



SOIL CARBON NOTES / SCIENTIFIC AND TECHNICAL COMMITTEE

SAFEGUARDING SOIL CARBON IN RANGELANDS: A KEY TO CLIMATE AND ECOSYSTEM RESILIENCE

KEY POINTS

- **Rangelands** are extensive landscapes dominated by native herbaceous or shrubby vegetation that are grazed, or have the potential to be grazed, by wild herbivores and livestock. They exclude highly modified pastures and grassy landscapes which are included in the broad definition of *grasslands*.
- Over 500 million people rely directly on rangelands for their livelihoods, well-being and culture, and two billion more are indirectly dependent on rangeland ecosystem services and socio-economic benefits.
- Rangelands occupy over half of the global terrestrial land surface area, and include diverse ecosystems, often with high biodiversity value, many in arid and semi-arid climatic zones.
- Rangeland soils are typically infertile with low organic carbon content but, in total, are estimated to contain almost 30% of the world's terrestrial carbon.
- Up to 50% of rangelands are estimated to have evidence of degradation, including depleted organic matter.
- **Protecting** the huge carbon store in rangeland soils from loss through land use change, unsustainable land use and disturbance; **restoring** organic carbon in degraded soils; and, where possible, **sequestering** additional organic carbon through improved practices are priorities for addressing the critical global issues of climate change, food security, biodiversity, and ecosystem health, as advocated since 2015 by the "4 per 1000" Initiative¹.

WHAT ARE RANGELANDS?

Rangelands are extensive landscapes with natural vegetation dominated by grasses, grass-like plants, forbs, shrubs or hardy woodlands that are grazed, or have



the potential to be grazed, by livestock and wildlife². While the terms 'rangelands' and 'grasslands' are sometimes used interchangeably, they differ in vegetation and land use. Grasslands have vegetation dominated by grasses (usually *Poaceae* spp) and other herbaceous (non-woody) plants, and include highly modified pastures. In contrast, rangelands exclude intensively managed grasslands³ while including areas with woody vegetation such as grazed savannahs and woodlands (Fig. 1). An estimated 44% of the area of rangelands may also be classified as grasslands but the defining land use in rangelands is extensive livestock grazing on native or naturally growing grasses and shrubs. Clear definitions are needed for consistent data and communication on the biophysical and ecological properties and management options in rangelands.

Rangelands occupy 54% of the global terrestrial surface area (Fig. 2A) – for example, making up 59% and over 75% of the land area of Africa and Australia, respectively. They are highly diverse landscapes consisting of deserts and xeric shrublands (35%), tropical and subtropical grasslands, savannahs and shrublands (26%), tundra (15%), temperate grasslands, savannahs and shrublands (13%), montane grasslands and shrublands (6%), mediterranean forests, woodlands and scrub (4%), and flooded grasslands and savannahs (1%)⁴.

They have high environmental, economic and socio-cultural importance, with more than 500 million pastoralists and their communities directly dependent on rangelands for their livelihoods and well-being, and an estimated two billion people benefiting indirectly from ecosystem services, resources and productivity linked to the health of rangeland ecosystems. Production of nutrient-dense food (meat and milk) on the 84% of the total area of rangelands used for grazing ruminant livestock is vital to reducing under-nutrition and its negative physical and cognitive outcomes, particularly in the Global South⁵.

¹ www.4p1000.org

² ILRI IUCN FAO WWF UNEP ILC (2021) 'Rangelands Atlas.' <https://www.rangelandsdata.org/atlas/>

³ WWF (2012) Terrestrial Ecoregions of the World | Publications | WWF

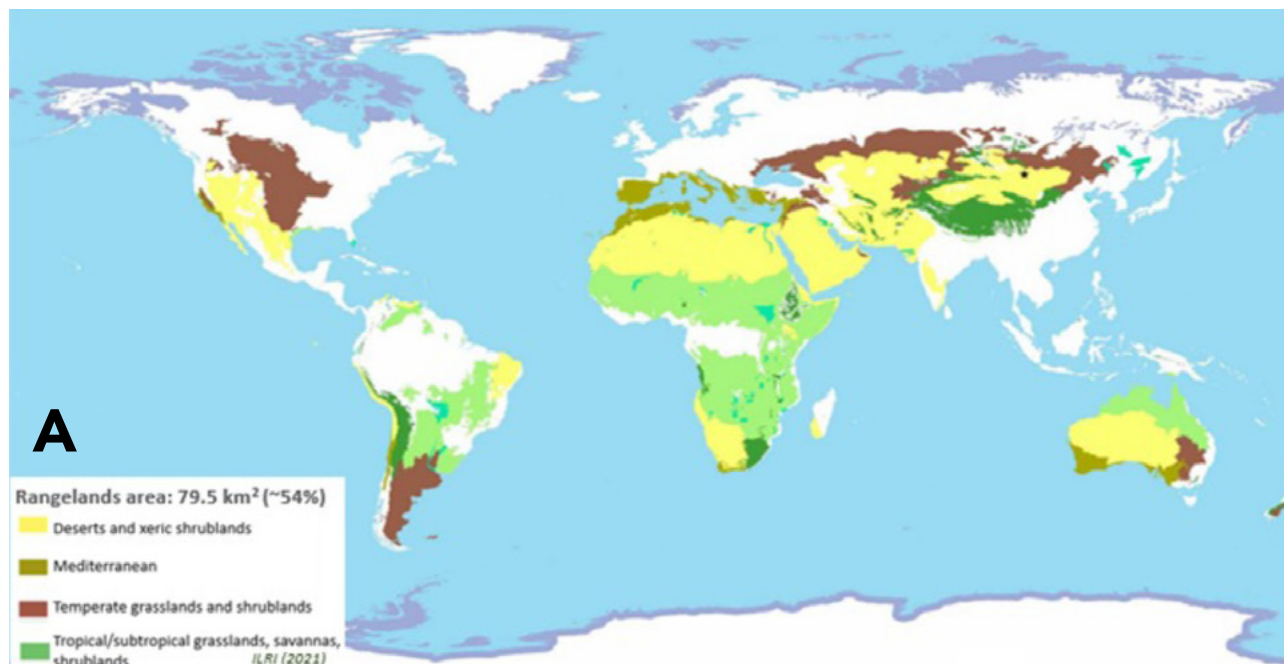
⁴ UNCCD (2024) Global Land Outlook Thematic Report on Rangelands and Pastoralism. UNCCD, Bonn.

⁵ Leroy et al. (2023). *Animal Frontiers* 13, 11-18.



Figure 1. Examples of rangeland landscapes – sheep grazing arid shrublands (left); tropical savannahs used for grazing beef cattle (right).

Figure 2. Rangeland extent and major ecosystems (A)⁷ ; and corresponding soil organic carbon (SOC) stocks (B)⁹ (B – top of page 3).



Rangelands are also valuable for their rich biodiversity and for their large stores of carbon, mostly belowground, which is estimated to be equivalent to around 30% of the world's terrestrial carbon.

RANGELAND SOIL CARBON AND SOIL HEALTH

Soil organic carbon (SOC) has long been recognized as fundamental to soil fertility and, therefore, soil health, agricultural productivity and ecosystem function. The amount of organic carbon stored in soil is determined by both natural and human factors that change the balance between carbon inputs and loss through impacts on processes such as plant growth, soil microbial activity, wildfire and erosion. Within the global carbon cycle, SOC dynamics plays a key part in regulating the earth's carbon and greenhouse gas balance, and since the Paris Agreement and launch of the International "4 per 1000" Initiative in 2015, there has been a growing focus on the potential role of soils in addressing climate change mitigation and adaptation. The extensive area (79.5 M sq km; Fig. 2A) and relatively undisturbed condition of rangelands has drawn attention to the potential role of carbon storage in rangeland soils as a natural climate solution.

In rangelands, SOC stocks to a depth of 30 cm have been estimated to be on average 53 t C ha⁻¹ (2010 data)⁶, but can be 10 t C ha⁻¹ or less in arid and semi-arid regions (Fig. 2B). This level is low compared to the global average for all terrestrial biomes of 62 t C ha⁻¹ and reflects the natural environmental characteristics of many rangeland areas – high climate variability with low or unreliable rainfall and extreme temperatures, and poor soil fertility and structure. These factors result in low net primary productivity (NPP) and elevated vulnerability of SOC storage to reversals. The risk of loss is exacerbated if management practices are unsustainable, and it is estimated that as much as 50% of rangelands is degraded to some degree⁷ due to past management such as over-grazing⁸.

Protecting rangeland soils from disturbance and implementing improved management to arrest loss and restore SOC stocks are high priorities for ongoing agricultural production and ecosystem services. More recently, interest has grown on the potential for improved management to sequester additional SOC for climate change mitigation.

EVIDENCE FOR MANAGEMENT IMPACTS ON SOC IN RANGELANDS

Livestock production, the major land use in rangelands, is based on low-input extensive grazing on native and naturally growing forages. Options for practical and economically feasible alternative management strategies that foster SOC storage are constrained by cost, labour, distance and remoteness. There are significant gaps in current understanding of the impact of different practices on SOC stocks in rangelands, due to the few long-term studies monitoring management effects and soil carbon across highly diverse landscapes. The impacts of management are often small relative to climate and soil factors that are the dominant drivers of SOC stock changes, and, therefore, difficult to detect over periods of <10 years. Field trials show that aridity and soil properties can explain as much as 90% of the difference in SOC stocks between rangeland sites¹⁰.

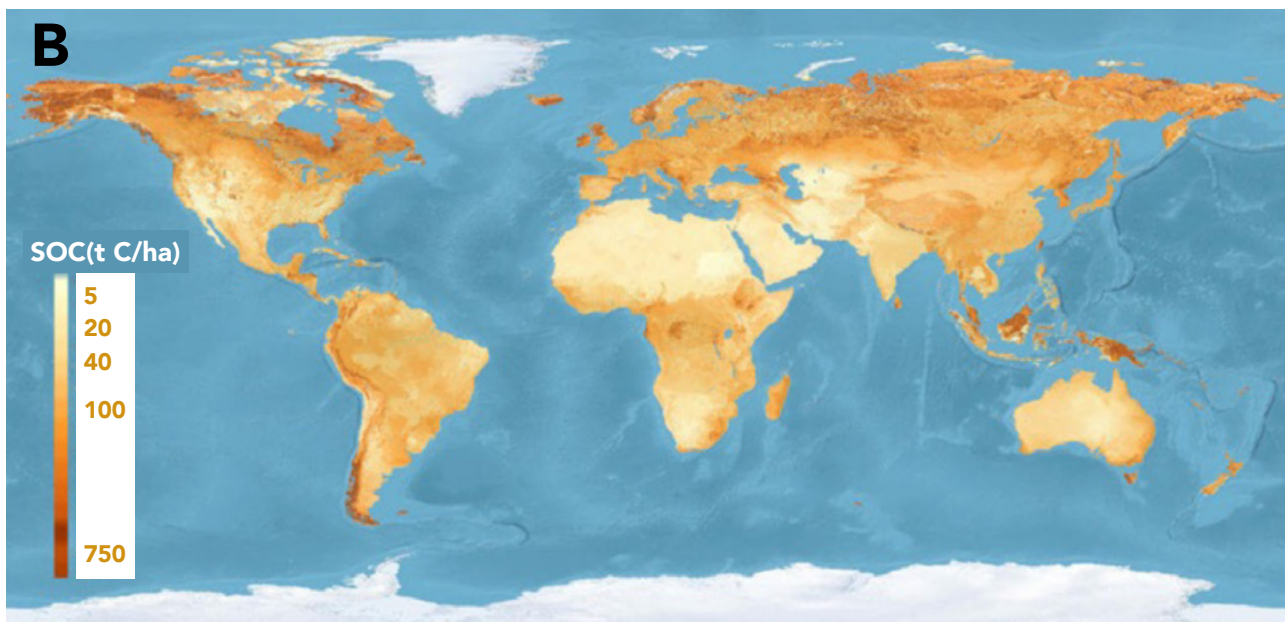
While there is considerable uncertainty, analyses combining past trials, transect surveys, and paired-site (space-for-time) comparisons have identified strategies that more consistently favour SOC sequestration. This available evidence provides valuable guidance on management options for safeguarding SOC in rangelands and indicates priorities to address gaps in knowledge and data for improving understanding of rangeland management actions for agriculture and ecosystem benefits as well as the role of rangeland soils in climate change mitigation. Examples in Table 1 and the following qualitative discussion consider practices under three broad categories: *land conversion*, *forage management* and *livestock grazing management*. Importantly, the biophysical suitability of management options will be influenced by regional conditions, and the realistic level of adoption and scale and effectiveness of SOC sequestration will depend on location-specific characteristics, including social factors and land use history.

LAND CONVERSION STRATEGIES

Only limited areas of rangelands are suitable for conversion from minimal disturbance grazing to more intensive land uses such as cropping, annual pasture or plantation forestry. Conversion of natural ecosystems is commonly associated with large losses of carbon from stable soil stores¹¹. Disturbance can also result in other negative environmental outcomes such as reduced soil

6 FAO (2023) Global Assessment of Soil Carbon in Grasslands <https://doi.org/10.4060/cc3981en>
7 UNCCD (2024): 'Silent demise' of vast rangelands threatens climate, food, wellbeing of billions. UNCCD | UNCCD
8 Sanderman et al. (2017) PNAS 114, 9575–9580. doi:10.1073/pnas.1706103114

9 FAO (2019) Global Soil Organic Carbon Map v1.5 (GSOC)
10 Henry et al. (2024). The Rangeland Journal, 46(3). 10.1071/RJ24005
11 Beillouin et al. (2023). Nature Communications 14(1): 3700



structure and health, and loss of ecosystem function and biodiversity¹². Conversely where rangeland previously used for cropping is returned to low impact grazing, field trials have shown positive potential to rebuild SOC, although recovery can be slow, especially where productivity is low¹¹. Afforestation (conversion from grass cover to forest) has been implemented in limited areas, with most studies showing no significant and persistent impact on SOC stocks. Although woody biomass accumulation results in higher total landscape carbon stores, afforestation may be accompanied by negative outcomes for soil health and biodiversity, and may pose risks for long-term sustainability¹³. Overall, land use decisions that protect soil health and long-term carbon stocks in rangelands through maintaining conservative land use appear the most positive for long-term SOC storage.

FORAGE MANAGEMENT STRATEGIES

Practices such as fertilisation, irrigation and periodic pasture renewal that are commonly used to improve forage quantity and quality in more intensive grazing farmland are generally not practical or economic in rangeland production systems. In some locations over-sowing native grasses with more productive grass species or fodder legumes as a once-off or infrequent intervention has been effectively used to improve production and drought resilience⁹. Because this strategy increases plant biomass production and the quantity and quality of soil organic matter (SOM) inputs, it can also increase SOC stocks. However, positive impacts were not observed in all studies¹⁴, and some found sequestration slowed after about a decade as a new steady state was reached. Rates of SOC sequestration of up to 0.4 t C ha⁻¹ yr⁻¹ (0–30 cm) over decadal periods have been observed in Australian rangelands¹⁵. Care in species selection is needed to avoid negative sustainability or biodiversity consequences in rangeland ecosystems. For example, weediness and/or aggravated soil acidity were found to be risks following introduction of the forage legume, *Leucaena leucocephala* in the grazed rangelands of northern Australia¹⁰. In summary, there is evidence for potential SOC sequestration with implementation of improved forage management practices in some rangeland areas, sometimes with co-benefits for soil health, livestock production, climate resilience and ecosystem services, such as water use efficiency. However, establishment and survival of introduced species is challenging in areas with high climate variability and frequent drought conditions, making the persistence of increased SOC storage uncertain.

GRAZING MANAGEMENT STRATEGIES

Improving grazing management by altering stocking rates or changing the timing of grazing and pasture rest periods has the potential to increase SOC stocks through effects on rates of organic matter input and decomposition of stored organic carbon. Outcomes depend on climate and soil factors and site-specific characteristics including past management and initial SOC content. Altering stocking rates within the range considered sustainable (low or moderate grazing pressure) for a rangeland location, have been found in published studies to result in variable, but generally non-significant changes in SOC stocks¹⁶. In contrast, prolonged high grazing pressure has been consistently shown in field trials and simulation studies to result in a net loss of SOC stocks especially where over-grazing causes loss of ground cover exposing bare soil. Removing livestock or excluding all herbivores are commonly (but not always) associated with an increase in SOC stocks (Table 1), particularly in degraded sites, although the rate of increase may be slow.

The potential for SOC sequestration from implementation of 'rotational' grazing management practices has received considerable interest as a nature-based climate change mitigation strategy since adoption of the Paris Agreement in 2015. Practices are referred to by various terms that include rotational, holistic, Adaptive Multi-Paddock (AMP), and regenerative grazing. Implementation details and the intensity of management vary, but all involve short-duration, high livestock density grazing followed by extended periods of forage rest. Comparing studies is difficult due to differences in definitions and frequent lack of detail on critical aspects such as baseline soil status, climatic conditions over the period of assessment, measurement protocols, and duration of monitoring. Reviews of published research, reports of field trials and anecdotal observations demonstrate contrasting outcomes for SOC sequestration, and ongoing research is seeking to better understand the role of these forms of management in improving soil health and in climate change mitigation. While results in high productivity grasslands have more consistently indicated positive results for SOC content and co-benefits for soil health¹⁷, at least over short periods, other peer-reviewed studies have not found persistent increases in SOC stocks¹⁸. For semi-arid and arid rangelands, several recent meta-analyses and reviews of published results have found no consistent evidence for SOC sequestration following a change from traditional or continuous grazing at moderate stocking rates to rotational grazing practices^{3,19}. However, even where no significant SOC sequestration was detected, some

12 Cook-Patton et al. (2021). Nature Climate Change 11(12), 1027-1034.
 13 Briske et al. (2024) Frontiers in Ecology and the Environment, 22, e2727
 14 Zhou et al. (2023). Nature Geoscience, 16(8), pp.710-716.
 15 Conrad et al. (2017) Agriculture Ecosystems and Environment, 248, 38-47

16 Derner et al. (2019). Ecosystems, 22, pp.1088-1094.
 17 Carrasco et al. (2025) EGUSphere 2025, 1-37
 18 McDonald et al. (2023) Journal of Environmental Management 347, 119146. doi:10.1016/j.jenvman.2023.119146
 19 Hawkins et al. (2022) Agriculture, Ecosystems & Environment 323, 107702. doi:10.1016/j.agee.2021.107702

Table 1. Examples of rangeland management strategies and their impacts on soil organic carbon stocks and other effects based on review of scientific literature. [C - carbon, SOC – soil organic carbon].

Management option (examples)	SOC change	Indicative impact on SOC stocks ¹	Other possible impacts (economic, environmental)
Rangeland conversion			
Range to cropping or annual pasture	Loss	- - -	Decreased soil health, biodiversity loss
Restoring cropland to permanent pasture	Increase	+++	Biodiversity, ecosystem services recovery
Range to tree/shrub cover	No change/variable	- to +	Biomass C > SOC; Biodiversity depends on species, density
Restore tree cover to grassland	Variable	- to +	Variable biodiversity impact
Vegetation management in grazed landscapes			
Over-sowing native grasses with more productive grass species	No change to short-term increase	+	Possible economic benefit (may be short-term), possible biodiversity loss
Over-sowing native grasses with legumes	Increase (depending on soil N status)	++	Economic benefits, drought resilience, possible biodiversity loss
Indigenous fire use to manage wildfire risk	No change to increase	+	Possible economic and biodiversity gain
Grazing management			
Destocking or exclusions ²	Variable	0 to +	May restore overgrazed areas
Prolonged high grazing intensity	Loss	- to - -	Decreased soil health, biodiversity loss
Low to conservative grazing intensity	No change (over long term)	0	Possible short-term decrease in ground cover
Rotational or holistic grazing vs conventional grazing ²	Variable from decrease to increase	0 to +	Possible impacts on biodiversity and land condition
Livestock species or genetics	Variable	Uncertain	Climate-species interaction

¹ Indicative direction (positive (+) or negative (-)) and magnitude of change.

² Results depend on initial land condition and total grazing pressure, i.e. whether all herbivores or only livestock are excluded.

analyses have found evidence that a shift to rotational grazing may increase ground cover and improve soil function, consistent with benefits for long-term productivity and climate resilience²⁰.

SOIL CARBON IN RANGELANDS – KEY KNOWLEDGE GAPS

There is overwhelming scientific consensus amongst soil experts that protecting and restoring carbon in soils will provide multiple environmental and economic benefits. While there remains uncertainty in the potential role of soil carbon sequestration in rangelands as a nature-based solution for climate change, there is widespread support for urgent actions to accelerate adoption of management practices for improved soil fertility and soil health. Modelling has indicated that more sustainable management of rangeland livestock production systems, could not only benefit productivity and, ultimately, food security, but help preserve existing SOC stocks and, in some locations and conditions result in additional sequestration. One study estimated that adjusting grazing pressure to maximize forage production rather than offtake rates, could sequester, on average, 0.06 t C ha⁻¹ yr⁻¹, giving a theoretical increase in storage of 30 Mt C yr⁻¹ across global rangelands²¹. However, translating such theoretical projections to an estimate of achievable potential

sequestration considering socio-economic constraints on the adoption and maintenance of new management options requires more research.

Priorities to help address gaps in data and knowledge to support policy and management decisions include:

- Establishing protocols for designing and monitoring trials to improve data quality for evaluation of management strategies for impacts on rangeland soils with an expanded focus on climate change mitigation as well as co-benefits for soil health, ecosystem function and productivity²².
- Developing more accurate, cost-effective monitoring, reporting and verification (MRV) methods that can reliably detect small changes in SOC stocks across vast and diverse rangeland production systems, many operated by smallholder pastoralists.
- Establishing and maintaining long-term trials to understand carbon dynamics and the persistence of SOC in rangeland soils subject to high and increasing climate variations and extremes.

²⁰ Sutton et al. (2025) Computers and Electronics in Agriculture 234, 110278.

²¹ Henderson et al. (2015) Agriculture, Ecosystems & Environment 207, 91-100 (data converted to mass C from rates reported as mass CO₂).

²² Smith et al. (2024) PNAS 121(4), e2309881120