

Article

On the Potential of Biochar Soil Amendments as a Sustainable Water Management Strategy

Steve W. Lyon ^{1,2,3,*}, Benjamin M. C. Fischer ^{3,4}, Laura Morillas ⁵, Johanna Rojas Conejo ⁶, Ricardo Sánchez-Murillo ⁷, Andrea Suárez Serrano ⁶, Jay Frentress ^{8,9}, Chih-Hsin Cheng ¹⁰, Monica Garcia ¹¹ and Mark S. Johnson ^{12,13}

- ¹ School of Environment and Natural Resources, The Ohio State University, Wooster, OH 44691, USA
 - ² Department of Physical Geography, Stockholm University, 10691 Stockholm, Sweden
 - ³ Bolin Centre for Climate Research, Stockholm University, 10691 Stockholm, Sweden; benjamin.fischer@geo.uu.se
 - ⁴ Department of Earth Sciences, Uppsala University, 75105 Uppsala, Sweden
 - ⁵ Centre for Sustainable Food Systems, University of British Columbia, Vancouver, BC V6T 1Z4, Canada; laura.morillas.gonzalez@gmail.com
 - ⁶ Water Resources Center for Central America and the Caribbean (HIDROCEC-UNA), Universidad Nacional de Costa Rica, Liberia 50101, Guanacaste, Costa Rica; johanna.rojas.conejo@una.cr (J.R.C.); andrea.suarez.serrano@una.cr (A.S.S.)
 - ⁷ Department of Earth and Environmental Sciences, University of Texas, Arlington, TX 78712, USA; ricardo.sanchezmurillo@uta.edu
 - ⁸ Faculty of Science and Technology, Free University of Bolzano, 39100 Bolzano, Italy; jasonfrentress@gmail.com
 - ⁹ Water Resources, Ramboll Sverige AB, 10462 Stockholm, Sweden
 - ¹⁰ School of Forestry and Resource Conservation, National Taiwan University, Taipei 10617, Taiwan; chengch@ntu.edu.tw
 - ¹¹ Research Centre for the Management of Agricultural and Environmental Risks (CEIGRAM), E.T.S.I. Agronomica, Alimentaria y de Biosistemas, Universidad Politécnica de Madrid, 28040 Madrid, Spain; monica.garciag@upm.es
 - ¹² Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, BC V6T 1Z4, Canada; mark.johnson@ubc.ca
 - ¹³ Institute for Resources, Environment and Sustainability, University of British Columbia, Vancouver, BC V6T 1Z4, Canada
- * Correspondence: lyon.248@osu.edu



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Abstract: Biochar has been put forward as a potential technology that could help achieve sustainable water management in agriculture through its ability to increase water holding capacity in soils. Despite this opportunity, there are still a limited number of studies, especially in vulnerable regions like the tropics, quantifying the impacts of biochar on soil water storage and characterizing the impacts of biochar additions on plant water composition. To address this critical gap, we present a case study using stable water isotopes and hydrometric data from melon production in tropical agriculture to explore the hydrological impacts of biochar as a soil amendment. Results from our 10-week growing season experiment in Costa Rica under drip irrigation demonstrated an average increase in volumetric soil moisture content of about 10% with an average moisture content of 25.4 cm³ cm⁻³ versus 23.1 cm³ cm⁻³, respectively, for biochar amended plots compared with control plots. Further, there was a reduction in the variability of soil matric potential for biochar amended plots compared with control plots. Our isotopic investigation demonstrated that for both biochar and control plots, there was a consistent increase (or enrichment) in isotopic composition for plant materials moving from the roots, where the average $\delta^{18}\text{O}$ was -8.1% and the average $\delta^2\text{H}$ was -58.5% across all plots and samples, up through the leaves, where the average $\delta^{18}\text{O}$ was 4.3% and the average $\delta^2\text{H}$ was 0.1% across all plots and samples. However, as there was no discernible difference in isotopic composition for plant water samples when comparing across biochar and control plots, we find that biochar did not alter the composition of water found in the melon plant material, indicating that biochar and plants are not competing for the same water sources. In addition, and through the holistic lens of sustainability, biochar additions allowed locally sourced feedstock carbon to be directly sequestered into the soil while improving soil water availability without jeopardizing production for

the melon crop. Given that most of the expansion and intensification of global agricultural production over the next several decades will take place in the tropics and that the variability of tropical water cycling is expected to increase due to climate change, biochar amendments could offer a pathway forward towards sustainable tropical agricultural water management.

Keywords: tropical agriculture; melons; biochar; hydrometric observations; stable water isotopes

1. Introduction

Biochar has been put forward as a potential soil amendment with multiple impacts that could increase sustainability. Biochar is a charcoal made by pyrolyzing organic feedstocks, e.g., biomass from woody or herbaceous vegetation, agricultural crop residues, or even waste material [1,2], in low-tech [3] or high-tech furnaces [4]. Of course, a central consideration from a sustainability perspective is the specifics of biochar production as there is a wide range of diverse activities globally that produce and provide biochar. Considering this range, from community development cookstove projects with smallholders to large-scale commercial biochar enterprises, the International Biochar Initiative [5] developed several guiding principles for an economically viable, socially responsible, and environmentally sound biochar industry. These principles highlight some of the potential impacts biochar can have, for example, on agricultural production globally and especially in developing regions where the potential for production and resource management improvement may be larger. Given future shifts in climate and demands on food production, understanding and exploring the viability of biochar as a strategy to move towards sustainable water management across various regions globally thus becomes paramount.

The tropics are an excellent region where biochar could realize various sustainability aspects for agricultural production and water management—especially given the soil qualities, water limitations, and inter-annual climatic vulnerability affecting livelihoods across the region. For example, according to the Intergovernmental Panel on Climate Change [6], Latin America and many other tropical geopolitical regions are expected to experience significant climate-driven impacts on social, economic, and environmental sectors in the near future [7]. There is a clear warming trend and shift in the seasonal distribution of rain anticipated in the tropics over the next century (e.g., [8]), which will cause longer periods of drought, earlier baseflow recessions, and increased flood severity [9]. All tropical agriculture, independent of the crop or the location, will be impacted by climate change altering growing conditions and leading to shifts in cropping patterns and the need for agronomic adaptation [10]. For example, Duku et al. [10] found that between 50% and 95% of cultivated areas for a large watershed in sub-Saharan Africa (Benin) that currently supports rainfed sequential cropping will be forced to revert to single cropping due to climate change in the future.

Agricultural production sustains human life across the globe, but nowhere does it face a more complex combination of socioeconomic and environmental constraints or play a more central role in supporting livelihoods than in the world's tropical regions [11]. As well, this importance is only expected to increase in the future as the tropics are expanding poleward driven by human-caused changes to climate (e.g., [12]). Variations of the tropic's width will shape the patterns of precipitation, heat waves, storm tracks, and ocean circulation and therefore have broad social and environmental implications [13]. Solutions to these issues depend on how we engage and educate future generations in connection with potential new innovations and approaches for sustainable water management [14]. A first step in this regard is clear recommendation and consensus around the impacts and implementations for water sustainability associated with the technique, which requires careful consideration when considering biochar.

Specifically, recent research on the water management impacts of biochar has been rather inconclusive. For example, as outlined by Fischer et al. [2], it is often unclear how, if at

all, biochar improves soil water availability, plant water consumption rates, and crop yields. Based on their literature synthesis, Fischer et al. [2] found that biochar amendments could increase crop yields in 75% of studies compiled but that biochar amendments were linked to simultaneous increases in crop yield and water use efficiencies (i.e., more crop and more “crop per drop”) for only 35% of studies compiled. Much of the variability in impacts on water use efficiencies (and ultimately water management) comes from the variations in how biochar can be implemented in an agricultural setting. For example, biochar can be applied on the soil surface or incorporated into the soil changing the infiltration capacity across the soil profile [15,16]. Working biochar into deeper soil layers alters soil physical properties as a function of biochar type (e.g., particle size, shape, and material) [16]. Since biochar disrupts the soil matrix by generally increasing porosity, aggregate stability, and saturated hydraulic conductivity, pore size distributions, the altered soil physical characteristics thus tend to increase the soil water holding capacity and the amount of soil water available at a given soil matric potential, but this depends on soil texture type and application rates [2,17]. Mixing biochar into deeper soil layers also influences the matric potential and modifies the soil water retention curve [2]. In turn, this affects the binding of water to the soil, the soil water content, and plant water availability. A meta-analysis by Omondi et al. [17] found that, on average, soil bulk density significantly decreased by 8% after biochar amendment. Soil porosity significantly and aggregate stability increased both by 8%, available water-holding capacity by 15%, and saturated hydraulic conductivity by 25%. However, the effects are highest with biochar application amounts above 80 t ha^{-1} and low to insignificant at less than 20 t ha^{-1} . Despite the growing knowledge base around the impacts of biochar on soils gained through lab and pot experiments, there is a need for more work leveraging multiple lines of data and evidence allowing for exploration of the variety of processes occurring in agroecosystems at the field scale [15,18,19]. Specifically, there is a knowledge gap in how biochar affects water stores and fluxes and eventually plant water availability as we look to biochar as a sustainable water management strategy. This is especially true in regions such as the tropics where the margin of error for production is slim and the impacts (and risks) are potentially large.

As such, the goal of this study is to assess the potential impacts of biochar as a soil amendment impacting water storage and plant water usage associated with tropical agriculture. Specifically, we target drip-irrigated melon production in Costa Rica, which as a crop is mainly intended for export, under treatment of biochar addition to soil for one growing season and measure the impacts through two relevant water perspectives. First, we look at the impact of biochar amendments on the ability of the soil to store and hold water through time series of soil volumetric moisture content and soil matric potential. Then, we look at the impact of biochar on the composition of water found in soil and in melon plant material (roots, stems, leaves, and fruit) using the stable water isotopes collected across the growing season. We anticipated an increased ability of soil amended with biochar to store water would be evidenced at the plot scale through increases in soil moisture contents; however, we hypothesized that any shift in terms of the composition of water being stored in the soil or being found in the plants would be minimal given the complexity of plant-water interactions occurring at the plot scale. The former perspective stems from previous literature efforts that have demonstrated increases in storage capacity achieved through biochar additions and the latter perspective comes from the complexity at play with regards to ecohydrological interactions across the soil-plant-atmospheric continuum. Collectively, this research seeks to help better understand how biochar amendments can ultimately contribute to sustainability in agriculture across the tropics and increase food security by reducing vulnerability to climatic shifts.

2. Materials and Methods

2.1. Site Description

The biochar experiment was conducted at the Enrique Jiménez Núñez Experimental Station (EEEJN) from the Instituto Nacional de Innovación y Transferencia en Tecnología

Agropecuaria (INTA) near the city of Cañas in the Guanacaste province of Costa Rica, which is at $10^{\circ}20'42.86''$, $85^{\circ}08'5.12''$ (Figure 1). Soils at the experimental site are loamy vertosols typically more than 2 m deep [20]. The soil texture in the top 20 cm at the experimental site was characterized as 34% sand, 30% silt, and 36% clay and contained about 2% Organic Carbon. Guanacaste province is part of the Dry Corridor of Central America [21] and is characterized by a seasonally dry tropical climate with marked dry and wet seasons and limited temperature variability over a year [22]. The annual average temperature at EEEJN-INTA is 27.4°C . The dry season typically spans from mid-November to April with virtually no rainfall. Melons are grown in the region as a dry season crop requiring supplemental irrigation. Wet season precipitation exhibits a bi-modal distribution dominated by the influence of the Intertropical Convergence Zone and easterly tropical waves with peaks occurring in May/June and September/October. The moderate dry period between these two peaks is usually referred to as the mid-summer drought [23]. The average annual rainfall in the area is approximately 1547 ± 473 mm based on a 100-year observation record from a meteorological station about 10 km away from the experimental site. The annual average actual evapotranspiration is around 1100 mm [24].

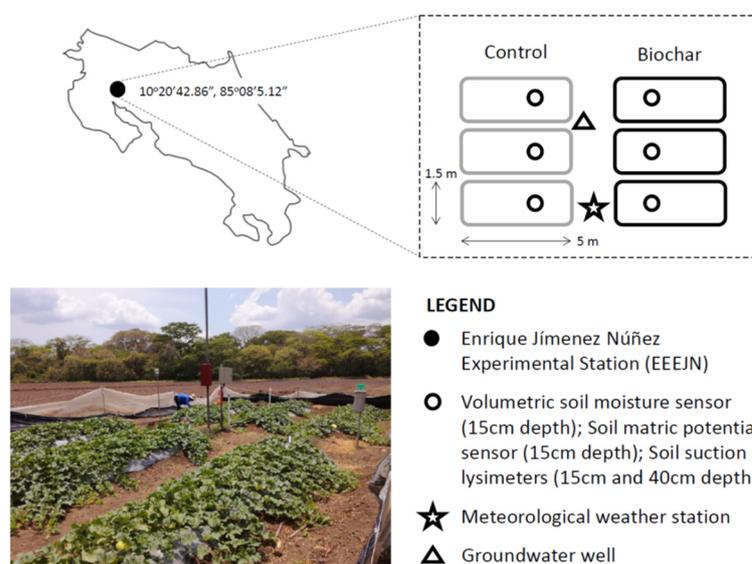


Figure 1. Site map showing the location of the experiment in Costa Rica. Photo of the experiment is taken on 6 April 2018.

2.2. Experiment Design

2.2.1. Biochar and Melon Plants

The biochar considered as a soil amendment in this study was made of locally-sourced bamboo (*Guadua angustifolia*) and produced at the Costa Rica Institute of Technology (TEC, Cartago, Costa Rica). The feedstock consisted of wood pieces up to 30 cm in length from construction waste, which were pyrolyzed using a pyrolysis furnace under a temperature ranging from $450\text{--}480^{\circ}\text{C}$. For the biochar treatments, the ≤ 2 mm particle size biochar was mechanically worked into the top 20 cm of the treatment field prior to planting achieving an application rate of 1 kg m^{-2} across the field. Similar mechanical working (without the addition of biochar) was performed for the control field prior to planting.

Both fields were planted with melons (Canary melon, *Cucumis melo*) on 21 February 2018 marking the beginning of the experiment. Our experimental field was divided into plots covering $5.0\text{ m} \times 1.5\text{ m}$ (Figure 1) such that we have three control plots (no biochar) and three treatment plots (biochar addition) to be monitored both for water content via in situ sensors and to allow for the collection of soil water and plant water samples for isotopic analysis. Planting followed standard practices for the region and consisted of seedlings transplanted to hilled soil (i.e., small earthen mounds created within the fields). Melons

were planted by hand every 0.3 m along the mounds in a single row. Spacing of about 0.8 m was left between the mounds to reduce any potential mutual influence of treatments; however, artificial spacer belts were not utilized. After hilling, plastic covering was placed on the ground to help trap heat and moisture with an opening made to allow for emergent melon plants. Drip irrigation was established at each melon mound and set at a constant daily irrigation rate providing 2 L h⁻¹ water per drip in a 12-min cycle daily as is common in this region. Irrigation water, with origin from the nearby mountains, was pumped from a nearby irrigation canal that provides water to EEEJN-INTA. Melons were harvested in two cuttings on 17 April 2018 and 27 April 2018 with all melons and plant materials harvested by the end of the 10-week experiment on 3 May 2018. Basic yield analysis (Table 1) showed that there was no demonstrated difference between the production of the biochar plots compared to the control plots. We provide these data on production as context here and focus our study on the impacts of biochar on water availability and management.

Table 1. Melon yield and production data averaged across plots.

Metric	Biochar Plots	Control Plots
Number of plants (plants)	15.0	16.3
Number of melons (melons)	59.7	58.3
Mass of all melons (kg)	51.0	54.7

2.2.2. Water Monitoring and Data Processing

For the physical water monitoring, each experimental plot was instrumented with a volumetric soil moisture sensor (model GS3, Decagon Devices Inc., Pullman, DC, USA) and a soil matric potential sensor (model MPS6, Decagon Devices Inc., Pullman, DC, USA) installed at 15 cm depth and collecting measurements every 30 min. Additionally, soil moisture measurements were collected at 15 cm soil depth from each plot at the beginning of the experiment and after harvest to perform a two-point calibration of the volumetric soil water content measurements derived from the sensors at each plot during the entire time series. In addition to the soil water monitoring, a meteorological weather station (Vaisala WXT520; 1.5 m height) was used to continuously monitor precipitation, air temperature, relative humidity, and atmospheric pressure at the site during the entire 10-week study period.

To facilitate comparison between control and biochar plots, data were averaged across the replicate plots to create daily timeseries of volumetric soil moisture, soil matric potential, and meteorological observations. These timeseries were then compared to characterize the impact of biochar additions on soil water characteristics under variations in daily meteorological factors. For all comparisons, variance tests (F-tests two-sample for variances) were used to assess the variability of the data in multiple groups, namely control versus biochar plots, defined for identified time periods and to determine whether the data were different.

2.2.3. Isotopic Sampling and Analysis

Water samples from different pools were collected for isotopic analysis. All water samples were stored in high-density polyethylene bottles with no head space and kept cool until analysis. Irrigation water was collected from the drip system, which had a common source, compositing a sample across all the plots. In each plot, soil suction lysimeters (Soil moisture equipment corp., Santa Barbara, CA, USA) were installed in the soil reaching to 15 cm and 40 cm soil depth to sample soil water. Soil water samples were extracted by applying 800-mbar of suction on each lysimeter for 15 min up to one hour. Groundwater samples were collected from a groundwater well installed near the experimental site. The groundwater well was purged and allowed to recharge before a water sample was collected. Irrigation water was collected daily across the entire experiment in order to characterize any changes to water inputs to the plots while ground and soil water were collected at

intervals during the experiment due to these being more labor-intensive to collect and as these pools were expected to change more slowly.

Plant material from the melon plants was also collected at approximately five biweekly sampling dates over the course of the growing season. For plant material sampling, we harvested the roots, stems, melons, and leaves of the extracted plants. These materials were separated immediately and transferred into doubled re-sealable zipper storage bags. To minimize post-sampling transpiration, storage bags were directly placed in a cooler with ice. All plant material was stored in the lab freezer before extracting the plant water for isotopic analysis. Upon returning to the lab, we used the cryogenic vacuum extraction technique described by Koeniger et al. [25] to extract water from plant materials for stable isotope analysis. The method uses a heated vial and a cold trap vial connected with stainless-steel capillary tubing and was selected as it has been shown to be an effective option for extracting water from plant materials [26].

For isotopic analysis, all non-plant water samples were filtered (0.45 μm) before analysis using a water isotope analyzer LWIA-45P (Los Gatos Research Inc., San Jose, CA, USA). All data were normalized and corrected for drift and memory effects. Stable isotope compositions in this research are reported as delta notations (δ) in ‰ that relate the ratios of $^{18}\text{O}/^{16}\text{O}$ and $^2\text{H}/^1\text{H}$ relative to the VSMOW-SLAP scale. The analytical long-term error was $\pm 0.5\text{‰}$ for $\delta^2\text{H}$ and $\pm 0.1\text{‰}$ for $\delta^{18}\text{O}$ for the isotopic analysis. Timeseries of stable water isotopic composition were compared statistically to assess differences in the stores of water both in plant material and soils between biochar and control plots. Again, variance tests (F-tests two-sample for variances) were used to assess the variability of the various isotopic composition data between control and biochar plots confirming whether the data were different.

In addition, the water isotopic compositions were also compared in dual isotope space plotting $\delta^2\text{H}$ against $\delta^{18}\text{O}$ relative to the global meteoric water line (GMWL) defined as $\delta^2\text{H} = 8 \cdot \delta^{18}\text{O} + 10\text{‰}$ from Craig [27] and the local meteoric water line (LMWL) defined as $\delta^2\text{H} = 7.6 \cdot \delta^{18}\text{O} + 6.2\text{‰}$ from Sanchez-Murillo et al. [28].

3. Results and Discussion

3.1. Hydrometric Observations

Volumetric soil moisture (Figure 2) was significantly ($p < 0.01$) higher on average in the biochar plots compared to the control plots. Over the course of the experiment, the volumetric soil moisture in the biochar plots was about 10% higher than in the control plots (average of $25.4 \text{ cm}^3 \text{ cm}^{-3}$ versus an average of $23.1 \text{ cm}^3 \text{ cm}^{-3}$, respectively, over the 10-week period) with a maximum difference of $4.2 \text{ cm}^3 \text{ cm}^{-3}$ occurring several times during the first few weeks of the experiment. After about 3 to 4 weeks into the experiment, volumetric soil moisture for both biochar and control plots dropped to the lowest values observed over the entire growing season. This drop corresponds with the rapid emergence of melons across all plots where the number of melons on each plot reached its approximate maximum on 23 March 2018.

The soil matric potential (Figure 2) also responded to this emergence of melons across the biochar and control plots. During the first few weeks before melons emerged, the soil matric potential for both biochar and control plots were similar and showed no significant difference. However, the additional volumetric water content available in the biochar plots versus the control plots for a similar level of soil matric potential is notable.

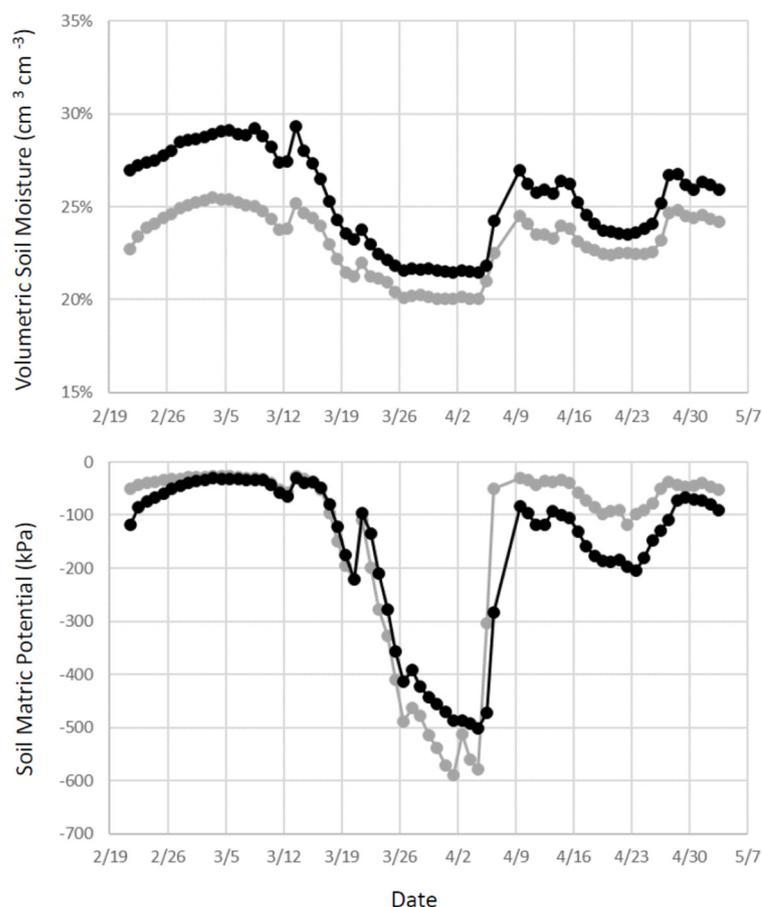


Figure 2. Timeseries of daily average volumetric soil moisture and soil matric potential averaged across the biochar plots (black dots) and control plots (gray dots).

After the melon plants reached the approximate maximum yield for fruit production (around 1 April 2018 onwards), there was a significant ($p < 0.01$) divergence for soil matric potential between the control and biochar treatment. Specifically, the soil matric potential in the biochar plots showed reduced variance (i.e., data were more moderated or limited with regards to fluctuations) such that the highest and lowest values were not as extreme as those in the control plots. During the middle two weeks of the experiment, the soil matric potential on average in the biochar plot was significantly ($p < 0.01$) less negative (i.e., wetter) than that in the control plots and averaged about 65 kPa higher. Counter to this period, for the last 4 to 5 weeks of the experiment, the matric potential in the biochar plots was on average significantly more negative (i.e., drier) than those in the control plots and averaged about 77 kPa lower.

Looking at the meteorological data (Figure 3), the air temperature was consistent over the experiment ranging from around 27 °C to 30 °C with an average of 28.8 °C. Relative humidity showed a marked increase comparing the first 5 to 6 weeks where the average was 48.7% with the last 4 to 5 weeks where the average was 58.5%. This latter period of elevated relative humidity corresponds to the period where soil matric potential was differentiated between the biochar and control plots and is consistent with the regional transition from dry to wet season that typically occurs in April.

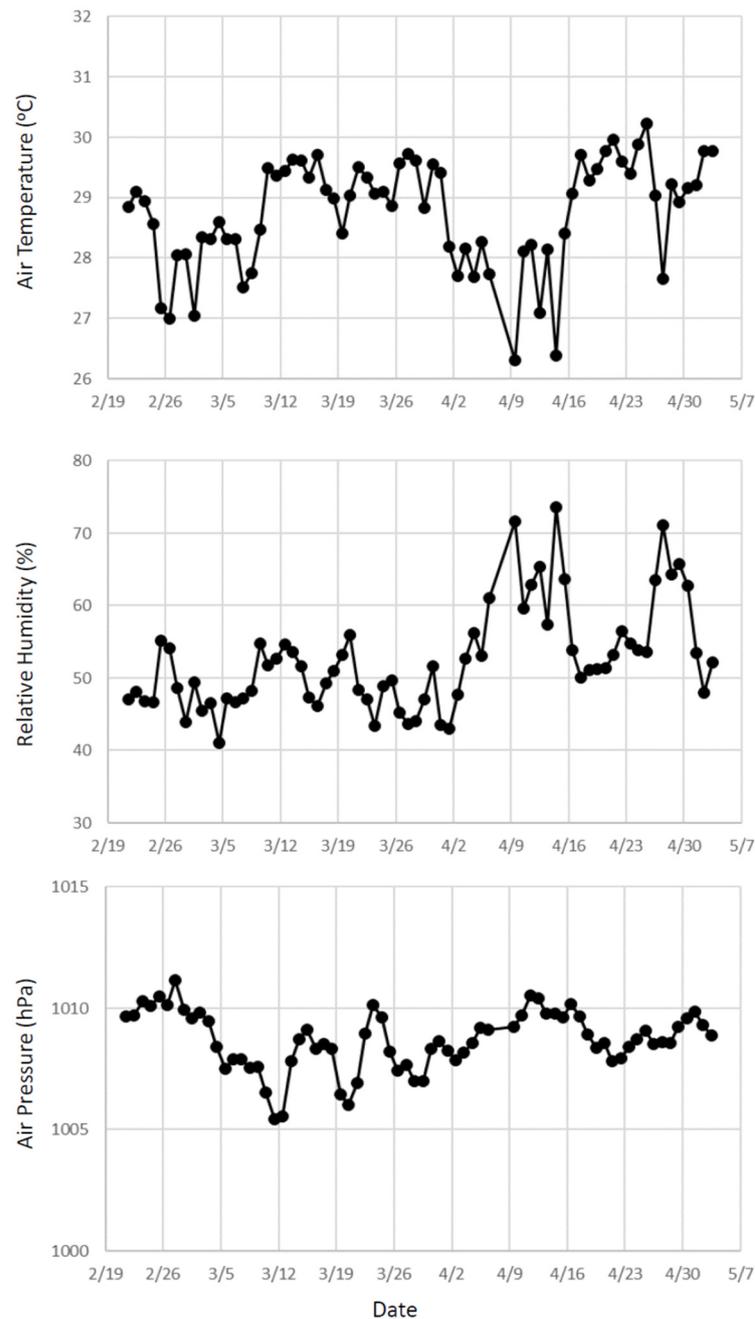


Figure 3. Daily averaged meteorologic data collected at the site.

Atmospheric air pressure averaged around 1008 hPa over the entire 10-week experiment and exhibited a higher range between 1005 hPa and 1012 hPa during the first 5 to 6 weeks relative to the more limited range between 1007 hPa and 1011 hPa during the last 4 to 5 weeks. Finally, there was relatively little precipitation during the entire period of observation. The total observed precipitation was 6 mm occurring on 14 April 2018; 9 mm occurring on 25 April 2018; and 11 mm occurring on 27 April 2018, respectively. The soil moisture and matric potential across both biochar and control plots responded to this precipitation with a moderate increase at the end of the experiment before harvest, but overall, the irrigation dominated the water input to the soil.

Collectively, biochar amendments to the soil tended to increase water holding capacity for our experiment as demonstrated through higher volumetric moisture contents and moderation of matric potential fluctuations. As such, more water could be stored in the ground

per similar irrigation practices. Taken another way, and considering the lens of sustainable water management, less water could potentially be used to irrigate to achieve the same volumetric moisture contents for these melon plots. Faced with increasing climatic variability and possible prolonged drought periods, biochar amendments could thus provide more and prolonged water availability in agricultural soils in support of production.

3.2. Isotopic Composition

There was no discernible difference in isotopic composition for soil or plant water samples when comparing across biochar and control plots (Table 2). There were consistent patterns in isotopic composition across the plant materials sampled. For both biochar and control plots, there was a consistent increase (or enrichment) in $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values moving from the roots through xylem through melon through the leaf, which could be expected when considering belowground versus aboveground plant tissue. Above-ground plant materials had higher standard deviations for observed $\delta^{18}\text{O}$ and $\delta^2\text{H}$ across both biochar and control plots compared to both irrigation and groundwater samples. Soil water had isotopic compositions that were somewhere between xylem and leaf water for these samples and exhibited more variability than either irrigation or groundwater samples.

Table 2. Observed isotopic composition based on samples collected in this study with values presented as averages both in time and across plots with standard deviations given in parenthesis.

Source Water	Sample Count	$\delta^{18}\text{O}$ (‰)	$\delta^2\text{H}$ (‰)
Precipitation	1	−1.9 (0.0)	+3.4 (0.0)
Irrigation	57	−5.6 (0.7)	−36.5 (4.1)
Ground	29	−5.9 (0.4)	−39.3 (1.8)
Biochar Plots			
Soil	19	−2.7 (1.3)	−24.8 (5.8)
Leaf	29	+4.4 (1.9)	+1.5 (12.0)
Melon	7	−0.7 (1.2)	−20.2 (14.7)
Xylem	32	−6.3 (1.1)	−43.6 (8.5)
Root	2	−7.6 (0.8)	−48.9 (1.5)
Control Plots			
Soil	11	−2.9 (1.1)	−25.1 (4.0)
Leaf	22	+4.1 (1.6)	−1.4 (10.7)
Melon	8	−0.3 (1.1)	−11.2 (11.3)
Xylem	22	−6.6 (1.2)	−47.9 (10.1)
Root	2	−8.6 (0.8)	−59.9 (4.4)

The variability in the soil water isotopic composition relative to that found in irrigation water and groundwater is seen strongly early in the experiment for both $\delta^{18}\text{O}$ and $\delta^2\text{H}$ (Figure 4). Given the lack of differentiation between the biochar and control plots (Table 2), we have opted to consider samples collected across all plots together when looking at timeseries (and subsequent dual isotope plots) to help increase the number of samples being considered. Despite this lumping of all samples, there were, unfortunately, fewer soil water samples available later in the experiment due to sampling error and mechanical failure of equipment which likely explains the decreased variability with time. We can also see the impact of the small precipitation event on the isotopic composition of the irrigation water. Specifically, irrigation water $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values both increase towards the isotopic composition sampled for the precipitation event. For the plant materials, the enrichment seen moving from below to above ground in Table 2 is evidenced in time in Figure 4. The root water $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values provide a lower bound for the plant material isotopic

composition except for a few of the xylem water samples. Given the limited number of root samples collected relative to xylem water samples (Table 2), it is likely we are not capturing the true range of isotopic variability in the root water across the biochar or the control plots.

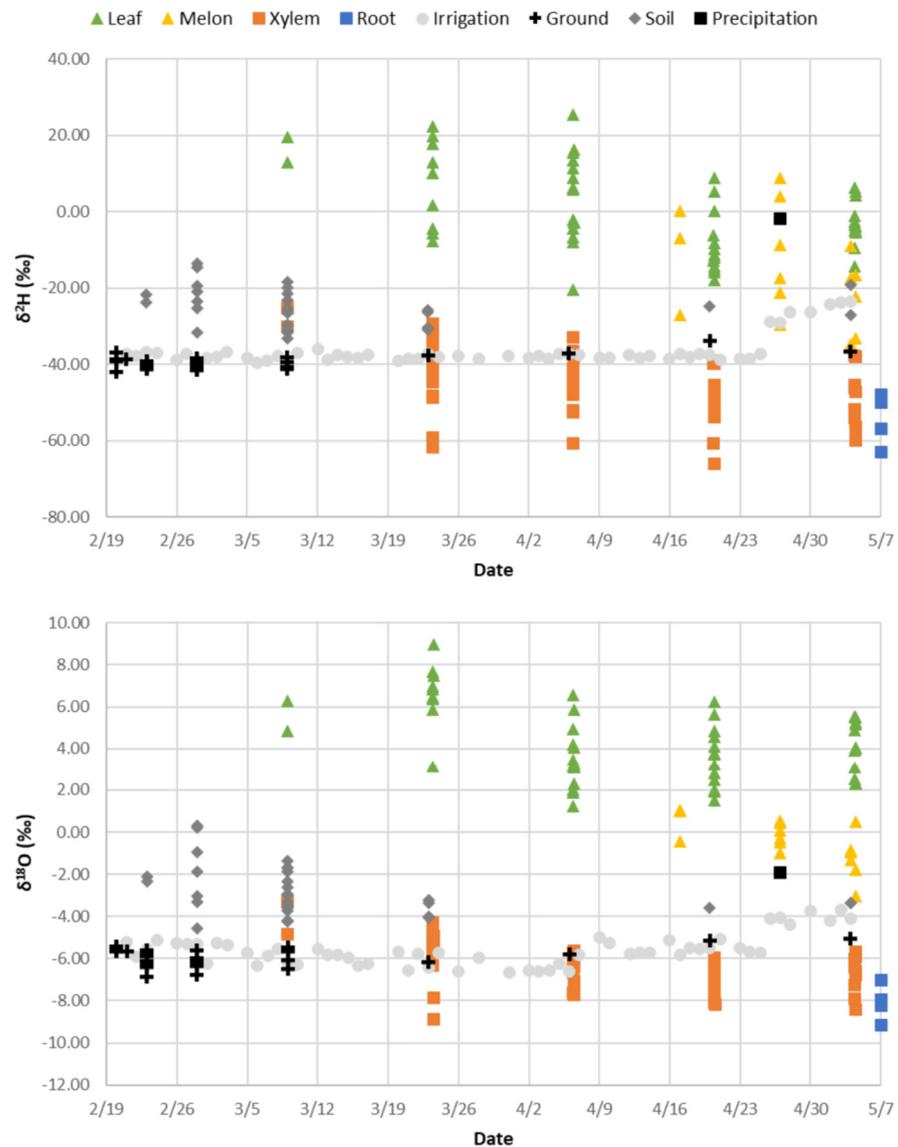


Figure 4. Timeseries of isotopic compositions measured in various source waters across the experiment.

Finally, we can explore the clustering of isotopic compositions by comparing between various water sources within dual isotope space (Figure 5). Here we can see that the samples (for the most part) fall below the global meteoric water line (GMWL) and the local meteoric water line (LMWL) as would be expected. Noting that the single precipitation sample falls above the line for both the GMWL and LMWL; however, we have too few samples and precipitation events to assess how much this is due to localized variability in combination with sampling and analytical errors [26]. Comparing isotopic compositions in the water samples to the GMWL and LMWL, we can see impacts of evaporation, expressed as systematic deviation from these lines, for the leaf and melon plant samples and the soil water samples. Further, while irrigation and soil water appear to provide a lower bound for some of the plant water isotopic compositions, they do not likely capture the complete isotopic composition of water being utilized by the plants. Consistent with the timeseries (Figure 4), it is actually the root water samples that appear to best reflect the bulk soil water that is being consumed by the melon plants in both the biochar and the

control plots. Given the shallow rooting systems for these melon plants, it is likely that water collected in our soil water samplers, located at 15 cm and 40 cm depth, does not represent the entire soil zone where the plants are taking water. This interpretation is consistent with results observed in previous studies using stable water isotopes to map out plant water sources [29–31].

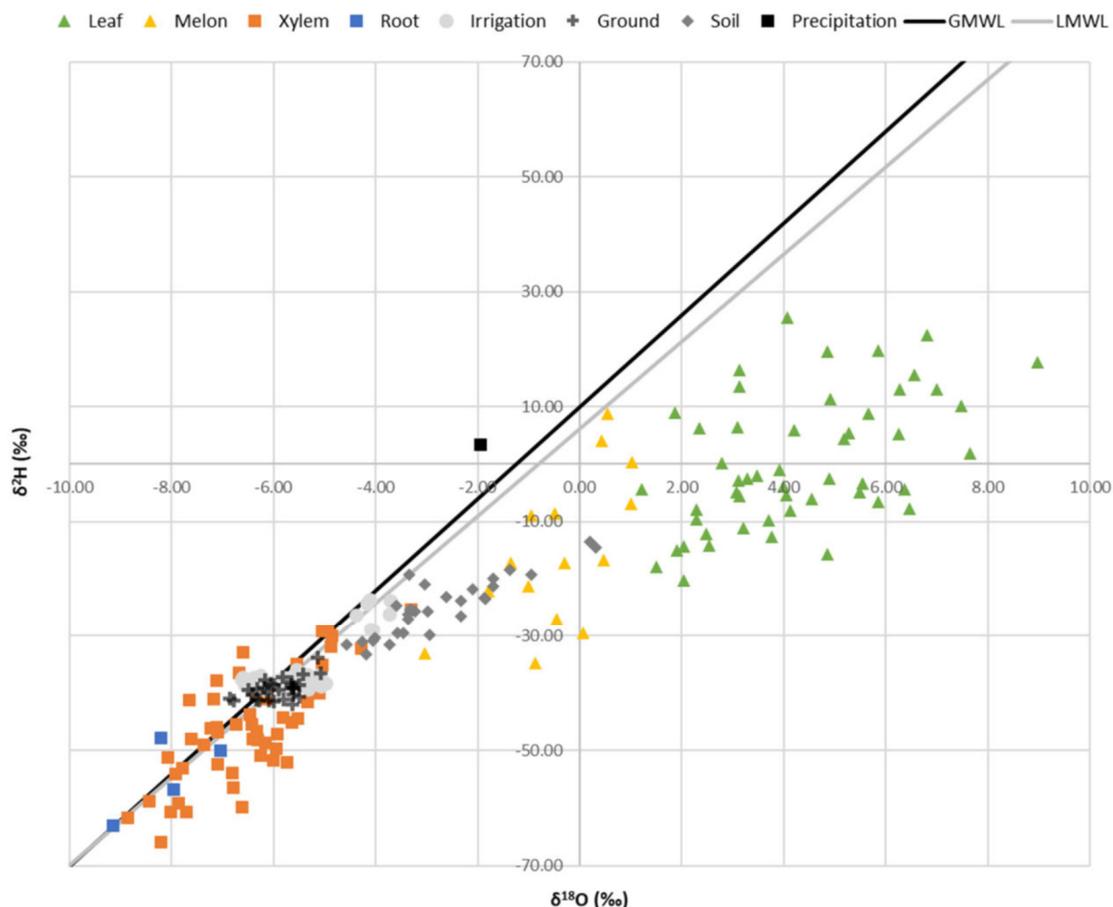


Figure 5. Source water isotopic compositions measured across the experiment in dual isotope space.

Also, it is possible that the plants are accessing water held at a high tension within the soil than our suction lysimeters can extract. Further, as the melon mounds are covered in plastic, there is a good chance that soil water, which derives from irrigation, evaporates such that the water vapor is trapped and condensed helping redistribute moisture towards the soil surface (depth less than 15 cm), which would be consistent with the isotopic compositions observed. As such, the addition of biochar did not appear to shift the sources of water being consumed by the melon plants in this experiment. So, while biochar has potentially increased the amount of water being stored in the soil (Figure 2), it apparently has not impacted how the plants interact with this water. This is a promising result from a sustainable water management perspective as it implies that biochar is not competing with the plants for the same water.

3.3. Practical Implications

Innovations that comprehensively address the food-water-energy nexus across a local-to-global axis are required to meet human demands for food while maintaining water and energy security—a trilemma entailing some of society’s greatest challenges. Given that most of the expansion and intensification of global agricultural production over the next several decades is projected to take place in tropical regions [32], innovations in tropical agricultural water management are particularly crucial. This need becomes more urgent

when considering that the variability of tropical rainfall patterns is expected to increase due to climate change, particularly in terms of the arrival, duration, and intensities of seasonal rainfall [33]. As such, there is an urgent need to develop methodologies to increase water use efficiencies in both rainfed and irrigated agriculture locally in order to improve food and water security globally. Based on this current study and several others, biochar seems to offer such a methodology with regards to sustainable water management.

It should of course be noted that while other studies have demonstrated generally increasing crop yields [34], our single-season experiment with drip irrigation did not see a significant impact of biochar on melon production (Table 1). Considering the biochar in a broader sustainability context [5], we find encouragement here as there is no negative influence of the biochar additions on production and, as such, biochar has not jeopardized production. Further, and again thinking beyond the water impacts, biochar additions to the soil represent a global negative emission potential of 0.7 Pg C yr^{-1} [35]. Our study is consistent with these global projections in the sense that we have utilized a local waste feedstock material and low-technology biochar production method to produce the biochar which is directly sequestered into the soil in our experiment.

There is still a clear need to explore the value of biochar across various conditions and settings in the tropics. Biochar may not be always a win-win technology for sustainable water resource management if not well synchronized with agro-ecological conditions of the application location and socio-economic status of the end-users [36]. Specific, since there are several variables at play around how biochar is made and implemented in agricultural and water management practices, we see a need to align social and environmental benefits of biochar technology with policy decisions (e.g., [36]). Through such alignment, with an appropriate understanding of long-term impacts and designing of biochar for conditions, biochar can begin to fulfill its potential to achieve sustainable water management.

3.4. On the Potential for Stacked Benefits

Intensification of water use in agriculture, water pollution, and climate-induced changes in freshwater availability are all increasing vulnerability within the global food system. Strategies to maximize agricultural production and minimize environmental impacts through the large-scale deployment of negative-emissions technologies (e.g., technologies that result in the net removal of greenhouse gases (GHGs) from the atmosphere [37]) are critical. Biochar-based soil amendments are exceptional in this context as they can target improvements in sustainable water management and ultimately agriculture.

Further biochar has been found to improve crop productivity and soil quality consistently through liming and fertilization effects in low pH and infertile soils under low-input conditions typical of weathered tropical soils [36]. There is a need for the reduction of costs of biochar production and application to increase the material's use efficiency need future development. A recent review by Basak et al. [36] highlights the need to link economic benefits with social and environmental issues for the successful implementation of biochar technology in weathered tropical soils. Further, they recommend that the identification of biochar properties suitable for tropical soils is important to obtain the maximum benefit of biochar application. Basak et al. [36] pointed out that suitable application strategies and the co-deployment of biochar with other suitable additives provide a promising area for improving the efficiency of biochar for agricultural application.

4. Conclusions

This study quantifies biochar as a potential approach to secure sustainable water management. Specifically, we assessed the impacts of a locally-sourced biochar on water storage in addition to the potential impacts on yield—which both must be considered when we think about achieving sustainable water management. Our findings add value, for example, when trying to motivate the adoption and application of biochar in tropic climates where we may need to consider multiple (or stacked) benefits from the sustainability perspective. Our results demonstrate this potential with regards to biochar in the tropics.

Strategies whereby additional benefits like increased water storage that can bring about reduced irrigation needs and longer periods of drought resistance for crops could help motivate farmer adoption of biochar as a management practice.

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