a) Journal: Ecosphere

b) Subject Track: Agroecosystems

c) Title: Organic amendments did not augment erosion control structure effectiveness in dry rangelands

d) Authors: Eva Stricker [1, 2] and Megan O'Connell[1]

e) Author Affiliations

1. Quivira Coalition, Carbon Ranch Initiative, 1413 Second St. Suite 1, Santa Fe, NM 87505
2. University of New Mexico, Department of Biology, MSC03 2020, 1 University of New Mexico, Albuquerque, NM, 87131

f) Corresponding author: Eva Stricker, eva@quiviracoalition.org

g) Open Research Statement

h) Key words/Phrases Erosion control, New Mexico, rock rundown, soil health, organic amendments, arid rangelands, regenerative ranching, compost, mulch.

Abstract

Rangelands in the Western US are crucial ecosystem services and the rural food system, but face degradation from erosion. Existing management activities to address active erosion leverages physical interventions of rocks structures, but little is known about how biological interventions such as seeding or organic amendments may build soil health to augment the effects of the rock structures. This study investigates the effectiveness of combining rock structures with organic amendments (wood mulch and compost) and native perennial grass seed addition to address erosion on rangelands. The study was conducted across five cattle ranches in New Mexico with 9-18 active head cuts. Rock rundown structures were built above each headcut and a plot above each structure received an organic amendment treatment (compost, mulch, or control) and seed addition treatment (seeded or control), but none of the plants established so we aggregated all seed addition treatments and focused only on organic amendments. We measured soil and vegetation characteristics after one year. Rock structures led to channel accretion, but neither organic amendments nor native seed addition had a significant effect on infiltration rate, aggregate stability, erosion/accretion, aboveground biomass, vegetation cover, plant richness, or soil organic carbon. Rock structures are an effective solution for addressing small headcuts on arid rangelands but organic amendments and native seed addition were not effective, potentially due to severe drought during much of the year in the region. Ranchers and field technicians noted trends of enhanced soil moisture in the amendments compared to controls and were thus interested in pursuing further investigation in amendments in the future, despite the lack of effect in this study.

Introduction

Approximately 60% of the Western United States is comprised of rangelands that are critical to the ecology of this region and the U.S. food system at large (Edwards et al. 2019) but are at risk of soil loss. Rangelands in the West are particularly susceptible to the impacts of habitat degradation and climate change due to the region's land-use history, aridity, and susceptibility to climatic extremes, drought, and wildfires (Briske et al. 2015). The degradation and loss of plant communities and ground cover on western rangelands due to improper grazing, conversion to crop agriculture, and mismanagement of recreation and other activities has brought water and wind erosion to the forefront of management concerns in the region. Unmanaged erosion can lead to cascading and multiplicative effects that impact soil nutrient availability, water retention, and plant community health, impacting soil quality and forage production on rangelands, in turn posing a major threat to our nation's food security (Archer and Predick 2008). As the effects of historic and current management and climatic conditions are experienced, steps to control erosion, retain topsoil, and increase vegetation growth are crucial to rangeland management.

Erosion can lead to negative feedback cycles if not managed. When vegetation cover is removed by ruminants, the infiltration and stabilization mechanisms of soil-root matrices are compromised and bare soil is exposed to rainfall and wind (van Oudenhoven et al. 2015). Erosion on arid rangelands tends to transition from raindrop splash erosion, to sheet-rill, then concentrated flow erosion, leading the the formation of gullies or arroyos, with more topsoil being detached from soil aggregates and transported elsewhere with each of these stages (Kinnell 2005, Weltz et al. 2021). As erosion continues unchecked, arid soils can harden and become less penetrable to water, compacting the soil and inhibiting its nutrient cycling, ultimately reducing the soil's overall ability to retain water and sustain rangeland plant and forage growth (Assouline 2004, Puigdefabregas 2005). As soils become less capable of supporting plant growth, the cycle of soil loss continues, creating an ongoing pattern of worsening erosion conditions that become more and more difficult to ameliorate if not dealt with in their early stages. Rangelands in the West are particularly susceptible to these patterns, due to the ecoregions in the area naturally being comprised of relatively low vegetation cover in combination with high intensity monsoon, or convective, rainfall events that accelerate soil loss and dislocation (Okin et al. 2009, West et al. 1983).

Several traditional techniques involving low-tech rock structures have shown promise for addressing erosion by adding a physical intervention to the system, and dryland ranchers in the Southwest have been employing such techniques for generations (Nichols et al. 2012). Structures such as one rock dams, Zuni bowls, rock rundowns and media lunas have been successfully employed in wet meadows and riparian areas to mitigate and reverse erosion (Maestas 2018), but the utility of such structures has not been as strongly demonstrated in dry uplands and grassland habitats. Such structures largely can be built by hand using purchased rocks, or materials found on site to address shallow, newly forming headcuts and slightly incised channels (< 4 ft deep) in areas with low-to-moderate gradients (< 3% slope). These structures act to slow and disperse water above the structures, capture sediment around the structures, increasing soil moisture retention and promoting vegetation establishment and recovery (Zeedyk and Jansens 2009).

Additional techniques for addressing erosion include biological interventions. Establishing plant cover and deep and resilient root infrastructures within soil substrates may be an important step to stop the negative feedback cycle of erosion, but vegetation establishment in unirrigated dry rangelands can be challenging. Vegetation provides above and belowground structure that significantly reduces the rate of runoff water flows, curtailing sheet erosion and stopping the erosion process by allowing water to better infiltrate into soils and improve soil health (Green et al. 1994, Wang et al. 2018). However, plant community establishment and persistence in erosion zones such as developing headcuts and incisions has proven difficult for various reasons; namely seeds are unlikely to germinate and survive without appropriate moisture and soil conditions or during times of extreme drought and high soil temperatures, and monsoon events and strong winds can easily wash away seeds from the critical sites at which they are needed (James et al. 2011, Hiernaux et al. 2009).

Emerging research suggests that interventions that add organic material and microbial activity to the soil can enhance restoration of actively degrading areas. Organic amendments such as chipped wood mulch and compost (i.e. decomposed feedstock such as food waste, manure, and woody material) have been shown to decrease soil erosion by decreasing runoff and increasing water retention in soils at application sites, as well as to promote water infiltration into soils (Singer et al. 2006, Risse et al. 2023). Mulch application has been found to confer long term enhancements to soil quality such as increases in available water capacity, porosity, and soil moisture retention (Mulumbi and Lal 2008). Compost has been found to increase total soil organic carbon contents, which has been strongly linked to improved soil aggregate stability (Annabi et al. 2011). In addition, these amendments may aid in native plant establishment and to improve aboveground net primary productivity on rangelands by increasing the soil nutrient content and reducing soil moisture loss (Gravuer et al. 2019). The benefits conferred by organic amendments to plant establishment and erosion control, therefore present potential means by which to enhance the mitigation effects of erosion control structures on rangelands facing rapid erosion and soil degradation.

In this study, we investigated the potential multiplicative benefits of adding organic amendments (wood mulch and compost) and native seeds to low-tech erosion control rock structures addressing small (<1m wide) head cuts on arid rangelands throughout New Mexico. Decades of mismanagement, unmonitored grazing, soil degradation, and soil loss to erosion have left New Mexico with the highest average bare ground (37.0%) on non-federal rangelands in the United States. This trend appears to be continuing with current management practices, as bare ground in the state increased at the highest rate among U.S. states from 2004-2015 (11.3%), making sheet-rill erosion and plant productivity the number four and number one top rangeland resource concerns in the state (USDA-NRCS 2018). Therefore, finding cost-effective methods to reverse and ameliorate the effects of soil erosion, build soil health, and support robust native plant rangeland plant communities will be paramount for improving ecosystem resilience and sustainable agriculture in New Mexico (Sawalhah et al. 2021). We hypothesized that the combination of physical and multiple biological interventions would lead to disproportionate impacts compared to individual interventions on the vegetation community, soil carbon, infiltration rate and aggregate stability above the restored head cut as well as changes to the channel structure below the interventions.

Methods

This study was conducted across five cattle ranches located throughout New Mexico that varied in management, climate, soil, and vegetation characteristics (Figure A1, Table S1). The ranches were spread across the state and identified to county level to protect privacy of the ranchers; two were in Rio Arriba county, one in Mora county, one in Santa Fe county, and one in Eddy County.

The five participating ranches were selected because they all reported that they are struggling with past and ongoing soil erosion issues to varying extents.

At each ranch, we identified 18 actively developing erosion zones (headcuts, or the start of an erosion incision) of management concern (with the exception of the ranch in Mora, which used nine headcuts). Rock rundown structures were built by staff, volunteers, and participating land managers according to specifications to meet NRCS approved erosion control methods as per Maestas et al. (2018). Rock rundowns are best utilized on low-energy headcuts (<1.5 ft tall), and the incline of the headcuts relative to surrounding soils was modified before rock placement so the slope was at a stable angle (3:1 slope), then it was armored with tightly packed rock to eliminate gaps and the center of the rundowns were lower than the sides, to encourage water to run down the middle and not around the structure.

In fall/winter of 2021, we worked with land managers and volunteers to build rock rundown structures. Above each structure, we marked a 5m x 5m plot (Fig. S2) where we implemented our treatment combination. We collected baseline measurements for infiltration rate and aggregate stability in the plots and measured the cross-sectional area of the channel below the headcut (see below). We then randomly assigned the the 5m x 5m plots to a treatment combination in a full factorial design: organic amendment (three levels: compost, mulch, or control [no amendment added]) and native seed addition (two levels: 2.5 lbs of native seeds applied across the plot by hand [Table S2], or control [no seed applied]) with three replicates per treatment combination. After one year, none of the seeded species were present in the vegetation community, so the seeding treatment is not considered further in our analysis; we analyze only the organic amendment treatment. Organic amendments were applied to a 0.64 cm depth using wheelbarrows, rakes, and shovels. Wood mulch was purchased from Soilutions in Albuquerque, NM and consisted of chipped blonde wood. Premium Compost was also purchased from Soilutions and was composed of approximately 46% organic matter, had a pH of 8, and a nutrient ratio of 0.62 of Nitrogen, 0.31 of Phosphorous, and 0.71 of Potassium (Soilutions.net) and used at the Mora, Santa Fe, and Eddy county ranches. Compost purchased from a local hog farm that composts waste and wood chips in windrows was used for the two ranches in Rio Arriba county and had was composed of 78% organic matter, pH of 7.8, and C:N ratio of 29.3 (Stricker et al. *in review* at Ecological Applications).

Several responses were measured in 2021 and after one year in 2022. Metrics related to water infiltration and erosion potential: Infiltration rate was measured with a single ring infiltrometer (15 cm diameter) in a randomly selected interspace in the plot. 444 mL of water was added and the time for infiltration was recorded, then the process was repeated with a second 444 ml. Aggregate stability was measured on 6 haphazardly -collected surface samples within the plot using methods from Herrick et al. (2001). This method would not capture soils that could not be collected on the sieve (category "0"). We measured the channel cross sectional area using the device described in Kornecki et al. (2008). The device is a linear instrument with 19 sliding pins that were placed perpendicularly across the headcut.

Other responses related to vegetation and soil carbon were measured only after one year. We assessed aboveground biomass within our study plots by collecting aboveground biomass using a randomly placed 45 x 45cm PVC square to clip all plants to ground level. Material was placed in paper bags, dried at 60 C for 3 days, oxidized material was removed with forceps to capture material that was likely to have been alive in the previous 1 year, and weighed to 0.01 g. Vegetative cover and species richness and diversity within our 5m x 5m study plot was captured using the line intercept method. We identified what dominant plants intersected the transect every 5 cm up to 50 cm or categorized bare ground or litter. Litter included fine and coarse herbaceous and woody debris and dung. Soil carbon was measured by taking one soil core in each study plot (2cm diameter, ~12 inch depth) and soil samples were sent to Ward Laboratories (https://www.wardlab.com/) where soil organic and inorganic carbon levels were analyzed using the combustion method.

Data were analyzed using R (version 4.2.3; R Core Team, 2012). For infiltration rate (natural log transformed in improve normality of model residuals) and aggregate stability, we used linear mixed effects models in the lme4 package (version 1.1-31) with plot as a random effect to account for repeated measures and maximum likelihood estimation with fully crossed main effects amendment, ranch, and time point (treated as factors). We calculated the total gain or loss of cross sectional area of the channel from 2021 to 2022 from the erosion/accretion device measurements and used linear models with fully crossed main effects of amendment and ranch. For aboveground biomass (square root transformed), proportion transect that was covered with vegetation, perennial grasses, and bare (all arcsin square root transformed), plant richness of the transects, and soil organic carbon we used linear models with fully crossed main effects of amendment and ranch.

Results

We detected differences across ranches by year in infiltration rate and aggregate stability (Table 1, Fig. 1), and differences by ranch for transect cover and richness characteristics, aboveground biomass, and soil carbon (Table 2, Fig. 2, Fig. 3), demonstrating that our study design had the power to detect differences. Our amendment treatment had no effect on any of the measured soil or vegetation characteristics. There were no differences in erosion/accretion by either amendment or ranch (Table 2, Fig. 1).

Discussion

Although organic amendments have been shown to improve some measures of erosion resistance and soil health previously (Gravuer et al. 2019), it was not effective to pair organic amendments with the rock structures. Partly, this was because the erosion control structures themselves are effective: on average across all ranches and treatments, the channels accreted 52 cm^2 (SE 42 cm^2; Fig. 1) between the baseline measurements in winter of 2021 and the next measurements after one year, which is considerable given that the average channel cross sectional area was 365 cm^2 (SE 6.5 cm^2) in 2021. Thus, range managers interested in addressing active head cuts could prioritize physical intervention through rock structure rather than biological intervention with organic amendments or seeding.

We did not find evidence of seed addition above the rock structures to be effective, even when we also added organic materials that have shown to increase soil moisture at the surface. Dryland seeding additions can frequently fail to germinate over relatively short time scales (Shackleford et al. 2021). The timing of seed addition may also have contributed to poor emergence because both seedling survival and growth are related to the total precipitation and cumulative precipitation (Farrell et al. 2023) and the dry periods in most counties between before June of 2023 meant that the added seeds were not receiving substantial moisture: In Eddy county, more than 15% of the county was in D3 (extreme) drought from January-August, in Mora county, more than 25% of the county was in D3 drought for the full year, in Rio Arriba county, more that 32% of the county was in D3 drought for the first six months of the experiment; and int Santa Fe County, more than 81% of the county was in D3 drought from November to July (National Drought Mitigation Center 2024). Unfortunately, in a global metaanalysis, the probability of successful establishment declines over time (Shackleford et al. 2021), so while the subsequent year had much less drought in the state, the seed additions may not have had substantial effect even longer-term. Of note is that there is current guidance from local practitioners in New Mexico to add seeds directly before adding the rocks to the treated part of the channel, where they can be protected from herbivory and have a microsite with higher moisture, but we did not test that technique instead focusing on addressing the area directly upslope of the headcut.

We did not find strong evidence that soil amendments of compost or mulch improved the metrics that we measured, which was surprising given that we had found up to doubling of soil carbon and substantial increase in infiltration rate after two an one year, respectively in a previous study at two ranches (Stricker et al. in review). The low magnitude of response may have been partially due to extreme drought conditions in the year. Anecdotally, our interns and field technicians noticed the soil moisture appeared higher due to darker color and more condensation of soil samples in plastic bags in mulch plots than control or compost within a ranch, but unfortunately we did not collect samples for soil moisture or have volumetric soil moisture probes with us to collect that data in the field. Ranchers also reported the persistence of snow for a longer time in some of the amended locations, identifiable by the square shape of the snow. Thus, several ranchers reported that they would be interested in trying organic amendments again despite the low magnitude of response in this single year trial.

Acknowledgments

We would like to thank all of our participating land managers and ranchers for opening their ranches to Quivira Coalition staff and workshop volunteers and for their generous and gracious support for this work and thank all volunteers who attended workshops at these ranches and participated in the installation of rock rundowns. Staff, contractors, and interns including C.J. Ames, J. Garcia, A. Larsen, M. Knapp, and T. Turk contributed to data collection and analysis. This material is based upon work that is supported by the National Institute of Food and Agriculture, U.S. Department of Agriculture, under award number G322-21-W8614 through the Western Sustainable Agriculture Research and Education program under project number OW21-362 and through National Institute of Food and Agriculture award number 2021-67019-34249. USDA is an equal opportunity employer and service provider. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the U.S. Department of Agriculture.

Author contributions

ES conceived of, set up and monitored field study, analyzed data, and wrote the results and discussion sections of the manuscript. MO contributed to data management and wrote the introduction and methods sections of the manuscript.

Conflict of Interest Statement

One ranch in this study is owned by an immediate family member of ES but there was no difference in compensation or technical support compared to other ranches.

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Tables

Table 1. Statistical results of linear mixed effect models of soil characteristics by organic amendment (control, mulch, compost), ranch (five ranches across four counties), year (2021 = baseline, 2022 = after 1 year) and interactions for infiltration rate and aggregate stability.

	Model Term	*Chi-square value*	df	*P*
Infiltration rate (cm min^{-1})	Amendment	0.79	2	0.672
$R^2_{\text{marginal}} = 0.70$	Ranch	191.79	4	**<0.001**
	Year	0.03	1	0.862
	Amendment x Ranch	8.34	8	0.400
	Amendment x Year	0.90	2	0.636
	Ranch x Year	48.41	4	**<0.001**
	Amendment x Ranch x Year	5.45	8	0.708
Aggregate stability	Amendment	1.65	2	0.437

$R^2_{marginal} = 0.64$	Ranch	124.25	3	**<0.001**
	Year	57.45	1	**<0.001**
	Amendment x Ranch	2.11	6	0.908
	Amendment x Year	1.35	2	0.508
	Ranch x Year	61.42	3	**<0.001**
	Amendment x Ranch x Year	4.41	6	0.621

Table 2. Statistical results of linear models of soil characteristics, vegetation characteristics, plant community, and soil organic carbon in 2022 (after 1 year of treatment) by organic amendment (control, mulch, compost), ranch (five ranches across four counties) and interactions for infiltration rate and aggregate stability.

	Model Term	F	Df	P
Erosion/Accretion (cm^2)	Amendment	0.48	2	0.620
$R^2_{adj} = 0.03$	Ranch	1.55	4	0.201
	Amendment x Ranch	1.12	8	0.366

Aboveground biomass (g) $R^2 = 0.27$	Amendment	1.2	2	0.312
	Ranch	5.3	4	**0.001**
	Amendment x Ranch	0.8	8	0.614
Proportion bare ground $R^2_{adj} = 0.15$	Amendment	1.30	2	0.280
	Ranch	4.11	4	**0.005**
	Amendment x Ranch	1.11	8	0.366
Proportion vegetation cover $R^2_{adj} = 0.50$	Amendment	0.63	2	0.537
	Ranch	20.86	4	**<0.001**
	Amendment x Ranch	1.07	8	0.398
Proportion perennial grass cover $R^2_{adj} = 0.59$	Amendment	0.14	2	0.868
	Ranch	30.34	4	**<0.001**
	Amendment x Ranch	0.54	8	0.823
Plant richness	Amendment	0.25	2	0.779
$R^2_{adj} = 0.22$	Ranch	7.10	4	**<0.001**
	Amendment x Ranch	0.92	8	0.508
Soil carbon (%)	Amendment	0.66	2	0.521

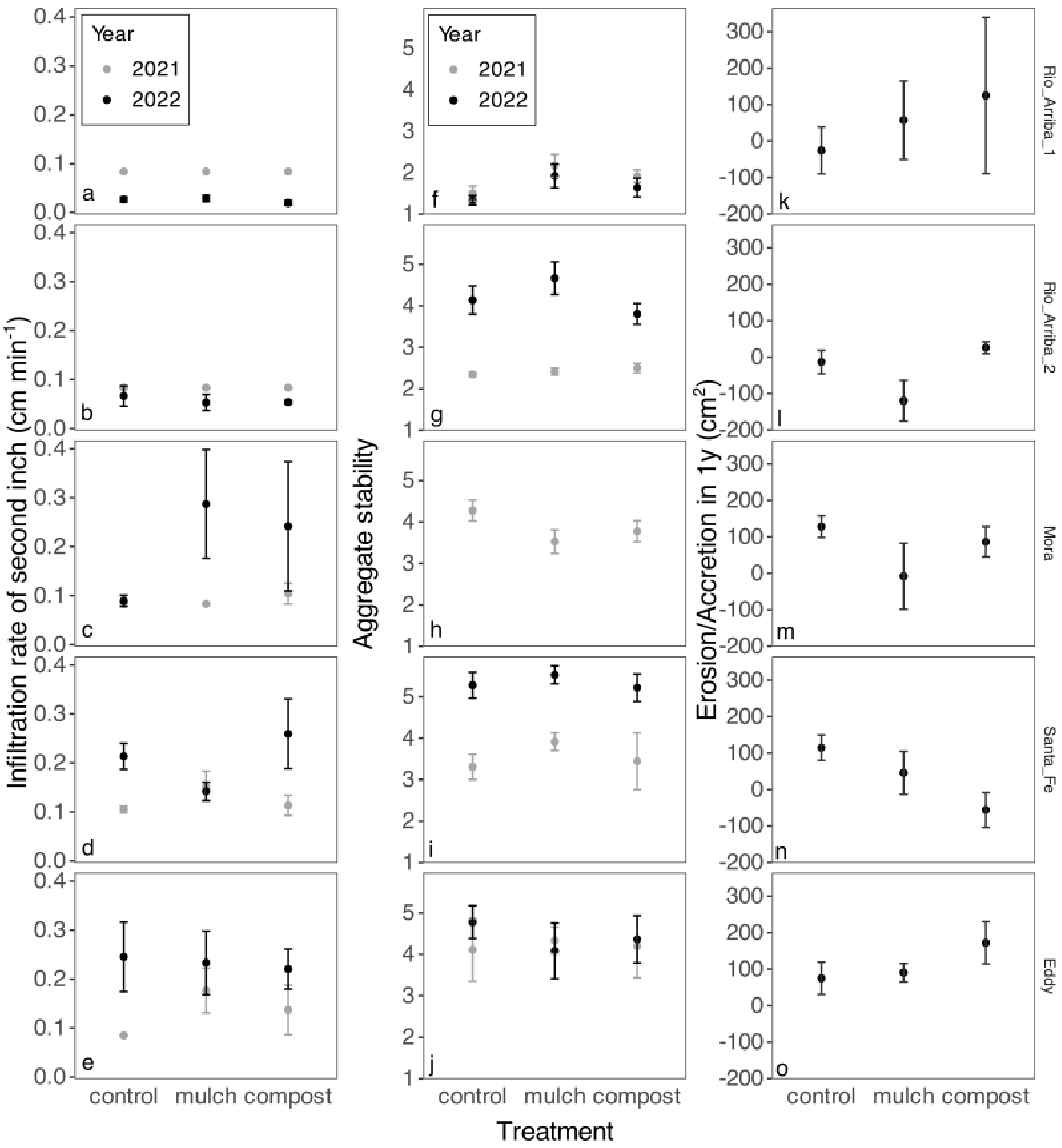
$R^2_{adj} = 0.65$	Ranch	23.42	4	**<0.001**
	Amendment x Ranch	1.11	8	0.382

Figure Captions

Figure 1. Soil characteristics (mean +- standard error) across five ranches (rows; designated to New Mexico county) by organic amendment treatment above rock rundown structure on active headcuts. a-e: infiltration rate (cm min^{-1}) of the second inch in the single ring infiltrometer by year (2021 = baseline; 2022 = 1 year after treatment). f-j: Aggregate stability (unitless) by year (2021 = baseline; 2022 = 1 year after treatment). k-o: erosion (negative numbers) or accretion (positive numbers) of cross-sectional area (cm^2) of the eroding channel from 2021 to 2022.

Figure 2. Vegetation and plant community characteristics (mean +- standard error) in 2022 (after one year of treatment; no baseline values collected) across five ranches (rows; designated to New Mexico county) by organic amendment treatment above rock rundown structure on active headcuts. a-e: vegetation biomass (g m^{-2}). f-j: Proportion cover of total vegetation cover (black), perennial grasses only (dark grey), and bare ground (light grey); litter is excluded from the figure but makes up the remaining proportion. k-o: plant species richness (integer).

Figure 3. a-e: soil organic carbon (%; mean +- standard error) in 2022 (after one year of treatment; no baseline values collected) across five ranches (rows; designated to New Mexico county) by organic amendment treatment above rock rundown structure on active headcuts.


Infiltration rate of second inch (cm min^{-1})
Aggregate stability
Erosion/Accretion in 1y (cm^2)
Treatment
Year
2021
2022
a
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e
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i
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o
control
mulch
compost
Rio_Arriba_1
Rio_Arriba_2
Mora
Santa_Fe
Eddy
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0.1
0.2
0.3
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1
2
3
4
5
-200
-100
0
100
200
300

Figure 1.

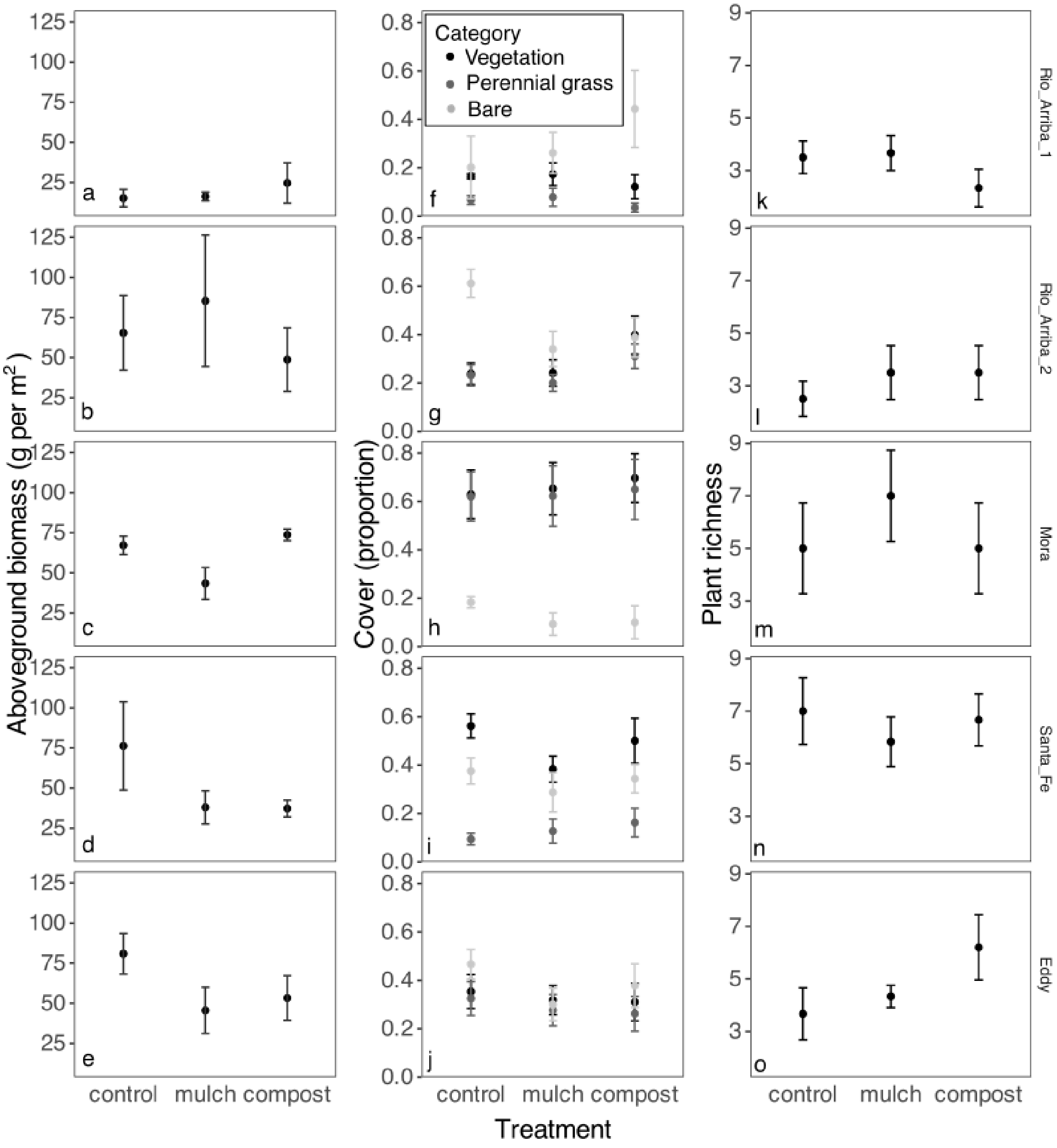
Aboveground biomass (g per m^2)
Cover (proportion)
Plant richness
Category
Vegetation
Perennial grass
Bare
Rio_Arriba_1
Rio_Arriba_2
Mora
Santa_Fe
Eddy
a
b
c
d
e
f
g
h
i
j
k
l
m
n
o
125
100
75
50
25
0.0
0.2
0.4
0.6
0.8
3
5
7
9
control
mulch
compost
Treatment

Figure 2.

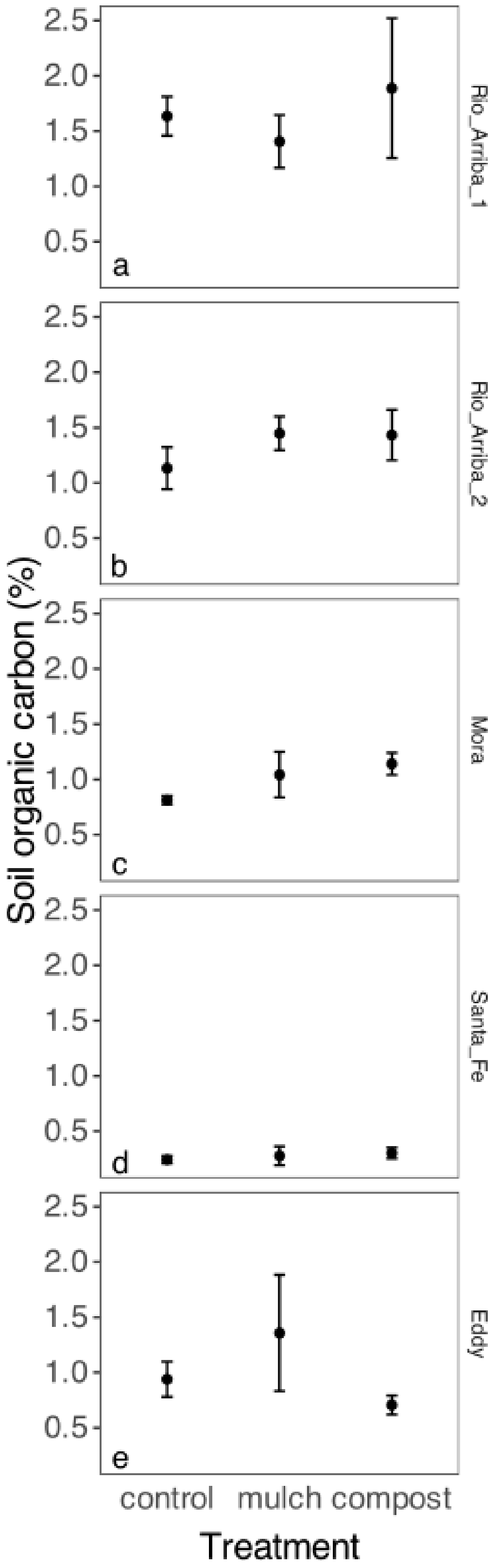
Soil organic carbon (%)
2.5
2.0
1.5
1.0
0.5
a
Rio_Arriba_1
b
Rio_Arriba_2
c
Mora
d
Santa_Fe
e
Eddy
control
mulch
compost
Treatment

Figure 3.