Low quality evidence dominates discussion of carbon benefits of alternative grazing strategies

Jonathan Sanderman[1,*], Colleen Partida[1], Yushu Xia[2], Jocelyn M. Lavallee[3], Mark A. Bradford[4,5]

[1]Woodwell Climate Research Center, 149 Woods Hole Road, Falmouth MA 02540 USA
[2]Lamont Doherty Earth Observatory, Columbia University, New York NY
[3]Environmental Defense Fund, Boulder CO
[4]The Forest School, Yale School of the Environment, New Haven CT
[5]Yale Center for Natural Carbon Capture, Yale University, New Haven CT

*corresponding author: jsanderman@woodwellclimate.org

Abstract

A critical review of alternative grazing strategies and their impact on soil organic carbon (SOC) found most studies (n = 47) failed minimum quality criteria. Ten rigorous studies showed no significant SOC change, yet thirteen less robust studies suggested SOC increases. This divergence highlights that low-quality evidence is prevalent, underscoring a critical need for stronger evidence before asserting climate change mitigation benefits from alternative grazing practices.

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Main text

Grazing of domesticated ruminant animals is the largest land use globally. There are ~32 million km^2 of land that cannot support crop production but produce about one third of global protein[1]. Inappropriate management of rangelands has led to large-scale degradation and desertification[2], resulting in losses of 10's of billions of tons of soil organic carbon (SOC)[3]. Reversing rangeland degradation through regenerative grazing practices is being pursued by governments and civil society as a key nature-based climate solution (NbCS), with an estimated potential to sequester 100s - 1000s millions of tons of CO_2 annually[4,5] and exploding interest in paying producers as part of various carbon programs. Yet, conflicting evidence of the impacts of grazing management on SOC has caused deep polarization of the scientific community, and there is a critical need for clarity to drive consensus around this potential NbCS pathway.

Regenerative grazing is a vague term and often refers to a suite of practices including adaptive grazing, holistic planned grazing, cell grazing, multi-paddock grazing, time-controlled grazing or short-duration rotational grazing[6]. At the core of these practices, which we call 'alternative grazing strategies', is development of grazing management plans that achieve various production and/or conservation outcomes. These plans typically have three key objectives[7]: 1) Improve grass productivity and species composition through adequate rest periods during the growing season; 2) Encourage livestock to consume a broader range of vegetation by increasing stocking density; and 3) More uniformly distribute grazers across the ranch through fencing and improved water distribution. When these objectives are met, there is evidence of improved floristic and productivity benefits[8,9] which could, in theory, translate into gains in SOC or at least reductions in soil degradation and associated SOC loss seen in many rangeland ecosystems.

There is a wealth of evidence that optimal grazing intensity (forage consumption per unit time), which for much of the world means lower livestock numbers per unit area can increase SOC levels[10]. In contrast, alternative grazing strategies do not decrease grazing intensity per se but instead spread grazing more evenly, meaning results from grazing intensity studies cannot be used to understand the SOC benefits of alternative grazing management. Further, quantitative syntheses of "improved grazing management" largely comprise individual studies that are not equivalent to alternative grazing strategies[11], questioning the generalizability of the reported management effects. The first meta-analysis[12] to specifically include a comparison of alternative

versus traditional continuous (or season-long) grazing strategies and found an ~28% improvement in SOC under alternative strategies, whereas a more recent meta-analysis focused on Australia[13] found no discernible SOC effect. Several recent syntheses, including Bai and Cotrufo[4], cite the values reported in Byrnes et al.[12] as the potential of alternative grazing strategies to increase SOC levels.

A notable shortcoming of these past meta-analyses is that, as is common in meta-analysis[14,15], the quality of evidence in primary studies is not rigorously considered. Building confidence in the accuracy of the estimated treatment effect – in this case, the effect of alternative grazing management – requires a balance of evidence between highly controlled, well-replicated interventional studies (high internal validity but often conducted at a small scale) and well-designed observational studies conducted at the scale of real-world grazing operations (high external validity). After conducting a systematic review and meta-analysis of the peer-reviewed literature and interpreting the findings using a causal inference lens[15,16,17], we conclude that low quality evidence dominates discussion of SOC benefits of alternative grazing strategies.

Our systematic review identified 70 primary research studies comparing SOC outcomes of conventional (continuous or season-long) versus alternative grazing strategies. Few studies had high internal or external validity, with 10 studies meeting all inclusion criteria (detailed in Table S1), whereas many failed multiple criteria. The most common reason for exclusion was lack of representative control (i.e. baseline) comparisons (Figure 1), a category including observational, paired-site studies where SOC was only measured once post-intervention and non-target controls were not demonstrated to be comparable. Where a paired-site observational study was excluded solely for a lack of – or inability to evaluate – representative controls (n = 13), we created a secondary category of studies. For 66% of secondary studies, site history information was not reported. Our quality criteria resulted in 27 comparisons of SOC stocks from 10 primary quality studies and 25 from 13 secondary quality studies (see Supplemental Materials).

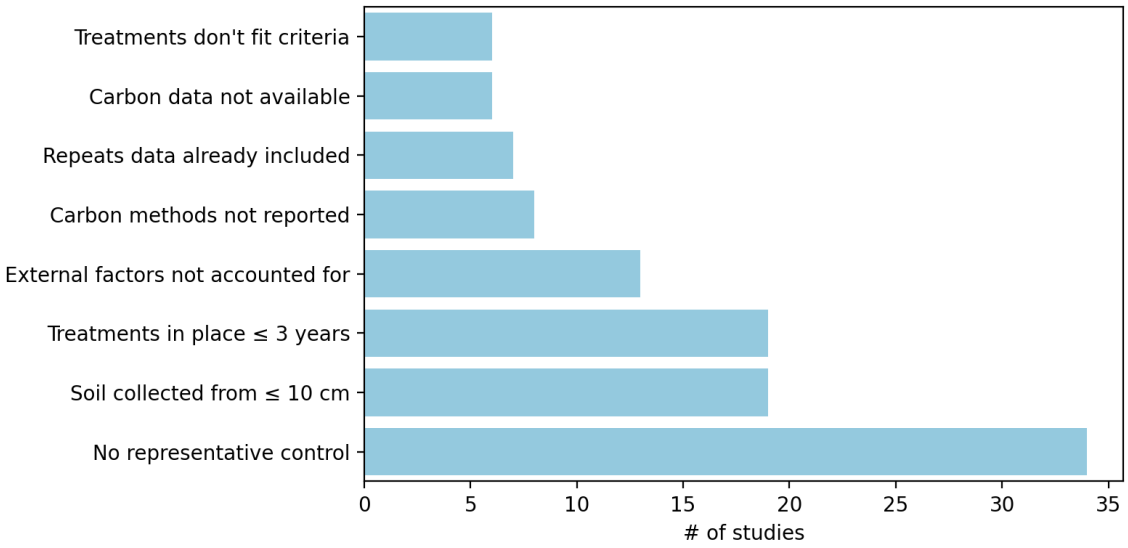

Figure 1. Counts of reasons for individual studies omitted from primary analysis of grazing management impacts on SOC change. Lack of representative control was most common exclusions criteria. Note: an individual study could fail multiple criteria.

A typical strength of meta-analysis is the ability discern small but real effects when the underlying studies often do not have the statistical power to differentiate between treatments. However, in our analysis when all primary and secondary quality studies were pooled together the mean ln(RR) of SOC was 0.05 (95% CI: -0.01 – 0.10) and the mean SOC sequestration rate was 0.27 (95% CI: -0.01 – 0.54) tC ha^{-1} yr^{-1} (Figure 2). When the results were narrowed to only primary studies, the mean SOC response to adoption of alternative grazing strategies was indistinguishable from zero (Figure 2). The net positive effect for ‘All’ studies was then driven by the secondary category, comprising paired-site studies with only post-intervention measurements and questions about the representativeness of the controls used for comparisons (Table S4).

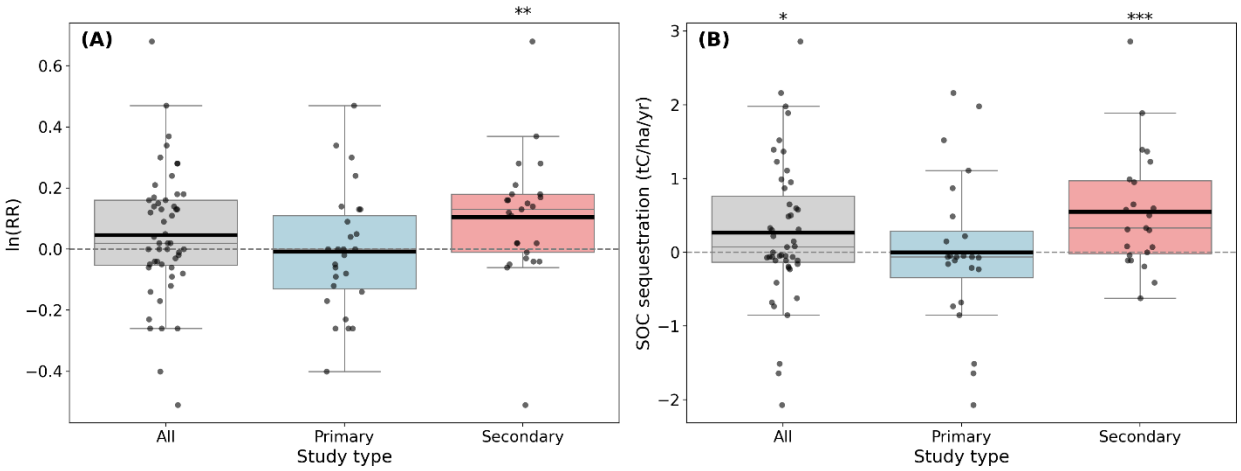

Figure 2. Change in soil organic carbon (SOC) after adoption of alternative grazing management measured as (A) the natural-log of the response ratio and (B) annual sequestration rate. Means shown as bold lines within box-and-whisker plots. Results are grouped by study quality while the results for All include both the primary and secondary studies. P-value results from two-tailed t-tests denoted above each box plot as * <0.1, **<0.05, ***<0.01

Despite hypotheses suggesting wetter, more productive rangelands should be able to sequester more SOC[18], our findings suggest no difference in efficacy between dryland and non-dryland aridity classes (Table S5) and no difference between native and improved/sown grasslands (Table S6). Whether the alternative grazing practice was adaptive (i.e. animal movements and density based upon observations of forage availability and quality) or prescribed also did not help explain the variability in the primary study quality category (Table S7).

Our findings suggest that the discussion of SOC benefits of grazing management has been predominantly informed by lower quality evidence. When these lower quality studies are filtered out, the ten remaining studies do not suggest that SOC responds to adoption of alternative grazing management (Figure 2). Reanalyzing previous meta-analyses (Supplement S8) using our systemic criteria suggest that conclusions in those studies of alternative grazing strategies are not justified.

An ideal grazing experiment would adopt a before-after-control-intervention design implemented on a commercial scale and follow SOC changes for 5-10 or more years to provide strong causal evidence. Because this is logistically difficult to achieve, especially given typical short funding

cycles, most investigations have taken a paired site approach with a one-time sampling campaign (i.e. a space-for-time substitution). Paired site studies can provide high quality evidence when there is careful consideration of differences between treatment and control sites. In addition to the need to pair sites by climate, vegetation, soil type and topographic position, the underlying assumption of a paired site study is that the treatment and control sites were managed similarly for at least several decades prior to the implementation of the alternative grazing plan, and the control site continues the same management. In our reading of the literature, 34 studies did not meet this criterion; albeit many of those studies simply did not report this critical information. When they did[19], the information exemplified the challenge of finding representative controls. For example, in one pairing the alternative grazing site was converted from cropland 29 years prior to soil sampling whereas the continuous grazing control was converted 17 years prior. The difference in SOC stocks found in this pairing may simply be due to the extra 12 years under perennial pasture relative to cropland.

Controlled experimental studies had representative controls but primarily because these studies were conducted at scales far smaller than the typical scale of management for commercial grazing operations[20], with some plots as small as a few hundred square meters[21,22,23,24]. Additionally, our finding of smaller effects size in controlled experiments than in observational studies runs counter to typical agronomic results where highly controlled plot-scale experiments have larger effect sizes than seen in farm-scale commercial settings[25]. It is difficult to know the scale-dependence of the SOC responses to grazing management, but it makes for a difficult case to say the study was representative of real-world conditions[26] and should stand as a call to the research community that large-scale interventional studies are needed.

A common thread in both the primary literature and influential meta-analyses on the topic of SOC response to grazing management[12] is lack of data transparency. Most of the studies only reported mean data, with 10 out of 23 neglecting to report variance metrics. Only one study provides the raw data behind the reported mean responses, and more than half did not include a data availability statement (see Supplemental Materials). Much has been written on this topic[27] but it bears repeating that science needs to be replicable and reproducible to build confidence that recommendations will have desired outcomes, requiring open sharing of underlying data.

The lack of strong evidence of SOC benefits upon adoption of alternative grazing management leaves a void where proponents of these grazing strategies can continue to either cite lower quality studies or rely on anecdotal accounts of positive experiences. Notably, the secondary quality studies were cited on average three times as often per year as our higher quality studies (Table S9). Given the strong and growing interest in alternative grazing management practices as a NbCS, there is a critical need to establish a much stronger evidence base[28]. Such evidence should include controlled longitudinal experiments, using fit-for-purpose causal designs with protocols and tools that can quantify SOC change due to management at the scale of whole ranch management[29]. Such evidence will permit confident evaluation of which grazing practices should be adopted where to give the greatest potential climate benefits.

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Supplemental Information

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S1. Methods

Literature search

Peer-reviewed investigations of the impact of switching from conventional continuous grazing to alternative grazing strategies on SOC were compiled using the four different sources. Slightly different search strings were used for each source due to limitations on the number of Boolean terms,

Web of Science search string:
search for:((ALL=(soil)) AND ALL=("grazing management" OR "rotational grazing" OR "continuous grazing" or "adaptive management" OR "time controlled grazing" OR "deferred grazing" OR "cell grazing" OR "holistic management" OR "grazing systems" OR "grazing strategies")) AND ALL=("soil organic carbon" OR "soil carbon" OR "carbon sequestration" OR "soil organic matter" OR "C sequestration" OR "SOC" OR "SOM" OR "soil C" OR "OC" OR "TOC"OR "chemical characteristics")

Elsevier Science Direct search string:
searched: ALL=(soil) AND ALL=("grazing management" OR "rotational grazing" OR "continuous grazing") AND ALL=("soil organic carbon" OR "soil carbon" OR "carbon sequestration")

Google Scholar (via Publish or Perish[1]) search string:
search for: Soil soil organic carbon "rotational grazing" OR "continuous grazing" OR "adaptive management" OR "time controlled grazing" OR "deferred grazing" OR "cell grazing" OR "holistic management" OR "grazing systems" OR "grazing strategy" AND "carbon sequestration" OR "SOC" OR "C stocks"

Scopus (via Publish or Perish[1]) search string:
search for: Soil soil organic carbon "rotational grazing" OR "continuous grazing" OR "adaptive management" OR "time controlled grazing" OR "deferred grazing" OR "cell grazing" OR "holistic management" OR "grazing systems" OR "grazing strategy" AND "carbon sequestration" OR "SOC" OR "C stocks"

These searches were conducted in June 2023. The completeness of our search was assessed by the successful retrieval of a short list of key studies including all of the papers used in the Byrnes et al.[2] meta-analysis[3,4,5,6,7,8,9,10,11,12,13,14]. Five additional primary publications were found in a meta-analysis of grazing impacts on SOC in Australia[15] that were not included in our initial search, but none were found to pass our inclusion criteria.

Filtering and Inclusion criteria

Abstracts from all returned studies were analyzed by asking the following three questions:

1. Is there a comparison of alternative (defined using any of our keywords above) and conventional (i.e. continuous or season-long) grazing strategy? Studies that only tracked SOC under alternative practice without a comparable continuous control baseline were

excluded because of the difficulty in disentangling management from climate induced changes in SOC[16]

2. Are SOC outcomes reported?
3. Is this primary research? Often multiple studies will use the same primary dataset in different ways such as for modeling or life cycle analyses. We wanted to be sure that the same field measurements weren't being utilized more than once in our meta-analysis.

Papers were only retained if the answer to all three of these questions was yes.

Table S1. Inclusion or exclusion criteria.

CRITERIA	OMIT	INCLUDE AS PRIMARY
Is the carbon data available in a table or figure, or as a supplemental dataset?	- No	- Yes
What methods were used to determine carbon content?	- Missing methodological detail	- Uses loss on ignition (LOI) - Uses dry combustion and reported carbonate removal if carbonates may be present - Uses Walkley-Black
How long have the treatments been in place?	- Less than 3 years - Cannot be determined	- Greater than or equal to 3 years
To what depth was soil collected?	- Depth of 10 cm or less	- Greater than 10-cm depth
Are there significant external factors that may affect SOC sequestration between treatments that are NOT accounted for in data analysis?	- Yes, i.e. differing climate, topography, parent material, soil type NOT accounted for in data analysis (raw means reported)	- No, i.e. no significant factors OR factors are accounted for in data analysis (conditional means reported)
Is the control representative of the pre-intervention management in the treatment plot?	- No - Cannot be determined	- Yes

After this filtering, the retained papers were read in detail to determine whether the study met our predefined inclusion criteria (Table S1). After reading the papers in detail, it was determined that several studies actually failed at least one of the initial questions – e.g. an alternative grazing management might have been mentioned in the abstract but upon reading the methods, there wasn't an actual comparison with conventional grazing.

Knowledge of the method of carbon determination, especially in semi-arid systems where carbonates are often present, is important for determining the quality of the SOC data. We

317 chose three years as the minimum study duration as SOC changes slowly and it is extremely
318 unlikely that real differences can arise in treatments in less than three years. The topsoil (≤ 10
319 cm) in grasslands only contains a small fraction of the total SOC stocks and changes in this
320 layer may not be representative of changes in the entire profile. The question on significant
321 external factors was included because the raw means in regional survey studies cannot be
322 compared until potential confounding factors (climate, soil, topographic, etc.) that also influence
323 soil carbon stocks and their rate of change are accounted for (see Allen et al.[7] for a good
324 example in the grazing-SOC literature). Accounting for these factors builds confidence that
325 estimates of soil carbon change are due to the grazing management and not non-target causal
326 variables like mean annual precipitation. Similarly, the representativeness of the control site in
327 observational paired-site studies must satisfy expectations that treated and control sites are
328 similar enough with regards other potential causal variables, such as soil texture and longer-
329 term management history, to permit differences in soil carbon stocks to be attributed to grazing
330 management. When such paired-site studies are conducted at a single point in time, as
331 opposed to including pre-intervention data on soil carbon stocks that can be used to calculate
332 differences due to treatment versus control of changes in time, appropriate matching of pairs by
333 other potential causal variables becomes critical because SOC levels are unknown at the time
334 of practice adoption, invoking the assumption that they were approximately equal at that time.
335 That is, we have to be confident that the baselines (i.e. controls) for the sample of sites that are
336 measured are representative enough in terms of environmental, soil, land use and historical
337 management variables for them to allow confidence that estimated effects of grazing
338 management are not due to non-random bias in observed and/or non-observed non-target
339 causal variables.
340
341 Studies that met all these criteria are termed primary studies in all subsequent analyses. If a
342 study met all the criteria except the final one on representativeness of the control site, the study
343 was retained but flagged as secondary quality. These secondary studies were kept in the
344 analysis because the majority of studies of alternative grazing management studies have this
345 paired-site design.
346

347 ***Data extraction***

348 For all retained studies, the following information was extracted or at least attempted to be
349 extracted: study year, experimental design, treatments, whether the alternative grazing strategy
350 was adaptive or prescriptive (i.e. decisions on animal density and movements made based on
351 observations of forage availability/quality vs. following a set plan regardless of seasonal
352 conditions), controls used, land use history, duration of treatment on land prior to sampling,
353 grassland type (native or improved) and species, methods for improved pasture, size of
354 treatment area/study scale, grazing animal type, stocking rate, tools used for soil sampling,
355 maximum depth of sampling, soil sampling strategy, method for determining SOC content,
356 carbonate removal information, SOC content and stock data, bulk density (BD) data, country,
357 coordinates, mean annual precipitation (MAP), mean annual temperature (MAT), and world soil
358 order. If climate data or soil order was not available it was extracted using location data from

ClimateCharts.net[17] and SoilGrids[18]. Aridity index (AI) was also extracted using location data from the Global-Aridity_ET0[19].

A mean SOC concentration (wt%) was calculated for the 0-30 cm and 0 to maximum depth increments by taking the BD-weighted means for each horizon within the specified depth range. SOC stocks (tC ha^{-1}) were either directly extracted from the study or calculated based on SOC concentration and BD and depth. No attempt was made to correct for equivalent soil mass.

All data from this study, including the full list of studies retrieved from the literature search, the short list of 70 studies along with their assessment against our inclusion criteria, and the extracted data from the final list of studies are included in the supplementary materials. The locations of the final primary and secondary studies are shown in Figure S1.

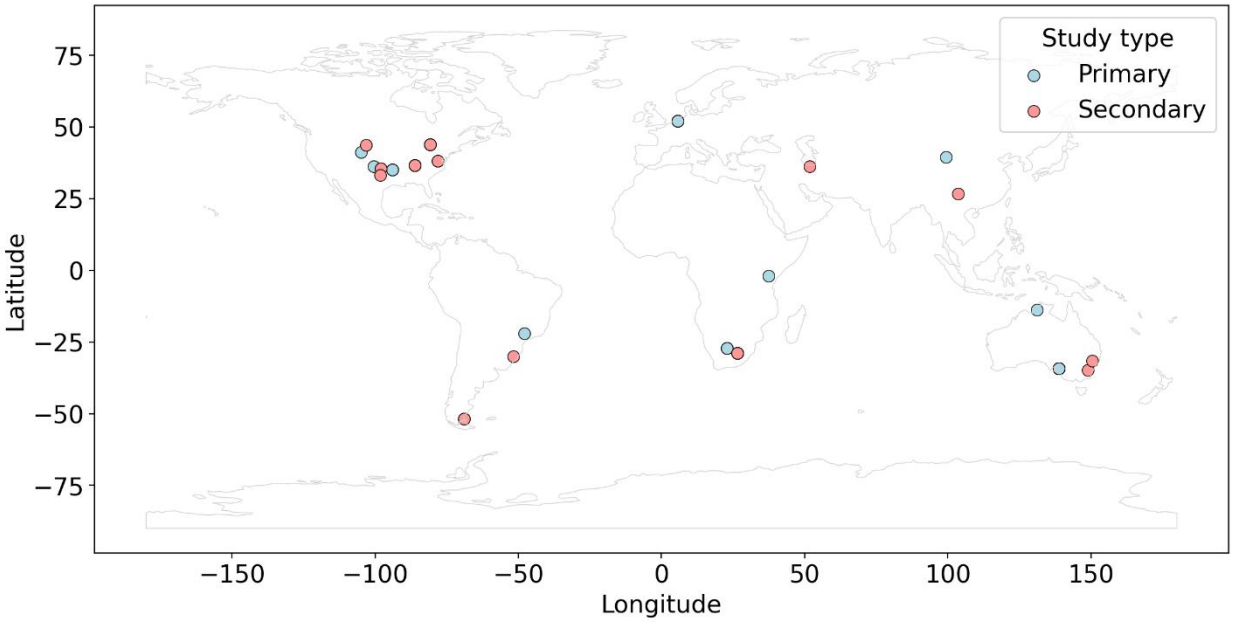

Figure S1. Locations of primary and secondary studies.

Data analysis

Differences between continuous and alternative grazing practices were summarized in two ways. First, an effect size measured as the natural log of the alternative grazing strategy SOC response divided by the continuous grazing SOC response (ln(RR)) was calculated for different categories. Second, when all the necessary data was available, relative SOC sequestration rates (tC ha^{-1} yr^{-1}) were also calculated for the 0-30 cm and 0-maximum depth ranges.

Initial analyses indicated that the effect size calculated from SOC concentration and SOC stocks were nearly identical (see Figure S2) and that there were no differences between studies that only reported SOC to < 30 cm, 30-50 and >50 cm (see Table S3). These two findings allowed us to simplify our analyses by only reporting the one effect size as the average of ln(RR) of SOC

concentration and ln(RR) of SOC stocks and by only reporting the results for 0-maximum depth range.

Two-tailed t-tests were then conducted to explore whether individual effect sizes were statistically different from zero for the following categories: study quality, experimental design, alternative grazing strategy, aridity index and rangeland type (natural versus introduced/improved grasses). For experimental design, the groups were limited to controlled experiment and paired site design because those two groups represented 94% of the data. Similarly for pasture type, the groups were limited to improved or native pasture. All analyses and plotting was done in Python using the Pandas[20], Seaborn [21], Matplotlib[22] and SciPy[23] libraries.

S2. Reporting SOC concentration or stocks did not matter

The ln(RR) results from SOC concentration (wt%) and SOC stocks were nearly identical (Figure S2. As such, in subsequent analyses the ln(RR) was calculated as the average of the ln(RR) for SOC% and SOC stocks. This allowed the maximum number of comparisons to be included in statistical tests because not all studies reported SOC% and stocks.

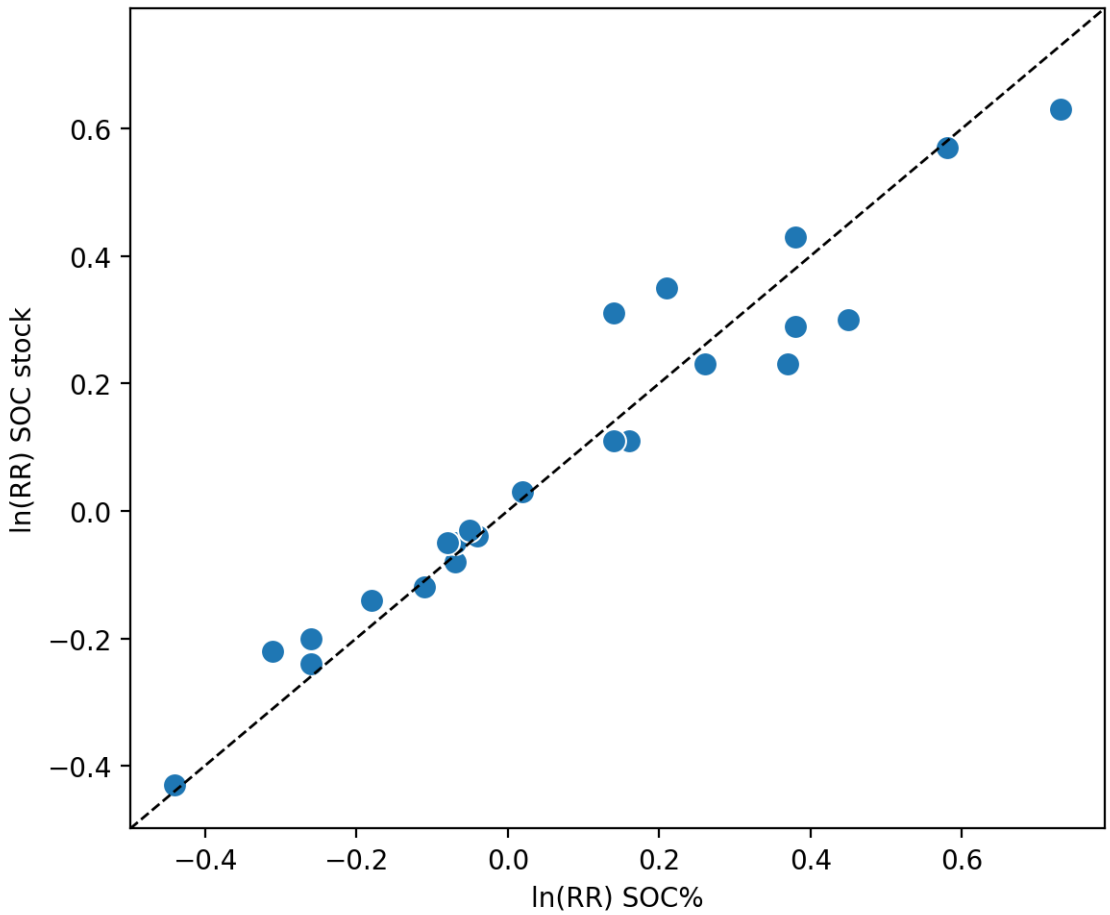

Figure S2. Comparison of natural-log of the response ratio (ln(RR)) calculated for SOC concentration (wt%) and for SOC stocks (tC ha^{-1}) where data was available to calculate ln(RR) both ways (n = 22) indicates that there is no systematic difference in ln(RR) allowing pooling of data to maximize sample size in the meta-analysis.

410 ***S3. No clear effect of soil measurement depth***

411 Perhaps due to our inclusion criteria that sampling depth needed to be greater than 10 cm, the
412 mean sampling depth was 50 cm and, importantly, there was no difference in results between
413 studies measuring to less than 30 cm, those that measured to between 30-50 and those that
414 measured greater than 50 cm (Table S3). Single factor ANOVA p-values were 0.99, 0.88 and
415 0.81 for primary studies, secondary studies and all studies, respectively. Results for SOC
416 sequestration rates were similar (data not shown). This result gave us confidence in grouping all
417 depths together for the main statistical analyses shown in Table 1.
418
419 **Table S3**. Natural-log of the response ratio for soil organic carbon grouped by depth and study
420 quality.

Depth range (cm)	Primary			Secondary			All		
	n	mean	95% CI	n	mean	95% CI	n	mean	95% CI
<30	6	-0.02	(-0.27, 0.22)	5	0.02	(-0.25, 0.29)	11	-0.01	(-0.18, 0.17)
30-50	10	-0.01	(-0.05, 0.04)	12	0.14	(0.02, 0.26)	22	0.07	(0.00, 0.15)
>50	11	0.00	(-0.13, 0.13)	8	0.11	(0.03, 0.18)	19	0.04	(-0.04, 0.13)
all	27	-0.01	(-0.08, 0.07)	25	0.11	(0.02, 0.19)	52	0.05	(-0.01, 0.10)

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S4. Paired site studies dominate positive responses

There were four study designs found in our final paper list: controlled experiments where an area of was divided into multiple control and intervention plots, unreplicated experiments where an area was divided into just one replicate of each control and intervention, paired site designs where two “paired” fields under contrasting management were compared, and survey designs where a number of ranches with varying management practices across a region were measured. Table S4 indicates that nearly all the positive SOC responses were associated with paired site studies rather than controlled experiments (p = 0.02 and 0.04 for ln(RR) and SOC sequestration rate, respectively) but these were the same studies that dominated the secondary class based on inclusion/exclusion criteria.

Table S4. Soil organic carbon (SOC) response measured as the natural-log of the response ratio and annual sequestration rate in response to adoption of alternative grazing practices. Results combined for primary and secondary studies and grouped by experimental design.

	ln(RR)			SOC sequestration (tC/ha/yr)		
Experimental design	**n**	**mean**	**95% CI**	**n**	**mean**	**95% CI**
Controlled experiment	13	-0.01	(-0.07, 0.05)	10	-0.07	(-0.34, 0.26)
Paired sites	36	0.07	(-0.01, 0.15)	34	0.40	(0.04, 0.76)
Survey	1	0.15				
Unreplicated experiment	2	-0.05	(-0.08, -0.02)	2	-0.30	(-0.51, -0.09)

S5. Aridity index

It has been hypothesized that there might be more of a positive SOC response in more mesic environments where productivity isn't so constrained by available soil moisture[24]. When grouping studies by aridity class - where AI > 0.65 was considered 'non-dryland', and AI < 0.65 considered 'dryland' - there was little difference in ln(RR) between categories (Table S5). Results for SOC sequestration rates were nearly identical with no separation between aridity class (data not shown).

Table S5. Soil organic carbon (SOC) response measured as the natural-log of the response ratio response to adoption of alternative grazing practices. Results grouped by aridity class.

Aridity class	Primary			Secondary			All		
	n	mean	95% CI	n	mean	95% CI	n	mean	95% CI
non-dryland	8	-0.03	(-0.11, 0.17)	13	0.11	(0.06, 0.17)	21	0.06	(0.01, 0.11)
dryland	19	0.00	(-0.10, 0.10)	12	0.10	(-0.07, 0.26)	31	0.04	(-0.05, 0.13)

453 ***S6. Native versus improved rangeland***

454 It has also been hypothesized that alternative grazing strategies may be more responsive on
455 improved grasslands (some combination of sowing improved varieties, fertilizing or irrigating)
456 that typically have greater productivity than native grasslands in the same climatic zone[25].
457 Overall, there was no difference in SOC effect size between improved or native grasses (Table
458 S6). However, when just focusing on the secondary study class the improved grasses but not
459 the native grasses had ln(RR) values significantly greater than zero (Table S6). This trend also
460 held for SOC sequestration rates (data not shown).
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463 **Table S6**. Soil organic carbon (SOC) response measured as the natural-log of the response
464 ratio response to adoption of alternative grazing practices. Results grouped by grassland type.

	Primary			**Secondary**			**All**		
Grass type	**n**	**mean**	**95% CI**	**n**	**mean**	**95% CI**	**n**	**mean**	**95% CI**
Improved	20	-0.01	(-0.09, 0.07)	14	0.15	(0.06, 0.25)	34	0.06	(-0.01, 0.12)
Native	7	0.00	(-0.19, 0.20)	8	0.07	(-0.12, 0.26)	15	0.04	(-0.09, 0.17)
Unclear				3	-0.03	(-0.07, 0.02)	3	-0.03	(-0.07, 0.19)

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S7. Specific management practices

One of our objectives was to try to understand if specific grazing management practices had more or less of an SOC benefit after implementation. To achieve this objective, the improved grazing management styles were defined as either adaptive or prescribed based on information provided in each publication. One of the secondary studies[26] could not be categorized and as such was excluded from this analysis. Five of the nine primary studies were classified as using adaptive grazing management, but these studies represented only about one third of the primary pairs of data. All but one of the secondary studies were defined as adaptive making it difficult to make any conclusions about the impact of grazing management style within this study quality category.

Despite the mean SOC sequestration rate for the primary studies appearing to separate out by grazing management style (+0.22 vs. -0.12 tC ha^{-1} yr^{-1} for adaptive and prescribed, respectively), the ln(RR) for these two categories were both essentially zero and a single-factor analysis of variance suggests the mean sequestration rates are not different from each other ($p = 0.50$) due to the large variance within each category (Table S7).

Table S7. Soil organic carbon (SOC) response measured as the natural-log of the response ratio and annual sequestration rate in response to adoption of alternative grazing practices. Results presented by grazing management style nested within study quality category.

Study quality	Grazing management style	ln(RR)			SOC sequestration (tC/ha/yr)		
		n	mean	95% CI	n	mean	95% CI
Primary	Adaptive	9	-0.01	(-0.17, 0.16)	6	0.22	(-0.32, 0.73)
	Prescribed	18	-0.01	(-0.09, 0.07)	18	-0.07	(-0.59, 0.45)
Secondary	Adaptive	22	0.13	(0.06, 0.20)	22	0.53	(0.19, 0.87)
	Prescribed	2	-0.24	(-0.75, 0.27)	0	n/a	n/a

S8. Reconsidering existing literature

Given that Byrnes et al.[2] has been one of the main studies cited when supporting the notion that the adoption of alternative grazing strategies leads to SOC sequestration, we tried to determine why our conclusions varied so much from the conclusions in that study. Byrnes et al.[2] supply a list of studies that were used in estimating effect sizes but not the detailed data themselves making it difficult to reproduce their results. We re-extracted the data and attempted to recreate their analysis but couldn't replicate their findings (Table S8). Byrnes et al.[2] report a mean effect size of 0.25 (95% CI: 0.10 - 0.41) for 44 comparisons of alternative and conventional grazing strategies but we could only reconstruct a mean effect size of 0.15 for the same number of comparisons for the Byrnes et al.[2] dataset.

More importantly, most of the data sources used by Byrnes et al.[2] did not meet our inclusion criteria (Table S8), highlighting the need to consider the quality of the studies being assembled for quantitative syntheses if one is to have confidence in the average effect across studies[27,28]. In fact, 7 of the 12 studies listed were omitted from our meta-analysis for failing at least one of our inclusion criteria or repeating data already included in another study. Another 4 studies made our secondary list and only one study was on our primary study list. To approximate the same sample size for each study as reported in Byrnes et al.[2], it appears that each soil depth increment must have been included as an independent observation (i.e. if a study measured 0-5, 5-15 and 5-30 cm there were three data points used instead of just one data point for 0-30 cm).

A notable inclusion by Byrnes et al.[2], which we excluded because it failed exclusion criteria #5 (Table S2), was Allen et al.[7]. In this regional survey in Queensland, Australia, the authors measured much higher SOC stocks under alternative grazing strategies than under conventional grazing. However, after the authors of the original paper conducted a statistical analysis that removed the confounding effect of climatic differences between sites (all the alternative grazing sites were in wetter regions of the state), they concluded that pastures under alternative grazing strategies had less SOC than conventionally grazed pastures. Byrnes et al.[2] apparently extracted and included the raw data without consideration of the need to account for confounding in the study design.

There are a few high-profile papers that examined a shift from cropland to alternative grazing management of grasses[29,30] which are often incorrectly used to support the notion that alternative grazing strategies can have large SOC benefits. Both studies focused on chronosequences of improved pastures seeded into former cropland in the SE of the United States. Large gains in SOC typically occur when croplands are converted to pastures regardless of grazing management strategies[31]. A third highly cited paper concluding large sequestration rates under an adaptive grazing plan[32] was also excluded from our study because there was no comparison to continuous grazing making attribution of any change over time in SOC to the grazing management strategy difficult.

533 **Table S8**. Comparison of our attempt to reconstruct results from Byrnes et al.[2] and our
534 extraction (this study) of the same data sources. Studies were classified using our inclusion
535 criteria (see methods).
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	Byrnes reconstruction			**this study**		
Study quality	**n**	**Mean**	**95% CI**	**n**	**mean**	**95% CI**
Primary	9	-0.01	(-0.31, 0.29)	3	0.01	(-0.57, 0.59)
Secondary	17	0.22	(0.15, 0.29)	6	0.24	(0.13, 0.35)
Omitted	18	0.17	(0.05, 0.28)			
All	**44**	**0.15**	**(0.07, 0.23)**	**9**	**0.16**	**(-0.04, 0.36)**

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S9. Citation frequency

We utilized Google Scholar to capture the number of times each study was cited as of June 2025 because Google Scholar picks up both peer-reviewed and grey literature articles and reports making it a more inclusive measure of the impact of a particular study. The 10 primary studies were cited 225 times, while the 13 secondary studies were cited a total of 1508 times with, on average, 3 times as many citations per year (Table S9).

Table S9. Google Scholar citation rate for studies group by study quality.

Study quality	**Sum of citations**	**Average citations per study**	**Average citations per study per year**
Primary	287	29	4.3
Secondary	1508	116	12
All	**1795**	**78**	**8.7**

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