630

A review of the evidence linking management and soil carbon sequestration in rangelands

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Abstract

While the agronomic benefits of organic matter in soils have long been established, debate continues regarding the potential for increasing carbon storage in soils to help combat anthropogenic climate change. Of all the world's biomes, rangelands have arguably the highest expectations, and the greatest uncertainty, for soil organic carbon (SOC) sequestration, i.e. removing carbon dioxide from the atmosphere via photosynthesis and securely storing the assimilated carbon in soil. Our review of evidence for persistent increases in SOC stocks following implementation of new management strategies showed significant methodological limitations and inconsistencies in reported outcomes. A major challenge is that detection and attribution of management impacts are difficult in low productivity, high diversity rangelands where 90% or more of sampled differences in SOC stocks may be determined by climate and soil factors. Caution is needed in interpreting results, but strategies with more consistent evidence for SOC sequestration include over-sowing forage legumes into grass pastures, conversion from cropping to permanent pasture and avoiding prolonged high grazing intensity. Our analysis did not find evidence for significant, persistent increases in SOC stocks with the implementation of other livestock management options (e.g. rotational grazing). We conclude from the available evidence that the potential for SOC sequestration in rangelands is likely modest. However, uncertainty is high, and we recommend research priorities to improve data and understanding of SOC in rangelands for production and environmental benefits.

Introduction

The mass of carbon (C) in soils is very large, estimated at three times that in the atmosphere, and 80% of the total C stored in terrestrial ecosystems (IPCC 2023). Of this C pool, the organic component is more responsive to management than inorganic C, and 25−75% of soil organic carbon (SOC) has been lost globally since 1850 largely through inappropriate agricultural practices (Sanderman et al. 2017). There is strong interest in the prospects for improved management to restore SOC in degraded lands for agricultural productivity, ecosystem services and food security benefits and increasingly as a climate change mitigation strategy since permanent increase in SOC storage (i.e., sequestration) represents a net removal of CO_2 via photosynthesis from the atmosphere (Bossio et al. 2020). Rangeland, as the most extensive biome, spanning 79.5 M sq km (ILRI et al. 2021), and holding a third of global soil organic matter (SOM), theoretically represents a substantial climate change mitigation potential, but there is considerable uncertainty in the achievable SOC sequestration.

The value of SOM for soil condition and functionality is well-established from centuries of agronomic research but how long-term increase in SOC in stable forms is affected by different pasture and grazing management practices is less well-understood (Rumpel et al. 2023, Salley and Brown 2023). To mitigate climate change by offsetting greenhouse gas (GHG) emissions, C sequestration must meet internationally recognised integrity standards for C removals, including additionality (whether management activities go beyond business-as-usual), evidence-base (scientific evidence linking human activity and SOC sequestration), permanence (persistence of stored SOC), and quantification (accurate, conservative measurement or modelling of SOC stock changes) (Dupla et al. 2024). Uncertainty is high for rangelands, due to their diversity and generally limited data. Here we present: (i) an overview of data and evidence for management-induced SOC sequestration in global rangelands; (ii) a case-study of management impacts on SOC sequestration in Australia's rangelands; and (iii) recommendations for research to reduce uncertainty for agriculture and climate policy.

Methods

Scope: The review covered published papers and reports on field trials, soil sampling surveys, and credible modelling studies with SOC data for grazed rangelands. For the global overview we did not undertake a new comprehensive literature search but drew on published reviews, meta-analyses and recent papers (e.g., Reinhart et al. 2021, Sanderson et al. 2020, Salley and Brown 2023). For the Australian case study, we expanded on recent reviews of the impacts of management on SOC stock changes in Australian rangelands (McDonald et al. 2023, Henry et al. 2024) to summarise the sequestration potential of strategies for: (i) grazing management; (ii) pasture improvement; and (iii) land conversion.

Data selection and analysis: Studies on SOC storage in rangelands have used a range of methods for experimental design, SOC quantification and management interventions. Based on recent scientific understanding and measurement protocols (Batjes et al. 2024, Zhang et al. 2024), a set of criteria was developed to select SOC stock change data and management strategies for evaluation (Table 1). Overall, few publications provided adequate information to reliably assess data quality and enable valid comparisons. Inconsistencies between studies affected the strength of evidence and were used to identify data and knowledge needs in rangeland systems.

Results

Global review: Our review revealed that few studies had credible data able to meet minimum requirements for quantifying the impacts on SOC *sequestration* of management strategies appropriate for implementation in rangeland production systems. The impacts reported for similar strategies were marked by inconsistencies in the magnitude (and, in some cases, direction) of SOC stock change, but there was some evidence of robust trends in response: (i) no clear effects of various rotational grazing practices; (ii) positive effects when more productive species were over-sown into grass pastures; (iii) negative impacts of prolonged high grazing intensity on SOC stocks; (iv) positive impacts of conversion from crop production to permanent pasture; (v) limited potential for SOC sequestration, and probable adverse impacts on ecosystem services, of conversion of grasslands to forest (Briske et al. 2024).

Table 1. Summary of criteria used to select credible SOC sequestration data from publications reviewed for analysis, and constraints for rangeland monitoring.

Criterion	Data requirement	Rangeland context
Consistent with SOC sequestration definition	SOC stock change relative to initial or baseline reference	Few long-term trials with SOC and bulk density measured (baseline, project) across the diversity of rangeland soils, climate, production systems
Baseline	SOC stocks under business-as-usual management.	Representative initial SOC stock measurements, preferably dynamic baseline monitored over multi-decadal periods, accounting for variance and climate
Management strategy	Details of baseline and new management	Poor/no data limits the evidence-based attribution and comparisons for SOC change due to new management
Measurement (in-field; lab. or proximal sensors)	Depth ≥30 cm; bulk density; sampling protocols; variance	Vast areas, high spatial and temporal variability and low Net Primary Production (NPP) mean small/slow rates of change that are hard to detect and costly to monitor
Measure – model approaches	Calibrated and verified models	Few data across rangelands for calibration; model representation of C and N dynamics often inadequate
Monitoring periods	Monitor at 5-10 year intervals for decades/ centuries (>10 years)	Dominant impacts of rainfall and soil type, high risks of reversal under low/unreliable rainfall mean detection and attribution of change need longer monitoring

Australian rangeland study: The Australian rangelands cover around 75% of the continental area, with a range of management systems across diverse climates, soils and landscapes. Results of the literature review and analysis of data extracted from studies (field trials, surveys or credible simulations) meeting criteria for monitoring SOC stock changes were broadly consistent with the global observations. While data were insufficient to reliably quantify the potential for SOC sequestration under different initial soil conditions (e.g., nutrient status) and management options, some strategies provided indicative values (Table 2). For example, over-sowing native grass pastures with more productive grasses or with forage legumes provided consistent evidence of sequestration (up to 0.1 t C ha^{-1} yr^{-1}; ~0.3 t C ha^{-1} yr^{-1}, respectively), and conversion from cropping to permanent pasture increased SOC stocks (median value ~0.2 t C ha^{-1} yr^{-1}). Conversely, data from long-term studies indicated that implementing rotational or other grazing strategies had negligible persistent impacts on SOC stocks. Across all studies, the permanency of any SOC sequestration could not be assessed.

Table 2. Summary results from Australian rangeland SOC studies quantifying SOC sequestration (0-30 cm depth). (Adapted from Henry et al. 2024.)

Management strategy	Number of studies[1]	Estimation period (yr)	Baseline[2] C (t C ha^{-1})	SOC seq. range (median) (t C ha^{-1} yr^{-1})
Grazing management				
Lower grazing intensity	2	16 –26	13 – 19	0 – 0.09 (0.03)
Destocking or exclosure	7	7 –58	5 – 80	0 – 1.68 (-0.03)
Rotational vs continuous	4	5 –10	5 – 75	-0.11 – 0.01 (0.08)
Pasture improvement				
More productive grasses[3]	5	Various	>10 – 50	0.02 – 0.11 (0.06)
Oversowing with legumes[3]	3	22 – 50	19 – 52	0.27 – 0.45 (0.38)
Water ponding	1	20 – 25	19	0.28 (0.28)
Fire management	1	58	33	0.03 – 0.04 (-0.07)
Land conversion				
Cropland to grassland	3	15 – 20	23 – 121	0.06 – 0.48 (0.16)
Forest to grassland[4]	7	<11 – 73	20 – 121	-2.42 – 0.72 (-0.22)
Grassland to forest[4]	1	10 – 58	16 – 76	0 (0)

[1] Studies included field trials, field surveys and models; [2]Reported as either *Initial* or *Control* site C stocks; [3]Results include modelled data; [4]Results include data from a survey of 45 sites in northern Australia.

Discussion

Assessment combining an overview of global studies and analysis of Australian research indicated that the potential for management-induced SOC *sequestration* in rangelands is uncertain, variable and unlikely to contribute substantially to climate change mitigation or income for livestock producers C offsets. Other recent publications have reached similar conclusions (Don et al. 2023, Dupla et al. 2024, Reinhart et al. 2021). The analysis is also consistent with evidence that the dominant drivers of SOM inputs and losses, and of the long-term net SOC stocks, are rainfall, temperature, and the soil properties that determine SOC stabilisation and persistence. The challenges of maintaining and increasing SOC stocks are exacerbated in rangelands by typically infertile soils and high seasonal variations in NPP (Cotrufo and Lavallee 2022). At a property scale, in rangelands the large areas and low and reversible rates of storage make accurate and cost-effective quantification of SOC stocks and stock change a barrier to ‘C farming’ (Derner et al. 2019, Batjes et al. 2024, Dupla et al. 2024). Measurement uncertainty adds to the difficulty in attributing changes in SOC to implementation of a new practice when management may be responsible for as little as 10% of measured differences between sites (Allen et al. 2013, Salley and Brown 2024). These factors contribute to the lack of consistency in results from published rangeland trials (Sanderson et al. 2020, Henry et al. 2024). Additionally, studies have varied in whether emissions of other GHGs arising from a management change were counted in the estimated climate change mitigation benefit of SOC sequestration and whether standards for integrity of C offsets, particularly additionality and permanence, were adequately established. To improve understanding of the potential for SOC sequestration, investment is needed in long-term trials using best practice experimental design, multi-decadal monitoring of control and treatment sites for SOC stocks to >30cm with sufficient replicates for statistical analysis of spatial and temporal variance supported by site information on historic management, baseline soil condition and initial SOC stocks. Based on our review, we caution against over-expectation for the environmentally and economically achievable quantity of SOC sequestration in rangeland soils. However, while C farming market opportunities are likely modest, there is value in expanding investment in well-designed, long-term field and modelling studies over spatial and temporal scales representative of the diverse rangelands to better quantify the potential for maintaining or increasing SOC stocks and to understand the value for rangeland resilience now and under future climatic conditions.

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