Regenerative Grazing as a Climate Change Mitigation Strategy: A Systematic Review

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Abstract

Ruminant livestock production is a significant contributor to global greenhouse gas (GHG) emissions. Regenerative grazing has been proposed as a potential climate change mitigation strategy by offsetting GHG emissions with soil organic carbon (SOC) sequestration. We evaluate this evidence in the peer-reviewed literature, ranking them by ascending study design quality: observational, cross-sectional and longitudinal. Reported and inferred SOC sequestration rates varied widely, with the highest values reported in lower-quality observational studies, while SOC sequestration from cross-sectional studies and longitudinal studies were mixed, with 95% confidence intervals of median SOC sequestration overlapping zero indicating no difference from conventional grazing. Currently, high-quality evidence does not support widespread claims of SOC sequestration from regenerative grazing. To clarify its potential as a climate mitigation tool, a greater number of longitudinal studies are needed.

Keywords: regenerative agriculture, livestock, climate mitigation, SOC, grazing, carbon sequestration

1. Introduction

Ruminant meat and dairy production account for 9% to 13% of global anthropogenic greenhouse gas (GHG) emissions (FAO, 2022; Halpern et al., 2022). One practice with GHG mitigation potential has sparked popular imagination: “regenerative grazing”, which may result in soil organic carbon (SOC) sequestration. Regenerative grazing lacks an agreed-upon definition, but encompasses a host of livestock management practices aimed at improving soil and ecosystem health, farm profit, and resiliency of the food system (Dillon and Machmuller, 2021). These practices often involve rotating herds across smaller pastures at high stocking densities to mimic natural grazing. Highly-visible public presentations have asserted that regenerative grazing methods meaningfully offset emissions of cattle in the life cycle of beef and dairy production, or even offset emissions from other economic sectors (Leu 2024).

Recent scientific assessments reach diverging conclusions about the carbon sequestration potential of regenerative grazing (Eshel et al., 2025; Pelton et al., 2024). However, these studies derived their carbon sequestration estimates from only a few specific studies, omitting others and limiting their scope. Additionally, these reviews omit a critical analysis of study design; they do not rate estimates based on their ability to establish the extent and quality of the relationship between management and SOC outcomes, i.e. whether regenerative grazing itself is responsible for additional SOC sequestration.

Our systematic review assembles and evaluates evidence addressing the question: does regenerative grazing induce SOC sequestration? Specifically, what is the quantity and quality of evidence that SOC sequestration occurs, *and* that it would not have occurred under counterfactual conditions, e.g. under conventional grazing? We assemble SOC sequestration outcomes from all regeneratively-managed ruminant livestock grazing experiments to date. We systematically organize and evaluate SOC results based on a hierarchy of evidence, categorizing studies by the evidentiary strength of their experimental design.

2. Methods

2.1 Grazing management definitions

To facilitate comparison between regenerative and conventional grazing, we define "conventional grazing" as methods that allow animals to access pastures for the entirety of the grazing season without providing rest. This is also commonly referred to as "continuous grazing," "traditional grazing," and "set-stocking". We define "regenerative grazing" as a suite of methods that subdivide larger pastures into "paddocks" that are alternatively intensively grazed by the entire herd or subdivisions of it, then rested intermittently with periods of no grazing. This rotational approach is a frequent but not universal tenet of regenerative agriculture, a term that lacks a consensus definition (Giller et al., 2021). Many other terms in scientific and agricultural parlance meet our functional definition, including: adaptive multi-paddock grazing, mob grazing, management intensive grazing, and holistic planned management.

2.2 Literature review

We conducted a systematic review of the literature following PRISMA guidelines (Fig. S1), for results quantifying SOC outcomes of regenerative grazing. To compile these articles, we conducted series of database searches from 2002 extending to the present (accessed: Feb 5, 2025) using Web of Science and Google Scholar. We searched Web Of Science for all studies containing a wide array of search terms related to regenerative grazing and its synonyms, plus soil carbon outcomes (Box S1). This query returned 86 studies. We included studies that A) compare regenerative grazing and/or conventional grazing management; B) report soil organic matter (SOM%, SOC%, SOC stocks, or SOC flux; C) present original in-situ soil carbon measurements; and D) report the duration of time pastures were under either grazing treatment. A total of 23 of the 86 Web Of Science retrieved studies met our initial criteria.

Additional Google Scholar searches returned 1 unique study. Searching references from literature reviews appearing in the initial search resulted in 4 more studies that met our criteria.

Lastly, references cited by the regenerative grazing SOC analyses that met our search criteria were carefully examined for inclusion, but none met all of our criteria. In total, we found 28 unique studies meeting our inclusion criteria. Several studies (N = 11) reported data using a management type falling outside of our definition of conventional grazing as a counterfactual for regenerative grazing management. These data are accounted for in our auxiliary analysis but were not suitable for our main analysis. In addition to SOC, we catalogued the studies' location, species, animal stocking densities and rates, soil sampling depth(s), and land use history.

2.3 Categorization of studies

We categorized the 28 studies that met our criteria into four experimental design categories according to a hierarchy of evidence: (1) Time-Series Observational studies, which reported SOC from regeneratively grazed sites without conventional controls, using either true time series or chronosequence measurements; (2) Comparative Observational studies, that compared adjacent sites that differed in one or more biotic or abiotic confounding variables (e.g., soil texture, climate, land use history) and reported only a single SOC measurement; (3) Matched Quasi-Experimental (MQE) studies, which directly compare adjacent regenerative and conventional sites that are otherwise similar with respect to all biotic and abiotic properties that are likely to affect SOC, but only report SOC at a single time point, and; (4) MQE Longitudinal studies reporting at least two SOC measurements over a period of ≥1 year. MQE designs were ranked higher than comparative observational studies because they attempt to control for confounding variables. No true experimental studies, which would randomize grazing treatments, were found in our literature search.

2.4 SOC stocks

We converted all studies' SOC stock data into common units of metric tons of carbon per hectare (MgC ha^{-1}) which some studies report directly (N = 16). For conversion from soil C concentration (%SOC or SOC g/kg) to C stock, we used the following equation:

$$Cstock\ (MgC/ha)\ = \sum_{i}^{n} (SOC_i(\frac{g}{100g}) \times BD_i(\frac{g}{cm^3}) \times D_i(cm)) \times 100$$

where BD = bulk density of a soil sample at depth *i*, D = the depth in centimeters of each stratum of soil, SOC = soil organic carbon concentration at depth *i*, and 100 is the conversion factor of gC cm^{-2} to MgC ha^{-1}. When soil C concentration was reported in %SOM, we first converted SOM to SOC using a 0.58 conversion factor (McClelland et al., 2021; Lunt, 1931; Broadbent, 1953; Howard, 1965). In cases where we were limited by a lack of BD measurements by depth, we applied a single value to all depths. [1] Where only one BD was reported (N = 1), we applied this to all depths. [2] Where none was reported (N = 3), an estimated value from literature (USDA, 2019) was applied to all depth strata based on the soil texture reported within the respective regenerative grazing studies.

2.5 SOC fluxes

Annual fluxes from these studies (MgC ha^{-1} y^{-1}) were either reported directly, or we calculated them according to the common method within other studies in their evidentiary category. All time-series observational studies reported their own SOC flux rates which we incorporated directly. However, for the comparative observational studies that did not quantify flux, we took the difference in total reported SOC stock between treatment and control sites divided by the duration of the treatment.

For cross-sectional studies, differences in C stock between treatment and control sites were divided over the duration of time (years) that the experimental site was subdivided into the contrasting forms of management. If treatment durations differed between conventional and regenerative sites, we calculated the mean of the durations. Some studies did not explicitly organize adjacent regenerative and conventional pasture sites into pairs. We paired these sites according to most similar animal stocking densities/rates. In cases where no stocking information was available, SOC was averaged across all treatment sites and compared to the average across all control sites.

For longitudinal studies, fluxes were calculated by taking a difference of differences: the difference in SOC stock from the first (baseline) and last (most recent) sampling year and the difference between the regenerative and conventional sites' time differences, then dividing the result by the duration of time between the first and last sampling years. Calculated fluxes from conventionally grazed sites were subtracted from those of regeneratively grazed sites where study design allowed for such a pairing. Otherwise, differences between regenerative and conventional fluxes were calculated based on pairing methods in this section.

When fluxes were reported directly we collected them from their parent study regardless of how the authors calculation methods differed from those we outline above.

2.6 Statistical analysis

All statistical analysis was conducted using R version 4.3.2 (R Core Team, 2023). Data manipulation and visualizations were facilitated by use of the "tidyverse", "_matrixStats", and "_ggrepel" packages (Wickham et al. 2019; Bengtsson, 2025; Slowikowski 2024). Means and medians for each category were calculated with 95% confidence intervals using bootstrapping by randomly resampling SOC fluxes over N = 1001 synthetic vectors with replacement (Efron, 1979).

3. Results

We compiled 28 studies in which SOC fluxes from regenerative grazing were either reported or could be inferred using methods common in the literature. Combined, these studies report results from 49 pasture sites (one pair of co-located continuous vs. regenerative case-control pastures = one pasture site). Most studies were on pastures grazed by cattle (N = 16), while others were grazed by sheep (N = 5), and some had mixed cattle with sheep and/or goats (N = 5). The Americas and Australia were disproportionately represented: 93% of studies, i.e. all but two studies quantified soil C sequestration in these continents. In descending order: 46% of studies or 57% of sites were in North America; 32% of studies or 27% of sites

were in Australia; 14% of studies and 10% of sites were in South America. The remaining two studies, with a combined three sites, concerned sheep grazing in China and Spain.

Time-series observational studies show the greatest maximum values for annual SOC sequestration. Median and mean SOC sequestration among time-series observational studies were 3.59 (2.29 - 7.10 95% CI) MgC ha^{-1} y^{-1} and 4.33 (2.29 - 7.10 95% CI) MgC ha^{-1} y^{-1}, respectively, both of which were significantly greater than zero (Table 1). Comparative observational studies' median SOC sequestration was 0.33 MgC ha^{-1} y^{-1} and was not significantly greater than zero; the mean was significantly greater than zero at 2.42 (0.02 - 4.93) MgC ha^{-1} y^{-1}, but overlaps zero when studies with insufficient soil depth data are excluded (-0.43 - 6.61) MgC ha^{-1} y^{-1}. This category also showed the greatest range of values (Table 1).

The largest study category was MQE Cross-Sectional (N = 16). Median SOC sequestration was 0.09 MgC ha^{-1} y^{-1} and was not significantly greater than zero (-0.05 - 0.42 95% CI). This lack of statistical significance remained when SOC data from studies with sparse depth measurements were excluded (Table 1). In both cases, however, mean SOC sequestration in the MQE cross-sectional study category was significantly greater than zero (Table 1) due to a non-symmetrical distribution of SOC outcomes in this category.

MQE longitudinal studies (N = 5) showed the smallest range of soil carbon fluxes, with median sequestration of 0.24 MgC ha^{-1} y^{-1}, which was not significantly greater than zero (-0.13 - 0.89 95% CI), nor was the mean (Table 1). Three out of the five longitudinal studies measured surface soil only (10 cm).

Generally, the same tendencies were observed in medians and means when we excluded studies with sparse soil depth data (Table 1), treated sites as replicates rather than studies (Fig S2), normalized SOC numbers to a common depth (Figs, S3 & S4), and/or differentiated among farmed livestock species (Fig S5).

To evaluate the potential for farmed livestock species as a confounding variable (Fig S5), we calculated summary statistics for our dataset separating categories by grazed species (Table

S1). A Mann-Whitney U test was used to evaluate the significance of SOC sequestration on cattle-grazed vs all other grazed ruminant categories (Mixed Large and Small + Small Ruminants). This returned a p-value of 0.0879, which is not significant at the 95% confidence level. We performed this test on only studies within the MQE cross-sectional category as this provided the largest and most even sample size of cattle-grazing (N = 9) and non-cattle ruminant grazing (N = 6) studies.

The 2019 case-controlled study conducted by Alemu et al. (2019) collected SOC measurements over time, and provides sufficient data to calculate results in both a cross-sectional and longitudinal manner (Fig 1). We incorporated both, to highlight the difference in apparent SOC sequestration effect size that can be inferred from a cross-sectional study versus a more robust longitudinal analysis.

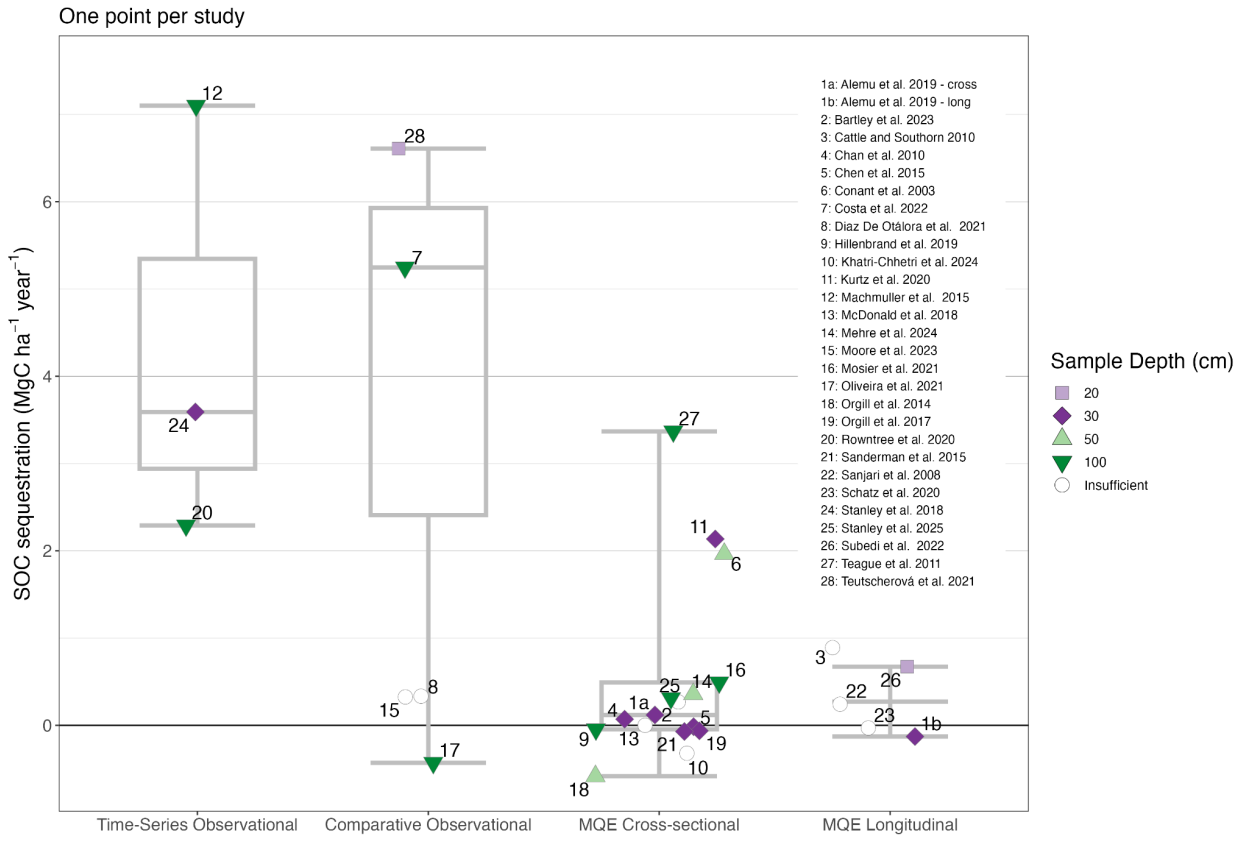

Fig. 1: Mean SOC sequestration rates in each regenerative grazing study (numbers) and ranges. Colors represent the maximum depth at which SOC measurements were conducted. Studies with depth measurements of <20 cm or with only one depth stratum were classified as having insufficient depth data, for possible exclusion from analysis (white points). Box plots represent full ranges (whiskers), interquartile ranges (box edges), and medians (middle line) for studies conducted with robust SOC depth data. The SOC sequestration flux was calculated as the difference in time or across chronosequence sample points in the time-series observational category, as the differences between paired plots in pasture sites (averaged over all sites in each study) divided by number of years of management differentiation in the MQE Cross-Sectional category, and as the difference-in-difference across paired plots and over time in the MQE Longitudinal category.

	All Studies				**Sparse depth data excluded**			
Category	**Studies**	**Range**	**Median (95% CI)**	**Mean (95% CI)**	**Studies**	**Range**	**Median (95% CI)**	**Mean (95% CI)**
Time-Series Observational	3	2.29 - 7.1	3.59 (2.29 - 7.1)	4.33 (2.29 - 7.1)	3	2.29 - 7.1	3.59 (2.29 - 7.1)	4.33 (2.29 - 7.1)
Comparative Observational	5	-0.43 - 6.61	0.33 (-0.43 - 6.61)	2.42 (0.02 - 4.93)	3	-0.43 - 6.61	5.25 (-0.43 - 6.61)	3.81 (-0.43 - 6.61)
MQE Cross-Sectional	16	-0.58 - 3.37	0.09 (-0.05 - 0.42)	0.5 (0.06 - 1.05)	13	-0.58 - 3.37	0.12 (-0.05 - 0.49)	0.62 (0.06 - 1.24)
MQE Longi-tudinal	5	-0.13 - 0.89	0.24 (-0.13 - 0.89)	0.33 (-0.02 - 0.66)	2	-0.13 - 0.67	0.27 (-0.13 - 0.67)	0.27 (-0.13 - 0.67)

Table 1: Summary statistics and bootstrapped 95% confidence intervals in MgC ha^{-1} y^{-1} (positive numbers = sequestration). Columns on the right were calculated from data excluding those studies with depth measurements deemed insufficient.

4. Discussion

4.1 Carbon sequestration outcomes from regenerative grazing practices

Different experimental designs produced seemingly diverging conclusions about SOC outcomes from regenerative management. More robust MQE longitudinal studies do not demonstrate consistent evidence for SOC sequestration. A lack of statistically significant soil carbon accumulation across multiple studies may be due to the small number of MQE longitudinal studies (N = 5). Only two MQE longitudinal studies were conducted with suitable depth measurements, only one of which found an additive effect of regenerative grazing upon SOC over time (Subedi et al., 2022). At this site, the authors found that all regeneratively and conventionally grazed pastures lost carbon, but the SOC loss was smaller under regenerative

grazing. Two additional longitudinal studies found SOC accumulation at their two respective locations (Sanjari et al., 2008; Cattle and Southorn, 2010). However, both of these studies only sampled soils at one 10 cm depth. Extrapolating these findings to the entire soil profile would be tenuous (Figs. S3, S4) because SOC can move throughout a soil column without resulting in net SOC loss or gain (Hao et al. 2017).

We found limited evidence from high-quality MQE longitudinal studies, but a net positive mean SOC enhancement in regenerative sites across MQE Cross-Sectional studies, which may suggest that regenerative grazing promotes higher SOC sequestration than conventional grazing. However, this is a weaker form of evidence given the experimental design. Without repeated measurements (i.e., longitudinal studies) in addition to case-control, it is not possible to attribute SOC responses to regenerative grazing per se; case-controlled cross-sectional studies only directly compare differences between SOC stocks at regenerative versus conventionally grazed sites, but measured differences in SOC could be an artifact of different baselines from the start of the regenerative grazing experiment.

Despite this limitation in study design, language that suggested SOC *sequestration* and/or *enhancement* was *due to* regenerative grazing, was commonplace in the authors' interpretations of their results, e.g. "AMP grazing can contribute to climate change mitigation through SOC sequestration" (Stanley et al. 2018) or "...with significant [SOC] accumulation in the improved grassland area" (Costa et al. 2022), across N = 12 studies. These claims overstate the conclusions warranted by the experimental design, because measured differences may be due to coincidental differences in baseline SOC and confounding variables that the study designs do not control for.

In all studies, differences in SOC could also readily arise from interventional or observational biases. No studies included in our analysis used a randomized design. This introduces bias where, when working on-farm, ranchers may select more productive pastures to try novel or risky management methods, or the inverse.

4.2 Future experimental design improvements are necessary

To make substantive claims about regenerative grazing enhancing or sequestering more carbon than conventional grazing practices, longitudinal studies are needed to rule out differences in baseline SOC. Future improvements to study design are feasible. Among MQE Cross-Sectional study sites, additional work could be done to turn some into MQE longitudinal studies; if management methods at these sites are presently the same as the reported baseline measurements, a single additional set of soil measurements in a comparable style would be sufficient to more directly infer the role or causation of regenerative grazing for affecting SOC fluxes. Ideally, multiple more years of measurement should occur at every site to demonstrate that any net sequestration is not due to an anomalous year of climatic or ecological conditions. Furthermore, additional studies should commence with randomized assignment to control for site selection bias.

Observational studies are especially weak evidence that regenerative grazing results in SOC sequestration because land use history is a confounding variable. While all three Time-Series Observational studies reported positive SOC sequestration, all of their study sites had a history of annual cropping or intensive agriculture (Machmuller et al. 2015; Stanley et al. 2018; Rowntree et al. 2020). Any transition in land use away from annual cropping toward a system with perennial roots (e.g. conventional pasture, mowed meadow, orchard, wetland, savanna, or forest) will result in SOC sequestration because tillage and other soil disturbance were removed (Yang et al. 2020). Nonetheless, all three studies use causal language that suggest that the regenerative grazing itself possibly or definitively induces SOC sequestration. In the future, studies should test whether regenerative grazing was additive to conventional grazing or other forms of land management on former cropland sites through matched (quasi-)experimental longitudinal design. One longitudinal study was on a site with a history of cropping (Alemu et al. 2019), and found no additional benefit from regenerative grazing when compared with conventional grazing.

We use conventional continuous grazing as a counterfactual for regenerative grazing because it represents a directly comparable land use with the same fundamental goal of livestock production. While other non-continuous land management practices—such as grazing exclusion, hay harvesting, or wild grazing—exist and were not uncommon in the literature (N = 11), they were not suitable for our main analysis. These counterfactuals were relegated to our auxiliary analysis (Figs. S6 & S7) because they do not involve a comparable animal impact or a similar management intensity, making them fundamentally different from a production standpoint.

Relaxed rotational grazing, defined by a lower frequency and/or stocking rate than typical regenerative practices, was also deemed an inappropriate counterfactual for our main analysis and was placed in the auxiliary analysis as it does not represent a distinct alternative land use. When comparing regenerative grazing to these non-continuous counterfactuals, the additional soil organic carbon fluxes were negligible, with values clustering near zero (Figs S6 & S7).

We found no significant difference in soil organic carbon (SOC) between sites grazed by cattle and those grazed by other ruminants ($p = 0.09$). This indicates that livestock species may not be a major confounding factor in our assessment. Although studies on cattle grazing appeared to show slightly higher average SOC sequestration from regenerative sites, the limited sample size for each study design category prevents us from making definitive claims about species-specific SOC gains (Fig. S5, Table S1). Therefore, our pooled results are likely not heavily biased by the type of animal used.

5. Conclusion

Our analysis finds little support for the idea that regenerative grazing management can meaningfully sequester carbon in soil organic matter. Relatedly, there is little robust evidence that this sequestration could potentially offset an appreciable quantity of ruminant enteric

fermentation methane or other greenhouse gas emissions. In order to test this hypothesis more rigorously, more case-controlled longitudinal studies are needed. At a minimum, cross-sectional study sites would need only an additional soil measurement of similar quality, if previous grazing management methods have continued, to provide higher-quality evidence that SOC sequestration is occurring, and to attribute that SOC sequestration to regenerative grazing itself. Ideally, however, multiple more years of measurement should be conducted.

Author Contributions

Docker Clark: data curation (lead); formal analysis (supporting); investigation (equal); visualization (equal); writing - original draft preparation (equal). **Jasmine Dillon:** methodology (supporting); visualization (supporting); writing - review and editing (equal). **Matthew Hayek:** conceptualization (lead); data curation (supporting); formal analysis (lead); funding acquisition (lead); investigation (equal); methodology (lead); project administration (lead); supervision (lead); visualization (equal); writing - original draft preparation (equal); writing - review and editing (equal). **Shelby McClelland:** formal analysis (supporting); methodology (supporting); visualization (supporting); writing - review and editing (equal).

Funding Statement

This work was supported in part by donations from the Humane America Animal Foundation and by a grant from NYU's Center for Environmental and Animal Protection (CEAP). Funders had no influence over research design, methods, or findings.

Conflict of Interest Statement

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