permanent grassland or pasture into cropland results in loss of SOC, with the rate of decline dependent mainly on soil type, climate, ecosystem productivity, plant species, and intensity of management [60]. In addition, ecosystem function is affected through altered biodiversity and soil quality, with impacts differing across biomes and continents. In the tropics, the extent of degradation is normally greater due to higher temperature and often less sustainable soil management practices that accelerate decomposition and nutrient loss [60]. Similarly, conversion of native pasture and forest soils into cropland may increase soil bulk density (16%), plasticity index (30%), and soil erodibility (51%), as well as decrease SOC (50%), total N (50%), tilth index (40%), and available water capacity (40%) for surface soils [61]. There is a potential for restoration to a higher SOC level over time if arable lands are reverted to pasture. In the Mediterranean region, the recent dramatic changes in the development of industrial and tourism economies, with alteration of the composition and spatial structure of the traditional landscape, have had critical consequences for soil processes and management. European agricultural policies and the growing population have promoted intensive production systems, showing a negative effect on SOC storage in areas like Southern Spain.

3.2 Cultural and socio-economic views of grassland management

Livestock farming systems differ widely in terms of their use of resources, degree of intensification, species and orientation of production, local/regional socio-economic and market context, cultural roles, etc. [15]. Pasture-based livestock farming systems in the European Mediterranean basin play a key role in the management and conservation of large high nature value lands and that are highly relevant in both environmental and social terms, with great ecological, landscape, and cultural diversity. Accordingly, agricultural policies have begun to recognize their productive, environmental, and societal functions [62]. In the second half of the twentieth century, modernization and intensification of agriculture and the establishment of new economic and commercial relationships with urban areas have caused depopulation and a continuous reduction or abandonment of livestock farming in rural areas across Europe [63]. Within this context, the continuity of small family farms is a key aspect when assessing the sustainability of agropastoral systems. Within the EU, approximately 74 M ha of permanent grassland (including 17 M ha in upland areas), 10 M ha of temporary grassland, and 35 M ha of land in forage cereal crops (equal to 60% of the total planted area) are dedicated to feeding the European livestock herd [64]. Though grass-based systems require more land area than poultry or swine, ruminants can make use of grasslands and rangelands or land unsuitable for cultivation, thus not competing with biomass production for human food.

There are potential risks and benefits of diverse grazing land management due to the numerous episodes of land degradation associated with drought and overgrazing [27]. There is strong need for adopting sustainable practices at lower intensification management to prevent and avoid further soil degradation [65]. Implementation of land management practices with positive C storage outcomes may have a large impact on the economic factors of livestock production and can be limited by social and cultural issues. It has been suggested that reducing stocking rates to improve perennial grass basal cover could sequester 315 M t of C in the top 10 cm of soil over a 30-year period [66]. Besides, allocation of more time to grazing in pastures, rather than to feeding on mown herbage could be beneficial. Possibilities to expand grazing areas and period should also be explored. Abandonment of grasslands should be avoided to enrich biodiversity and limit the spread of invasive species [67].

Moreover, many farms are technically producing organic meat, although not yet officially accredited due to the high administrative procedures required [68]. Expansion of grazing management is possible but its feasibility and the full climate change mitigation potential in time and space on broader ecological, socio-economic, and political aspects should be evaluated [20]. The achievement of integrated systems promoting SOC accumulation and maintenance largely depends on good management practices successfully followed over time. Grasslands are among the ecosystems with the highest SOC density and stocks, and that serious concern is imperative [69]. Indeed, the EC Regulation1782/03 has introduced the concept of cross-compliance, with direct payments for farmers if they meet specific environmental requirements (Good Agricultural Environmental Conditions—GAEC).

3.3 Possible synergies and co-benefits or conflicts of livestock management with other practices

The emerging environmental and resource vulnerabilities may help adjustments in land use and farm practices, motivation and application of cultural beliefs, and a broader understanding of economic value associated with markets, technology, and administrative and policy frameworks. Importantly, we should consider the SOC stock in permanent grassland and the losses due to land use change and allocate C emission to milk and to the other products and ecosystem services to reduce the emission of GHGs from extensive systems [15]. Extensive livestock farming and pastoralism is a synergistic practice with the FAO recommendations to reduce meat consumption per capita, that is, to eat less meat but of higher quality and in the context of environmental sustainability [15]. On average, carbon emission is 4 times higher and erosion prevention is 10% lower in areas with a high grazing intensity compared to areas with a low grazing intensity [70].

Site-specific management practices could play a key role to moderate intensification of grassland production systems [71], and to mitigate some environmental impacts resulting from intensive agriculture. There are enormous opportunities across landscape mosaics to achieve an equilibrium between crops and grasslands to optimize trade-offs between food production and environment preservation as well as for offsetting unavoidable enteric CH_4 by C sequestration in grassland soils [72]. Integration of livestock systems with other agricultural activities (e.g., production of grain crops or biomass for energy) increases diversity within agricultural systems, better regulates biogeochemical cycles, decreases environmental fluxes, and supports diverse habitats and trophic networks. Thus, modern integrated crop-livestock-forestry systems could improve many ecosystem services, such as C sequestration, and environmental sustainability.

Trampling by livestock may reduce the cover and connectivity of plant, litter, and biocrust cover [73] and make soil vulnerable to wind and water erosion [74]. Strategic integration of crops, livestock, forage, and agroforestry increases the complexity of production systems, thus reducing problems of specialization, captures economic and ecological synergies, and offers a range of novel opportunities to conduit natural processes, from carbon sequestration and site remediation to nonchemical vegetation management. Mixed cropping-pasture rotation systems are likely to be significant in increasing SOC at low N application during cropping phases.

While increased complexity likely brings about ecological and economic benefits over highly specialized production systems, it may hamper its adoption and long-term maintenance. Land tenure, common property, and privatization issues also control competition from cropping, including biofuels and other land uses that limit grazing patterns and areas. Technical support for producers is imperative for the continued practice of mixed production, particularly for small- and medium-scale farmers, as well as sound complementary policies and good governance so that a "rebound effect" does not lead to any social and environmental impacts. Public extension services, in collaboration with the private sector, that strengthen information flow and enable investment in infrastructure have been and remain crucial to the success of integrated systems [37].

4. Conclusions

Globally, grazing is the largest anthropogenic land use, and a clear understanding of potential impacts of livestock management practices is essential to sequester C in the soils. Over-grazing decreases productivity, feeding efficiency, and C sequestration and increases GHG emissions from the systems. To enhance SOCρ and attain environmental sustainability in the systems, improved livestock management and the associated measures to cover soils, maintain biodiversity, select appropriate grazing time, control animal density and trampling, distribute dung and urine properly, keep soil moisture favorable, and improve livestock quality and productivity could have huge benefits. Further measures to make the system a C sink to offset any increased GHGs are to (i) optimize stocking rates to reduce land degradation, (ii) introduce improved pasture species and legumes to increase biomass production and SOCρ, (iii) apply recommended rate of inorganic fertilizers and manure to stimulate biomass production, and (iv) bring degraded land under pasture to reduce erodibility.

It is vital to understand the spatial pattern of livestock grazing intensity and its effects on ecosystem functions, address the range of natural resources and social dimensions, and encourage holistic approaches and partnership processes to achieve effective sustainable livestock-based systems. These include adaptation to climate change, promotion of technically advanced management options, introduction of consistent policies to enhance development capacity, and minimization of desertification, drought, and loss of biodiversity. Besides, recognition, awareness, behavioral change, and investments with due worldwide pro-extensive livestock policies are essential. Involvement of stakeholders, various organizations, development agencies/practitioners, community donors, relevant networks, and researchers is desirable to fully exploit the opportunities lying within the systems. Emphasis on spatially explicit global studies should be given to explore the impacts of livestock managements, adopt better technologies, and quantify trade-offs/off-setting potential and synergies among ecosystems. Further research should be targeted to value natural grasslands and livestock-based ecosystems, developing quantifiable methods for SOC measurement, strategic monitoring and verification of management-induced C sequestration. This is to ensure full GHG accounting and balance while generating improved understanding of the economic and institutional aspects of C sequestration involving people engaged in livestock farming.

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