Draft for comments. Please email comments and suggestions to info@biocharresearch.org

Vertical-Point Injection: Novel Soil Architecture Modification to Improve Drought Resilience in a Western Colorado Perennial Grass System Using Biochar



Michael H. Lobato, PSM[1], Holly E. Stanley, B.S.[1], Gerald C. Nelson, PhD[2]

Matrix Resource Technologies, LLC[1]

Professor Emeritus – University of Illinois Urbana-Champaign[2]

November 10, 2026

TABLE OF CONTENTS

PREFACE 7

1. ABSTRACT....7

2. INTRODUCTION....8

3. TRIAL FIELD SETTING....10

3.1 DESCRIPTION & LOCATION....10

3.1.1 Climate....10

3.1.2 Soil....10

3.1.3 Experimental Design....11

3.1.4 Installation of Soil Sensors and Loggers....14

3.2 FIELD AND LAB DATA COLLECTED....14

3.2.1 Pre-Trial Soil Fertilization and Baseline Sampling....14

3.2.2 Pre-Trial Seeding....15

3.2.3 Biochar Source and Application....15

3.2.4 Irrigation Method....17

3.2.5 Soil Sensor Data Collection....18

3.2.6 Hay Sampling Method....19

3.2.7 Statistical Analysis and Limitations....19

3.3 ANCILLARY DATA METHODS....21

3.3.1 Soil Bulk Density Testing Method....21

3.3.2 Normalized Difference Vegetation Index (NDVI) Sampling Method....21

3.3.3 Soil Plant Analysis Development (SPAD) of Proportional Chlorophyll Present Method....22

4. RESULTS....22

4.1 PROJECT WEBSITE....22

4.2 VOLUMETRIC WATER CONTENT (VWC)....22

4.2.1 Matched Station and Drying-Rate Comparisons....25

4.3 BULK ELECTRICAL CONDUCTIVITY (EC)....26

4.4 TEMPERATURE....26

4.5 HAY YIELD....27

4.6 LABORATORY RESULTS....29

4.6.1 Fertilizer Recommendations....29

4.6.2 Hay Quality (NIRS) *29*
4.6.3 Soil Health Analysis (SHA) *30*
4.6.4 Soil Biology (PLFA – Balser) *33*

5. ANCILLARY DATA RESULTS **35**
5.1 Bulk Density **35**
5.2 NDVI **35**
5.3 SPAD **37**

6. INTERPRETATION **38**
6.1 Soil and Plant Indicators **38**
6.2 VWC, SHA, PLFA **38**

7. DISCUSSION **39**
7.1 Mechanistic Discussion **39**
7.2 Economics **40**

8. CONCLUSION **41**
8.1 Future Research **41**
8.2 In Conclusion **41**

9. ACKNOWLEDGEMENTS **43**

10. CONFLICTS OF INTEREST DISCLOSURE **43**

11. ARTIFICIAL INTELLIGENCE (AI) DISCLOSURE **43**

12. PROJECT FUNDING AND UPDATES **43**

APPENDICES **45**

REFERENCES **61**

Table of Figures

Figure 1. Water consumptive use graphs of the Colorado River (Richter et al. 2024).....9

Figure 2. The research field is in the west-central area of western Colorado, U.S.A., 19 miles east of the Utah border (trial field region depicted in the red circle). The study site is comprised of an Orthent dominant suborder of Entisols (USDA n.d.-a).....11

Figure 3. Map of contiguous United States Soil Moisture Regimes (USDA/NRCS 2009). The study site is located within a Typic Aridic moisture regime in western Colorado.....11

Figure 4. Experimental design field map. The four strip names are abbreviated with their respective treatments, and the logger and sensor locations are denoted. Satellite image was captured May 6, 2023.....13

Figure 5. Boring 12 in. diameter holes using a skid-steer-powered soil auger (left). A sensor hole showing streaks of carbon in the soil after the biochar application (middle). Soil sensor installation at 6, 12, and 18 in. depths below the surface (right).....14

Figure 6. Lobato conducts pre-trial soil sampling using a Giddings soil probe during spring 2023.....15

Figure 7. Scanning Electron Microscope images of biochar derived from pistachio shells. The scale is noted at the bottom right of each photo.....16

Figure 8. Applying biochar while Nelson assists with moving the water supply hose (left). Photo showing injection points on the soil surface (right).....17

Figure 9. An AI-generated image portraying the concept of vertical-point injection.....17

Figure 10. The installed flow meter, bump, tee, and valve assembly.....18

Figure 11. Nelson checking logger and sensor function.....19

Figure 12. Stanley collects hay samples.....21

Figure 13. Monthly VWC averages at 6 in. depth of BC50 and CON50 for irrigation seasons (April–October) 2023–2026.....23

Figure 14. Monthly VWC averages at 6 in. depth of BC100 and CON100 for irrigation seasons (April–October) 2023–2026.....23

Figure 15. Monthly 10th-percentile VWC minima at 6 in. depth for BC50 and CON50 for irrigation seasons (April–October) 2023–2026.....25

Figure 16. Monthly 10th-percentile VWC minima at 6 in. depth for BC100 and CON100 for irrigation seasons (April–October) 2023–2026.....25

Figure 17. Hay yield per cutting (tons per acre) in strips BC50 and CON50, 2023–2026.....28

Figure 18. Hay yield per cutting (tons per acre) in strips BC100 and CON100, 2023–2026.....28

Figure 19. Photo taken June 20, 2023, looking northwest, showing all sensor stations installed. Darker green strips in BC50 and BC100 can be observed.....36

Figure 20. Multi-spectral drone image captured July 28, 2026, used to calculate NDVI.....37

TABLE OF TABLES

TABLE 1. STRIP TREATMENTS AND CORRESPONDING ABBREVIATIONS....12

TABLE 2. A TWO-WAY ANOVA OF MONTHLY MEAN VWC, APRIL–OCTOBER 2023–2026 (N = 26–27 MONTHS PER TREATMENT × DEPTH; MONTHS SERVE AS REPEATED MEASURES)....24

TABLE 3. A TWO-WAY ANOVA OF MONTHLY MEAN BULK EC, APRIL–OCTOBER 2023–2026 (MONTHS SERVE AS REPEATED MEASURES). 26

TABLE 4. HAY YIELD (TONS PER ACRE) BY SAMPLING DATE, WITH ANNUAL TOTALS....29

TABLE 5. A TWO-WAY DELTA ANOVA MODEL OF ALL STATISTICALLY SIGNIFICANT VARIABLES (P ≤ 0.05). N = 24 (4 STRIPS × 6 POST-BASELINE SAMPLING EVENTS, FALL 2023–SPRING 2026). RESULTS SORTED BY VARIABLE AND THEN H^2 (EFFECT SIZE) LARGE-TO-SMALL. Q = BENJAMINI–HOCHBERG FALSE-DISCOVERY-RATE-ADJUSTED P-VALUE ACROSS ALL 90 SHA TESTS; BOLD = Q ≤ 0.05..30

TABLE 6. FUNCTIONAL GROUPING OF STATISTICALLY SIGNIFICANT SHA VARIABLES....33

TABLE 7. A TWO-WAY DELTA ANOVA MODEL OF PLFA DATA (CHANGE FROM BASELINE). N = 24 (4 STRIPS × 6 POST-BASELINE SAMPLING EVENTS, FALL 2023–SPRING 2026). RESULTS SORTED BY FACTOR AND H^2 EFFECT SIZE. N = 23 FOR PRE 18:1W7C:CY19:0. Q = BENJAMINI–HOCHBERG FALSE-DISCOVERY-RATE-ADJUSTED P-VALUE ACROSS ALL 78 REPORTED PLFA TESTS; BOLD = Q ≤ 0.05....34

TABLE 8. FUNCTIONAL GROUPING OF SIGNIFICANT PLFA VARIABLES....35

TABLE 9. NDVI SUMMARY STATISTICS COLLECTED WITH A GREENSEEKER HANDHELD CROP SENSOR....35

TABLE 10. MULTI-SPECTRAL NDVI DRONE DATA, 2026....36

TABLE 11. SPAD SUMMARY STATISTICS....38

Table of Appendices

Appendix A. NRCS Soil Report....46
Appendix B. Fertilizer Recommendations and Applications....48
Appendix C. Dates of Project Activities....49
Appendix D. Biochar to Soil Volume Calculation....50
Appendix E. Irrigation Totals, 2023–2026....50
Appendix F. VWC Summary Statistics....51
Appendix G. EC Summary Statistics....52
Appendix H. Temperature Summary Statistics....53
Appendix I. Avg. Monthly VWC & % Gain....54
Appendix J. Avg. Monthly VWC Minima & % Difference....54
Appendix K. Nutrient Totals of Biochar Strips/Control Strips....55
Appendix L. Partial Factor Productivity of Nitrogen....55
Appendix M. Hay NIRS Summary Stats....56
Appendix N. Significant SHA Summary Statistics....57
Appendix O. Functional Grouping of Significant SHA Mean Δ....58
Appendix P. Significant PLFA Summary Statistics....59
Appendix Q. Functional Grouping of Significant PLFA Mean Δ....60

Preface

Lobato was first introduced to biochar in the spring of 2022 by hosting a small garden plot experiment at Lobato Farms in Fruita, CO, where the nonprofit, citizen science organization Citizens for Clean Air was looking at biochar as an option to reduce agricultural burning in the Grand Valley. Later, biochar was used in the market garden to improve soil quality. The improvement of water-holding capacity was immediate and profound. Fast forward to when this concept was born in the fall of 2022: Lobato was looking for a way to improve his livestock pasture, which was a former sheep feedlot; thus, soluble salts are high, and aggregate stability and structure are poor. The pasture is planted in western U.S. native grass species, primarily Western Wheatgrass (Pascopyrum smithii, var. Arriba) and Thickspike Wheatgrass (Elymus lanceolatus), and is irrigated with a water reel sprinkler. Can a native-grass pasture that is already inherently drought-resilient be modified to further withstand increasing extreme climate and drought stress; if so, how?

From the improvements experienced in the market garden, biochar was chosen as a potential solution. But therein lies the problem: there was no readily available way to optimally install biochar (or similar materials) in the soil without mass disturbance. Once the concept was envisioned, Lobato searched the internet for a machine that could do such a thing. A company that specifically designed and built a machine for hydraulically injecting sand into sports turf, primarily golf putting greens, for the purpose of aeration, was the only viable option found to test this idea. The following is the culmination of four years of our efforts to answer this question.

1. Abstract

Confronted with volatile climatic conditions, degraded and saline soil, reduced access to arable land and extreme drought, the daunting task of addressing human food security is one of the greatest challenges and opportunities of our time. Regionally, the future of agriculture within the Colorado River basin in the Western United States is increasingly under threat. Globally, biochar amendments in agricultural soil have shown positive improvements in soil health metrics and water-holding capacity. However, existing methods to apply biochar or similar amendments are limited to surface broadcasting, which may or may not be followed by tillage, and less commonly, banding. These application methods do not strategically place the biochar in the common root zone of about 6–8 in. where soil water is most rapidly depleted due to evaporation, drainage, and transpiration.

This four-year study examines the benefits of modifying soil architecture using ‘vertical-point injection’ of biochar in a furrow-irrigated Western Colorado hay field. To quantify the water-holding capacity, and other potential benefits of vertical-point injection using biochar, a two-by-two factorial experimental design was used. The field was divided into four north-south oriented strips and outfitted with a dense soil sensor network consisting of twelve Campbell Scientific data loggers and thirty-six soil sensors at three depths. From west to east, strips 1 (BC50) and 2 (CON50) had a deficit irrigation treatment, receiving irrigation once per month while strips 3 (BC100) and 4 (CON100) were irrigated twice per month, typical of a grass hay crop in Western Colorado. BC strips were treated with biochar, injected at a rate of 1.56 tons·acre^{-1}, while CON strips had no soil amendment.

Through 2023–2026 irrigation seasons (April–October), average volumetric water content (VWC – soil moisture) at 6 in. depth was 42.5% higher in BC50 than in CON50 and 11.4% higher in BC100 than in CON100. Average VWC minima (driest periods each month) at 6 in. was 58.3% higher in BC50 compared to CON50 and 14.5% higher in BC100 compared to CON100. BC100’s 6 in. advantage faded to less than 1 VWC point by 2025–2026. After irrigation in 2024–2026, BC50 lost moisture 37–41% more slowly than CON50 at 6 and 12 in., while BC100 lost moisture 22% more slowly than CON100 at

12 in. and at about the same rate at 6 in. After treatment, BC50 averaged 16.5% more total soil microbial biomass (PLFA) than CON50 and BC100 averaged 24.2% more than CON100, although change from baseline did not differ significantly. CO2 soil respiration started within 5% of controls and then averaged 58% higher in BC50 and 39% higher in BC100, and soil health scores averaged 35% and 18% higher, with those gaps narrowing by spring 2026. Grass hay yield in BC50 trailed CON50 by 6.3% and BC100 trailed CON100 by 9.9%; however, recommended macronutrients in the biochar strips (based on a 2-ton-per-acre yield goal) were 34% less N, 12% less P and 27% less K than in the control strips. Monthly irrigation used 35% less water than twice-monthly irrigation, with no loss in yield or forage quality, although irrigation level was assigned by field half. Because each treatment was applied to a single unreplicated strip, these are strip-level comparisons rather than proven treatment effects. They suggest that vertical-point injection using biochar can increase shallow soil moisture and slow the drying rate in an Entisol with a loam-texture surface horizon, particularly under deficit irrigation, although that moisture did not increase hay yield. Because Entisols are widespread, this methodology could have substantial agronomic, natural resources, or soil health benefits in arid soils or drought-prone regions. Independent of these outcomes, the study showed that granular soil amendment can be placed at 6–8 in. in an established perennial stand without tillage, and the results justify further investigation.

2. Introduction

It is estimated that over 50% of the water in the Colorado River is used for agriculture (Figure 1); thus, the opportunity to increase water use efficiency is enormous (Richter et al. 2024). The Colorado River Basin has been experiencing drought conditions since at least 2000, as climate change drives an increasingly warm, dry semi-arid West (Udall and Overpeck 2017). The arid southwestern agricultural region relies on water from the Colorado River Basin and is an example of the extreme effects of a changing climate. It is the primary geographical focus of this novel concept evaluation study.

Soil organic carbon (SOC) is a well-proven source of water-holding capacity. In addition, it is estimated that global carbon inputs would need to be increased by 29% to maintain present SOC stocks in agricultural soils (Wiesmeier et al. 2016). In general, increasing SOC stocks requires an increase in biomass production through practices such as cover cropping or reduced tillage. These processes take years to build a soil rich in carbon, especially when starting with a soil that is very low in organic matter. A common practice to increase both soil organic carbon and water-holding capacity is the addition of organic matter either through continuously growing cover crops or by the direct addition of manure, compost, or other organics. Biochar offers an alternative to compost or manure. Its recalcitrant properties allow it to persist in the soil for hundreds of years (Wang et al. 2016).

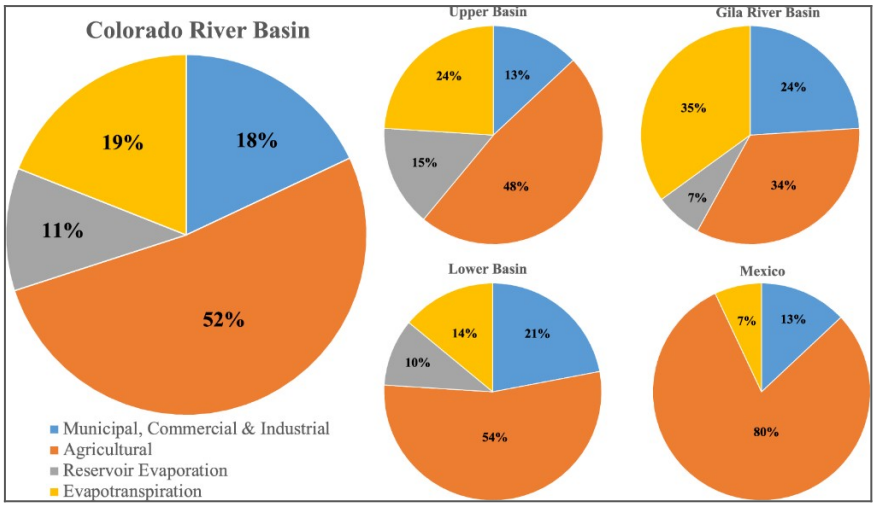


Figure 1. Water consumptive use graphs of the Colorado River (Richter et al. 2024).

A key challenge to using biochar is how to place it in the root zone. Minimizing soil disturbance is a core principle of good soil health, as disturbance contributes to unnecessary erosion, disrupts soil biota, and requires replanting of a crop or vegetation afterward (Natural Resources Conservation Service, Organic Farming Research Foundation. 2026). Existing methods of incorporating biochar amendments into soil, such as surface broadcasting, tillage, and banding, have demonstrated generally positive results across various soil textures. However, these methods present a fundamental trade-off. Surface application minimizes soil disturbance but may not optimize biochar's effects within the root zone or plow layer (Xie et al. 2021), while tillage achieves deeper incorporation at the cost of significant soil disruption (Yan et al. 2022).

Moreover, these methods may not be an option for existing or perennial systems such as orchards or specialty crops found in Western Colorado and throughout many Western U.S. agricultural communities (Lowstuter 2024). In field conditions, hoe-dug pit applications demonstrated a strong positive correlation between subsurface biochar placement and increased maize yields (Cornelissen et al. 2013) and pumpkin yields by up to a factor of four (H. Schmidt et al. 2015). Schmidt et al. also demonstrated that biochar applied at low dosage (below about 0.45 tons per acre) directly to the root zone produced substantial pumpkin yield increases even in fertile soils, suggesting that placement precision, rather than application volume, may be the more critical variable.

In a controlled laboratory setting, two pipe experiments that varied depth placement of biochar produced differing results: one showed a positive correlation between biochar placement depth at the surface (0–2 in.) and plow layer (0–12 in.) and decreased water drainage and nitrate leaching (Hamada, Nakamura, Kanda, et al. 2024b), while the other found that plow layer application (0–12 in.) worsened nitrogen absorption and induced frequent dry stress in the shallow-soil layer, inhibiting root growth in that zone (Hamada, Nakamura, and Kuniyoshi 2024a). These findings suggest that while plow layer incorporation of biochar may hold significant agronomic potential, its effectiveness has varied in laboratory settings and needs to be tested under crop-farming conditions.

This study tests a novel “vertical-point injection” technology for biochar in a hay field in Western Colorado. This technology minimizes soil disturbance while modifying soil texture and structure with a low-dose stable carbon amendment (biochar), resulting in a semi-permanent/permanent conduit extending from the soil surface vertically down into the root zone. This method can be thought of as acting on the soil in two ways. Physically, the resulting structure and deposits of material act as a conduit for water infiltration into the soil and gas exchange and oxygenation of roots. Biogeochemically, biochar deposits may act as micro-reservoirs or “hot spots” for water, nutrients, and microbes. Conceptually, the “vertical-

point injection” can be thought of as a “soil battery”, storing resources for later use. In this study, biochar is treated not as a general soil amendment, but as a structural resource applied to address specific functional limitations within the soil system. We hypothesize that biochar systematically installed into the soil using this method will increase soil moisture and water retention, while having the added benefits of promoting beneficial microbiological activity, increasing soil health metrics, and decreasing the needed rate and frequency of fertilizer applications.

3. Trial Field Setting

3.1 Description & Location

Located at Colorado State University's Western Colorado Research Center in Fruita, Colorado, the trial field encompasses about 1.6 acres established with perennial dryland grass originally planted at 30 lb. per acre on March 27, 2017. The Buffalo Brand Seed (Greeley, CO) was composed of Dahurian wildrye (24.8%), perennial ryegrass (19.8%), orchard grass (14.6%), intermediate wheatgrass (14.4%), smooth brome (13.7%), and Russian wildrye (9.61%). The trial field measures approximately 184 ft. wide (east-west) by 370 ft. long (north-south) and gently slopes south towards the Colorado River, located roughly 2.4 miles to the south. This area is largely representative of agricultural system soils found in the arid Grand Valley of Western Colorado. The northeastern corner of the research field site is located at coordinates 39.179927° N, 108.696670° W.

3.1.1 Climate

The area is situated at an elevation of about 4,590 ft. above mean sea level, receiving an average of 6–9 in. of precipitation per year, and has a mean annual air temperature of 50–55°F, with 140–180 frost-free days.

3.1.2 Soil

The soil of the trial field is defined as 94.5% Sagrlite loam (Re) and 5.5% Glenton very-fine sandy loam as outlined in the Custom Soil Resource Report using the Web Soil Survey tool (https://websoilsurvey.nrcs.usda.gov/app/). The Sagrlite series consists of very deep, well-drained soils that are formed in alluvium from shale and sandstone and are on alluvial fans and terraces. The taxonomic order of these soils is classified as Entisols (young soils with little horizon development) and sub-order, Torriorthents (Entisols that form on unstable landscapes like alluvial fans, terraces or steep slopes in arid climates) (Figure 2). Entisols are the most prevalent soils on Earth and account for an estimated 18% of the Earth's ice-free land area (University of Idaho 2026); yet peer-reviewed articles explicitly studying biochar in Torriorthents, or Entisols broadly, as a primary focus are rare in the literature, and no studies were identified using biochar in the Torriorthent suborder specifically, highlighting a significant gap in biochar research for one of the world's most widespread soil orders. Thus, in general, the methods and results of this study are applicable and relevant to soil types and moisture regimes found in the United States and beyond (Figure 3). The complete climate and soil description can be found in the Soil Report (Appendix A).

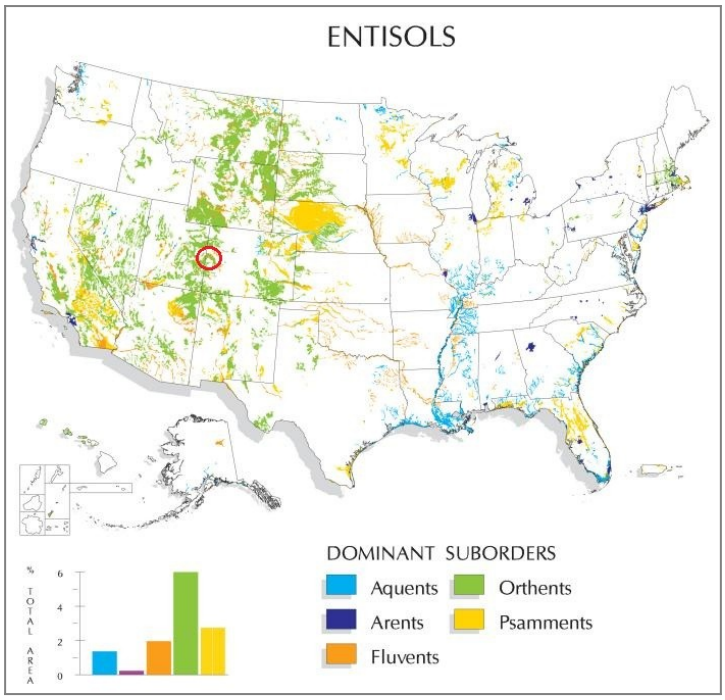


Figure 2. The research field is in the west-central area of Western Colorado, U.S.A., 19 miles east of the Utah border (trial field region depicted in the red circle). The study site is comprised of an Orthent dominant suborder of Entisols (USDA n.d.-a).

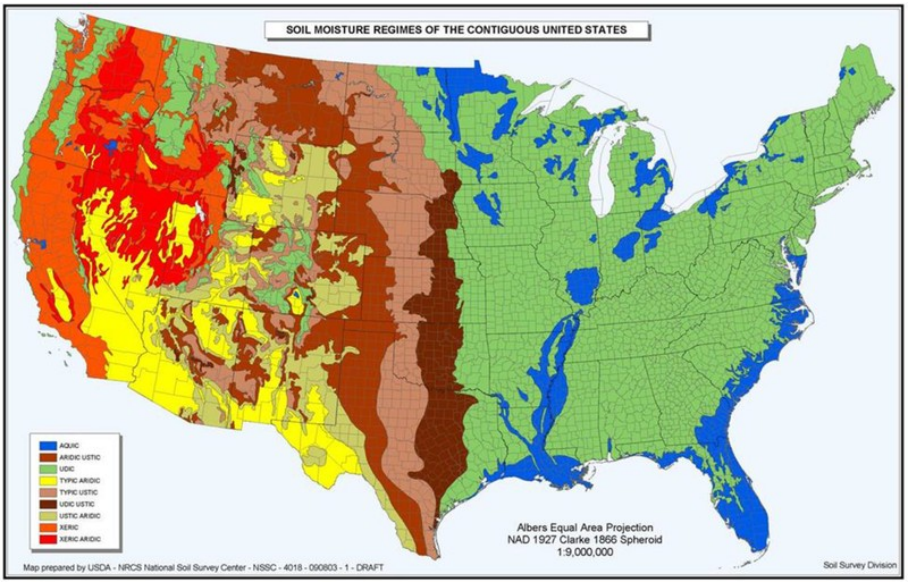


Figure 3. Map of contiguous United States Soil Moisture Regimes (USDA/NRCS 2009). The study site is located within a Typic Aridic moisture regime in Western Colorado.

3.1.3 Experimental Design

To best fit our budget, time and resources available, the trial is a 2 × 2 factorial experimental design. The field was divided into four strips, each approximately 47 ft. wide by 370 ft. long (0.4 acres), north to south. Each strip has 3 datalogger and sensor locations (stations) – located near the top, middle

and bottom of each strip (Figure 4). We use T (top), M (middle), and B (bottom) to describe the location of that strip's loggers. For example, S1T is the top (north-most) logger in strip 1. These locations are in the middle of each strip to reduce influence from neighboring strips. From west to east, strip 1 (BC50) and strip 3 (BC100) were treated with biochar, injected at a rate of 1.56 tons per acre while strip 2 (CON50) and strip 4 (CON100) had no soil amendment. BC50 and CON50 had a deficit irrigation treatment, receiving irrigation once per month while BC100 and CON100 were irrigated twice per month, typical of a grass hay crop in western Colorado.

Table 1. Strip treatments and corresponding abbreviations.

Strip	**1**	**2**	**3**	**4**
Treatment	Biochar	Control	Biochar	Control
Irrigations per Month	1	1	2	2
Treatment Abbreviation	BC50	CON50	BC100	CON100



Figure 4. Experimental design field map. The four strip names are abbreviated with their respective treatments, and the logger and sensor locations are denoted. Satellite image was captured May 6, 2023.

3.1.4 Installation of Soil Sensors and Loggers

Soil sensors and loggers were installed using a skid-steer-mounted auger, and sensors were each measured for their precise installation at depths of 6, 12, and 18 in. (Figure 5).



Figure 5. Boring 12 in. diameter holes using a skid-steer-powered soil auger (left). A sensor hole showing streaks of carbon in the soil after the biochar application (middle). Soil sensor installation at 6, 12, and 18 in. depths below the surface (right).

3.2 Field and Lab Data Collected

The following data were collected in this four-year study:

- At 15-minute intervals – weather data from a Colorado State University weather station, soil volumetric water content (VWC; also known as soil moisture), bulk electrical conductivity (EC) and soil temperature (T).
- Once a month for S1 and S2 and twice per month for S3 and S4 during the growing season – irrigation application duration, frequency, rate, and volume.
- At least twice per year, spring and fall – biomass yield, near-infrared spectrometry (NIRS) forage analysis, soil health analysis (SHA), and phospholipid fatty acid (PLFA) soil microbiological analyses.
- Spring fertilizer applications.
- Ancillary data include bulk density (2024), normalized difference vegetation index (NDVI; 2023 and 2026), and soil plant analysis development (SPAD; 2023). These additional data were collected to help explain or support other findings in the study. NDVI is a common metric that is used to evaluate the overall general health of a crop based on its reflectance of red and infrared light (Tucker 1979).

3.2.1 Pre-Trial Soil Fertilization and Baseline Sampling

The experiment uses soil tests to determine both fertilizer application and soil health metrics. Except for the pre-trial sample, all test results were prepared by Ward Laboratories (Kearney, NE). The pre-trial fertilization testing (spring 2023) consisted of two composite soil samples, one from BC50 and CON50 and another from BC100 and CON100. To create the composite, five soil samples were collected

in each half of the field in an “X” pattern at a depth of 0–12 in. using a Giddings truck-mounted soil probe on February 8, 2023 (Figure 6). The field was fertilized based on the soil sample results provided by American Agricultural Laboratory, Inc. (McCook, NE).

Using a three-point granular broadcast spreader on March 17, 2023, all strips received 69 lb./acre of nitrogen and 75 lb. per acre of phosphate. BC50 and CON50 both received 25 lb per acre of potassium and BC100 and CON100 both received 100 lb./acre of potassium. Based on local farmers’ recommendations, more fertilizer was applied than the test results recommended (Appendix B). Fertilizer sources for this and all subsequent fertilizations were from Urea (46-0-0), Mono-Ammonium Phosphate (11-52-0), and Potassium Sulfate (0-0-50).

After the pre-trial fertilization and prior to field treatment, baseline soil sampling was conducted to characterize soil health indicators across each strip of the experimental field. Four soil samples were collected at each of the three logger locations in each strip. The samples were collected using a manual metal auger from the cardinal directions, within approximately a 60 in. radius from the datalogger. Cores were collected to a depth of 12 in., corresponding to the primary root zone. The 4 cores at each of the three locations in a strip were combined and thoroughly homogenized to form a single composite sample. Composite sampling was used to reduce microscale spatial variability while providing a representative sample for each location. The composite samples were submitted to Ward Laboratories for soil health and biological analysis. All soil sampling procedures were applied uniformly across all strips and sampling locations. A total of 32 composite soil samples were collected over four years (Appendix C).



Figure 6. Lobato conducts pre-trial soil sampling using a Giddings soil probe during spring 2023.

3.2.2 Pre-Trial Seeding

On March 29, 2023, a seed drill was used to overseed the field with 30 lb. (18.75 lb per acre) of dryland grass seed mix sourced from Southwest Seed (Dolores, CO). The mix was comprised of smooth brome (29%), orchard grass (19.6%), pubescent wheatgrass (19.6%), crested wheatgrass (14.8%), Russian wildrye (9.7%), and annual ryegrass (5%).

3.2.3 Biochar Source and Application

The biochar used in this experiment was purchased from VGrid Energy Systems (Camarillo, California). It is made from pistachio shell waste processed in a mobile pyrolysis system at high temperatures (>2,372°F). The product is a hard, durable, and highly porous biochar that closely resembles

an activated carbon rather than a low-temperature, friable wood biochar (Figure 7). It contains 84.9% carbon, as tested by Control Laboratories (Watsonville, CA) or 90% carbon as tested by Wyoming Laboratories (Laramie, WY) (see https://biocharresearch.org/?tab=biochar-analysis). The bulk density of this material is 13.2 lb.·ft.-3. The granular size used in this study was the 'standard' size of approximately 0.04–0.08 in.

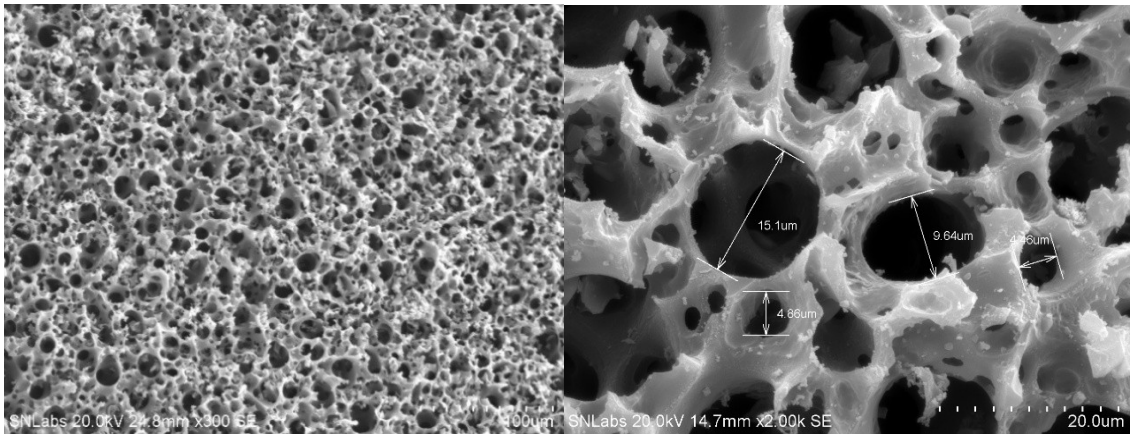


Figure 7. Scanning Electron Microscope images of biochar derived from pistachio shells. The scale is noted at the bottom right of each photo.

Scientific research suggests that low-dose biochar placement near the root zone is optimal (H. P. Schmidt et al. 2015), yet no known replication of these results has been conducted in a Western Colorado hay field. The project took advantage of equipment normally used to inject sand into golf putting greens and athletic fields. Owned and operated by DryJect Colorado, the machine hydraulically aerates turf while simultaneously depositing sand, resulting in improved water infiltration rates and playing surfaces. This machine was selected for this study because it was the closest available means of placing low-dose biochar directly into the root zone, consistent with the approach suggested by Schmidt et al. (2015), and of carrying out what the lead author conceptualized in the fall of 2022.

Using the DryJect equipment, biochar was injected raw (without charging or inoculation) into the soil profile in a grid-like pattern, to a depth of 6–8 in. (Figure 8) on May 9, 2023. A total of 7.0 cubic yds of biochar was applied to strips BC50 and BC100, each 0.4 acres (1.56 tons per acre), which accounts for about 0.8% by volume within the applied soil depth (Appendix D). In the absence of prescribed biochar application rates using this method, the rate for this study was selected to balance practical application logistics with the goal of achieving meaningful soil benefits at the lowest feasible input and cost. This approach is reinforced by evidence of persistent biochar effects in arid and semi-arid agricultural soils (Idowu and Brewer 2018). CON50 (S2) and CON100 (S4) did not receive any soil amendment. The soil aeration machine used approximately 6,000 gallons of water to inject the biochar into the soil.



Figure 8. Applying biochar while Nelson assists with moving the water supply hose (left). Photo showing injection points on the soil surface (right).

Below is an AI-generated conceptual image to depict the deposition of biochar in the soil. To the best of our knowledge, this technique has not been attempted or studied elsewhere. We refer to this method as vertical-point injection (VPI) (Figure 9).

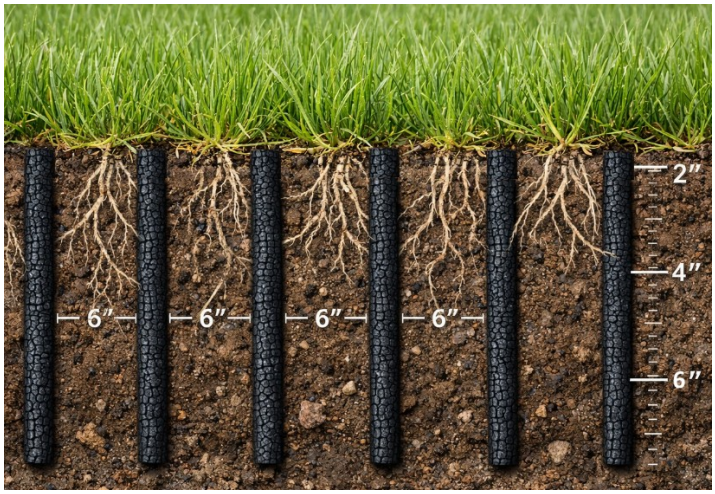


Figure 9. An AI-generated image portraying the concept of vertical-point injection.

3.2.4 Irrigation Method

A McCrometer Flowmeter was used to obtain irrigation flow rates and total water applied (Figure 10). The trial field is flood furrow irrigated using furrows on 30 in. centers using 6 in. aluminum gated pipe. The furrows were creased and cleaned May 2023 and in April 2024 – 2026. This method of irrigation is common in the Grand Valley and in much of Western Colorado. Six-inch elbows were purchased to create a "bump" consistent with the manufacturer's installation specifications. A tee and two valves were installed to direct water to either the western or eastern half of the field, depending on the irrigation schedule. BC50 and CON50 were irrigated approximately once per month, while BC100 and CON100 were irrigated approximately twice per month. The applied irrigation totals for each year and each treatment can be found in Appendix E. Complete irrigation data can be downloaded at https://biocharresearch.org/?tab=bulk_downloads



Figure 10. The installed flow meter, bump, tee, and valve assembly.

3.2.5 Soil Sensor Data Collection

Soil sensor data were collected at 15-minute intervals using 12 Campbell Scientific CR206X dataloggers, each connected to three CS650 sensors that measure volumetric water content (VWC; soil moisture), temperature, and electrical conductivity (EC) (Figure 11). Data were transmitted via spread-spectrum radio from the dataloggers to a central base station, then relayed through a satellite internet connection (Starlink) to a remote data management system (See https://biocharresearch.org/?tab=technical-details). Data were stored as time-stamped records and downloaded for subsequent filtering, aggregation, and statistical analysis.

Results for EC, Temp, and VWC were calculated from raw sensor data collected at 15-minute intervals. Blank and non-numeric records were removed, along with VWC values ≤ 0% or > 50%, EC values outside the sensor's 0–8 dS/m measurement range, and soil temperatures outside 10–120°F. The 15-minute data were then averaged to daily values for each sensor (days with at least 12 hours of readings), and extreme daily outliers beyond the mean ± 4 SD were removed. Additionally, data from the 18 in. sensor at S3B were excluded from all analyses because many values were inconsistent and substantially lower than those recorded by other sensors at the same depth across all locations and strips. That sensor may have been faulty or obstructed by a foreign object, such as a rock, large root, or debris which may have affected its measurement. The 18 in. VWC sensor at S3T was also excluded from June 2026 onward, when more than 20% of its readings exceeded 50% VWC. The same sensor was excluded from the EC analysis from August 2025 onward, when its EC readings rose sharply and abnormally. To discern which effects (biochar, irrigation, interaction) accounted for statistically significant signals, we used a two-way analysis of variance (ANOVA) model on monthly strip means. Because each treatment combination was applied to a single strip, months were treated as repeated measures in place of independent field replicates, and the resulting statistics describe differences among these four strips. Daily sensor values were averaged to monthly values (months with at least 15 valid days), and the three sensors at the same depth in each strip were then averaged to produce one value for that month, per strip, per depth; only months with data from all four strips were used. Sensor data from the irrigation seasons beginning April 1 and ending October 31, 2023 – 2026 (up to 27 months) were examined (Appendix F to Appendix H.



Figure 11. Nelson checking logger and sensor function.

3.2.6 Hay Sampling Method

Composite biomass (hay) samples were collected at four cardinal locations (north, south, east, and west) around each of the three datalogger stations within each of the four strips (Figure 12). Sampling was conducted 2–3 ft. from each datalogger at each location. A PVC sampling frame with internal dimensions measuring 19.7 in. × 19.7 in. (2.7 ft²) was placed at each sampling location, and all biomass within the frame, above its top, was cut, collected, bagged, and labeled in a black plastic bag for storage. All bags were stored in a shaded area until they could be brought to the lab for weighing. Once all samples were collected, each bag was taken to the lab and weighed. Before each fresh composite biomass sample was weighed, a 1.6-oz. sub-sample was removed. This 1.6-oz. sample was sent to Ward Laboratories for near-infrared spectrometry (NIRS) forage quality analysis. The remaining amount was then placed into labeled brown paper bags and oven-dried at 131°F for 24 hours. Samples were then reweighed and returned to the oven for an additional 24 hours at 131°F to ensure constant mass, resulting in a total drying time of 48 hours. Final dry weight measurements were recorded following the 48-hour drying period. A total of 44 hay samples were submitted to Ward Laboratories for forage quality analysis. The field was maintained by using a tractor-mounted 60 in. wide rotary cutter “brush hog” to cut the grass to a length of 2–4 in. after each hay sampling event.



Figure 12. Stanley collects hay samples.

3.2.7 Statistical Analysis and Limitations

To fit the available budget and field layout, each treatment combination was applied to one strip, and irrigation was assigned by the west and east halves of the field. Months, cuttings, and sampling dates are therefore repeated measurements of four strips rather than independent field replicates, and biochar, irrigation, and field position cannot be fully separated. Control strips received no sham injection pass, and the sensor record begins in May 2023, the month of injection, so no pre-treatment sensor baseline exists. ANOVA and false-discovery-rate results in this report describe differences among these four strips, not proven treatment effects. This limitation applies to all results. Because each treatment combination occupies one strip, the F, p, and q values in this report use repeated measurements (months, sampling dates, or irrigation events) as the error term. They show how consistently a strip-to-strip difference held over time, not that the treatment caused it. In addition, each biochar strip lies directly west of its paired control (strips 1 and 3 vs. 2 and 4), so a west-to-east soil gradient within the field could appear as a consistent biochar–control difference at both irrigation levels. Terms such as “biochar effect” in the tables and text refer to this biochar-strip versus control-strip contrast.

All ANOVAs in this report used the same two-way fixed-effects model, response = biochar + irrigation + biochar × irrigation, fitted by ordinary least squares with Type II sums of squares (Python statsmodels). Each factor has two levels, so each effect has one numerator degree of freedom. Sampling time (month, cutting or sampling event) was not included as a blocking factor, so variation over time remains in the error term. Effect size is reported as η^2 (effect sum of squares ÷ total sum of squares), and effects were considered significant at $p \leq 0.05$. The response and replication differed by data set. For the soil sensor data (VWC, EC and temperature), the response was the monthly strip mean, and each depth was analyzed separately for April–October months (N = 104–108; 26–27 months per strip); temperature was also analyzed for all months (N = 160; 40 months per strip). For VWC minima, the response was the average of the driest 10% of days in each month for each strip and depth (N = 104–108). For hay quality (NIRS), the response was the dry-basis value for each strip at each of the 11 cuttings (N = 44; N = 12 for variables reported only in 2024). For soil health (SHA) and PLFA, the response was the change from each strip’s March 2023 pre-treatment baseline at each of six post-baseline sampling events (N = 24). For SHA, PLFA and hay quality, *p*-values were also adjusted for multiple comparisons with the Benjamini–Hochberg false-discovery-rate procedure across all tests in each data set and are reported as *q*.

After the initial ANOVA, two further comparisons were added to account for this design and for baseline differences. Biochar and control strips were compared directly within each irrigation level on each date, and the sensor comparison used matched stations and depths for April–October months. For the drying analysis, daily April–October VWC data from 2024–2026 were used because many 2023 readings were unreliable. Irrigation events were identified from rises of at least 3 VWC points per day in 6 in. strip means, and moisture loss was compared over days 2–11 after each event at matched stations, depths, and dates, using 22 events in the monthly strips and 32 in the twice-monthly strips. Results were similar with a 5-point threshold.

3.3 Ancillary Data Methods

3.3.1 Soil Bulk Density Testing Method

The authors used a Madera bulk density soil sampler to collect two samples from each strip on October 30 and November 1, 2024. The sample locations were between the top and middle logger stations and between the middle and bottom logger stations. Samples were weighed before and after oven drying in soil tins, and the bulk density was calculated. Data from both sampling events were used to calculate the bulk density. See section 5.1Bulk Density.

3.3.2 Normalized Difference Vegetation Index (NDVI) Sampling Method

Vegetation biomass and vigor were assessed using the Normalized Difference Vegetation Index (NDVI) measured with a Trimble GreenSeeker handheld crop sensor. The GreenSeeker is an active optical sensor that emits red and near-infrared light and calculates NDVI based on the proportion of reflected wavelengths, producing values ranging from 0.00 to 0.99, with higher values indicating greater plant biomass and vigor; it is primarily used at the field scale.

NDVI measurements were collected at each installed datalogger at the three sampling stations per strip. At each location, the sensor operated at a height of approximately 48 in. above the field while the operator walked a full circular transect at a radius of approximately 5 ft. from the datalogger, maintaining continuous measurement by holding the trigger throughout the transect. NDVI values recorded during each circular pass were averaged to generate a representative NDVI value for each sampling location. NDVI data were collected on August 24 and October 5, 2023, corresponding to mid-season and late-season crop growth stages.

NDVI data were also collected using a DJI Matrice 350RTK drone fitted with a MicaSense Altum-PT multi-spectral camera flown on July 28, 2026.

3.3.3 Soil Plant Analysis Development (SPAD) of Proportional Chlorophyll Present Method

Leaf chlorophyll content and relative nitrogen (N) status can be assessed using Soil Plant Analysis Development (SPAD). In general, higher values indicate more chlorophyll in the leaf tissue of the sample; it is best used at the leaf tissue scale. Randomly selected composite samples of individual grass blades were collected for chlorophyll assessment using a Minolta Chlorophyll Meter SPAD-502. The SPAD meter estimates chlorophyll concentration by measuring leaf light absorbance in the red and near-infrared wavelength regions, producing a unitless SPAD index proportional to chlorophyll concentration within the leaf tissue. For each strip, SPAD measurements were taken approximately 3 ft. from each datalogger at four cardinal locations (north, south, east, and west). Individual grass blades were randomly selected at each sampling location, and measurements were consistently taken from the lower one-third of each blade to minimize within-leaf variability. SPAD data were collected on July 10, August 24, and October 5, 2023. See Table 11.

4. Results

4.1 Project Website

Please visit ***www.biocharresearch.org*** to explore all current and historical field, lab and sensor data from this project. Detailed data or information not included in this report can be accessed on the website.

4.2 Volumetric Water Content (VWC)

Volumetric water content (VWC) is the percentage of the total soil volume occupied by water. This project asks whether injecting biochar to a depth of approximately 6–8 inches below the soil surface improves water retention in a pasture field. VWC means were consistently greater overall in biochar-amended strips than in controls at all depths, as were VWC minimums. Over the four irrigation seasons (April–October, 2023–2026), at the 6 in. depth, BC50 averaged 25.4% VWC, CON50 averaged 17.8%, BC100 averaged 23.6% and CON100 averaged 21.2% (Appendix E). When calculating % gain, average VWC % gain (Δ BC50-CON50) was 42.5%, 20.6%, and 8.9% at 6, 12, and 18 in., respectively. In the twice-monthly irrigated strips, VWC % gain (Δ BC100-CON100) was 11.4%, 8.8%, and 19.8% at 6, 12, and 18 in., respectively (Figure 13, Figure 14; Appendix I).

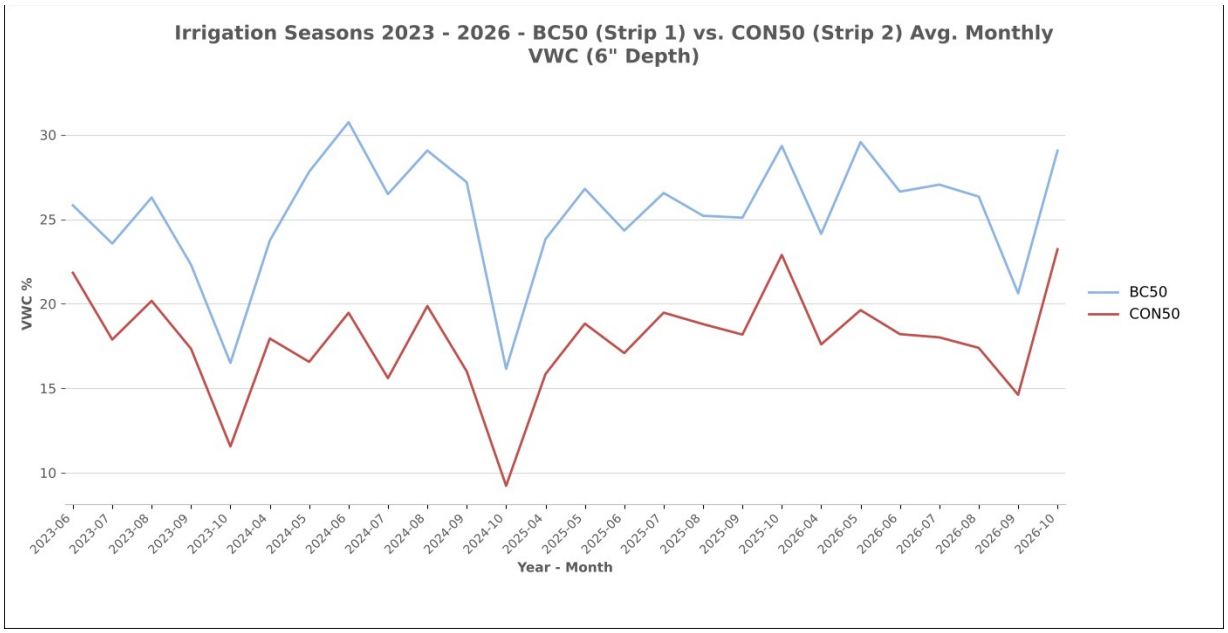


Figure 13. Monthly VWC averages at 6 in. depth of BC50 and CON50 for irrigation seasons (April–October) 2023–2026.

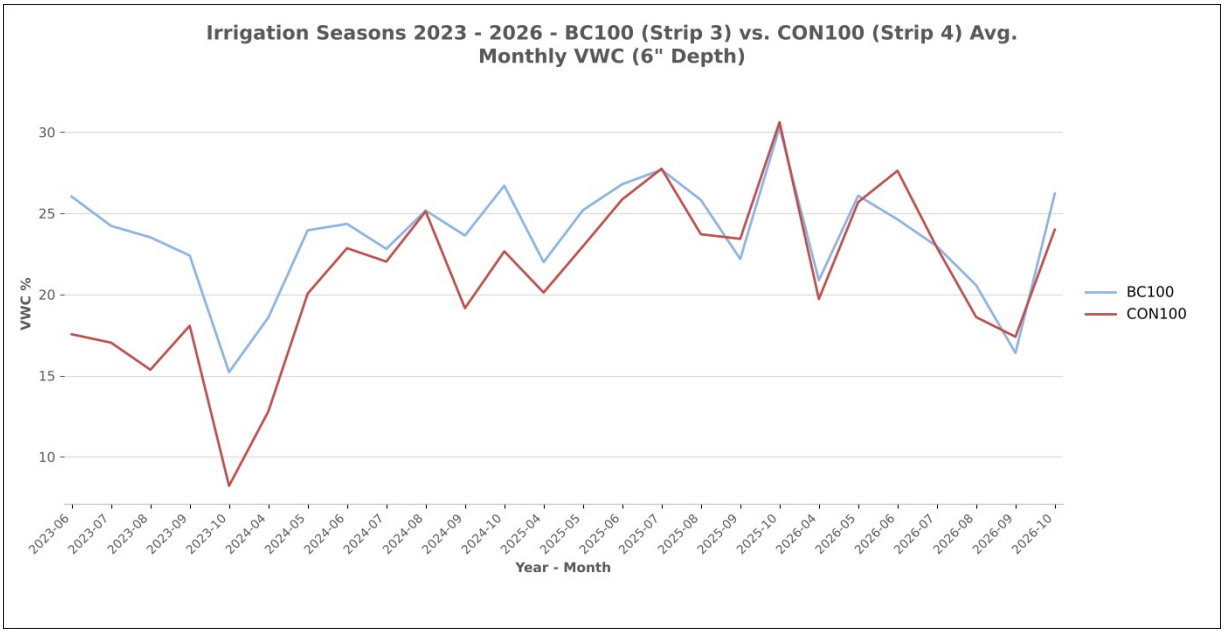


Figure 14. Monthly VWC averages at 6 in. depth of BC100 and CON100 for irrigation seasons (April–October) 2023–2026.

Using a two-way ANOVA of monthly strip means for April–October, the biochar–control strip difference in VWC was significant at all three depths: a very large effect at 6 in. ($F = 45.3$, $p < 0.001$, $\eta^2 = 0.29$) and large effects at 12 in. ($F = 22.0$, $p < 0.001$, $\eta^2 = 0.16$) and 18 in. ($F = 17.9$, $p < 0.001$, $\eta^2 = 0.14$). Biochar × irrigation interaction had a moderate effect at 6 in. ($\eta^2 = 0.08$) influenced by a larger biochar effect under deficit irrigation (BC50). Irrigation frequency had smaller, but significant effects at 12 in. ($\eta^2 = 0.06$) and 18 in. ($\eta^2 = 0.04$) (Table 2). Only effects significant at $p \leq 0.05$ are shown in Tables 2, 3, 5, and

7. In this report, η^2 effect sizes are labeled small (< 0.07), moderate (0.07–0.13), large (0.14–0.25), and very large (≥ 0.26).

Table 2. A two-way ANOVA of monthly mean VWC, April–October 2023–2026 (N = 26–27 months per treatment × depth; months serve as repeated measures).

VWC 2x2 ANOVA April 1 - Oct 31, 2023-2026						
Depth (in)	**Factor**	**F**	**p-value**	**η^2**	**Effect Size**	**Direction**
6	Biochar	45.3	<0.001	0.29	Very Large	↑ with Biochar
12	Biochar	22.0	<0.001	0.16	Large	↑ with Biochar
18	Biochar	17.9	<0.001	0.14	Large	↑ with Biochar
6	Interaction	12.0	<0.001	0.08	Moderate	Biochar effect greatest in BC50
12	Irrigation	7.8	0.006	0.06	Small	↑ with twice-monthly irrigation
18	Irrigation	4.7	0.032	0.04	Small	↑ with twice-monthly irrigation

Focusing only on the 10th-percentile monthly minima (for each strip and depth, the three sensors were averaged by day, and the driest 10% of days in each month were averaged) using the same filtering methods as above, VWC % gain (Δ BC50-CON50) was 58.3%, 31.9%, and 13.6% at 6, 12, and 18 in., respectively. In the twice-monthly irrigated strips, VWC % gain (Δ BC100-CON100) was 14.5%, 13.4%, and 27.8% at 6, 12, and 18 in., respectively (Figure 15 and Figure 16 Appendix J). A two-way ANOVA of these monthly minima showed a significant biochar–control strip difference at every depth (6 in.: $F = 49.6$, $p < 0.001$, $\eta^2 = 0.30$; 12 in.: $F = 31.1$, $p < 0.001$, $\eta^2 = 0.18$; 18 in.: $F = 21.6$, $p < 0.001$, $\eta^2 = 0.15$). Irrigation frequency also raised the minima at 12 and 18 in. ($\eta^2 = 0.22$ and 0.11) but not at 6 in., and a biochar × irrigation interaction at 6 in. ($\eta^2 = 0.08$) indicated that the biochar benefit during the driest periods was greatest under deficit irrigation.

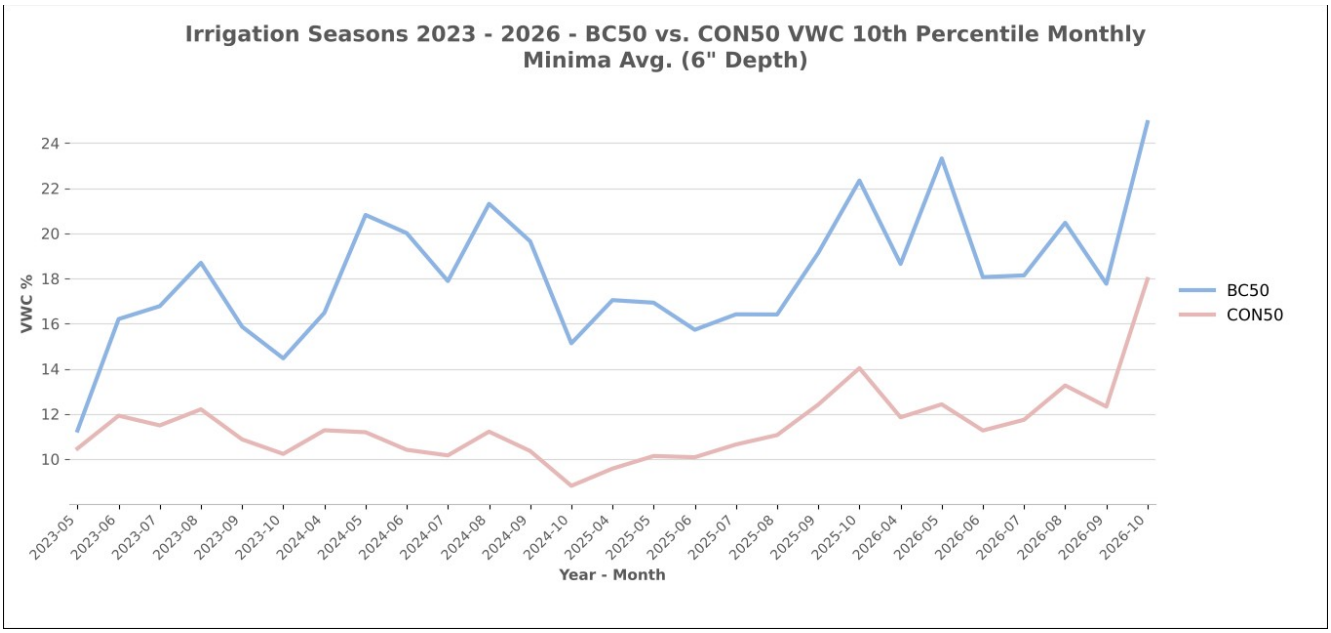


Figure 15. Monthly 10th-percentile VWC minima at 6 in. depth for BC50 and CON50 for irrigation seasons (April–October) 2023–2026.

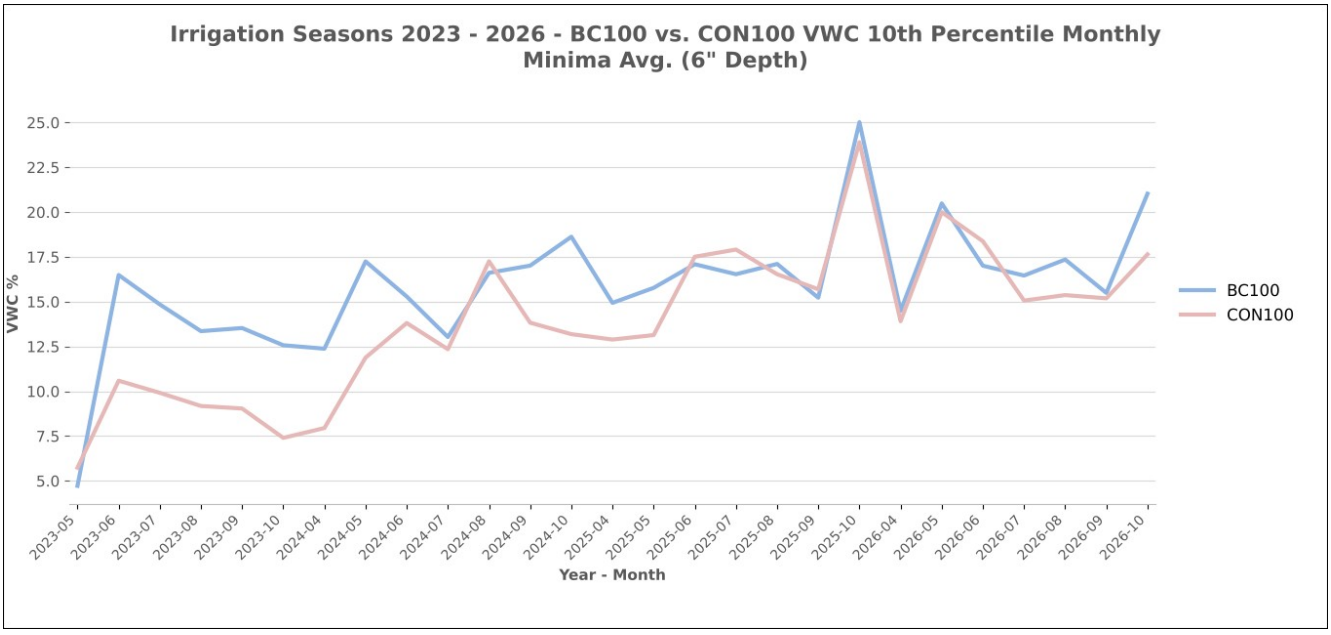


Figure 16. Monthly 10th-percentile VWC minima at 6 in. depth for BC100 and CON100 for irrigation seasons (April–October) 2023–2026.

4.2.1 Matched Station and Drying-Rate Comparisons

When the same stations and depths were compared by month, BC50 exceeded CON50 by 7.3 VWC percentage points at 6 in. (26 of 27 months) and 4.2 percentage points at 12 in. (25 of 27 months). BC100 exceeded CON100 by 2.5 percentage points at 6 in. (21 of 26 months), but that gap fell from 7.5 percentage points in 2023 to 0.8 in 2025 and 0.5 in 2026. At 18 in., below the injection zone, the gap was

inconsistent in BC50 (15 of 26 months) and persistent in BC100 (7.1 percentage points, 27 of 27 months, two stations). At 6 in., only the top stations favored biochar at both irrigation levels (11.2 and 6.6 points); differences were 1.1 and 3.2 points at the middle stations and 9.6 and −5.3 points at the bottom stations.

After irrigation, BC50 lost 0.74 VWC percentage points per day at 6 in. and 0.56 at 12 in., compared with 1.18 and 0.95 in CON50. BC50 dried more slowly on 20 of 22 events at 6 in. and 21 of 22 events at 12 in., at all three stations and in all three years. Over days 2–11, BC50 lost 18% of its starting 6 in. moisture and CON50 lost 36%. BC100 and CON100 dried at similar rates at 6 in. (1.09 and 1.05 points per day; 17 of 32 events), while BC100 dried more slowly at 12 in. (0.46 and 0.59; 24 of 32 events), mainly at its top station. During days 12–16, CON50's 6 in. moisture loss slowed to 0.60 points per day while BC50 continued at 0.92, consistent with a larger water reserve in BC50. The twice-monthly strips were typically rewatered after about 14 days, compared with about 30 days for the monthly strips, so this late-cycle response could not be fully evaluated in BC100.

4.3 Bulk Electrical Conductivity (EC)

Electrical conductivity (EC) measures how readily the soil–water system conducts electricity. Conductivity increases as the concentration and mobility of dissolved ions increase, and as temperature and soil moisture rise. Ions contributed to EC include plant nutrients and soluble salts. Since biochar does not typically include water-soluble material, the expectation is that a ratio of biochar to non-biochar strip ECs would be determined by other differences between the strips. Bulk EC was analyzed with the same two-way ANOVA (Table 3; summary statistics in Appendix G). The biochar–control strip contrast was significant at all three depths ($\eta^2 = 0.12$ at 6 in., 0.11 at 12 in., and 0.06 at 18 in.), and irrigation had two significant effects, decreases with twice-monthly irrigation at 6 in. ($\eta^2 = 0.03$) and 18 in. ($\eta^2 = 0.08$). Biochar × irrigation interactions were also significant at all depths ($\eta^2 = 0.28$ at 6 in., 0.26 at 12 in., and 0.43 at 18 in.). Mean EC was higher in BC50 than in CON50 at every depth (for example, 0.63 vs. 0.29 dS/m at 6 in. and 0.94 vs. 0.46 dS/m at 18 in.), whereas BC100 was lower than CON100 at every depth (0.35 vs. 0.43 dS/m at 6 in., 0.55 vs. 0.63 dS/m at 12 in., and 0.43 vs. 0.65 dS/m at 18 in.). Biochar did not consistently raise or lower EC by itself; the size and direction of its effect depended on irrigation frequency, with the largest increases under deficit irrigation. Most of BC50's EC gap came from its bottom station (0.88–1.11 dS/m across depths). BC50 and CON100 were also the saltier strips in the laboratory data, so the EC interaction appears to reflect a tail-of-field pattern more than a biochar response.

Table 3. A two-way ANOVA of monthly mean bulk EC, April–October 2023–2026 (months serve as repeated measures).

EC 2x2 ANOVA, April 1–Oct 31, 2023–2026						
Depth (in)	**Factor**	**F**	**p-value**	**η^2**	**Effect Size**	**Direction**
6	Biochar	21.4	<0.001	0.12	Moderate	↑ with biochar (driven by BC50)
12	Biochar	18.2	<0.001	0.11	Moderate	↑ with biochar (driven by BC50)
18	Biochar	14.6	<0.001	0.06	Small	↑ with biochar (driven by BC50)
18	Interaction	103.2	<0.001	0.43	Very Large	↑ in BC50, ↓ in BC100
6	Interaction	52.2	<0.001	0.28	Very Large	↑ in BC50, ↓ in BC100
12	Interaction	42.1	<0.001	0.26	Very Large	↑ in BC50, ↓ in BC100
18	Irrigation	20.5	<0.001	0.08	Moderate	↓ with twice-monthly irrigation
6	Irrigation	5.9	0.017	0.03	Small	↓ with twice-monthly irrigation

Note: Results sorted by factor and then η^2 effect size

4.4 Temperature

There were no statistically significant effects of biochar, irrigation or their interaction on soil temperature at any depth, and mean temperatures differed by less than 1°F among strips (Appendix H).

The 2023 temperature records (June–October) were nearly constant at about 32.4°F in all strips, which is not plausible for summer soil and likely reflects a sensor or logger fault. They are not retained in the summary statistics and ANOVA as provided, so the temperature data is primarily from 2024–2026.

4.5 Hay Yield

An initial hypothesis that hay yields would be higher in the biochar strips because of greater water (and possibly nutrient) availability, with a larger effect in the deficit-irrigated strip was not supported. Table 4 shows the hay yield for each strip. Three sampling events were conducted each year except for 2026, where only two hay sampling events occurred. Biochar strips averaged lower yields than controls within the same irrigation treatment; CON50 had the highest average yield and BC100 the lowest. From 2023 through October 2026 (11 cuttings), average yield per cutting (tons per acre) was 0.47 ± 0.18 (mean ± SD), 0.51 ± 0.25, 0.43 ± 0.21, and 0.48 ± 0.24, and cumulative yield was 5.22, 5.57, 4.75, and 5.27 tons per acre for BC50, CON50, BC100, and CON100, respectively (Table 4). While BC strip averages and maximum yields were less than their respective CON strips, BC strips displayed less error and variability. BC strip minimum yields are also notably higher (Figure 17 and Figure 18). Through October 2026, BC50 produced 6.3% less grass hay than CON50, while BC100 produced 9.9% less grass hay than CON100 (Table 4). Due to scheduling and funding uncertainties, fertilizer was applied much later than in previous years (June 27, 2026); as a result, grass growth was minimal and there was no spring 2026 cutting.

The table includes the yearly total yield for each strip. Lower biomass production in the biochar strips during 2024 and 2025 coincided with lower nitrogen applications, and in 2024 with substantial differences in phosphorus and potassium as well (Appendix B). The available annual totals cannot yet distinguish a direct biochar effect from differences in nutrient management, water availability, pre-existing strip conditions, or sampling variability.

Table 4. Hay yield (tons per acre) by sampling date, with annual totals.

Hay Yield (tons·acre⁻¹) 2023–2026				
Strip	**1**	**2**	**3**	**4**
Treatment	**BC50**	**CON50**	**BC100**	**CON100**
6/12/2023	0.23	0.32	0.16	0.32
7/26/2023	0.33	0.19	0.15	0.12
10/6/2023	0.25	0.13	0.40	0.15
5/31/2024	0.64	0.84	0.57	0.54
7/25/2024	0.71	0.85	0.27	0.43
9/9/2024	0.56	0.76	0.49	0.59
6/6/2025	0.25	0.32	0.23	0.30
7/28/2025	0.47	0.40	0.43	0.77
10/28/2025	0.55	0.64	0.55	0.71
7/28/2026	0.60	0.58	0.76	0.55
10/16/2026	0.63	0.53	0.74	0.79
Total Tons/Acre 2023	0.81	0.64	0.70	0.59
Total Tons/Acre 2024	1.91	2.46	1.33	1.56
Total Tons/Acre 2025	1.26	1.36	1.21	1.79
Total Tons/Acre 2026	1.23	1.12	1.51	1.34
Cumulative Tons/acre	**5.22**	**5.57**	**4.75**	**5.27**
Avg. Annual Tons/Acre	**1.30**	**1.39**	**1.19**	**1.32**
Std. Error of Mean	0.23	0.39	0.17	0.26

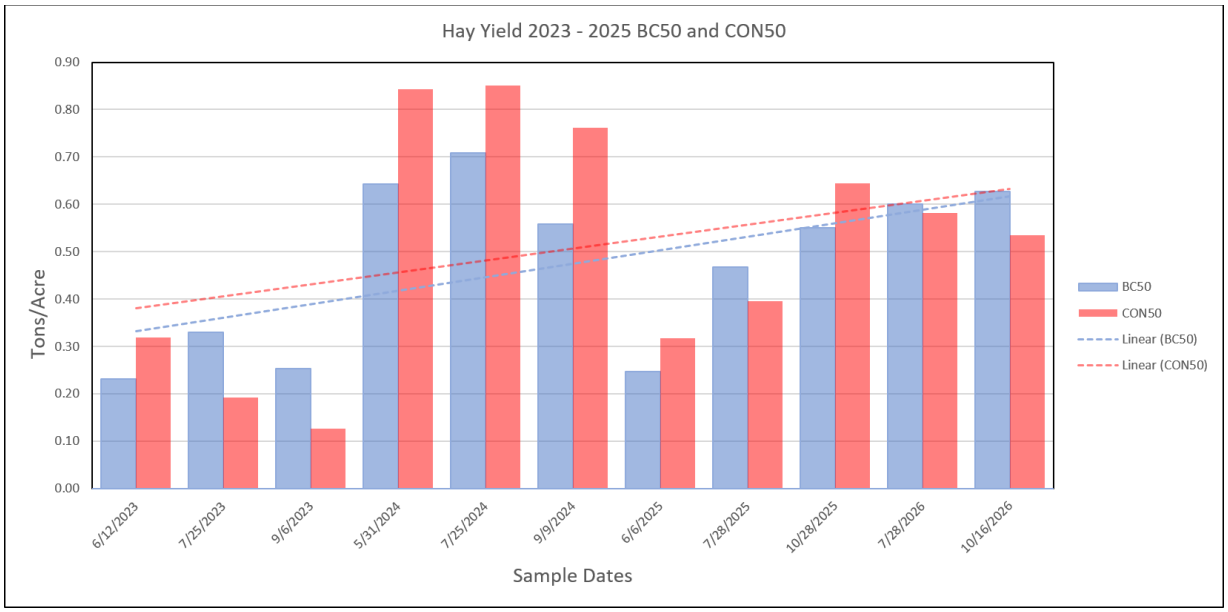


Figure 17. Hay yield per cutting (tons per acre) in strips BC50 and CON50, 2023–2026.

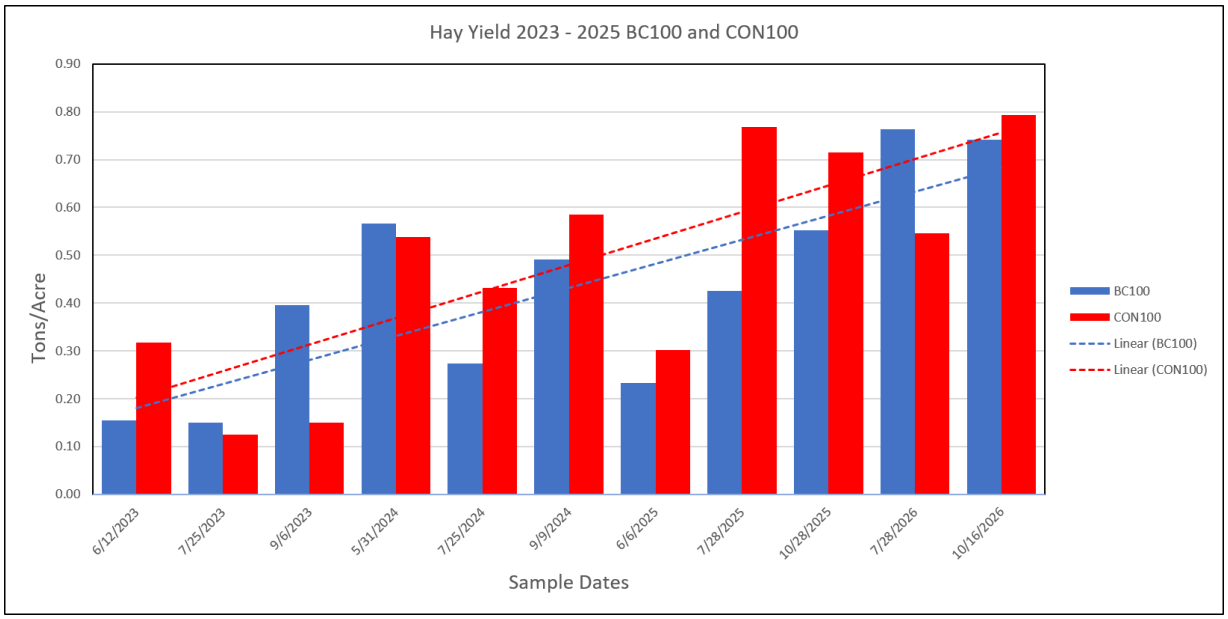


Figure 18. Hay yield per cutting (tons per acre) in strips BC100 and CON100, 2023–2026.

4.6 Laboratory Results

4.6.1 Fertilizer Recommendations

In 2023, prior to amendment application, each irrigation treatment received the same fertilizer based on their initial samples, i.e., BC50 and CON50 received the same amount of fertilizer and BC100 and CON100 received the same amount of fertilizer (Appendix B). In four years, 34% less nitrogen, 12% less phosphorus, and 27% less potassium were recommended for the biochar strips. Finally, 13% more

manganese was recommended for the biochar strips in this naturally manganese-deficient soil. All fertilizer recommendations were for a 2-ton-per-acre annual yield goal for dryland grass and were provided by the lab reports. Applied rates, which were generally higher than the recommended rates, are listed in Appendix B, and totals are summarized in Appendix K.

Nitrogen use efficiency (NUE), measured as the partial factor productivity of nitrogen (PFPN; tons of hay per lb. of N applied), was 33.5% higher in BC50 than in CON50 and 17.7% higher in BC100 than in CON100 (Appendix L). However, due to the limited number of fertilization replicates, this difference was not statistically significant at p-value ≤ 0.05. The NUE difference is largely driven by the 2024 recommendations, where nearly no fertilizers were recommended or applied for the BC strips.

4.6.2 Hay Quality (NIRS)

Hay quality was analyzed from the Ward Laboratories NIRS reports for all 11 cuttings (2023–2026; 44 samples) using dry-basis values. Average relative forage quality (RFQ) was higher in BC50 (122.6) and CON50 (123.1) than in BC100 (113.3) and CON100 (109.2), and a two-way ANOVA showed this irrigation effect was statistically significant ($F = 4.2$, $p = 0.048$, $\eta^2 = 0.09$). TDN % was similar within each irrigation level (60.1% in BC50 vs. 60.2% in CON50; 58.4% in BC100 vs. 57.1% in CON100), and crude protein was slightly lower in the biochar strips (12.2% vs. 12.5% in the 50s; 10.8% vs. 11.1% in the 100s) (Appendix M). No hay quality variable showed a significant biochar main effect at $p \leq 0.05$. Metabolizable energy, reported only for the three 2024 cuttings, showed a significant interaction ($p = 0.041$), but with N = 12 this result is not considered robust.

4.6.3 Soil Health Analysis (SHA)

Because soil health metrics in each strip can start at differing values, this two-way delta ANOVA was calculated by using the first soil test (pre-soil treatment) as a baseline and analyze how values change from the baseline over time (Table 5). Each strip contributed a single baseline sample, and the 24 post-baseline deltas (4 strips × 6 post-baseline sampling events, fall 2023 through spring 2026) were treated as repeated observations; with one strip per treatment combination, these describe differences among the four strips rather than replicated treatment effects. Summary statistics of statistically significant variables only are presented, and complete SHA statistics are in Appendix N.

Soil is a complex and dynamic system, and it is helpful to sort variables into groups of effects to assist in parsing out the overarching theme of what changes are taking place. Because several metrics are statistically significant, the SHA data is sorted by variable, then effect size (η^2), so the main driver of the variable can be identified. In the analysis, significant biochar and interaction effects appear 24 times, while significant irrigation effects appear 11 times. Because 30 SHA variables were each tested for three effects (90 tests) without correction for multiple comparisons, some of these results are expected by chance; after Benjamini-Hochberg false-discovery-rate adjustment across all 90 tests, 17 effects remained at $q \leq 0.05$ (all three nitrate-N effects; the irrigation effects on %K saturation, %Mg saturation, soil pH, iron, magnesium and Olsen P; the interaction effects on %Ca saturation, magnesium, manganese, organic N and sodium; and the biochar effects on manganese, sulfate and total N). Five further effects narrowly missed this threshold ($q = 0.0502$): the interaction effects on %Na saturation, %Mg saturation, sulfate and total N, and the biochar effect on potassium. Of the 11 significant biochar effects, only those on nitrate-N, manganese, sulfate and total N remained at $q \leq 0.05$, and each reflects strip differences more than a consistent biochar response: BC50's high nitrate-N baseline, CON100's high manganese baseline, sulfate accumulation in CON100, and higher total N baselines in the biochar strips. Effects with $q > 0.05$ should be treated as exploratory (Table 5).

Table 5. A two-way delta ANOVA model of all statistically significant variables ($p \leq 0.05$). N = 24 (4 strips × 6 post-baseline sampling events, fall 2023–spring 2026). Results sorted by variable and then η^2 (effect size) large-to-small. q = Benjamini–Hochberg false-discovery-rate-adjusted p-value across all 90 SHA tests; bold = $q \leq 0.05$.

Soil Health Analysis Two-Way Delta ANOVA						
Variable	**Effect**	**F**	**p-value**	**q-value**	**η^2**	**Effect Size**
%Ca Sat	Interaction	9.8	0.005	**0.036**	0.30	Very Large
%K Sat	Irrigation	46.5	<0.001	**<0.001**	0.66	Very Large
%Mg Sat	Irrigation	10.9	0.004	**0.029**	0.28	Very Large
	Interaction	7.6	0.012	0.0502	0.20	Large
%Na Sat	Interaction	8.1	0.010	0.0502	0.24	Large
	Biochar	5.9	0.024	0.081	0.17	Large
1:1 Salts (mmho/cm)	Interaction	6.2	0.022	0.078	0.21	Large
1:1 Soil pH	Irrigation	12.0	0.002	**0.022**	0.30	Very Large
	Biochar	6.9	0.016	0.062	0.18	Large
Calcium (ppm)	Irrigation	5.0	0.037	0.105	0.20	Large
CEC/Sum of Cations (me/100g)	Irrigation	6.3	0.021	0.078	0.21	Large
Iron (ppm)	Irrigation	15.2	<0.001	**0.011**	0.36	Very Large
Magnesium (ppm)	Irrigation	12.3	0.002	**0.022**	0.29	Very Large
	Interaction	8.5	0.008	**0.047**	0.20	Large
Manganese (ppm)	Interaction	27.3	<0.001	**<0.001**	0.44	Very Large
	Biochar	9.8	0.005	**0.036**	0.16	Large
	Irrigation	5.3	0.032	0.097	0.08	Moderate
NO3-N H2O (ppm)	Irrigation	164.0	<0.001	**<0.001**	0.53	Very Large
	Biochar	63.3	<0.001	**<0.001**	0.21	Large
	Interaction	60.8	<0.001	**<0.001**	0.20	Large
Olsen P (ppm)	Irrigation	9.6	0.006	**0.037**	0.26	Very Large
Organic C H2O (ppm)	Biochar	4.4	0.048	0.125	0.16	Large
Organic C:N H2O	Biochar	5.7	0.027	0.086	0.18	Large
	Interaction	4.5	0.046	0.125	0.14	Large
Organic N H2O (ppm)	Interaction	17.4	<0.001	**0.007**	0.36	Very Large
	Biochar	6.1	0.023	0.078	0.13	Moderate
	Irrigation	5.0	0.037	0.105	0.10	Moderate
Potassium (ppm)	Biochar	7.8	0.011	0.0502	0.21	Large
	Interaction	5.4	0.031	0.097	0.15	Large
Sodium (ppm)	Interaction	8.5	0.009	**0.047**	0.26	Very Large
	Biochar	4.4	0.049	0.125	0.13	Moderate
Sulfate (ppm)	Biochar	8.4	0.009	**0.047**	0.22	Large
	Interaction	7.7	0.012	0.0502	0.20	Large
Total N H2O (ppm)	Biochar	14.7	0.001	**0.012**	0.35	Very Large
	Interaction	7.7	0.012	0.0502	0.18	Large

4.6.3.1 Soil Chemical Environment

Chemical environment results include soil pH and cation exchange capacity (CEC)/sum of cations. Soil pH is driven primarily by irrigation and displayed a mean delta increase from baseline in BC50 and CON50 (0.06) while BC100 and CON100 displayed a decrease (-0.29). CEC was driven primarily by irrigation and displayed the same pattern with an increase in 50s treatments (0.51) and a decrease in 100s (-1.22) (Table 6).

4.6.3.2 Ionic Balance/Salinity

Ionic balance/salinity includes %Ca Sat, %Mg Sat, %Na Sat, 1:1 Salts, and Sodium. All but %Mg Sat were driven primarily by an interaction between biochar and increased irrigation frequency (2x irrigations per month). %Ca Sat increased in BC100 (1.33), was unchanged in CON50, and decreased in

BC50 (-1.50) and CON100 (-3.17). %Mg Sat was driven primarily by irrigation, with an interaction as a secondary driver; it increased in the 50s (0.17) and decreased in the 100s (-0.83), with the greatest increase in BC50 (0.67) and the greatest decrease in BC100 (-1.17). %Na Sat increased in BC50 (1.50) and in both controls (most in CON100, 3.67) and decreased only in BC100 (-0.67); biochar was a secondary driver of both %Na Sat and sodium. 1:1 Salts decreased only in BC100 (-0.23) and increased in all other strips, most in CON100 (0.49). Sodium (ppm) only decreased in BC100 (-40.50), while CON100 increased the most (173.50), reinforcing a strong interaction effect of biochar and increased irrigation frequency on saline minerals.

4.6.3.3 Nutrient Retention and Storage

Nutrient retention and storage include Potassium and Total N, both of which were driven primarily by biochar followed by an interaction as a secondary driver. Biochar strips decreased in both potassium (-14.83) and total N (-8.57) while controls displayed a larger decrease in potassium (-40.00) and a smaller decrease in total N (-4.89). The potassium result came mainly from BC50 (4.00), which stayed near its baseline while the other strips declined, and its biochar effect narrowly missed the false-discovery threshold ($q = 0.0502$). Total N remained higher in the biochar strips after treatment (13.13 ppm vs. 11.31 ppm), so their larger delta reflects higher baselines (21.70 ppm vs. 16.20 ppm) rather than faster N loss. The BC50 baseline values for water-extractable nitrate, total N and organic N were much higher than those of the other strips, so part of the apparent decline in BC50 reflects its starting value.

4.6.3.4 Organic Matter/Nutrient Cycling

Organic Matter/Nutrient Cycling includes water-extractable organic C and organic C:N, both driven primarily by biochar (with an interaction as a secondary driver of C:N), and organic N, driven primarily by an interaction followed by biochar and irrigation. Water-extractable organic C declined from baseline in all strips, but less in the biochar strips (-18.58) than in the controls (-34.00). Biochar strips displayed an increase in organic C:N (2.97) while controls displayed a smaller increase (1.15). Regarding organic N, CON100 displayed the smallest decrease (-3.43) while BC100 displayed the greatest decrease (-9.87).

4.6.3.5 Soluble Nutrient Dynamics

Soluble Nutrient Dynamics includes %K Sat, calcium, iron, magnesium, manganese, nitrate, Olsen P, and sulfate. These variables are driven primarily by an irrigation effect, except manganese, which is primarily driven by an interaction effect, and sulfate, which is primarily driven by biochar. %K Sat displayed a mean delta decrease in the 50s (-0.83) while the 100s increased slightly (0.08). Calcium increased in the 50s (18.17) and decreased in the 100s (-226.00), while iron decreased in the 50s (-8.59) and decreased more in the 100s (-11.74). Magnesium was driven by irrigation, followed by an interaction effect, increasing in the 50s (13.42) and decreasing in the 100s (-34.92). Manganese was driven by an interaction followed by biochar and irrigation and decreased in all strips, least in BC100 (-1.78) and most in CON100 (-2.78). Nitrate had the most ambiguity, with two secondary drivers: biochar and interaction. Nitrate decreased in the 50s (-1.79) and increased in the 100s (0.36). Olsen P decreased in the 50s (-1.58) and decreased more in the 100s (-4.48). Finally, sulfate increased far less in the biochar strips (26.63) than in the controls (103.30), with the largest change in CON100 (157.68) and the smallest in BC100 (7.63) (Appendix O).

Table 6 below groups statistically significant variables by their respective functional groups and only the largest effect size for a given variable (primary driver) is presented along with the observed pattern. Chemical environment variables were driven primarily by irrigation, ionic balance/salinity mostly by an interaction of irrigation and biochar, nutrient retention & storage by biochar, organic matter/nutrient cycling by biochar and an interaction, and soluble nutrient dynamics largely by irrigation, with manganese driven by an interaction and sulfate by biochar. 1:1 salts, calcium, CEC, organic C, organic C:N, potassium and %Na Sat had no effect at $q \leq 0.05$, so their patterns are exploratory.

Table 6. Functional grouping of statistically significant SHA variables.

Functional Grouping of Statistically Significant SHA Variables			
Primary Group	**Variable**	**Primary Driver**	**Observed Pattern**
Chemical Environment	1:1 Soil pH	Irrigation	Δ increase in 50 irr. (0.06), decrease in 100 irr. (-0.29)
	CEC/Sum of Cations (me/100g)	Irrigation	Δ increase in 50 irr. (0.51), decrease in 100 irr. (-1.22)
Ionic Balance / Salinity	%Ca Sat	Interaction	Strongest mean Δ BC100 (1.33), lowest CON100 (-3.17)
	%Mg Sat	Irrigation	Δ increase in 50 irr. (0.17), decrease in 100 irr. (-0.83)
	%Na Sat	Interaction	Strongest mean Δ CON100 (3.67), lowest BC100 (-0.67)
	1:1 Salts (mmho/cm)	Interaction	Strongest mean Δ CON100 (0.49), lowest BC100 (-0.23)
	Sodium (ppm)	Interaction	Strongest mean Δ CON100 (173.50), lowest BC100 (-40.50)
Nutrient Retention and Storage	Potassium (ppm)	Biochar	BCs decrease in Δ (-14.83) vs. CONs (-40.00)
	Total N H2O (ppm)	Biochar	BCs decrease in Δ (-8.57) vs. CONs (-4.89)
Organic Matter / Nutrient Cycling	Organic C H2O (ppm)	Biochar	BCs decrease in Δ (-18.58) vs. CONs (-34.00)
	Organic C:N H2O	Biochar	BCs increase in Δ (2.97) vs. CONs (1.15)
	Organic N H2O (ppm)	Interaction	Strongest mean Δ CON100 (-3.43), lowest BC100 (-9.87)
Soluble Nutrient Dynamics	%K Sat	Irrigation	Δ decrease in 50 irr. (-0.83), increase in 100 irr. (0.08)
	Calcium (ppm)	Irrigation	Δ increase in 50 irr. (18.17), decrease in 100 irr. (-226.00)
	Iron (ppm)	Irrigation	Δ decrease in 50 irr. (-8.59), decrease in 100 irr. (-11.74)
	Magnesium (ppm)	Irrigation	Δ increase in 50 irr. (13.42), decrease in 100 irr. (-34.92)
	Manganese (ppm)	Interaction	Strongest mean Δ BC100 (-1.78), lowest CON100 (-2.78)
	NO3-N H2O (ppm)	Irrigation	Δ decrease in 50 irr. (-1.79), increase in 100 irr. (0.36)
	Olsen P (ppm)	Irrigation	Δ decrease in 50 irr. (-1.58), decrease in 100 irr. (-4.48)
	Sulfate (ppm)	Biochar	BCs increase in Δ (26.63) vs. CONs (103.30)

4.6.4 Soil Biology (PLFA – Balser)

We hypothesized that biochar might improve overall soil microbial activity or function. PLFA results showed several statistically significant biochar, irrigation, and interaction effects on community structure and membrane-lipid stress indicators (Table 7). As with the SHA data, each PLFA variable was analyzed as the change from its strip's March 2023 baseline (N = 24; 4 strips × 6 post-baseline sampling events). The CON100 baseline sample was atypical for several ratios, so many of the largest deltas reflect its starting point, and post-baseline values were broadly similar between biochar and control strips. Biochar strips did average higher fungi:bacteria ratios and total microbial biomass than controls after treatment, but no total biomass, bacteria or fungi effect was significant. Post-baseline total biomass averaged 16.5% higher in BC50 than CON50 and 24.2% higher in BC100 than CON100. Only relevant or statistically significant results are presented in Table 7; summary statistics are in Appendix P. The monounsaturated:polyunsaturated ratio is not reported because its CON50 baseline value (209.97, versus 3–15 in all other samples) appears to be a laboratory error that dominates the analysis. After excluding that ratio, 26 PLFA variables were each tested for three effects (78 tests) without correction for multiple comparisons; after Benjamini-Hochberg false-discovery-rate adjustment across all 78 tests, 13 of the 16 significant effects remained at $q \leq 0.05$. The fungi:bacteria, saprophytes % and Pre 18:1w7c:cy19:0 interaction effects did not pass this test. PLFA results will be updated when fall 2026 data are available.

Table 7. A two-way delta ANOVA model of PLFA data (change from baseline). N = 24 (4 strips × 6 post-baseline sampling events, fall 2023–spring 2026). Results sorted by factor and η^2 effect size. N = 23 for Pre 18:1w7c:cy19:0. q = Benjamini–Hochberg false-discovery-rate-adjusted p-value across all 78 reported PLFA tests; bold = q ≤ 0.05.

PLFA Two-Way Delta ANOVA						
Variable	**Effect**	**F**	**p-value**	**q-value**	**η^2**	**Effect Size**
Sat:Unsat	Biochar	89.9	<0.001	**<0.001**	0.52	Very Large
Pre 16:1w7c:cy17:0	Biochar	152.4	<0.001	**<0.001**	0.47	Very Large
Pre 18:1w7c:cy19:0	Biochar	27.9	<0.001	**<0.001**	0.45	Very Large
Gram(+):Gram(-)	Biochar	27.0	<0.001	**<0.001**	0.34	Very Large
Gram (-) %	Biochar	10.2	0.005	**0.029**	0.24	Large
Pre 16:1w7c:cy17:0	Interaction	122.1	<0.001	**<0.001**	0.38	Very Large
Fungi:Bacteria	Interaction	7.0	0.015	0.085	0.25	Very Large
Saprophytes %	Interaction	5.3	0.032	0.155	0.20	Large
Sat:Unsat	Interaction	29.1	<0.001	**<0.001**	0.17	Large
Gram(+):Gram(-)	Interaction	12.8	0.002	**0.015**	0.16	Large
Pre 18:1w7c:cy19:0	Interaction	6.5	0.020	0.103	0.10	Moderate
Gram (-) %	Irrigation	10.7	0.004	**0.027**	0.25	Very Large
Gram(+):Gram(-)	Irrigation	19.0	<0.001	**0.003**	0.24	Large
Sat:Unsat	Irrigation	34.9	<0.001	**<0.001**	0.20	Large
Pre 18:1w7c:cy19:0	Irrigation	9.3	0.007	**0.040**	0.15	Large
Pre 16:1w7c:cy17:0	Irrigation	28.7	<0.001	**<0.001**	0.09	Moderate

4.6.4.1 Community Balance

Community Balance consists of the Fungi:Bacteria ratio and the saprophytic fungi share of total biomass, both driven only by an interaction effect, although neither effect remained at q ≤ 0.05. For Fungi:Bacteria, the strongest mean delta from baseline occurs in CON100 (0.059), while the largest decrease is in CON50 (-0.009). The Fungi:Bacteria ratio was higher on average in the biochar strips BC50 (0.38), BC100 (0.37) and lower in the controls CON50 (0.35), CON100 (0.32). Saprophytes (% of total biomass) increased most in CON100 (2.06) and BC50 (1.02) and decreased slightly in BC100 (-0.45) and CON50 (-0.08), although average saprophyte shares were higher in the biochar strips (BC50 12.2%, BC100 12.5%) than in the controls (CON50 10.6%, CON100 10.3%). Additionally, across all seven sampling events (including baseline), total microbial biomass averaged higher in the biochar strips BC50 (3419.2 ng/g), BC100 (3477.1 ng/g) compared to the controls CON50 (2894.6 ng/g), CON100 (2851.0 ng/g) (Appendix Q).

4.6.4.2 Community Structure

Community Structure consists of gram (-) % driven primarily by irrigation with a secondary biochar driver, and gram(+):gram(-) with a primary driver of biochar and secondary drivers of irrigation and interaction. Gram (-) % displayed a small increase in the 50s (0.97) and a larger increase in the 100s (6.25). Gram(+):gram(-) decreased in biochar strips (-0.10) with a large decrease in the controls (-0.76).

4.6.4.3 Stress/Membrane Dynamics

Significant findings in Stress/Membrane Dynamics, which encompass two monounsaturated fatty acid to cyclopropyl fatty acid ratios, Pre 16:1w7c:cy17:0 and Pre 18:1w7c:cy19:0, and a Saturated:Unsaturated ratio, are driven primarily by biochar, followed by interaction and irrigation. Mean delta of Pre 16 ratios decreased more in BC50 (-1.79) than CON50 (-1.52) while BC100 had the largest decrease (-2.97) and CON100 had the only increase (1.88). Mean delta of Pre 18 ratios decreased in both biochar strips BC50 = -0.15, and BC100 = -0.06, while the ratio increased in both controls CON50 = 0.47, and CON100 = 1.76. Saturated: Unsaturated fatty acid ratios decreased in both BC50 and BC100 (Avg. = -0.16) while the ratios had a greater decrease in CON50 and CON100 (Avg. = -0.62) (Appendix Q). These deltas are strongly influenced by the baseline sample. The CON100 baseline (March 31, 2023)

was atypical for these ratios (Sat:Unsat = 2.28 vs. 1.40–1.65 in the other strips; Pre 16:1w7c:cy17:0 = 2.01 vs. 5.39–6.80; Pre 18:1w7c:cy19:0 = 0.56 vs. 2.02–2.53), so the CON100 deltas largely reflect its starting point; post-baseline mean values of these ratios were similar in biochar and control strips.

Table 8 groups statistically significant variables by their respective functional groups and only the largest effect size for a given variable (primary driver) is presented along with the observed pattern. Community balance (fungi:bacteria and saprophytes) is driven by an interaction of irrigation and biochar, community structure by both irrigation (gram -) and biochar (gram +:gram -), and stress/membrane dynamics driven by biochar.

Table 8. Functional grouping of significant PLFA variables.

Functional Grouping of Statistically Significant PLFA Variables			
Primary Group	**Variable**	**Primary Driver**	**Observed Pattern**
Community Balance	Fungi:Bacteria	Interaction	Strongest mean Δ CON100 (0.059), lowest CON50 (-0.009)
	Saprophytes %	Interaction	Strongest mean Δ CON100 (2.06), lowest BC100 (-0.45)
Community Structure	Gram (-) %	Irrigation	Δ increase in 50 irr. (0.97), increase in 100 irr. (6.25)
	Gram(+):Gram(-)	Biochar	BCs decrease in Δ (-0.10) vs. greater decrease in CONs (-0.76)
Stress / Membrane Dynamics	Pre 16:1w7c:cy17:0	Biochar	BCs decrease in Δ (-2.38) vs. CONs (0.18)
	Pre 18:1w7c:cy19:0	Biochar	BCs decrease in Δ (-0.10) vs. CONs (1.12)
	Sat:Unsat	Biochar	BCs decrease in Δ (-0.16) vs. CONs (-0.62)

5. Ancillary Data Results

5.1 Bulk Density

Both biochar strips averaged less bulk density than the controls. Treatment BC50 averaged 82.4 lb./ft³, while CON50 averaged 91.1 lb./ft³, a 9.4% difference. Bulk density in BC100 averaged 89.9 lb./ft³, while CON100 averaged 92.4 lb./ft³, a 2.6% difference.

5.2 NDVI

NDVI data collected on August 24 and October 5, 2023, revealed that both biochar strips had higher mean NDVI values within their respective irrigation treatments. CON50 had the lowest mean (0.405) while BC100 had the highest mean (0.502). Additionally, biochar strips regardless of irrigation treatment displayed higher minimum and maximum NDVI values (Table 9). Visibly greener biochar strips can be observed in the photo below (Figure 19).

Table 9. NDVI summary statistics collected with a GreenSeeker handheld crop sensor.

NDVI - August 24 and October 5, 2023				
Strip	**1**	**2**	**3**	**4**
Treatment	**BC50**	**CON50**	**BC100**	**CON100**
Mean	0.493	0.405	0.502	0.425
SD	0.071	0.055	0.073	0.061
Min	0.420	0.350	0.430	0.340
Max	0.580	0.470	0.600	0.520
Med	0.480	0.395	0.480	0.425



Figure 19. Photo taken June 20, 2023, looking northwest, showing all sensor stations installed. Darker green strips in BC50 and BC100 can be observed.

Biochar treatments displayed larger mean NDVI in both BC50 and BC100, a modest gain in BC50 (0.293) vs. CON50 (0.270) and a larger gain in BC100 (0.325) vs. CON100 (0.284). Increased irrigation frequency alone also increased NDVI in BC100 and CON100, but the combination of biochar and twice-monthly irrigation (BC100) produced the healthiest vegetation signal overall, both mean and median NDVI while CON50 displayed the lowest overall NDVI mean. All four plots showed minimal negative NDVI, so there is little bare soil, water, or shadow interference skewing the numbers (Table 10, Figure 20).

Table 10. Multi-Spectral NDVI drone data, 2026.

Multi-Spectral NDVI Data - July 28, 2026				
Strip	**1**	**2**	**3**	**4**
Treatment	**BC50**	**CON50**	**BC100**	**CON100**
Pixel Count	659758	660002	659875	659943
Mean	0.293	0.270	0.325	0.284
Med	0.277	0.264	0.308	0.278
SD	0.156	0.132	0.158	0.139
Min	-0.231	-0.286	-0.268	-0.361
Max	0.834	0.807	0.847	0.830
Range	1.065	1.093	1.115	1.191
Kurtosis	0.621	0.004	0.487	0.620

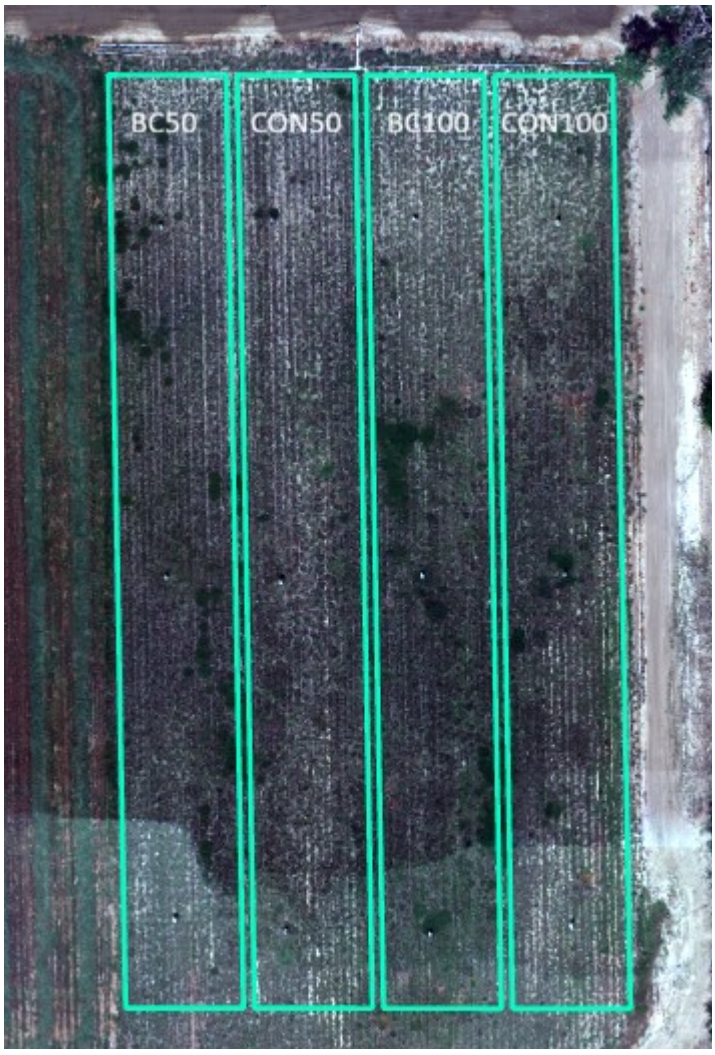


Figure 20. Multi-spectral drone image captured July 28, 2026, used to calculate NDVI.

5.3 SPAD

SPAD values varied by treatment, sampling date, and location within each strip (Table 11). A linear model using averages indicated a significant effect of sampling date ($F = 3.66$, $p = 0.038$) and station position ($F = 5.59$, $p = 0.009$), but no significant main effect of biochar treatment ($F = 1.53$, $p = 0.227$) or irrigation regime ($F = 3.85$, $p = 0.059$). These results indicate that SPAD chlorophyll content changed significantly over the season and treatment-level differences were present but were not statistically significant.

6. Interpretation

6.1 Soil and Plant Indicators

Vertical-point injection using biochar was associated with improved plant performance during the 2023 growing season, particularly under reduced irrigation. NDVI values were consistently higher in treated strips, indicating greater vegetation vigor and biomass production, with the strongest response

observed in the BC50 treatment. These trends suggest that biochar may help buffer plants against water stress by improving soil moisture availability and root-zone conditions (Yost et al. 2021; Razzaghi et al. 2020). Complementary soil moisture and field observations support a biologically mediated mechanism in which biochar enhances plant growth through improved soil–plant interactions.

SPAD chlorophyll measurements only partly followed the NDVI pattern, with a higher average in BC50 than CON50 (45.3 vs. 39.2) but a slightly lower average in BC100 than CON100 (38.2 vs. 40.9) (Table 11). The BC50 result suggests improved plant physiology under reduced irrigation, potentially linked to better water and nutrient availability. However, SPAD differences were not statistically significant, likely due to seasonal variability and spatial differences within strips. Overall, SPAD provided supportive, but less sensitive, evidence compared to NDVI, reinforcing the conclusion that biochar effects are more strongly expressed at the canopy and soil-water level than through leaf chlorophyll alone.

Table 11. SPAD summary statistics.

SPAD - July 10, Aug. 24, Oct. 5, 2023				
Strip	**1**	**2**	**3**	**4**
Treatment	**BC50**	**CON50**	**BC100**	**CON100**
N (test dates)	3	3	3	3
Avg	45.3	39.2	38.2	40.9
SD	8.4	7.3	8.6	8.5
Min	11.0	22.9	7.8	17.1
Max	57.9	52.3	51.7	58.1
Med	46.5	40.6	40.1	41.1

Hay yield lagged 6.3% in BC50 compared to CON50 and 9.9% in BC100 compared to CON100, yet 34% less N, 12% less P, and 27% less K were recommended for the biochar strips from 2023 through 2026. Despite slightly lower hay yields, biochar-injected strips improved nutrient use efficiency, indicating potential for optimization with adjusted fertility inputs at the time of biochar installation. The lower yields in the biochar strips, even though less fertilizer was recommended may be explained by the proliferation of soil biota outcompeting the plants for available nutrients (Azeem et al. 2020; Kerner et al. 2023). Interestingly, BC50 and CON50 had higher relative forage quality than BC100 and CON100 (a statistically significant irrigation effect), and CON50 had the highest cumulative yield. A logical explanation for this is that dryland grass mixes are species preconditioned to simply perform better under less frequent irrigations.

Differences in feed quality may be due to a modified soil changing a homogeneous environment to one that is heterogeneous, allowing species with inherently different feed qualities to emerge and outcompete other species as they adjust to their new environmental conditions.

6.2 VWC, SHA, PLFA

Vertical-point injection treatments appeared to rapidly improve soil-water physics while altering soil biological function and health metrics. In general, a higher ratio of PLFA suggests active microbial growth and favorable environmental conditions, while a lower ratio suggests nutrient limitations, drought or moisture stress, increased salinity, or general physiological stress.

Yu et al. (2013) demonstrated that the water-holding capacity of unamended loamy sand soil was 16% and was doubled by the addition of 9% by mass of biochar. Razzaghi et al. (2020) showed that bulk density decreased by 9% in their experiments and is nearly identical to the 9.4% decrease in bulk density that we found in BC50 versus CON50. Razzaghi et al.'s meta-analysis (2020) also showed how biochar tends to increase field capacity in coarse-textured soils (51%) more than medium-textured soils (13%) as well as increasing plant available water in coarse-textured soils (45%) vs. medium and fine-grained soils (21%, 14%). These findings are consistent with prior research in sandy loam soils, where biochar

amendments have been shown to increase gravity-drained water content by up to 23% and improve plant-available water (Basso et al. 2013).

Total microbial biomass, bacteria and fungi increased resulting in an expansion of soil biota in both treated strips, consistent with the broader literature showing biochar amendments increase microbial biomass and alter community composition in soil (Lehmann et al. 2011). This proliferation of life appeared to compete with the crop for resources such as nitrogen, minerals and water further reinforcing that the soil was amended into a dynamic state of flux undergoing rapid biological expansion. The expansion of soil biota in conjunction with reduced fertilizer inputs suggests that the system shifted from a slower-turnover system into a higher-turnover system that may be capable of processing applied nutrients more efficiently, storing water and nutrients for plants to use for longer periods of time, thus reducing overall system inputs.

Soil health indicators have trended positively overall except for the C:N ratio (Table 6). When the biochar was added without additional nutrient inputs, the C:N ratio can change meaningfully (Wang et al. 2016). Regarding Sat:Unsat fatty acids, higher Sat:Unsat (more saturated fats) ratios suggest that microbial membranes become more rigid to protect themselves from stressors such as drought, salinity, temperature, nutrient limitations or unfavorable conditions (Table 8). Low Sat:Unsat ratios suggest microbial membranes are more fluid which can indicate active growth and favorable conditions (Kerner et al. 2023).

Bryan Reed, Agricultural Professor at CMU Tech, in Grand Junction, CO and his students conducted experiments attempting to derive an optimal inoculation time of biochar soaked in compost tea. Pistachio shell biochar was submerged in compost tea for varying times and carbon dioxide measurements were collected at pre-determined intervals. Their experiments showed that optimal biological respiration occurred when soaking the biochar in the tea for 24 hours thus, future experiments should include inoculated biochar in soils to account for the C:N dynamic and to offset the presumed nitrogen depletion by expanding microbial activity.

7. Discussion

7.1 Mechanistic Discussion

Continuous sensor-based monitoring in soil amendment studies is rare and typically limited to single-depth or short-duration measurements. Existing studies tend to use isolated probes rather than a dense network of continuous data sensors, lack multi-depth spatial replication, and rarely extend beyond two to three seasons. Furthermore, many biochar studies use an applied rate of material anywhere from 5 to as much as 20 tons per acre, much greater than the 1.56 tons per acre rate used in this study. The method of biochar application used in this study is very different from common methods used in any studies found in scientific literature. To the authors' knowledge, no field studies have examined biochar amendments in Torriorthent soil specifically. The most analogous soil environment identified in the literature is Hoglund (2023) who conducted mesocosm experiments using soil from an arid alkaline cropland in southern Arizona classified as a Typic Torrifluvent, the closest suborder to the Torriorthents of this study within the same Entisol order and Torric moisture regime. Under those controlled conditions, rates exceeding 35.4 tons·acre^{-1} were required to improve available water capacity by up to 34%, further underscoring the potential significance of targeted placement over applied volumetric rate.

Partial factor productivity of nitrogen was 18–34% higher in the biochar strips (Appendix L), largely because less N was recommended and applied while yields declined only modestly. This is directionally consistent with Kerner et al. (2023), whose meta-analysis of 61 studies found that biochar increased nitrification rates by 40.8%, suggesting enhanced microbial N cycling, although nitrification rate and PFPN are not directly comparable measures. Our NUE result is also consistent with Zhao et al.

(2025), who found that combining biochar with a 15% reduction in N fertilizer improved fertilizer N utilization and reduced N losses by about 48%.

PLFA results in this study are consistent with what Kerner et al. (2023) found across 61 field and lab studies where biochar boosts microbial abundance and C and N-cycling enzyme functions. In that study, feedstock, pyrolysis temperature and soil pH were key predictors of microbial response direction. Our PLFA results show how biochar has revealed shifts in microbial community structures. Azeem et al. (2020) showed that the addition of compost to soils in need of microbiome change (reclamation projects) or biochar when the microbiome is functioning, with the long-term goal of carbon sequestration, are more desirable. Thus, biochar alone may improve the microbiology that exists in that location, while the co-application of biological support to the biochar can induce more dramatic and desired microbiome outcomes.

It could be argued that the improvements observed in this study could be explained in part by the physical disturbance or vertical holes that were created during the biochar application. While that may explain some increase in VWC at the 6 in. depth, it does not explain the positive effects observed beyond year 1, increase in VWC at deeper depths, the substantial increase in VWC minima, or decreased bulk density. When a soil is aerated, disturbed, or tilled, it will eventually return to its steady state of a cohesive soil matrix and once again reflect its natural soil properties. Simply aerating, ripping, or tilling is essentially temporary unless the soil is modified with a dissimilar material; in this case, biochar, then those effects may become semi-permanent to permanent (Guo et al. 2023; Wang et al. 2016). Continuous sensor data suggest improved water dynamics showing faster saturation of the soil profile.

7.2 Economics

The analyses above suggest biochar can retain water in the soil and can also provide soil health benefits. The topic for this section is the extent to which the costs of injecting biochar into the soil, purchase of the biochar, transport to the field location, and injection, can be offset by financial (and other) benefits to the producer or landowner.

Water is a valuable resource which is delivered at a wide range of prices. In addition, as seen in the 2026 growing season, it can be the case that for some farmers the irrigation system simply stops providing water or delivers a reduced volume; future irrigation water costs are projected to increase and water allotment, availability and flows are expected to decrease. For farmers in the Grand Valley, irrigation water costs vary by the irrigation companies. For example, with the Grand Valley Irrigation Company, a shareholder starts with a single A share which is assessed at an annual fee of $376.90 and each additional share after that are called B shares and are assessed at $18.03 each. The company endeavors to deliver 4.96 gallons per minute (about 4 acre-ft) for each share during the irrigation season.

As an example, suppose a farm with a pasture field stops receiving irrigation water on July 4. Pasture grasses typically require between 0.2 and 0.3 inches per day. A central 0.23-inch/day value corresponds to approximately 7 inches during July. CSU reports this magnitude for pasture near Delta, Colorado.

Regarding fertilizer reductions, if we assume we can effectively reduce our fertilizer inputs (34% less nitrogen, 12% less phosphorus, and 27% less potassium), then those costs could be reduced by those same percentages, in theory, though this may or may not hold true over many years.

The 1.25 tons of biochar applied in this study, including freight, cost $1,725.00, with an application cost of $3,113.60 for a total of $4,838.60 ($6,048.25/acre). As tested, this practice likely does not make fiscal sense in most situations. While most commercially available biochar remains relatively expensive, new production technologies are rapidly lowering costs. Some vendors sell high-quality biochar for about $385/ton. Lower material cost combined with industry-specific application technology such as our prototype ‘Aries’ (patent pending), assuming an application cost of $125/acre and applying

1.56 tons of biochar, could mean a projected cost of biochar application using vertical-point injection, of around $881/acre, allowing this practice to become a potentially effective option to improve soil health, mitigate drought effects and reduce fertilizer inputs in a warming climate with limited natural resources. Other amendments, materials or minerals that can achieve similar or better results that meet the needs of different soils could also be tested. In order to fully assess the economic benefits of this practice, one must consider the savings of water, electricity to pump, water leasing revenue, fertilizer efficiencies and reductions, tractor passes, labor, regenerative incentives, soil and plant improvements, social benefits, and carbon credits. Through creativity and necessity, economics can begin to change quickly and the possibilities become limitless.

8. Conclusions and Future Research

8.1 Conclusions

Through four growing seasons, this field-scale study evaluated a novel vertical-point injection method that strategically installed 1.56 tons per acre of biochar at 0–8 in. in a perennial dryland grass system without mass disturbance or tillage. These localized hotspots appear to store water, nutrients, and biological activity, particularly under limited irrigation, supporting greater system resilience during drought. Vertical-point injection using biochar reflects a biomimetic soil structure, with strategically installed conduits facilitating movement and storage of water, nutrients, gases, and microbes. Using a 2 × 2 factorial strip design, consistent patterns emerged in increased average VWC, soil health indicators (SHA), microbial (PLFA), plant (NIRS), yield, and management data. Vertical-point injection using biochar was associated with differences in soil biology, including higher total microbial biomass and shifts in the Gram-positive to Gram-negative balance and in lipid stress ratios. Soil chemistry showed smaller declines in potassium in biochar strips than in controls, while apparent changes in pH and water-extractable nitrate depended mainly on irrigation frequency and on differences in starting values among strips. While irrigation remained a dominant driver, interaction effects revealed that biochar modified how soils processed inputs rather than reacted to them. Outcomes depended strongly on initial soil condition, with greater benefits observed in more resource-limited systems.

Agronomically, biochar-amended strips reduced hay yields (by about 6–10%) while recommended N, P, and K decreased by 34%, 12%, and 27%, respectively, resulting in improved nutrient use efficiency. Seasonal yield fluctuations and variability are interesting to observe and are likely driven by a multitude of environmental factors such as air and soil temperature, humidity, UV index, precipitation, etc. (Zhang et al. 2025) demonstrated that ecosystem productivity in semiarid Western U.S. grasslands declines sharply when high vapor pressure deficit (VPD) coincides with low soil moisture. The increased volumetric water content and elevated VWC minima observed in BC50 and BC100 suggest that vertical-point injection may reduce the frequency and severity of soil-moisture-limited periods, thereby narrowing the conditions under which VPD exerts its most damaging effects on photosynthesis and, by extension in this case, harvestable hay yield. Water-use patterns suggest that vertical-point injection using biochar influenced soil–water–nutrient dynamics primarily through biological and structural changes, and retention effects rather than immediate yield gains. Overall, biochar functioned as a buffering agent, enhancing nutrient retention, microbial stability, and long-term soil performance that is consistent with Guo et al. (2023), who reported greater soil water (suction) retention and improved grass growth over three years of field monitoring in biochar-amended soil.

Finally, vertical-point injection of biochar substantially increased VWC, soil health, and biological activity, contributing to enhanced drought resilience. Possibly even more valuable is the fact that VWC minima were substantially higher, resulting in a crop and soil biology that is allowed a fortified chance of surviving extreme or sustained droughts. This approach shows potential for a range of applications, including orchards, vineyards, high-value crops, range, reclamation, and arid or compacted

soils. The results of this study support the hypothesis stated in the Introduction: that biochar systematically installed into the soil using this method can increase soil moisture and water retention, while having the added benefits of promoting beneficial microbiological activity, increasing soil health metrics, and decreasing the needed rate and frequency of fertilizer applications. Returning to the central question: “can an already drought-resilient pasture be made more resilient?” These results suggest that targeted subsurface soil modification using vertical-point injection with biochar can meaningfully enhance drought resilience in an accelerated timeframe.

8.2 Future Research

The authors recommend further research using this method in other crop types, with added biologicals or nutrients, or comparing it directly to the most common methods of soil amendment or biochar application. Executing this practice with other minerals or combinations thereof may reveal other discoveries. Additionally, more funding that includes rigorous trial designs and labor costs fully funded could further pinpoint the pros, cons and mechanisms of this soil modification method using biochar and other materials or minerals.

9. Acknowledgements

Lobato would like to extend gratitude to the following individuals and organizations, in no particular order: James Fry, Bill Szasz, and Charlie Richards, for assisting with various field tasks. Dr. Gigi Richard, who was always supportive of this project. Alex Dunlop and Bill Jaeger at LOR Foundation and Phil Brink and Greg Peterson of Colorado Ag Water Alliance, for their financial support. Dr. Todd Ballard for his agronomic knowledge. Julie Kallenberger of Camp 5, LLC and Brenna Mefford of Wilson Water Group, LLC. Jeff Pieper, for suggesting the use of the SPAD device. Ray Hedgecoke for the use of his skid steer and auger. Bryan Reed, for his encouragement, and biochar inoculation work. CMU Environmental Science student Gavin Fitch for helping with spring 2026 sampling. Dr. Megan Machmuller, Dr. Lexi Firth, Rebecca Even, M.Sc., and Dr. Jim Ippolito of the IN-RICHES team for including this field into their expansive soil health studies. Dr. Albert Grable, retired USDA Soil Scientist, for his encouragement and sharing his knowledge. Entrepreneur Mark Shoemaker of DryJect Colorado for his time and his spirit of adventure to try something inherently difficult and extraordinary with his machines. Dr. Perry Cabot for the use of the Campbell Scientific hardware and sharing the drone images. Kateryna Bakova for post-processing of drone image data. VGrid Energy Systems and Jeff Norton for supplying the biochar. Southwest Seed, Inc. for the dryland grass seed mix. Everyone at Citizens for Clean Air Grand Junction for their unwavering continued support. Finally, Gerald Nelson and Holly Stanley for their many hours of dedication to this four-year study. Without these incredible organizations and people, this study would not have been possible, especially to this depth and extent. A final, special thank you to my father William Anthony “Tony” Lobato (*1952 – 2021*), Uranium Miner, Estimator and Entrepreneur, for calling me after seeing Citizens for Clean Air on the local news who were looking for small plots of farmland in the valley to host their biochar experiment. Without that phone call, this paper and research would not exist.

10. Conflicts of Interest Disclosure

Michael Lobato and Holly Stanley are disclosing that they have an interest in the continued research and development of this process and technology. Only after we observed the benefits from the study did we realize that this concept is worthy of pursuing so it could be further tested, accessible and act as a viable tool in the toolbox of repairing and sustaining soils. Additionally, this process cannot be easily replicated without further developing the technology and means to do so; it is currently limited by the specific machine that was used in the study and is exclusively used in the sports turf industry. Whether our machine prototype becomes adopted, commercialized or not, the need to further explore and test this concept warranted its creation. This prototype, subsequent technology and method are U.S. Patent Pending and is being developed by Matrix Resource Technologies, LLC.

11. Artificial Intelligence (AI) Disclosure

The Artificial Intelligence (AI) platform ChatGPT was used in the generation of the conceptual image in Figure 9, as well as for tasks such as handling large raw data sets, calculating summary statistics of field, lab and soil sensor data, and condensing text. The Anthropic platform Claude was used to edit and merge drafts.

12. Project Funding and Updates

This concept and field trial was conceived and executed entirely on the authors' own accounts and was funded over four consecutive years with grants from Citizens for Clean Air, Colorado Ag Water Alliance and LOR Foundation, totaling $21,857.20.

Appendices

Appendix A. NRCS Soil Report

Appendix B. Fertilizer Recommendations and Applications

Fertilizer Recommended and Applied 2023–2026						
Year	**Nutrient**	**lb./acre**	**BC50**	**CON50**	**BC100**	**CON100**
2023	**N**	Recommended	30.00	30.00	30.00	30.00
		Applied	69.11	69.11	69.11	69.11
	P	Recommended	60.00	60.00	60.00	60.00
		Applied	75.00	75.00	75.00	75.00
	K	Recommended	20.00	20.00	80.00	80.00
		Applied	25.00	25.00	100.00	100.00
2024	**N**	Recommended	0.00	35.00	5.00	15.00
		Applied	0.00	53.06	6.25	30.39
	P	Recommended	0.00	20.00	0.00	25.00
		Applied	0.00	25.00	0.00	31.25
	K	Recommended	0.00	35.00	0.00	0.00
		Applied	0.00	43.75	0.00	0.00
2025	**N**	Recommended	25.00	35.00	20.00	35.00
		Applied	42.89	55.39	38.97	55.39
	P	Recommended	25.00	25.00	30.00	25.00
		Applied	31.25	31.25	37.50	31.25
	K	Recommended	0.00	25.00	40.00	35.00
		Applied	0.00	31.25	50.00	43.75
2026	**N**	Recommended	20.00	20.00	15.00	20.00
		Applied	36.64	34.31	30.39	34.31
	P	Recommended	25.00	20.00	25.00	20.00
		Applied	31.25	25.00	31.25	25.00
	K	Recommended	20.00	30.00	25.00	30.00
		Applied	25.00	37.50	31.25	37.50
Totals	**N**	Recommended	75.0	120.0	70.0	100.0
		Applied	148.6	211.9	144.7	189.2
	P	Recommended	110.0	125.0	115.0	130.0
		Applied	137.5	156.2	143.8	162.5
	K	Recommended	40.0	110.0	145.0	145.0
		Applied	50.0	137.5	181.2	181.2

Appendix C. Dates of Project Activities

Field Activity Dates	2023	2024	2025	2026
Biochar Injection	5/9/2023			
Creased Furrows	5/31/2023	4/9/2024	4/1/2025	4/10/2026
Fertilization	3/17/2023	4/9/2024	4/12/2025	6/27/2026
Hay Sample 1	6/12/2023	6/6/2024	6/6/2025	No Cutting
Hay Sample 2	7/26/2023	7/25/2024	8/8/2025	7/28/2026
Hay Sample 3	10/6/2023	9/9/2024	10/28/2025	10/16/2026
NDVI Sample 1	8/24/2023			
NDVI Sample 2	10/5/2023			
NDVI Drone Flight				7/28/2026
Pre-Trial Seeding	3/29/2023			
Soil Sample 1	3/31/2023	4/3/2024	4/2/2025	4/23/2026
Soil Sample 2	10/9/2023	11/5/2024	11/3/2025	10/16/2026
SPAD Sample 1	7/10/2023			
SPAD Sample 2	8/24/2023			
SPAD Sample 3	10/5/2023			

Appendix D. Biochar to Soil Volume Calculation

Volume of Biochar:Soil %	**Strip Area (sq ft)**	**Depth (ft)**	**Volume (ft^3)**	**Volume (yd^3)**
Biochar				7
Soil	34780	0.66	22955	850
Volume of Biochar:Soil %				**0.8%**

Appendix E. Irrigation Totals, 2023–2026

Irrigation Summary	Applied (acre-ft)	Applied (acre-ft)
Strips	1, 2	3, 4
Treatment	BC50, CON50	BC100, CON100
2023	2.02	4.06
2024	2.77	4.06
2025	3.40	4.18
2026	1.82	3.16
4 Year Volume Totals (Acre-Ft.)	10.01	15.46
4 Year Duration Totals (H:M:S)	239:57:00	369:59:00
Acre-Ft. (1&2)/(3&4) %	**64.7%**	
Duration (1&2)/(3&4) %	**64.9%**	

Appendix F. VWC Summary Statistics

VWC Summary Stats April 1-Oct 31, 2023-2026					
Depth (in)	**Statistic**	**BC50**	**CON50**	**BC100**	**CON100**
6	**Mean**	25.4	17.8	23.6	21.2
	SD	3.6	3.0	3.4	4.9
	SE	0.7	0.6	0.7	1.0
	CV%	14.0	17.0	14.3	23.2
	Med	26.3	18.0	24.1	22.3
	Min	16.1	9.2	15.2	8.2
	Max	30.7	23.2	30.3	30.6
	Range	14.6	14.0	15.1	22.4
12	**Mean**	25.1	20.8	25.9	23.8
	SD	3.5	3.3	2.2	4.6
	SE	0.7	0.6	0.4	0.9
	CV%	14.1	15.7	8.7	19.5
	Med	25.3	21.5	26.3	24.4
	Min	16.0	11.6	19.8	12.3
	Max	31.4	26.1	29.3	30.9
	Range	15.4	14.5	9.5	18.6
18	**Mean**	29.4	26.9	32.9	27.4
	SD	4.3	5.0	4.4	5.2
	SE	0.8	1.0	0.9	1.0
	CV%	14.5	18.6	13.4	18.8
	Med	29.3	26.3	33.3	27.5
	Min	18.6	13.1	25.5	18.6
	Max	37.2	35.6	40.9	35.6
	Range	18.6	22.5	15.5	17.0

Appendix G. EC Summary Statistics

EC Summary Stats, April 1–Oct 31, 2023–2026 (dS/m)					
Depth (in)	**Statistic**	**BC50**	**CON50**	**BC100**	**CON100**
6	**Mean**	0.63	0.29	0.35	0.43
	SD	0.21	0.07	0.09	0.19
	SE	0.04	0.01	0.02	0.04
	CV %	32.9	25.3	25.3	44.0
	Med	0.63	0.27	0.35	0.44
	Min	0.31	0.12	0.10	0.09
	Max	1.08	0.44	0.49	0.77
	Range	0.77	0.32	0.39	0.68
12	**Mean**	0.76	0.38	0.55	0.63
	SD	0.20	0.08	0.20	0.20
	SE	0.04	0.01	0.04	0.04
	CV %	26.6	19.6	36.4	32.4
	Med	0.73	0.38	0.51	0.65
	Min	0.39	0.19	0.28	0.19
	Max	1.22	0.53	1.11	0.92
	Range	0.83	0.34	0.83	0.73
18	**Mean**	0.94	0.46	0.43	0.65
	SD	0.17	0.16	0.15	0.22
	SE	0.03	0.03	0.03	0.04
	CV %	18.7	35.9	33.8	33.9
	Med	0.90	0.39	0.38	0.66
	Min	0.68	0.25	0.26	0.30
	Max	1.30	0.78	0.94	1.00
	Range	0.62	0.53	0.68	0.71

12.1

Appendix H. Temperature Summary Statistics

Temperature Summary Stats, 2023–2026, all months (°F; N = 40 monthly values per strip)					
Depth (in)	**Statistic**	**BC50**	**CON50**	**BC100**	**CON100**
6	**Mean**	58.6	58.4	58.2	58.7
	SD	15.3	15.4	15.1	15.3
	SE	2.4	2.4	2.4	2.4
	CV %	26.2	26.5	26.0	26.1
	Med	60.2	59.4	59.2	60.3
	Min	31.9	31.4	32.7	32.6
	Max	79.5	79.4	79.0	78.9
	Range	47.6	48.0	46.3	46.3
12	**Mean**	58.6	58.4	58.5	58.7
	SD	14.5	14.7	14.4	14.6
	SE	2.3	2.3	2.3	2.3
	CV %	24.7	25.1	24.6	24.8
	Med	60.9	60.5	60.5	60.7
	Min	33.6	33.2	33.9	33.9
	Max	77.6	78.1	78.2	78.6
	Range	43.9	45.0	44.2	44.7
18	**Mean**	58.5	58.1	58.1	58.6
	SD	13.7	13.9	13.7	13.9
	SE	2.2	2.2	2.2	2.2
	CV %	23.4	24.0	23.6	23.7
	Med	60.9	59.7	60.5	61.0
	Min	35.3	34.8	35.0	35.1
	Max	76.3	77.8	77.0	78.0
	Range	41.0	42.9	42.1	42.9

Appendix I. Avg. Monthly VWC & % Gain

VWC % Gain April 1-Oct 31, 2023-2026					
	Strip	**1**	**2**	**3**	**4**
Depth (in)	**Treatment**	**BC50**	**CON50**	**BC100**	**CON100**
6	Mean	25.4	17.8	23.6	21.2
	% Gain	**42.5%**		**11.4%**	
12	Mean	25.1	20.8	25.9	23.8
	% Gain	**20.6%**		**8.8%**	
18	Mean	29.4	26.9	32.9	27.4
	% Gain	**8.9%**		**19.8%**	

Appendix J. Avg. Monthly VWC Minima & % Difference

VWC % Gain 10th pct. Minima April 1-Oct 31, 2023-2026					
	Strip	**1**	**2**	**3**	**4**
Depth (in)	**Treatment**	**BC50**	**CON50**	**BC100**	**CON100**
6	Mean	18.1	11.5	15.9	13.9
	% Gain	**58.3%**		**14.5%**	
12	Mean	18.3	13.9	21.2	18.7
	% Gain	**31.9%**		**13.4%**	
18	Mean	24.5	21.6	30.3	23.7
	% Gain	**13.6%**		**27.8%**	

Appendix K. Nutrient Totals of Biochar Strips/Control Strips

Nutrient Totals (lb per acre) 2023–2026		N	P	K	Mn
Recommended	Biochar Strips	145	225	185	27
	Control Strips	220	255	255	24
	Biochar Strips Δ	**-34%**	**-12%**	**-27%**	**13%**
Applied	Biochar Strips	293	281	231	0
	Control Strips	401	319	319	0
	Biochar Strips Δ	**-27%**	**-12%**	**-27%**	**n/a**

Appendix L. Partial Factor Productivity of Nitrogen

Partial Factor Productivity of Nitrogen (PFPN)				
Strip	**1**	**2**	**3**	**4**
Treatment	**BC50**	**CON50**	**BC100**	**CON100**
Total Yield (tons/ac)	5.22	5.57	4.75	5.27
Total N Applied (lb./ac)	148.64	211.87	144.71	189.20
PFPN (tons hay per lb. N)	0.0351	0.0263	0.0328	0.0279
BC PFPN Increase over Control	**33.5%**		**17.7%**	

Appendix M. Hay NIRS Summary Stats

Hay NIRS Analysis Select Summary Stats, 2023–2026 (Ward Laboratories reports, 11 cuttings; ME reported for 2024 cuttings only)																				
Strip	**1**					**2**					**3**					**4**				
Treatment	**BC50**					**CON50**					**BC100**					**CON100**				
Variable (dry basis)	**Avg**	**SD**	**Min**	**Max**	**Med**	**Avg**	**SD**	**Min**	**Max**	**Med**	**Avg**	**SD**	**Min**	**Max**	**Med**	**Avg**	**SD**	**Min**	**Max**	**Med**
Neutral Detergent Fiber %	58.0	5.8	49.5	69.5	56.0	58.7	3.7	51.6	65.1	58.6	60.6	5.1	53.5	70.1	60.4	59.8	5.9	47.0	66.8	61.8
Crude Protein %	12.2	2.7	8.4	16.5	11.3	12.5	3.2	7.7	18.0	12.1	10.8	1.9	7.5	14.4	10.1	11.1	2.0	7.6	13.9	10.9
IVTDMD % 48 hr	76.9	4.8	67.0	82.9	78.2	77.1	4.4	71.9	85.5	75.6	75.7	4.4	63.1	79.0	76.8	74.7	4.5	66.3	80.0	76.1
Metabolizable Energy (Mcal/kg)	1.92	0.03	1.89	1.95	1.91	2.07	0.08	1.98	2.14	2.08	1.96	0.06	1.89	2.01	1.98	1.95	0.03	1.93	1.99	1.94
NDFD 48 hr (digestibility) % of NDF	60.8	6.5	52.0	72.0	59.3	61.4	6.0	52.0	70.0	61.0	60.7	6.6	48.0	72.0	61.6	58.3	8.2	40.0	69.0	59.1
Relative Forage Quality (RFQ)	122.6	19.7	97.0	149.0	122.0	123.1	17.2	95.0	148.0	121.0	113.3	14.7	91.0	143.0	111.0	109.2	22.9	59.0	138.0	107.0
TDN %	60.1	5.9	52.3	70.3	60.3	60.2	4.5	53.7	67.0	59.5	58.4	4.8	52.4	67.1	56.2	57.1	8.2	38.4	70.0	55.6

Appendix N. Significant SHA Summary Statistics

Soil Health Analysis (SHA) Summary Stats of Statistically Significant Variables, 2023–2026 (7 sampling events, spring 2023–spring 2026)																				
Strip	**1**					**2**					**3**					**4**				
Treatment	**BC50**					**CON50**					**BC100**					**CON100**				
Stats	**Avg**	**SD**	**Min**	**Max**	**Med**	**Avg**	**SD**	**Min**	**Max**	**Med**	**Avg**	**SD**	**Min**	**Max**	**Med**	**Avg**	**SD**	**Min**	**Max**	**Med**
%Ca Sat	79.7	2.7	75.0	83.0	80.0	81.0	1.2	79.0	83.0	81.0	79.1	2.3	75.0	82.0	79.0	77.3	2.6	74.0	81.0	77.0
%K Sat	1.4	0.5	1.0	2.0	1.0	1.1	0.4	1.0	2.0	1.0	1.1	0.4	1.0	2.0	1.0	1.0	0.0	1.0	1.0	1.0
%Mg Sat	13.6	0.8	12.0	14.0	14.0	13.7	0.5	13.0	14.0	14.0	14.0	0.8	13.0	15.0	14.0	14.6	0.8	14.0	16.0	14.0
%Na Sat	5.3	2.3	3.0	10.0	5.0	4.0	1.0	3.0	6.0	4.0	5.4	1.9	3.0	9.0	5.0	7.1	2.5	4.0	10.0	8.0
1:1 Salts (mmho/cm)	0.7	0.4	0.4	1.6	0.5	0.4	0.2	0.1	0.7	0.3	0.4	0.2	0.1	0.6	0.5	0.8	0.5	0.1	1.8	0.8
1:1 Soil pH	8.0	0.2	7.8	8.3	7.9	8.3	0.3	7.9	8.6	8.4	8.3	0.2	8.1	8.6	8.2	8.3	0.3	8.0	8.6	8.2
Calcium (ppm)	3617.1	262.2	3311.0	3979.0	3556.0	3553.0	224.8	3237.0	3865.0	3583.0	3339.7	302.1	2970.0	3864.0	3304.0	3410.9	210.5	3129.0	3642.0	3319.0
CEC/Sum of Cations (me/100g)	22.8	2.2	20.3	26.7	22.5	21.9	1.4	19.9	23.8	21.8	21.1	1.7	19.4	24.0	20.5	22.1	0.7	21.2	23.2	22.0
Iron (ppm)	8.0	3.4	5.0	15.4	6.9	8.5	3.5	5.1	15.8	8.2	9.7	4.5	5.0	18.4	9.3	9.6	5.5	4.8	21.0	8.4
Magnesium (ppm)	376.4	47.7	330.0	458.0	361.0	358.6	22.9	329.0	386.0	359.0	354.4	36.6	323.0	416.0	343.0	385.7	18.1	365.0	406.0	376.0
Manganese (ppm)	1.1	0.8	0.6	2.9	0.9	1.1	0.8	0.5	2.7	0.7	1.1	0.7	0.5	2.6	0.8	1.2	1.1	0.4	3.6	0.8
NO3-N H2O (ppm)	1.2	1.3	0.2	3.9	0.7	0.7	0.3	0.3	1.1	0.9	0.4	0.3	0.1	1.0	0.4	0.4	0.3	0.1	0.7	0.4
Olsen P (ppm)	10.9	2.1	7.5	13.2	11.4	9.9	1.2	8.0	11.4	10.0	10.2	3.0	7.9	16.1	8.9	10.8	3.2	7.0	16.2	10.0
Organic C H2O (ppm)	137.9	19.0	112.0	163.0	139.0	116.9	19.3	90.0	150.0	115.0	121.3	21.4	95.0	147.0	120.0	111.9	18.2	80.0	137.0	116.0
Organic C:N H2O	10.1	1.9	8.4	13.9	9.4	11.0	2.2	9.4	15.5	10.2	10.7	2.1	7.1	13.9	10.9	10.3	1.5	8.4	12.4	10.4
Organic N H2O (ppm)	13.9	2.6	10.0	17.0	13.3	10.9	2.5	8.2	15.5	10.3	12.0	4.4	8.1	20.5	12.1	11.2	2.9	6.5	14.1	10.8
Potassium (ppm)	135.4	23.9	100.0	168.0	132.0	94.0	17.2	81.0	130.0	91.0	95.1	32.2	65.0	153.0	76.0	84.4	18.2	63.0	117.0	83.0
Sodium (ppm)	280.4	147.8	162.0	589.0	226.0	204.6	52.0	143.0	287.0	196.0	265.3	79.2	189.0	417.0	244.0	361.7	111.9	213.0	492.0	394.0
Sulfate (ppm)	108.1	82.4	39.4	283.5	78.1	52.6	27.0	10.7	91.4	52.9	71.7	35.5	43.4	130.9	54.6	177.8	96.9	42.6	332.6	166.8
Total N H2O (ppm)	15.6	3.5	11.1	21.8	15.6	12.0	2.8	9.1	17.3	10.9	13.1	4.3	8.5	21.6	12.9	12.0	3.0	7.3	15.5	11.1

Appendix O. Functional Grouping of Significant SHA Mean Δ

Functional Grouping of Statistically Significant SHA Variables								
Primary Group	**Variable**	**Primary Driver**	**Secondary Driver(s)**	**BC50 Mean Δ**	**CON50 Mean Δ**	**BC100 Mean Δ**	**CON100 Mean Δ**	**Observed Pattern**
Chemical Environment	1:1 Soil pH	Irrigation	Biochar	0.23	-0.12	-0.20	-0.38	Δ increase in 50 irr. (0.06), decrease in 100 irr. (-0.29)
	CEC/Sum of Cations (me/100g)	Irrigation	—	1.15	-0.13	-1.80	-0.63	Δ increase in 50 irr. (0.51), decrease in 100 irr. (-1.22)
Ionic Balance / Salinity	%Ca Sat	Interaction	—	-1.50	0.00	1.33	-3.17	Strongest mean Δ BC100 (1.33), lowest CON100 (-3.17)
	%Mg Sat	Irrigation	Interaction	0.67	-0.33	-1.17	-0.50	Δ increase in 50 irr. (0.17), decrease in 100 irr. (-0.83)
	%Na Sat	Interaction	Biochar	1.50	1.17	-0.67	3.67	Strongest mean Δ CON100 (3.67), lowest BC100 (-0.67)
	1:1 Salts (mmho/cm)	Interaction	—	0.20	0.11	-0.23	0.49	Strongest mean Δ CON100 (0.49), lowest BC100 (-0.23)
	Sodium (ppm)	Interaction	Biochar	106.67	71.83	-40.50	173.50	Strongest mean Δ CON100 (173.50), lowest BC100 (-40.50)
Nutrient Retention & Storage	Potassium (ppm)	Biochar	Interaction	4.00	-42.00	-33.67	-38.00	BCs decrease in Δ (-14.83) vs. CONs (-40.00)
	Total N H2O (ppm)	Biochar	Interaction	-7.23	-6.22	-9.90	-3.57	BCs decrease in Δ (-8.57) vs. CONs (-4.89)
Organic Matter / Nutrient Cycling	Organic C H2O (ppm)	Biochar	—	-10.67	-38.67	-26.50	-29.33	BCs decrease in Δ (-18.58) vs. CONs (-34.00)
	Organic C:N H2O	Biochar	Interaction	1.78	1.58	4.15	0.72	BCs increase in Δ (2.97) vs. CONs (1.15)
	Organic N H2O (ppm)	Interaction	Biochar, Irrigation	-3.67	-5.32	-9.87	-3.43	Strongest mean Δ CON100 (-3.43), lowest BC100 (-9.87)
Soluble Nutrient Dynamics	%K Sat	Irrigation	—	-0.67	-1.00	0.17	0.00	Δ decrease in 50 irr. (-0.83), increase in 100 irr. (0.08)
	Calcium (ppm)	Irrigation	—	71.33	-35.00	-224.33	-227.67	Δ increase in 50 irr. (18.17), decrease in 100 irr. (-226.00)
	Iron (ppm)	Irrigation	—	-8.63	-8.55	-10.20	-13.28	Δ decrease in 50 irr. (-8.59), decrease in 100 irr. (-11.74)
	Magnesium (ppm)	Irrigation	Interaction	40.17	-13.33	-48.50	-21.33	Δ increase in 50 irr. (13.42), decrease in 100 irr. (-34.92)
	Manganese (ppm)	Interaction	Biochar, Irrigation	-2.13	-1.88	-1.78	-2.78	Strongest mean Δ BC100 (-1.78), lowest CON100 (-2.78)
	NO3-N H2O (ppm)	Irrigation	Biochar, Interaction	-3.10	-0.47	0.35	0.38	Δ decrease in 50 irr. (-1.79), increase in 100 irr. (0.36)
	Olsen P (ppm)	Irrigation	—	-1.47	-1.70	-2.68	-6.27	Δ decrease in 50 irr. (-1.58), decrease in 100 irr. (-4.48)
	Sulfate (ppm)	Biochar	Interaction	45.63	48.92	7.63	157.68	BCs increase in Δ (26.63) vs. CONs (103.30)

Appendix P. Significant PLFA Summary Statistics

PLFA Summary Stats of Statistically Significant Variables + Total Biomass, 2023–2026 (7 sampling events, spring 2023–spring 2026)																				
Strip	**1**					**2**					**3**					**4**				
Treatment	**BC50**					**CON50**					**BC100**					**CON100**				
Variable	**Avg**	**SD**	**Min**	**Max**	**Med**	**Avg**	**SD**	**Min**	**Max**	**Med**	**Avg**	**SD**	**Min**	**Max**	**Med**	**Avg**	**SD**	**Min**	**Max**	**Med**
Fungi:Bacteria	0.38	0.06	0.31	0.49	0.35	0.35	0.02	0.32	0.37	0.35	0.37	0.06	0.31	0.47	0.36	0.32	0.03	0.27	0.36	0.32
Gram (-) %	22.01	3.72	18.84	27.88	19.89	22.20	3.69	17.62	27.84	22.04	25.42	3.75	21.96	30.81	23.05	22.29	5.11	13.95	27.99	22.17
Gram(+):Gram(-)	0.92	0.34	0.62	1.63	0.78	0.85	0.27	0.68	1.37	0.70	0.75	0.24	0.47	1.19	0.74	0.97	0.56	0.53	2.05	0.72
Pre 16:1w7c:cy17:0	3.85	0.74	3.18	5.39	3.63	4.15	0.68	3.35	5.46	4.16	4.25	1.14	3.57	6.80	3.92	3.62	1.06	2.01	5.60	3.59
Pre 18:1w7c:cy19:0	2.36	0.26	1.94	2.66	2.38	2.42	0.42	1.98	3.20	2.36	2.48	0.84	1.11	3.95	2.53	2.07	0.74	0.56	3.01	2.17
Saprophytes %	12.15	1.59	10.76	15.44	11.98	10.63	0.63	9.28	11.27	10.81	12.49	2.74	8.61	15.94	12.82	10.26	1.60	8.44	12.63	10.43
Sat:Unsat	1.30	0.15	1.12	1.50	1.24	1.36	0.14	1.23	1.65	1.34	1.25	0.15	1.05	1.47	1.24	1.51	0.35	1.27	2.28	1.43
Total Bacteria Biomass	1457.31	994.14	665.60	3383.30	969.93	1209.96	905.66	538.44	2832.96	734.83	1563.34	1019.31	582.27	2927.97	1080.94	1220.88	764.10	595.09	2423.12	859.17
Total Biomass	3419.23	2015.94	1271.71	7345.00	3001.63	2894.55	1946.29	1269.41	6521.00	2176.04	3477.10	2063.28	1209.87	6308.28	3098.01	2850.99	1525.11	1237.69	5017.00	2418.26
Total Fungi Biomass	555.56	329.20	206.66	1183.67	520.11	429.03	291.11	191.03	965.72	326.11	561.83	328.72	245.30	1046.01	560.17	403.69	226.92	180.89	727.94	292.22

Appendix Q. Functional Grouping of Significant PLFA Mean Δ

Functional Grouping of Significant PLFA Variables								
Primary Group	**Variable**	**Primary Driver**	**Secondary Driver(s)**	**BC50 Mean Δ**	**CON50 Mean Δ**	**BC100 Mean Δ**	**CON100 Mean Δ**	**Observed Pattern**
Community Balance	Fungi:Bacteria	Interaction	—	0.034	-0.009	-0.007	0.059	Strongest mean Δ CON100 (0.059), lowest CON50 (-0.009)
	Saprophytes %	Interaction	—	1.02	-0.08	-0.45	2.06	Strongest mean Δ CON100 (2.06), lowest BC100 (-0.45)
Community Structure	Gram (-) %	Irrigation	Biochar	-0.70	2.64	2.77	9.73	Δ increase in 50 irr. (0.97), increase in 100 irr. (6.25)
	Gram(+):Gram(-)	Biochar	Irrigation, Interaction	-0.05	-0.25	-0.15	-1.26	BCs decrease in Δ (-0.10) vs. greater decrease in CONs (-0.76)
Stress / Membrane Dynamics	Pre 16:1w7c:cy17:0	Biochar	Interaction, Irrigation	-1.79	-1.52	-2.97	1.88	BCs decrease in Δ (-2.38) vs. CONs (0.18)
	Pre 18:1w7c:cy19:0	Biochar	Irrigation, Interaction	-0.15	0.47	-0.06	1.76	BCs decrease in Δ (-0.10) vs. CONs (1.12)
	Sat:Unsat	Biochar	Irrigation, Interaction	-0.14	-0.34	-0.17	-0.90	BCs decrease in Δ (-0.16) vs. CONs (-0.62)

References

Azeem, Muhammad, Lauren Hale, Jonathan Montgomery, David Crowley, and Milton E. McGiffen. 2020. “Biochar and Compost Effects on Soil Microbial Communities and Nitrogen Induced Respiration in Turfgrass Soils.” *PLOS ONE* 15 (11): e0242209. https://doi.org/10.1371/journal.pone.0242209.

Basso, Andres S., Fernando E. Miguez, David A. Laird, Robert Horton, and Mark Westgate. 2013. “Assessing Potential of Biochar for Increasing Water-holding Capacity of Sandy Soils.” *GCB Bioenergy* 5 (2): 132–43. https://doi.org/10.1111/gcbb.12026.

Cornelissen, Gerard, Vegard Martinsen, Victor Shitumbanuma, et al. 2013. “Biochar Effect on Maize Yield and Soil Characteristics in Five Conservation Farming Sites in Zambia.” *Agronomy* 3 (2): 256–74. https://doi.org/10.3390/agronomy3020256.

Guo, H., C. W. W. Ng, J. Ni, Q. Zhang, and Y. Wang. 2023. “Three-Year Field Study on Grass Growth and Soil Hydrological Properties in Biochar-Amended Soil.” *Journal of Rock Mechanics and Geotechnical Engineering*.

Hamada, Kosuke, Satoshi Nakamura, Takashi Kanda, and Minako Takahashi. 2024. “Effects of Biochar Application Depth on Nitrate Leaching and Soil Water Conditions.” *Environmental Technology* 45 (23): 4848–59. https://doi.org/10.1080/09593330.2023.2283403.

Hamada, Kosuke, Satoshi Nakamura, and Daichi Kuniyoshi. 2024. “Pipe Experiment Elucidates Biochar Application Depth Affects Nitrogen Leaching under Crop Present Condition.” *Scientific Reports* 14 (1): 22823. https://doi.org/10.1038/s41598-024-73621-3.

Hoglund. 2023. “Contrasting Effects of Biochar Application Rate in an Alkaline Desert Cropland Soil.” *Journal of Arid Environments*. https://experts.arizona.edu/en/publications/contrasting-effects-of-biochar-application-rate-in-an-alkaline-de/.

Idaho, University, College Agricultural, and Life Sciences. 2026. “Entisols.” https://www.uidaho.edu/agricultural-life-sciences/soil-orders/entisols.

Idowu, J., and C. E. Brewer. 2018. “Biochar for Arid and Semi-Arid Agricultural Soils (Circular 690). New Mexico State University Cooperative Extension Service.” https://pubs.nmsu.edu/_circulars/CR690/.

Kerner, Patricia, Ethan Struhs, Amin Mirkouei, et al. 2023. “Microbial Responses to Biochar Soil Amendment and Influential Factors: A Three-Level Meta-Analysis.” *Environmental Science & Technology* 57 (48): 19838–48. https://doi.org/10.1021/acs.est.3c04201.

Lehmann, Johannes, Matthias C. Rillig, Janice Thies, Caroline A. Masiello, William C. Hockaday, and David Crowley. 2011. “Biochar Effects on Soil Biota – A Review.” *Soil Biology and Biochemistry* 43 (9): 1812–36. https://doi.org/10.1016/j.soilbio.2011.04.022.

Lowstuter, D. 2024. *Biochar in Colorado*. Updated. Colorado State University Extension. https://extension.colostate.edu/resource/biochar-in-colorado-2024/.

Natural Resources Conservation Service, Organic Farming Research Foundation. 2026. “Tillage Tools and Practices in Organic Farming Systems: Limiting Soil Disturbance to Build Soil Health in Organic Cropland.” U.S. Department of Agriculture, July. https://ofrf.org/wp-content/uploads/2026/07/OFRF-Tillage-Tools-and-Practices-in-Organic-Farming-Systems_Print.pdf.

Razzaghi, Fatemeh, Peter Bilson Obour, and Emmanuel Arthur. 2020. “Does Biochar Improve Soil Water Retention? A Systematic Review and Meta-Analysis.” *Geoderma* 361 (March): 114055. https://doi.org/10.1016/j.geoderma.2019.114055.

Richter, Brian D., Gambhir Lamsal, Landon Marston, et al. 2024. “New Water Accounting Reveals Why the Colorado River No Longer Reaches the Sea.” *Communications Earth & Environment* 5 (1): 134. https://doi.org/10.1038/s43247-024-01291-0.

Schmidt, H. P., B. H. Pandit, V. Martinsen, G. Cornelissen, P. Conte, and C. I. Kammann. 2015. “Fourfold Increase in Pumpkin Yield in Response to Low-Dosage Root Zone Application of Urine-Enhanced Biochar to a Fertile Tropical Soil.” *Agriculture* 5 (3): 723–41.

Schmidt, Hans, Bishnu Pandit, Vegard Martinsen, Gerard Cornelissen, Pellegrino Conte, and Claudia Kammann. 2015. “Fourfold Increase in Pumpkin Yield in Response to Low-Dosage Root Zone Application of Urine-Enhanced Biochar to a Fertile Tropical Soil.” *Agriculture* 5 (3): 723–41. https://doi.org/10.3390/agriculture5030723.

Tucker, Compton J. 1979. “Red and Photographic Infrared Linear Combinations for Monitoring Vegetation.” *Remote Sensing of Environment* 8 (2): 127–50. https://doi.org/10.1016/0034-4257(79)90013-0.

Udall, Bradley, and Jonathan Overpeck. 2017. “The Twenty-first Century Colorado River Hot Drought and Implications for the Future.” *Water Resources Research* 53 (3): 2404–18. https://doi.org/10.1002/2016WR019638.

Wang, Jinyang, Zhengqin Xiong, and Yakov Kuzyakov. 2016. “Biochar Stability in Soil: Meta-analysis of Decomposition and Priming Effects.” *GCB Bioenergy* 8 (3): 512–23. https://doi.org/10.1111/gcbb.12266.

Wiesmeier, Martin, Christopher Poeplau, Carlos A. Sierra, et al. 2016. “Projected Loss of Soil Organic Carbon in Temperate Agricultural Soils in the 21st Century: Effects of Climate Change and Carbon Input Trends.” *Scientific Reports* 6 (1): 32525. https://doi.org/10.1038/srep32525.

Xiao. 2025. “Fate of fertilizer nitrogen in the field 2 years after biochar application.”

Xie, Yingxin, Cheng Dong, Zhiyong Chen, et al. 2021. “Successive Biochar Amendment Affected Crop Yield by Regulating Soil Nitrogen Functional Microbes in Wheat-Maize Rotation Farmland.” *Environmental Research* 194 (March): 110671. https://doi.org/10.1016/j.envres.2020.110671.

Yan, Sihua, Shaoliang Zhang, Pengke Yan, and Muhammad Aurangzeib. 2022. “Effect of Biochar Application Method and Amount on the Soil Quality and Maize Yield in Mollisols of Northeast China.” *Biochar* 4 (1): 56. https://doi.org/10.1007/s42773-022-00180-z.

Yost, M., J. Holt, J. Austin, et al. 2021. *Biochar Impacts on Crop Yield and Soil Water Availability [Fact Sheet*. Utah State University Extension. https://extension.usu.edu/crops/biochar-factsheet.

Yu, Ok-Youn, Brian Raichle, and Sam Sink. 2013. “Impact of Biochar on the Water Holding Capacity of Loamy Sand Soil.” *International Journal of Energy and Environmental Engineering* 4 (1): 44. https://doi.org/10.1186/2251-6832-4-44.

Zhang, Fangyue, Joel A. Biederman, Nathan A. Pierce, et al. 2025. “Temporal Repackaging of Rainfall Magnifies Negative Impacts of Vapor Pressure Deficit on Semiarid Ecosystem Productivity.” *New Phytologist* 248 (2): 615–27. https://doi.org/10.1111/nph.70431.