Regenerative Ranching:
Exploring Organic Amendments on New Mexican Rangeland






QUIVIRA COALITION

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Contents:

1. Executive Summary **3**
2. Introduction **4**
3. Organic Amendment Overview **6**
COMPOST 6
BIOCHAR 7
BALE GRAZING 8
4. Case Studies: Organic Amendments on New Mexico Ranches **9**
Ranch #1: Sandoval County 11
Ranch #2: Roosevelt County 13
Ranch #3: Mora County 15
4. Ecological Results **17**
6. Average Costs of Organic Amendments **20**
7. Conclusions **22**
APPENDIX **23**

1. Executive Summary

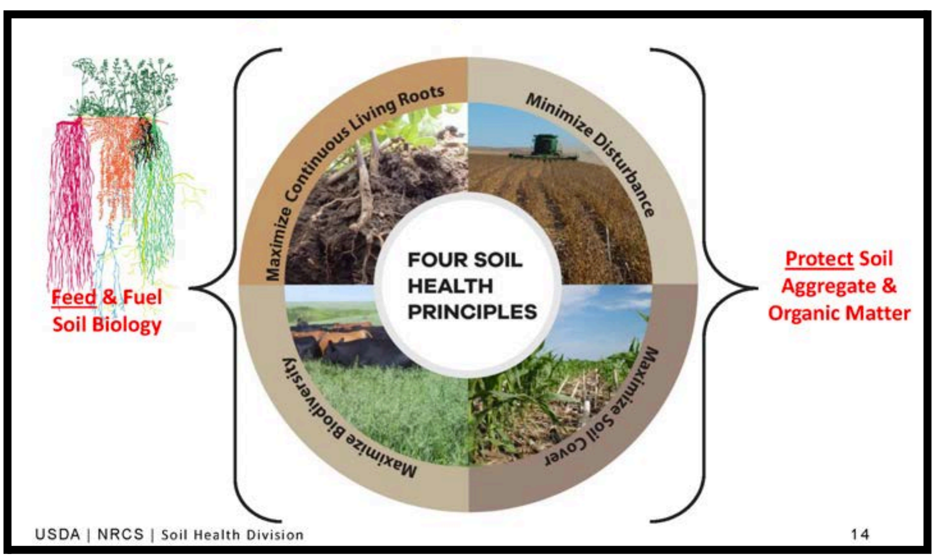
Rangelands - where livestock and wildlife roam - are vital food systems that support rural ecologies and economies. Despite their many benefits, these systems have faced escalating challenges including drought, lack of personnel, economic insecurity, and pressures to sell land for development. Ranchers are looking for new ways to integrate soil health practices into their management systems as a means to develop resilience towards these external challenges. Quivira Coalition partnered with three ranches in New Mexico that were interested in conditioning their soils with organic amendments including compost, biochar and bale grazing. Some were recovering plots from historic over-use, while others wanted to see if organic amendments would aid in combating erosion. This paper reflects the operational, social, and economic considerations of the process from the perspective of ranchers. Each case study is divided into profiles that explore rancher experience, recommendations and true costs of the process. Quivira Coalition has included average cost considerations and ecological analysis results for economic and scientific perspectives. Our case studies found that organic amendments have the potential to decrease bare ground by over 50%, increase aboveground biomass by over 75%, increase microbial activity, and increase infiltration rates slightly. Financially, bale grazing was the most affordable, while compost was the most expensive between organic amendment costs, equipment and labor. This work demonstrates ranchers are interested in improving soil health, but price points act as barriers to implementation.

2. Introduction

Historically and to present day, ranching has been central to the culture, ecosystems, and economy of the state but faces ongoing and emerging challenges. Dryland ecosystems in New Mexico have experienced challenges with soil degradation from prolonged drought and historic mismanagement from the era of the Dust Bowl and prior. New Mexico rangelands operate within these ecosystems, and many do not utilize irrigation infrastructure or much agricultural machinery. With recent prolonged drought, reduced active rangeland management and increased financial insecurity in rural communities, there is a growing need and interest to develop dryland soil health and ranch resiliency.

Exposed soil without vegetative growth is a problem many New Mexican ranchers face. Overgrazing, extreme heat and inconsistent rains can all aid in the appearance of bare ground on rangelands. According to the Natural Resource Conservation Service (NRCS) National Resources Inventory Rangeland Resource Assessment, New Mexico had the highest average bare ground (37.0%) on non-federal rangelands. Alarmingly, this rate has increased by 11.3% from 2004-2015 (2018).

Regenerative agriculture is an approach to land management that has taken the spotlight in recent years. Although there are many different approaches to implementing "regenerative" practices, the common denominator lies within improving soil health. A graphic generated detailing the four principles of soil health can be found in Figure 1. Management aligned with healthy soil principles serves to feed and protect the soil.



Soil Health Principles by the NRCS

General knowledge implies maximizing soil health can lead to more forage growth, improved water holding capacity and reduce erosion potential. The Quivira Coalition team wanted to explore if integrating organic amendments - compost, biochar and managed bale grazing - into soil could produce these trends within a year and contribute to overall ranch resiliency.

Resiliency of range lands includes their ability to sustain life, commerce and biodiversity - all of which depend on the soil. There are multiple approaches to achieve healthy soil and its benefits - some emphasizing active management. Many have investigated the effects of prescribed/rotational grazing management and other regenerative grazing practices, which require ongoing labor costs and are promising approaches to build soil health. However, when labor sufficient for maintaining practices like rotational grazing is scarce, the up-front cost and effort of applying organic amendments may be a useful approach that requires less ongoing involvement.

Quivira Coalition partnered with three ranches to investigate the efficacy of utilizing organic amendments on dryland range ecosystems in New Mexico. The following paper introduces two page profiles on each of the three ranches detailing their environmental, social and economic context. Each operation decided where and how they wanted to utilize the organic amendments rather than having the use prescribed on all of them. The ranchers reflected on recommendations for future applications and true costs of the process. Average ecological data aggregating all locations is shared as well as average expected costs to integrate these organic amendments.

3. Organic Amendment Overview

We compiled data and observations on three ranches that tried using three organic amendments: biochar, compost and bale grazing with livestock. All three organic amendments have distinct potential benefits which can be found below.

COMPOST

Photo: Quivira workshop participants observing compost in the process of curing

Compost is organic material that has decomposed into a stable and nutrient dense compound that can be used as a soil conditioner. There are many ways to create compost, including aerated static piles and worm composting.

Compost addition to the soil aligns with the healthy soil principles by covering the soil and adding biodiversity (through microbes). Compost additions have been shown to increase carbon stocks on rangelands and may improve forage quality. Additionally, compost holds water well and thus may improve water dynamics in amended soils.

You can find detailed information about both these processes on our website https://quiviracoalition.org/rural-dryland-composting/

BIOCHAR

Photos left to right. Applying biochar to test plot; biochar in truck bed.

Biochar is a material similar to charcoal made from controlled burning of biomass such as woody debris, brush or farm waste as well as other various organic materials. The burning process limits oxygen and prevents the material from turning into ash, instead delivering a final product as chunks of char that retain most of the carbon from the original biomass. One benefit of making biochar is that it diverts material that would otherwise go to the landfill, burn in a wildfire, or take up space on the landscape (e.g. piling).

Biochar addition to the soil aligns with the healthy soil principles by covering the soil. Emerging evidence suggests that biochar can improve water dynamics when added to soils, and that it may support healthy microbial systems if it is properly inoculated with nutrients and/or organic material. You can learn more about biochar at our website https://quiviracoalition.org/sw-biochar/

BALE GRAZING

Photo: Cattle bale grazing on a ranch in central New Mexico

A more familiar technique to many ranchers, bale grazing on rangeland benefits the soil through integration of hay to the soil through hoof action, along with the urine and manure of the animals. This technique must be managed so that livestock do not consume the last 20% of the hay to ensure it is left to integrate with the soil. The bales can be placed intact or flaked throughout an area.

Bale grazing aligns with the healthy soil principles by covering the soil and adding biodiversity (through livestock integration). Bale grazing increases organic material in the soil and therefore as subsequent benefits of structure and moisture in the soil.

4. Case Studies: Organic Amendments on New Mexico Ranches

Quivira Coalition partnered with three separate ranches in New Mexico to study how compost, bale grazing, and biochar affected their soil health and the likelihood of adoption into ranch management practices. Compost and biochar additions were targeted to ~⅓ acre at ~¼" depth. Bale grazing was also at the scale of ~⅓ acre, but often more patchily distributed due to how the bales were deployed. Quivira staff aided additions at most locations, and conducted a series of interviews to measure soil health indicators and assess efficacy. Several ranchers utilized volunteer help from friends and neighbors that drastically subsidized material, transport, organic amendment cost and labor. Detailed deployment methods and cost details are found in the Appendix.

All organic amendment expenses were covered by the funding agency. The primary focus of these studies was to pursue both quantitative soil data and qualitative observations pertaining to rancher experience and observed change over time.

Each ranch has different capacities and business models ranging from resource conservation to grass-fed beef sales. Each ranch has been identified only by the county where they are located: Sandoval, Roosevelt and Mora County. Specific locations and identifying information have been left anonymous to retain privacy and draw focus to the general findings.

The following pages are designed to provide quick overviews of the methods of obtaining and deploying the organic amendments. Then, we zoom in on case studies for each operation to provide the context of the ranch, rancher reflections on observed changes and what they might do differently the next time.

Where was organic amendment material obtained?

	Ranch #1 - Sandoval	Ranch #2 - Roosevelt	Ranch #3 - Mora
Compost	Certified biosolids compost, typically comprising 25% animal stable bedding, 40% biosolids (sewage sludge) and 30% green waste (pulverized yard trimmings), and 5% woodchip by volume	Composted food + pig waste from Polk's Folly Farm	Composted food + pig waste from Polk's Folly Farm

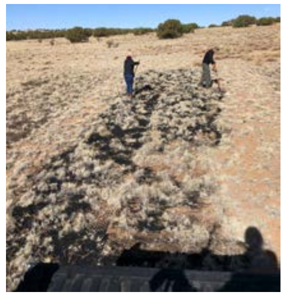
Biochar	Purchased in supersacks + delivered from a trailer	Purchased in supersacks + delivered from a trailer	Purchased in supersacks + delivered from a trailer
Bale Grazing	Local purchase	Local purchase	Local purchase

How was organic amendment material spread and *what time of year*?

	Ranch #1 - Sandoval	Ranch #2 - Roosevelt	Ranch #3 - Mora
Compost	Manure spreader + tractor; Added an exclosure to compare grazed+ungrazed. *Early spring*	Hydraulic trailer dumped in a long strip; Compost was not spread thin, but left sometimes in piles up to 4” thick. *Late summer*	Hydraulic trailer dumped in a long strip; interested cows moved it around a bit; riding mower helped spread it further. *Summer*
Biochar	Loaded onto truck with forklift; one person drove slowly and two others shoveled. Added an exclosure to compare grazed+ungrazed. *Early spring*	Manure spreader + tractor *Early spring*	Had to partially empty supersacks into a vehicle because too heavy to move. Spread with shovels from truck. *Early spring*
Bale Grazing	Large bales onto trailer; roped to tree and pulled off of trailer. *Early spring*	Rolled out round bales; neighbor’s cows grazed for several days. *Early spring*	Flakes spread in goat night pens along a long head cut and on a berm *Spring*

Ranch #1: Sandoval County






Photos left to right: Satellite view of area treated showing high bare ground; compost addition plot (one of five); biochar addition plot (one of five); bale grazing location example (one of twenty).

Ranch Context:
This ranch operation is part of Tribal lands and Indigenous management practices. The cattle are managed by five Tribal members and their families, and is considered a cow/calf operation. If sold, calves are brought to market at around six months. The operation was interested in observing any benefit of organic amendments to their soils.

Quantitative & Qualitative Values of Operation:
The cattle provide supplemental income for Tribal members, as well as accessible local meat for traditional and cultural events. Grazing has also been an instrument of the Tribal group being able to buy back land from historic colonial land acquisitions.

Quick Facts:

Number of Livestock: 35
Livestock use: traditional uses & emergency capital
Soil Type: loamy fine sand

Comparing Organic Amendment Application Process:

Amend.	Time	People	Equipment	Recommended Process Modifications
Compost	4 hours	1 person	Tractor, spreader & shovels	"One would need close observation of cattle to avoid overgrazing on compost plots"
Biochar	4 hours	3 people	Pick up truck, shovels & rakes	"I'd prefer to apply [biochar] after the growing season...for fall and winter precipitation. [The biochar] moved around with the wind"
Bale Grazing	4 hours	2 people	Pick up truck and forklift to load bales	"Ideal time of application is before winter precipitation."

Qualitative Producer Observations

Amendment	Forage Change	Other Notable Changes	Rancher Quote
Compost	Lots of vegetation growth	Attracted the cows significantly	"The production value doubled on native vegetation…and the cows gravitated towards the compost plots, (suggesting) the value of that forage greatly increased. The cows trekked miles to go to that plot."
Biochar	Some vegetation growth	Attracted the cows significantly	"There hasn't been enough precipitation to tell if the change is significant. Maybe in 3-4 years."
Bale Grazing	Hard to tell without much precipitation	Added forage value winter	"The cattle heavily compacted the soils, which could be a good thing." Wildlife scat was found in great numbers on these plots, too"

True Costs for Project

Amendment	Transport of amendment	Equipment	Amendment Cost	Total
Compost	0	0	0 : Compost left over from previous grant	0: No associated compost charges for this ranch
Biochar	Included in amendment cost	0	$1500	$1500
Bale Grazing	Included in amendment cost	0	$1250	$1250

Producer Quotes Reflecting on Overall Experience:
"From a rancher perspective, using biochar or compost (on a large scale) would not be cost effective - between the labor, time and cost of the amendment…However, the application of compost and biochar are academically fascinating and have a lot of potential for native soils in New Mexico."

Ranch #2: Roosevelt County




Photos left to right: Satellite view of area treated showing dunes along pre-Dust Bowl fence lines; compost addition strip; biochar addition close-up; bale grazing location.

Ranch Context:
This ranch is located in the far east of New Mexico. The operations are primarily dedicated to conservation and research. Profit is not a motivator and cattle have not been a substantial part of the operation for over 10 years. A herd was integrated temporarily for this study. Most of the soil is heavily eroded and previously impacted by events surrounding the Dust Bowl. Recovery efforts for the region's soil are made even more challenging as rainfall is rare, averaging less than 18 inches a year. Wildfires are a high risk for the region.

Quantitative & Qualitative Values of Operation:
Ranch partners on the property are inspired by their passion for conservation. Although profit is not a motivator for operating ranchers, they see value in the preservation and conservation of this land for wildlife such as the prairie chicken, an endangered keystone species in the western United States.

Quick Facts:

Number of Livestock: 15
Livestock use: Cow/Calf
Soil Type: loamy fine sand/eroded soils

Comparing Organic Amendments Application Process:

Amend.	Time (h)	People	Equipment	Recommended Process Modifications
Compost	1	4	Dump trailer, shovels and rakes	This application process was likely not practical for large scale applications. If we were to do it again, a manure spreader would be ideal to cover more area.
Biochar	2	2	Rented spreader, tractor	Application could be done when winds are low and grass is high.
Bale Grazing	1.5	1	Pickup Truck	Rolled out to spread material instead of as one unit. Could be meshed in with cattle management and done any time of year.

Qualitative Producer Observations

Amendment	Forage Change	Other Notable Changes	Rancher Quote
Compost	Loss of forage	Compost plots actually inhibited forage growth	"The compost was potentially too hot, and left the ground bare. [Potentially inhibiting seed germination]...Operations that have irrigated fields have great results...without the moisture we might be blowing smoke"
Biochar	Not much change was seen	Visual trend towards increased diversity of forbs	"Not much visible improvement of vegetation."
Bale Grazing	Slight improvement with growth of native and invasive forage species		"Could be easy to scale and most practical. There was a visible improvement with forage growth."

True Costs for Project

Amendment	Transport	Equipment	Amendment Cost	Total
Compost	$920	0	$400 For 16 cubic yards	$1320
Biochar	$75	$100, rented fertilizer spreader	$1500	$1675
Bale Grazing	$50		$410	$450

Producer Quotes Reflecting on Overall Experience:
"There's not a lot of regularity in our weather patterns except for dryness...These amendments are the kind of thing that takes time to see results. The rain makes everything, and if it rained here, I imagine we would see results. "

"With generations of eroded soils, if we could get moisture, these applications could do something to kickstart their recovery... If they prove useful, they could be one more tool in the tool box."
"...A mixture of biochar and compost could be (interesting) to see."

Ranch #3: Mora County

Photos top left to right: Satellite view of two berms upslope of a perennial creek with high bare ground downslope; compost addition strip along the downslope side of the berm; biochar addition close-up after 1 year on downslope side of berm; satellite view of berms with high bare ground downslope near top of the watershed; bale grazing location at top of watershed.

Ranch Context

This ranch has operated since 2016 and dedicates itself to the sale of grassfed beef to a variety of clients including local grocers, schools and businesses in Mora County, Albuquerque, and Las Vegas. They operate a herd of cattle and bulls bred on-ranch. Their business is interested in adapting circular economy elements that address people, planet and profit while minimizing waste. Goats were used for the bale grazing demonstration as the cattle are grazed on grass only.

Quantitative & Qualitative Values of Operation:

A generational ranch, this rancher has a lot of pride in their operation and interest in managing a healthy surrounding ecosystem in tandem with the business. They believe quality forage is key to quality livestock health as a source of balanced minerals and nutrients and recognize the economic benefit of investing in soil health.

Quick Facts:

Number of Livestock: >100
Livestock use: Cow/Calf
Soil Type: loamy/clay soil

Comparing Amendments Application Process:

Amendment	Time (h)	People	Equipment	Recommended Process Modifications
Compost	1	4	Shovel, rake, flat bed	Placement was along a berm. Neighbors helped with the process, keeping costs low. Concern in this climate is the windy season. Application is more likely to be successful with moisture. June was a good time of year for this.
Biochar	2.5	3	Shovels, flat bed, skid steer	Placement was along a berm. Skid steer would be helpful for anyone considering using these amendments. A neighbor helped with skid steer and transported the bales into the barn.
Bale grazing	2	2	Skid steer, flatbed, straps for hay during transport	Placement happened in March to help mitigate erosion on a slope. Recommended placement month: July before the monsoon season. Consider moisture and standing growth when deciding on timing

Qualitative Producer Observations

Amendment	Forage Change	Other Notable Changes	Rancher Quote
Compost	"Plant species colonization and moisture retention was visible"	Hoof action presented some success with integration. From bare ground we saw notable improvement.	"A small scale operation might be interested in increased forb growth with widespread compost, whereas large scale would be less likely to adopt…To make my own compost, I would have to source manure as I don't have enclosures, and I don't have enough equipment to do large scale compost"
Biochar	There was more colonization with biochar. But not as much as compost.	The biochar seemed to migrate more than the compost with wind. Soil moisture levels were not as notable in comparison to compost	"I think [a compost and biochar combination] would help retain moisture and give species more structure to grow… I would be interested in producing my own biochar…as a way to deal with woody residual and a means of fire mitigation."
Bale grazing	There was almost immediate growth, and notable bands of vegetation - reflecting recruitment of species	Held more moisture in the soil when it snowed	"Bale grazing was the most effective treatment and the most accessible to producers (and effective in) reducing sheet erosion… I saw the differences on the ground…Great recruitment of vegetation once we had moisture…Our operation does not produce or generally feed hay. A bale would likely spook our cattle."

True Costs for Project

Amendment	Transport	Equipment	Amendment Cost	Total
Compost	$650	0	$400 for 16 cubic yards	$1050
Biochar	$75	0	$1500	$1575
Bale Grazing	0	0	$419 per medium round x 6 rounds	$2515

Producer Quotes Reflecting on Overall Experience:

"Bale grazing presents the amendment most likely to be adopted by ranchers due to its familiarity and price point."

"Compost tea with hoof action could be an interesting amendment to explore on areas of erosion if managers have water access."

"[After applying amendments]…you start to see that increase in forage…assuming you get the follow up years of rain. There could be [an] economic benefit. But I don't know if [large scale soil amendments] would be accessible without grants. Especially considering the labor component."

4. Ecological Results

Visual Observations by Ranchers:
Visual observations by ranchers affirmed bale grazing and compost to have the best results for beneficial changes in vegetation and moisture retention. Both Ranches 1 and 3 saw positive changes reflecting growth of forbs and increased moisture retention to the eye with these organic amendments. Ranch 2 however observed a reduction in desirable plant growth; a plausible cause is speculated to have been the thickness of application.

In-field and lab monitoring:
The methods, statistical results, and additional figures are detailed in full within the Appendix.

Soil chemical characteristics
Compost was the only treatment that provided a meaningful effect on soil pH or electrical conductivity (Fig. 1).

- Compost decreased soil pH to near neutral conditions; other treatments remained as alkaline as the control plots.
- Compost plots had at least 100% higher electrical conductivity than any other treatment; *if salt is a concern for the rangeland soils, compost will likely exacerbate that problem.*
- There was no effect of any treatment on cation exchange capacity

Compost was the only treatment that provided a meaningful increase in inorganic nutrient content of soils (Fig. 2).

- Inorganic nitrogen was at least 140% higher in compost than any other treatment.
- Phosphate was >500% higher in compost than any other treatment.
- Potassium was at least 80% higher in compost plots than control or biochar, with bale grazing plots intermediate.

Soil physical characteristics
After one year, there were not strong differences in how water moved into soil or resistance to water erosional forces (Fig. A1).

- There was a trend that bale grazing and biochar plots had higher infiltration rates than compost plots with control plots intermediate.
- There was a trend that compost and bale grazing had higher surface aggregate stability than control and biochar plots.

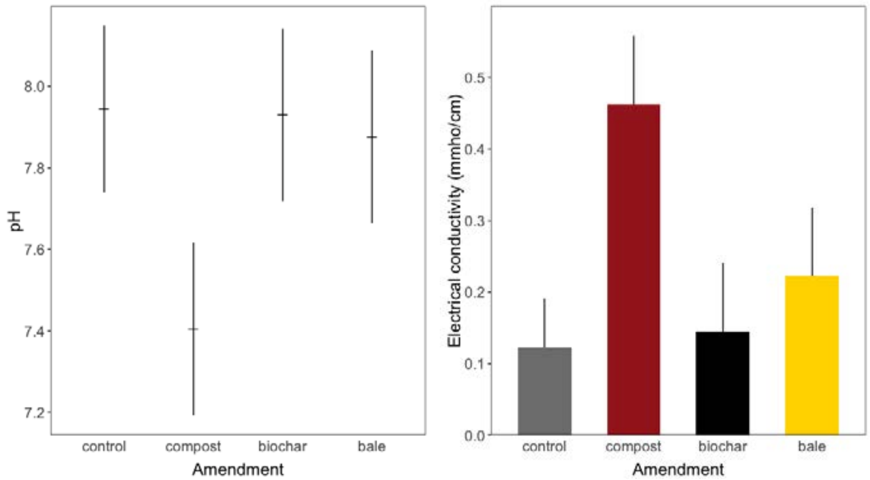


Figure 1. Soil chemical characteristics (0 - 15cm depth) by organic amendment treatment across three ranches after one year. From left to right: pH; electrical conductivity.

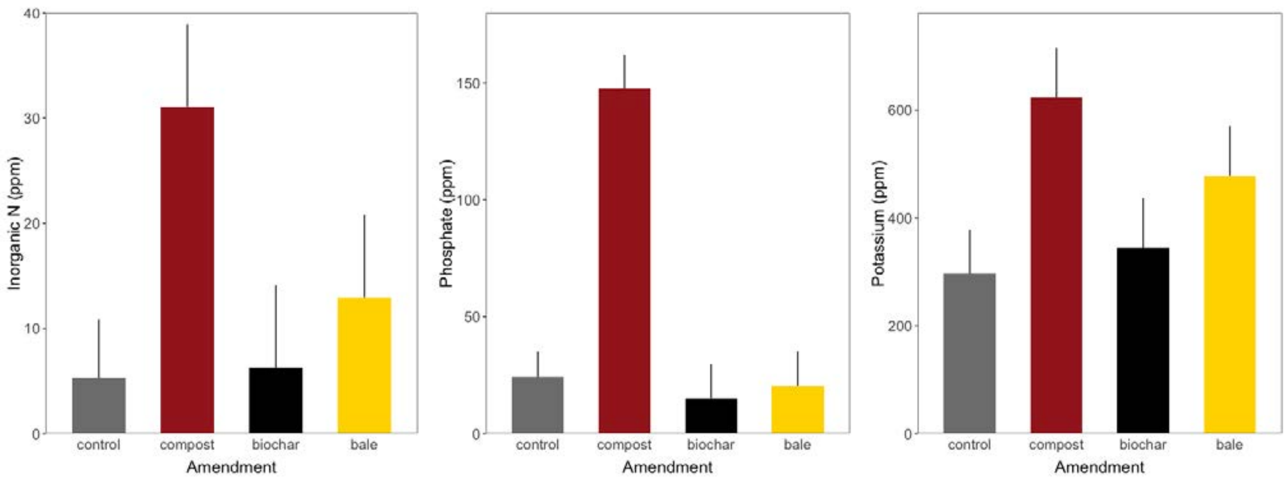


Figure 2. Soil nutrient characteristics (0 - 15cm depth) by organic amendment treatment across three ranches after one year. From left to right: Inorganic nitrogen, phosphate, and potassium content.

Soil microbial, carbon, and soil health characteristics

Compost and bale grazing had the strongest impact on the soil biota and organic matter (Fig. 3; Fig. A2).

- There was at least 86% more microbial biomass in compost or bale grazing plots than biochar or control plots.
- Organic carbon was 74% higher in compost than control plots, with biochar and bale grazing intermediate.
- The Haney Soil Health Calculation was lowest in the control and biochar plots, highest in the compost plots, and intermediate in the bale grazing plots.

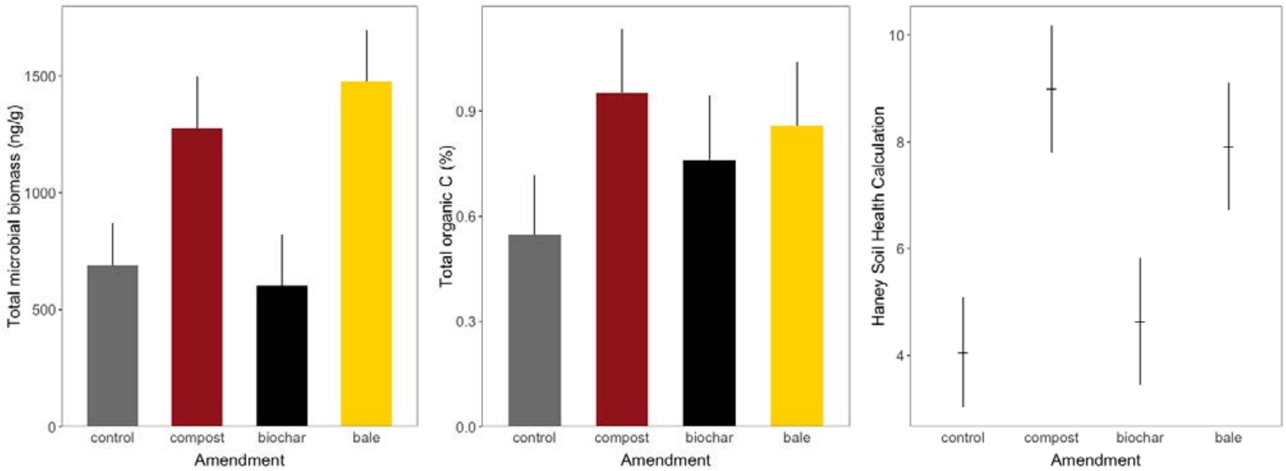


Figure 3. Soil microbial, carbon, and soil health characteristics (0 - 15cm depth) by organic amendment treatment across three ranches after one year. From left to right: total microbial biomass; total organic carbon, and the Haney Soil Health Calculation.

Aboveground characteristics

Compost and bale grazing plots had at least 60% lower bare ground and 75% higher aboveground biomass than control or biochar plots (Fig. 4).

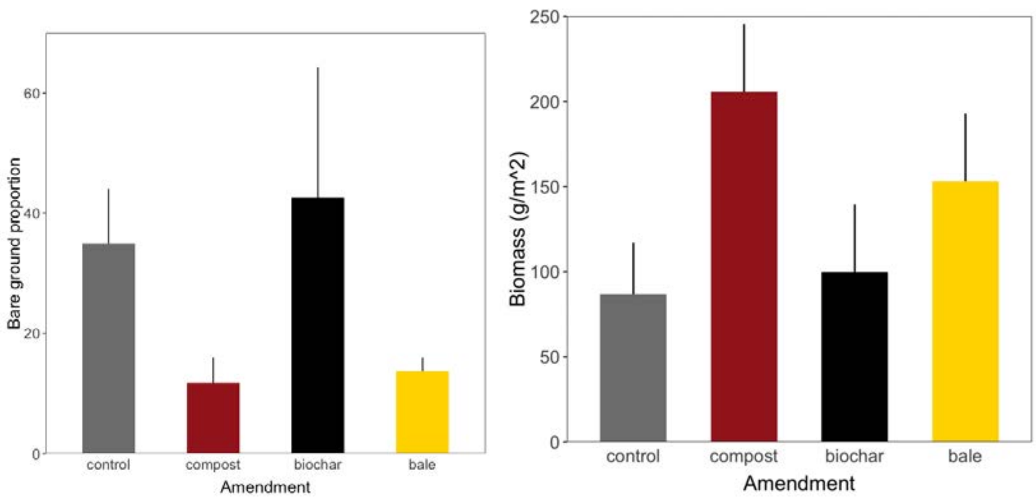


Figure 4. Proportion of bare ground and aboveground biomass by organic amendment treatment across three ranches after one year.

6. Average Costs of Organic Amendments

Average costs considered the price of the organic amendment, transport, labor and materials with the exclusion of heavy machinery. Bale grazing was the least expensive with these considerations at $887 total for 6 large rounds.

Any producers considering these organic amendments are advised to consider their intentions for applying amendments - balancing costs and potential results for soil health. Below you can find the average cost breakdowns for each organic amendment.

Prices are calculated based on the market average from summer and fall of 2023.

Compost	Assumptions	Total Cost
Compost	16 cubic yards priced at state average compost cost of $100/cubic yard	$1600
Transport	Average cost across ranches for transportation for 16 cubic yards	$785
Labor	Average 2 hours, 3 people at $17/hour	$102
Materials	2 shovels at $30 after tax	$60
TOTAL COMPOST		$2647

Biochar	Assumptions	Total Bio Char Costs
Biochar	6 cubic yards priced at $250/cubic yard	$1,500
Transport	Average 50 miles, 2 people, 3 hours with gas priced at $3.75	$108.25
Labor	Average 3 hours, 3 people at $17/hour	$153
Materials	1 shovel 1 rake at $30 after tax each	$60
TOTAL BIOCHAR		$1821

Bale Grazing	Assumptions	Total Cost
Hay	6 large rounds, averaged price in New Mexico 2023*	$660
Transport	Average 50 miles, 2 people, 3 hours with gas priced at $3.75	$108.25
Labor	Average 2.5 hours, 2 people at $17/hour	$85
Materials	1 rake	$34
TOTAL BALE GRAZING		$887

Rancher observations: Biochar presented challenges for ranchers in terms of material transport and soil integration. The material arrives in 2 cubic yard super sack totes that are only able to be moved and picked up with a skid steer, tractor or other similar equipment. When applying biochar, ranchers were very cognisant of its ability to transport in breezes or strong winds. In New Mexico, this presents challenges for integration during several months of the year when high winds are likely.

* New Mexico Direct Hay Report, November 24th 2023, https://www.ams.usda.gov/mnreports/ams_2939.pdf

7. Conclusions

Our case studies found that organic amendments have the potential to increase desirable soil conditions. Compost decreased bare ground by over 50%, increased available inorganic nutrients NPK, increased microbial activity and soil carbon, and also increased EC, which relates to salt levels. Bale grazing also strongly improved soil health compared to controls. Biochar had much weaker responses overall but a tantalizing trend of increasing infiltration rate. Ranchers observed positive qualitative changes of forb and plant growth where organic amendments were placed, with the exception of one case study with compost. Overall, ranchers in this study preferred amending their soils with the bale grazing method. This approach felt familiar and presented several added values to their operations; providing animal feed, assistance with directing the herds, and beneficial organic matter for soil ground cover.

Ranchers were excited about the prospect of what large scale applications would accomplish; however price, labor and time were foreseen as barriers to implementation. On-site or communal compost, biochar or hay bale production and procurement networks could help mitigate organic amendment and transportation costs. Compost would require an aggregation of feedstocks including manure, wood chips and other organic materials. As many ranches do not have access to sufficient amounts of compost feedstock for large scale applications, collaboration to acquire materials would be necessary. Producing biochar requires use of fire which can be a substantial risk even at relatively cool and low-wind times of year. Instructions surrounding creating compost and biochar can be found on Quivira Coalition's website at QuiviraCoalition.org/techguides.

Regenerative agriculture focuses on improving soil health and holistic resilience, and growing evidence suggests that investment in regenerative practices benefits businesses and bottom lines as well. Organic amendments are potential solutions to revive soils and provide accessible solutions to farmers and ranchers in New Mexico. However, integrating organic amendments will require significant resource support to become applicable on large scales. Presently, funding allocated to these kinds of projects and general systems familiarity for implementation are lacking. External interest, knowledge and financial resources can help agricultural operations see soil health as an opportunity to increase their system's resiliency. Climate change and associated threats can be overwhelming, but investment in these projects can offer a beacon of hope and multiple avenues for improvement. These interviews noted room for further research and studies surrounding variable solutions such as compost tea and biochar integrated with compost. The opportunity and demonstrated potential are there, but collective investment and interest are paramount.

APPENDIX

Detailed Methods
At Ranch 1, all treatments were conducted on similar soil types (Table A1) and all were within approximately 2000 feet of each other. The managers elected to distribute organic amendments in 3-5+ smaller plots separated by native soils.

At Ranch 2, the bale grazing and biochar were conducted on an old field that had been severely degraded during the Dust Bowl and thus those treatments plus an untreated control were statistically blocked (Table A1). The compost was added to an underperforming area near headquarters with a different soil type and an adjacent unamended area was together treated as a statistical block.

At Ranch 3, the bale grazing was conducted around historic berms that were actively eroding near the top of the watershed (6500'). The biochar and compost amendments were added to historic berms near the bottom of the watershed (6000';), approximately 2000 feet from a creek. We surveyed along regions of the berm not treated with amendments as a control for this block. While the soil type was the same for all amendments (Table A1), the difference in elevation and distance from the other treatments led us to collect data from a control area and amended area and treat those together as a block.

Table A1. Soil types (from Web Soil Survey) where each organic amendment was deployed on each ranch.

	Ranch 1	Ranch 2	Ranch 3
Bale Grazing	Penistaja-Zia complex, 1 to 8 percent slopes	Amarillo soils, 0 to 3 percent slopes, severely eroded	Onava-Carnero-Porvenir complex, plateau interfluves - MLRA 70A.1
Biochar	Penistaja-Zia complex, 1 to 8 percent slopes	Amarillo soils, 0 to 3 percent slopes, severely eroded	Onava-Carnero-Porvenir complex, plateau interfluves - MLRA 70A.1
Compost	Penistaja-Zia complex, 1 to 8 percent slopes	Ratliff sandy clay loam, 0 to 3 percent slopes	Onava-Carnero-Porvenir complex, plateau interfluves - MLRA 70A.1

In-field tests

Aboveground biomass:
We used 18 in x 18 in pvc quadrats randomly placed within treatment and control plots to collect aboveground biomass. We randomized by standing in the center of the treated area and tossing the pvc frame behind us and clipping all biomass to surface level where it landed. All biomass was placed in a paper bag and dried at 60° Celsius for 72 hours. Anything that was oxidized and gray was removed with forceps so that only material that had been alive in the last growing season was included to be measured as biomass. We did not distinguish between annual or perennial forbes or grasses but Woody material was not included in the biomass bags. With this sized quadrat, the grams collected x 40 gives the approximate number of pounds per acre.

Soil Cover and Vegetation functional group:
We used the line-intercept transect method to assess characteristics of vegetation or litter above the soil surface. Each transect was scaled in length to have at least 100 points per plot. For example, at Ranch 3 and Ranch 1, we used 5-10m transects and assessed cover at intervals of 5 or 10 cm. At Ranch 2 we had much longer, linear structures, so we used 50m transects with intervals of 50cm. At each point, we placed a pin flag vertically whether any plant was in the herbaceous layer and identified it to the finest taxonomic resolution possible by the observer. We then aggregated the plants to functional groups to enable robust comparison across time and different observers and these functional groups accounted for plant vs. forb and annual vs. perennial). At each location, we also identified what was on the ground layer: plant rooted, dead plant material (fine or coarse), dung, or bare ground. For analysis, we grouped litter and dung into a single category of litter.

For analysis, we used the criteria of "what would a raindrop intercept first" - and thus tallied each location where a plant was in the herbaceous layer. For remaining points that had not overhanging vegetation, we categorize them as litter or bare ground. Vegetation, litter, and bare ground together equaled 100% of the intercept points. To further address the interests of producers, we investigated what proportion of line intercepts were perennial grasses, a generally desirable functional group for these range managers.

Infiltration Rate:
We followed the NRCS infiltration rate protocol with a single ring infiltrometer. In each plot we randomly choose one location by standing in the center of the plot, facing north, and tossing a pen behind us. We cleared the sampling area of surface residue, and if the site was covered with vegetation, we trimmed it as close to the soil surface as possible. We installed the infiltration ring using a board and mallet to a depth of 3-4 inches. If the soil contained rock fragments, and the ring can not be inserted to depth, we tried a new random location. With the 6-inch diameter ring in place, we gently pressed the soil surface only around

Figure 3.1

the inside edges of the ring to prevent extra seepage, and we minimized disturbance to the rest of the soil surface inside the ring. We lined the soil surface inside the ring with a sheet of plastic wrap to completely cover the soil and ring to prevent disturbance to the soil surface when adding water. We measured out 444 mL of water and poured it into the ring lined with plastic wrap. We removed the plastic wrap by gently pulling it out, leaving the water in the ring and noted the time in minutes and seconds. We recorded the amount of time (in minutes) it takes for the 1" of water to infiltrate the soil until the entire surface was just glistening. We then repeated the infiltration test in the same ring with a second inch of water and used this value for comparison across treatments because we did not not the initial soil moisture and that could vary considerably; thus, we only analyzed the infiltration into wet soil.

Aggregate Stability:
Aggregate Stability was measured by the slake test (Herrick et al. 2001) which provides a rating according to the time required for the fragment to disintegrate during a five-minute immersion and the proportion of the soil fragment remaining on the mesh basket after the five extraction-immersion cycles.

We used a soil knife to remove six ~¼ diameter, ⅛ thick aggregates from the soil surface haphazardly at each of six paces across the plots. We only collected samples that retained integrity to be collected, thus excluding stability class 0 (see below). Aggregates were allowed to air dry on the piece of window screen up to one week if the surface was damp. We placed soil aggregates into a pvc basket with a window screen at the bottom, and lowered the aggregates into 1" of water, and started the timer. We observed the soil fragment for five minutes and assessed loss of structural integrity (see below). After five minutes, we raised the basket out of the water, then lower it to the bottom five times with one second for the basket to clear the surface and one second to return to the bottom. We recorded stability classes 3-6 using the stability class (below).

Stability class	Criteria for assignment to stability class (for "Standard Characterization")
0	Soil too unstable to sample (falls through sieve).
1	**50 %** of structural integrity lost within **5 seconds** of insertion in water.
2	**50 %** of structural integrity lost **5 - 30 seconds** after insertion.
3	**50 %** of structural integrity lost **30 - 300 seconds** after insertion or **< 10 %** of soil remains on the sieve after 5 dipping cycles.
4	**10 - 25%** of soil remaining on sieve after 5 dipping cycles.
5	**25 - 75%** of soil remaining on sieve after 5 dipping cycles.
6	**75 - 100%** of soil remaining on sieve after 5 dipping cycles.

Laboratory Assays

After one year, soil samples for laboratory tests were collected to a depth of 15 cm using rigid, 2 inch diameter metal cores. For Ranch 2 and 3, three to five cores were collected and aggregated before being sent to the lab. For Ranch 1, a single sample per plot was collected for a total of three replicates.

For each sample the bags were allowed to air dry and stored in the dark at room temperature for up to one month. While this storage method is not best practice for biological responses (Lane et al. 2022), many soils have been shown to typically be fairly unreactive under air dry storage conditions and preserve differences due to treatments (Wang et al. 2021). In our case, we were interested in the comparisons among the treatments that all received the same post processing activities, thus although we can not be confident of absolute values of our individual replicates, we can directly compare the magnitude of effects between treatments within a site.

After two years, we resampled at Ranch 1 and Ranch 3. Samples were stored in the refrigerator and shipped within 4 days of collection.

We selected the responses to analyze based on producer interests. We sent samples to Regen Ag labs for PLFA analysis, Haney test, their Routine conventional soil tests, and their total organic carbon + total nitrogen ratio tests to assess commercially available responses of interest to agricultural producers. PLFA uses the composition of the microbial cell walls to determine different microbial composition, as well as provides a measure of total microbial biomass. Responses from the Haney test included assays such as microbial respiration that assesses microbial activity not just composition or abundance. Finally, we selected relevant chemical and physical properties such as nutrient availability and pH.

Analysis

Treatments within each ranch often have only a single replicate, and are therefore provided simply as guidance; while the aggregated data across all three ranches provide sufficient replication to conduct statistical analysis. For analysis we averaged all values by treatment within a block at each ranch and used linear mixed effects models to assess responses by amendment treatment with block as a random effect. Response variables were transformed (e.g. square root for logarithmic) if transformation improved the normality of the model residual.

Results

Year 1

Table A2. Analysis of variance results of effects of organic amendment additions across three ranches in Year 1. Different letters in the contrasts column indicate that 95% confidence intervals do not span the mean. While a complete treatment of the statistical values is not appropriate for this case study, briefly: F Value: Used to test a null-hypothesis by dividing two mean squares; the degrees of freedom in the numerator were always three and the denominator varied due to the random effects; P value: Probability measure; Marginal R^2: Demonstrates the goodness of fit.

Response	*Chi square*; Num. df = 3	*P* value	marginal R^2	Contrasts
Soil Chemical characteristics				
pH	52.5	**<0.001**	0.23	Control - a Compost - b Biochar - a Bale grazing - a
Cation exchange capacity	2.8	0.417	0.05	-
Electrical conductivity	14.5	**0.016**	0.53	Control - a Compost - b Biochar - a Bale grazing - a
Inorganic N (ppm)	12.8	**0.005**	0.50	Control - a Compost - b Biochar - a Bale grazing - ab
Phosphate (ppm)	105.8	**<0.001**	0.88	Control - a Compost - b Biochar - a Bale grazing - a
Available K (ppm)	36.0	**<0.001**	0.40	Control - a Compost - b Biochar - a Bale grazing - ab
Soil Physical characteristics				
Infiltration rate (2nd inch)	11.66	**0.008**	0.05	Trend that compost and biochar has higher infiltration rate than compost with others intermediate.

Aggregate stability	11.7	**0.008**	0.11	Trend that compost and bale grazing have higher stability than control and biochar
Microbial characteristics				
PLFA: total microbial biomass (ng/g)	39.9	**<0.001**	0.52	Control - a Compost - b Biochar - a Bale grazing - b
PLFA: Fungal:bacterial ratio	12.3	**<0.001**	0.66	Control - a Compost - b Biochar - a Bale grazing - b
PLFA: Arbuscular mycorrhizal abundance (ng/g)	12.4	**0.006**	0.49	Control - a Compost - ab Biochar - a Bale grazing - b
Carbon Cycle and Soil health				
Total organic C (%)	24.1	**<0.001**	0.20	Control - a Compost - b Biochar - ab Bale grazing - ab
Respiration	9.9	**0.019**	0.30	Trend that bale grazing at least 140% higher than biochar and control, with compost intermediate.
Soil Health Calculation	51.9	**<0.001**	0.54	Control - a Compost - b Biochar - a Bale grazing - b
Aboveground characteristics				
Proportion bare ground	14.7	**.002**	0.49	Control - a Compost - b Biochar - a Bale grazing - b
Proportion litter	4.4	0.218	0.11	-
Proportion perennial grass	5.0	0.168	0.18	-
Proportion forbs	4.6	0.196	0.26	-
Aboveground biomass	13.87	**0.003**	0.41	Control - a Compost - b

				Biochar - ab Bale grazing - ab

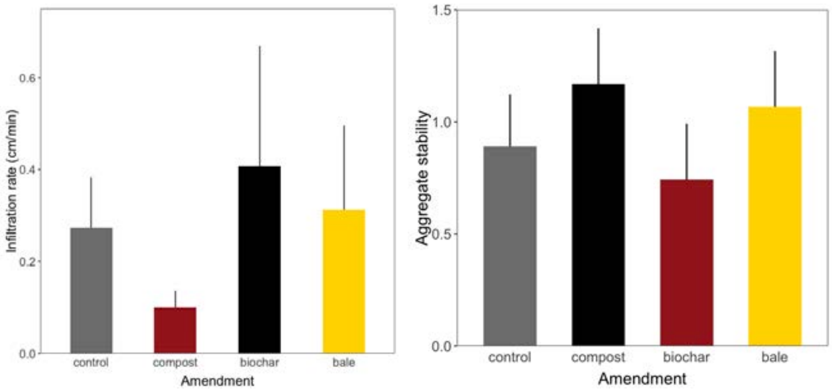


Figure A1. Soil physical characteristics by organic amendment treatment across three ranches after one year. Left: Infiltration rate of a second inch of water; Right: Aggregate stability.

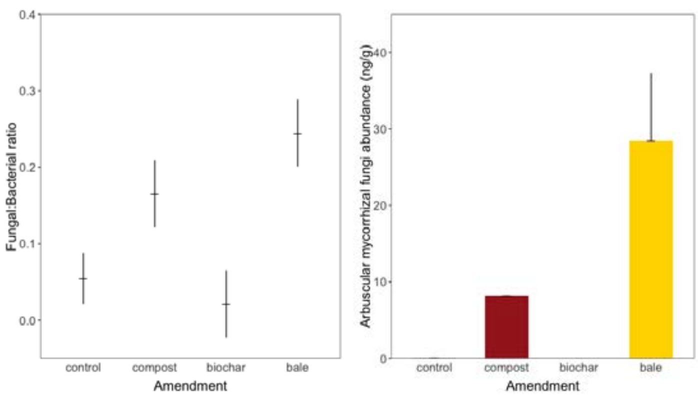


Figure A2. Soil microbial community characteristics (from PLFA) by organic amendment treatment across three ranches after one year. Left: fungal:bacterial ratio. Right: arbuscular mycorrhizal fungal abundance.

Year 2

The trends from Year 1 were broadly apparent from the two ranches in year two, indicating that effects of a single amendment persist beyond a single year.

Soil chemical characteristics

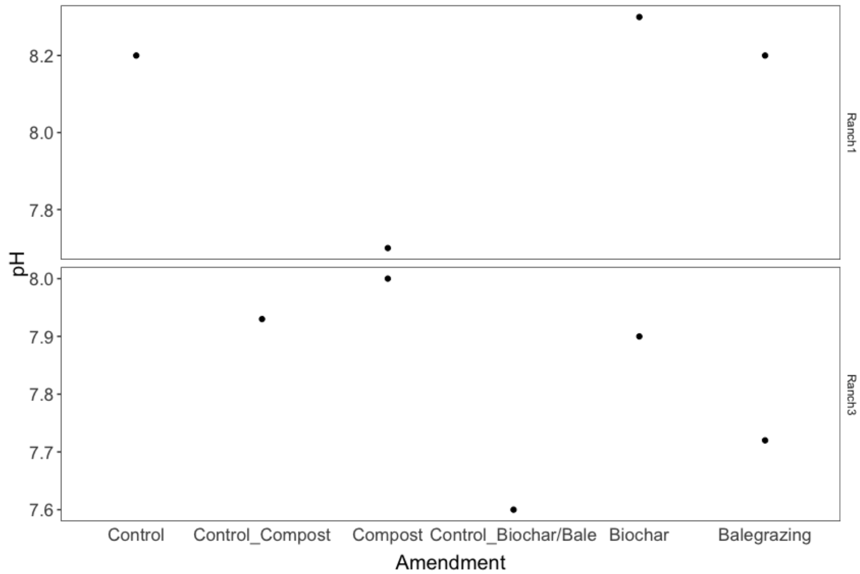


Figure A3. Data of soil pH (0-15cm depth) by organic amendment treatment at two ranches after two years. Note that there were blocks at Ranch 3 such that one control plot and compost treatment was in a different soil type than the control plot with the biochar and bale grazing plots.

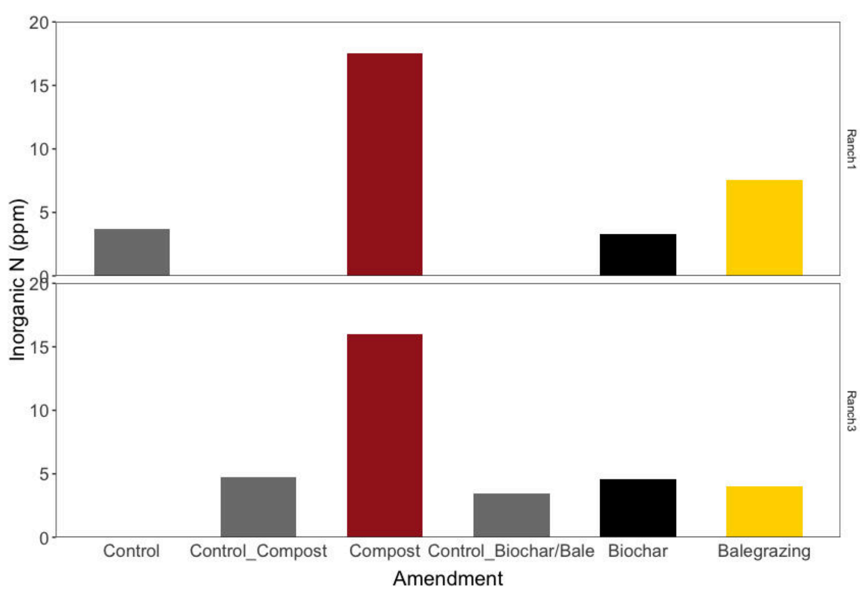


Figure A4. Data of soil inorganic nitrogen (0-15cm depth) by organic amendment treatment at two ranches after two years. Note that there were blocks at Ranch 3 such that one control plot and compost treatment were in a different soil type than the control plot with the biochar and bale grazing plots.

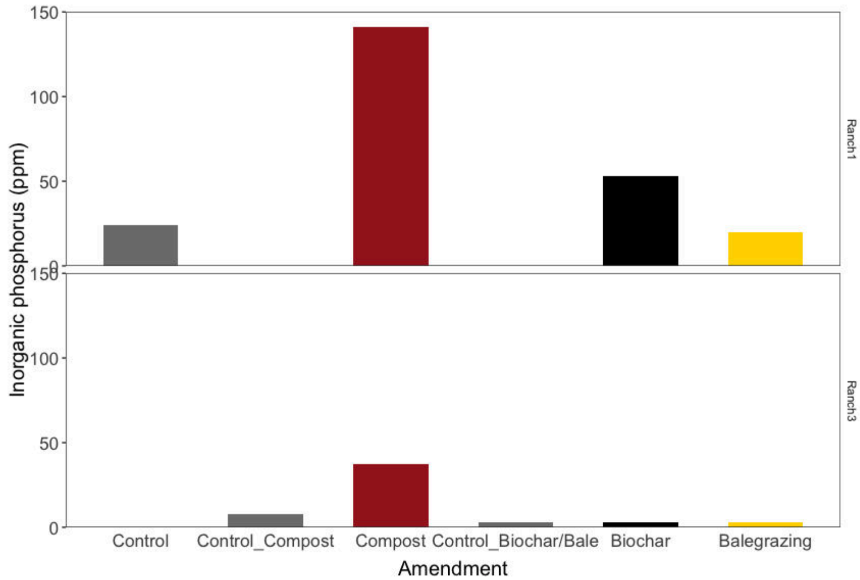


Figure A5. Data of soil phosphorus (0-15cm depth) by organic amendment treatment at two ranches after two years. Note that there were blocks at Ranch 3 such that one control plot and compost treatment were in a different soil type than the control plot with the biochar and bale grazing plots.

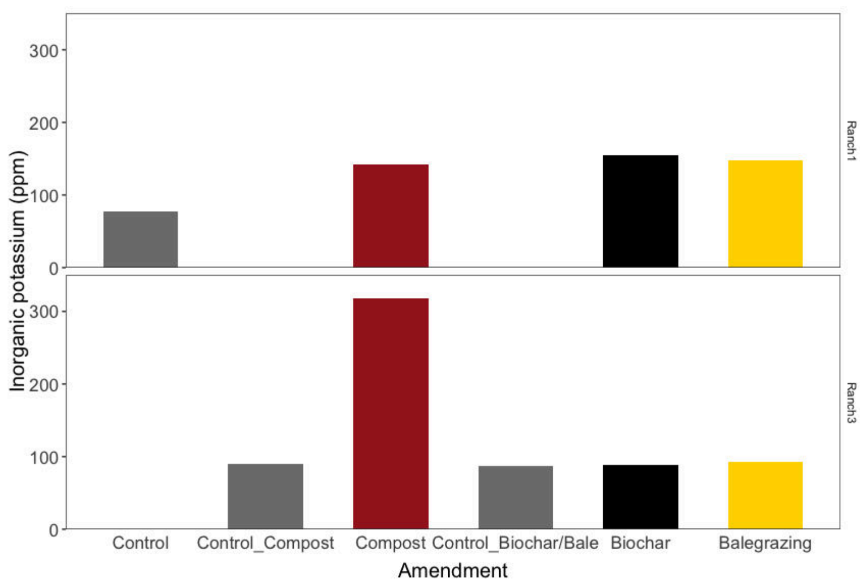


Figure A6. Data of soil potassium (0-15cm depth) by organic amendment treatment at two ranches after two years. Note that there were blocks at Ranch 3 such that one control plot and compost treatment were in a different soil type than the control plot with the biochar and bale grazing plots.

Carbon Cycle and Soil Health characteristics

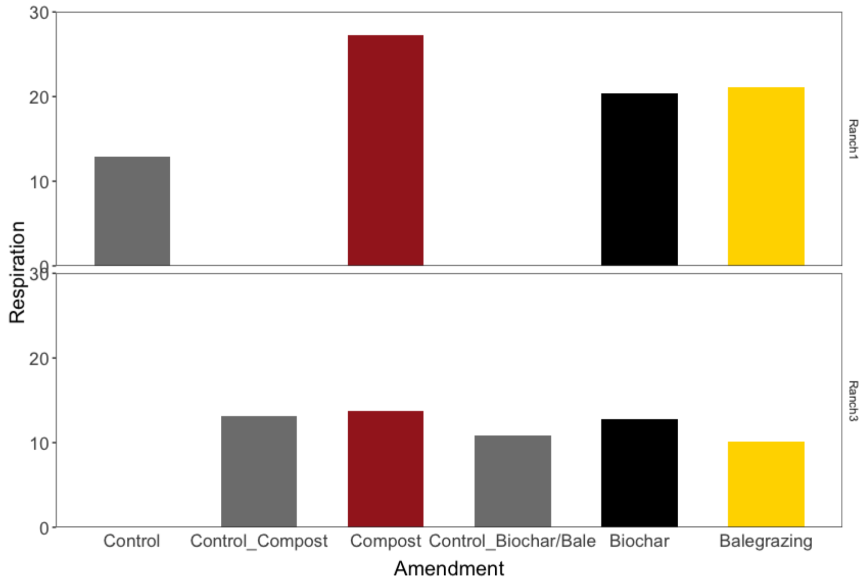


Figure A7. Data of soil respiration (0-15cm depth) by organic amendment treatment at two ranches after two years. Note that there were blocks at Ranch 3 such that one control plot and compost treatment were in a different soil type than the control plot with the biochar and bale grazing plots.

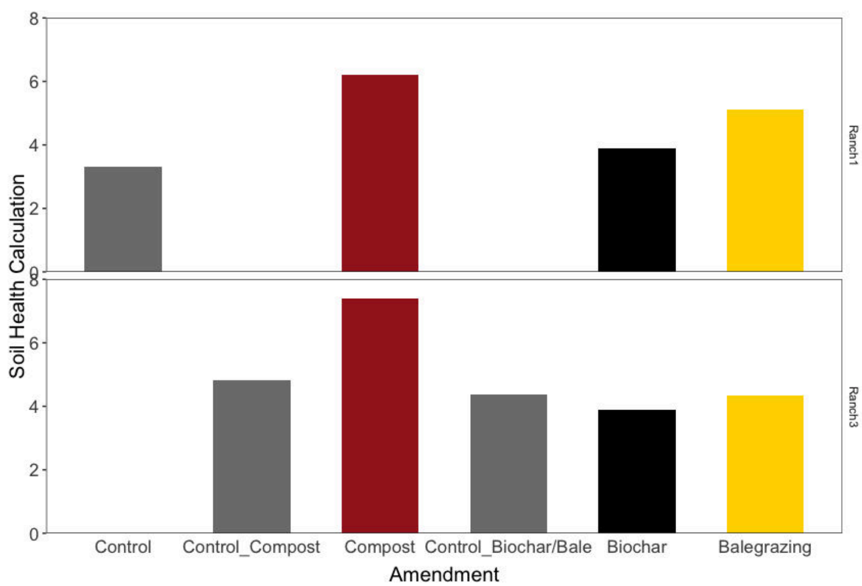


Figure A8. Data of the Haney Soil Health Calculation (0-15cm depth) by organic amendment treatment at two ranches after two years. Note that there were blocks at Ranch 3 such that one control plot and compost treatment were in a different soil type than the control plot with the biochar and bale grazing plots.

Ranch 3 in-field assessments of soil physical and aboveground characteristics
**Note, we were unable to collect in-field assessments at Ranch 1 due to snow accumulation.*

Table A3. Soil physical characteristics by treatment at Ranch 3 after two years. Note that there were blocks at Ranch 3 such that one control plot and compost treatment was in a different soil type than the control plot with the biochar and bale grazing plots.

Treatment	Aggregate stability	Infiltration rate of 2nd inch (mm/min)
Control - Compost	5.2	0.036
Compost	5.5	0.016
Control - biochar/bale area	4	0.090
Biochar	4.2	0.091
Bale grazing	3.3	0.041

Table A4. Aboveground characteristics by treatment at Ranch 3 after two years. Note that there were blocks at Ranch 3 such that one control plot and compost treatment was in a different soil type than the control plot with the biochar and bale grazing plots.

Treatment	Proportion bare ground	Proportion litter	Proportion perennial grass	Proportion forbs	Aboveground biomass (g)
Control - Compost	0.17	0.17	0.56	0.17	39.5
Compost	0.05	0.35	0.39	0.35	26.4
Control - biochar/bale area	0.22	0.23	0.47	0.23	28.0
Biochar	0.23	0.22	0.39	0.16	36.2
Bale grazing	0.30	0.16	0.38	0.16	55.7

Cost calculations

Costs by Soil Amendment	Ranch #2 Calculations		Ranch #1 Calculations		Ranch # 3 Calculation		Assumptions for average	AVERAGE COSTS FOR Ranches AMENDMENTS per unit
Bio Char								
Amendment Cost/cu yard		$250		$250		$250	1 cubic yard average across ranches	$250
Amendment Cost	6 cubic yards	$1,500	6 cubic yards	$1,500	6 cubic yards	$1,500	6 cubic yards	$1,500
Transport Cost		$75				$75	50 miles 2 people, 3 hours, 30 ppg avg gas cost 3.75	108.25
Labor Cost Est	2 hours 2 people		4 hours 3 people		2.5 hours 3 people		3 people 3 hour, $17/hr	153
Material	fertilizer spreader rented	$100					1 shovel , 1 rake	$60
TOTAL BIO CHAR COST		$1,675		$1,500		$1,575		$1,821
Bale Grazing								$45 small $110 large
Amendment Cost/medium ro	per round	$68		$208		$419	SOURCE, large round	$110
Amendment Cost	6 hay rounds	$410	6 hay rounds	$1,250	6 hay rounds	$2,516	large round x 6	$660
Transport Cost		$50				0	50 miles 2 people, 3 hours, 30 ppg avg gas cost 3.75	108.25
Labor Cost Est	1.5 hours 1 person		4 hours 2 people		$20/hr 2 ppl, 2.5 hours		2 people 2.5 hour, $17/hr	85
Material					truck and trailer with straps		rake	$35
TOTAL BALE COST		$460		$1,250		$2,516		$888
Compost								
Amendment Cost/cu yard		$25		$0.00		$25.00	average cost of compost in NM	100
Amendment Cost	16 cubic yards donated at cost	$400	16 cubic yards,		16 cubic yards donated at cost	$400.00	average cost across ranches for 16 cubic yards	1600
Transport Cost		$920	5.2 miles, on road, 6 mi estimated, half hour			$650	average cost across ranches for 16 cubic yards	$785
time	1 hour 4 people		4 hours 1 person		1 hour, 4 people		2 hours, 3 people, $17/hour	102
Material							shovels	$60
TOTAL COMPOST COST		$1,320		$0.00		$1,050.00	TOTAL AVERAGE	2647