California Department of Food and Agriculture
Fertilizer Research and Education Program
Final Report

A. Project Information

Project Title	*Evaluation of Biochar for On-Farm Soil Management in California*	
Project leaders	*Danielle L. Gelardi*[1], Graduate Student Researcher *Sanjai J. Parikh*[1], Associate Professor of Soil Chemistry *William R. Horwath*[1], Prof. Soil Biogeochemistry *Daniel Geissler*[1], Assoc. Coop. Ext. Specialist *Milt McGiffen*[2], Veg. Crops Spec. & Vice Chair for Coop. Ex. *Michelle Leinfelder-Miles*[3], Coop. Ex. Farm Adv. *Toby A. O'Geen*[1], Soil Resource Specialist *Kate M. Scow*[1], Professor of Soil Microbiology [1] Department of Land, Air and Water Resources, University of California, Davis, One Shields Avenue, Davis, CA 95618. [2] Department of Botany and Plant Science, University of California, Riverside, 4101 Bachelor Hall, Riverside, CA 92521 [3] Cooperative Extension San Joaquin County, 2101 East Earhart Ave., Stockton, CA 95206	
Grant Number	16-0662-SA-0	
Project Duration	Start Date: 01/01/2017	End Date: 12/31/21 (with NCE)
Email and Phone	sjparikh@ucdavis.edu; 530 752 1265	
Report Type	Final	
Reporting Period	Start Date: 01/01/2017	End Date: 12/31/21

B. Abstract

Although many studies have demonstrated that biochar can deliver agronomic benefits such as increased soil water and nutrient retention, increased fertility, and increased yield, these experiments are frequently small-scale and short-term. Furthermore, biochar has been observed to have the most significant benefits on crop growth in marginal soils, such as those with low fertility, coarse texture, contaminated, highly acidic, or receiving limited fertilizer and irrigation water inputs. This study aimed to determine the impact of biochar soil amendments on the fate of nitrogen and processing tomato production in two fertile soils in a Mediterranean climate. The effects of biochar on soil health and dust emissions were also considered. Seven biochars produced from different feedstocks at different temperatures were used in experiments at the microscopic, lab bench, pot, and field scale. The results indicate that biochar may confer limited agronomic benefits in fertile soils in Mediterranean climates. While there were no tangible agricultural improvements

nor significant impacts on nitrogen fate in this study, biochar may deliver benefits not captured in conventional agronomic measures. For example, this project demonstrated that biochar may provide soil health benefits in agricultural soils in a Mediterranean climate. However, increased soil health may not increase agricultural production within three years. Furthermore, soil health benefits were not consistent across soil texture and biochar type. Because biochar characteristically has low bulk density and high porosity, the material is susceptible to atmospheric release via natural or mechanical soil disturbance. This does not represent any inherent problem with biochar but serves as a reminder that proper measures should be taken to safeguard the health of those handling and applying biochar.

C. Introduction

The ability of biochar to chemically and physically alter soil environments for specific agronomic benefits is the subject of increased investigation, as evidenced by the recent rise in published biochar studies[1] and United States trademark and patent applications listing the word "biochar."[2] Biochar, or the carbonaceous material created from the thermochemical conversion of biomass in an oxygen-limited environment,[3] possesses unique chemical and physical properties, determined by variables such as its feedstock, production method, and production temperature. This process has clear waste management benefits and has been demonstrated to reduce greenhouse gases in multiple life cycle assessments.[4–6] Biochar properties typically include a low bulk density, high porosity, high surface area, reactive surface functional groups, and recalcitrant carbon.[7] These attributes make it a promising material for amendment to agricultural soils; biochar has been reported to deliver a suite of agronomic benefits when added to agricultural soils, including increased soil fertility,[8] increased soil water content,[9] and shifts in the soil chemical or microbial environment.[10,11] These benefits are often reported to increase crop yield, though results are inconsistent and vary widely. While many studies demonstrate increased yield following biochar addition,[10,12,13] others show little to no effect,[14–16] and in some rare cases, negative effects have been reported.[17] The efficacy of biochar to deliver agronomic outcomes depends on variables such as feedstock, production method, and production temperature, as well as soil, climate, and cropping conditions.

Despite increased interest and investigation, biochar's ability to deliver these agronomic benefits remains uncertain. While many studies show promising results where nutrient retention and soil water dynamics are concerned,[9,18–22] others have demonstrated no or only minor effects.[14,16,23] Several authors have concluded that, due to differences in biochar production parameters and those of the soil environment, material and site-specific investigation are required before conclusions can be drawn about the potential of biochar to provide agricultural benefits.[24–26]

Improvements in crop yield from biochar addition are frequently hypothesized to result from increased soil fertility, though biochar is not specifically a fertilizing material. While there may be short-term yield gains from the release of biochar-bound nutrients,[27] or slight, temporal gains from the weathering of endogenous biochar nutrients,[16] it is widely accepted that biochar should be used in conjunction with synthetic fertilizer, compost, or manure.[22,28–31] When applied to soils, biochar may enhance soil fertility by increasing cation exchange capacity (CEC), as negatively charged biochar surfaces adsorb to cations such as magnesium (Mg^{2+}), potassium (K^{+}), and calcium (Ca^{2+}).[32,33] Biochar has also been observed to bond covalently with ammonium (NH_4^{+}).[19] While a chemical affinity between biochar and nitrate (NO_3^{-}) is uncommon due to electrostatic repulsion,[34] biochar pores may physically entrap nitrate, making it more available for plant uptake.[21,31,35] As most biochars are alkaline, a shift in pH via a liming effect can also improve soil fertility by reducing aluminum toxicity or increasing phosphorous availability in soils of low pH.[20,36] Within studies that report a biochar-associated increase in soil fertility, the effect on crop yield is mixed, with some demonstrating increased yield,[10,12,32] minor or temporary increases,[15,37] soil-texture specific increases,[33,38,39] or no effect on yield.[8,40] Still other studies report no effect of biochar on soil fertility at all.[41,42]

The influence of biochar on soil water dynamics may also increase crop yields, though results appear largely dependent on soil texture. A recent meta-analysis concluded that biochar substantially increased soil water content at field capacity and permanent wilting point in coarse-textured soils.[43] Multiple authors have concluded that, overall, sandy soils have a greater response to biochar addition than finer-textured soils.[9,43] Despite these observed trends, biochar has been reported to improve soil water dynamics even in fine-textured soils. In field trials, biochar was observed to reduce maize crop water stress and increase yield in a silt loam,[44] prevent soybean crop loss in years of reduced precipitation in a sandy clay loam,[45] and increase wheat yield and quality under multiple deficit irrigation regimes in a silty clay loam.[46] By contrast, one study demonstrated that biochar-associated water savings in a clay soil were insufficient to reduce crop water stress or lead to increased maize yields.[47] Other authors have reported little to no effect, or transient effects, of biochar on soil water dynamics at the field-scale.[14,15,41]

The conditions in which biochar appears to deliver the most consistent agronomic benefits are those in which soils require conditioning or remediation for the successful growth of crops. A global meta-analysis concluded that biochar boosts yields in the tropics by 25%, but overall has no effect on yield in temperate latitudes.[48] Arable tropical soils are typically characterized by acidity, low fertility, and receive limited fertilizer inputs, and therefore may have the most to gain from the addition of biochar. Though the liming effect of biochar is widely reported,[25] it has been observed that up to 50 tons of biochar per hectare may be required to match the fertility benefits of just 3 tons per hectare of dolomite.[49] Biochar has also been observed to improve yields in saline and sodic soils, through the sorption of sodium (Na^{+}) or by releasing non-sodium base cations to decrease exchangeable sodium percentage.[50–52] Similarly, biochar can immobilize heavy metals or organic pollutants, thereby increasing yields and reduce the concentration of contaminants in crop biomass.[53,54] Collectively, this research suggests biochar has a promising role in remediating or conditioning soils that may otherwise pose challenges for agricultural production. However, applying biochar to temperate and fertile cropping systems appears to have fewer agronomic benefits.[48]

A lack of field-scale experiments is another challenge to determining if biochar may deliver agronomic benefits. One literature review concluded that, of nearly 800 studies evaluated, approximately 25% were conducted in the field.[24] Of those field studies, more than 50% were in plots less than 20 m^2 and under investigation for one year or less. This review highlights the limitations in biochar research, which pose obvious challenges to extrapolating results to production-scale agriculture. Indeed, it has been observed that laboratory results do not necessarily scale, as in Jones et al. (2012), where the short-term effects of biochar on soil and plant growth reported from laboratory studies were not observed in a three-year field trial using the same soil and biochar. Fortunately, there have been a number of large-scale field trials spanning 3 or more planting seasons published in recent years: Hale et al., 2020; Jin et al., 2019; Kätterer et al., 2019; Liu et al., 2019; Madari et al., 2017; McDonald et al., 2019; Nan et al., 2020; Oladele, 2019; Pandit et al., 2018; Sadowska et al., 2020; and Sánchez-Monedero et al., 2019. While multiple studies demonstrated the potential of biochar to remediate or condition low-quality agricultural soils,[36,47,55] benefits have also been observed in fertile soils,[10] though these are frequently limited in size or duration.[8,11,15,37,45] Inconsistencies emphasize the need for increased field-scale, long-term, and location- and material-specific research to inform the use and regulation of biochar in working lands.

D. Objectives

The overarching objective is to provide baseline data specific to CA regarding the potential for biochar to provide benefits as a soil amendment for increasing nutrient retention, C sequestration, and improving drought resilience for agriculture in CA's Central Valley. Specific project objectives are:

1. Characterize biochars produced from biomass locally available throughout California;
2. Evaluate the impact of biochar amendments on soil-water dynamics, fertilizer inputs, nutrient use efficiency (including leaching), carbon stocks, soil aggregation, and crop productivity;
3. Evaluate soil conditions and biochar parameters, including biochar and fertilizer application rates, which are most likely to lead to beneficial outcomes from biochar soil amendments; and
4. Conduct a life cycle analysis to obtain clear and objective information regarding the use of biochar in California agriculture.

Table 1. Project work plan

Tasks and Other Activities	Year					
	1		2		3	
Task 1: Produce and characterize biochar	✓					
Task 2. Field trials in Yolo and Fresno Counties		✓	✓	✓	✓	✓
Task 3. Lab and Greenhouse Bioassays		✓	✓	✓	✓	✓
Task 4. Economic analysis of biochar amendments in CA.				✓	✓	✓
Task 5. Conduct an outreach program	✓	✓	✓	✓	✓	✓
Interim, Annual, and Final Reports to FREP		✓		✓		✓
Presentations to stakeholders and publication preparation				✓		✓

E. Methods

E.1 Biochar characterization

Seven biochars from four commercial companies were obtained from the following feedstocks and produced at the following temperatures: almond shell at 500 and 800 °C (AS500, AS800), coconut shell at 650 °C (CS650), softwood at 500, 650, and 800 °C (SW500, SW650, SW800), and an additional softwood biochar produced at 500 °C and inoculated with a microbial formula (SW500-I). Unless otherwise stated, biochars were sieved to 2 mm and characterized using procedures recommended by the International Biochar Initiative (IBI, 2015): pH and electrical conductivity (EC) were measured at a 1:20 biochar to 18.2 MΩ-cm water (Barnstead nanopore, Thermo Fisher) dilution (w:v) after solutions were shaken for 90 minutes; total carbon, nitrogen, hydrogen, and oxygen were measured using a dry combustion-elemental analyzer (Costech ECS4010); and moisture, volatile, and ash content were measured as a percent of total dry weight through sequential increases in furnace temperature (105, 750, and 950 °C, respectively). Particle size distribution was measured by laser diffraction (Coulter LS230). CEC was measured using a combination of the modified ammonium acetate compulsory displacement method[57] and the rapid saturation method:[58,59] 0.25g of biochar was leached with 18.2 MΩ-cm water (w:v) under vacuum (-20 to -40 kPa). Leachate was stored and analyzed for dissolved organic carbon (DOC) through combustion (Shimadzu TOC-V). Biochar samples were then washed with 1 M sodium acetate (pH 8.2) until the EC of the elute was the same as the eluant. Samples were rinsed three times with 10 ml of 2-proponal, then dried under vacuum for 10 minutes. To displace sodium ions, biochars were washed with 1 M ammonium acetate in the same volume as was required sodium acetate. Leachate was collected and analyzed for sodium concentration through atomic absorption spectroscopy (Perkin Elmer AAnalyst 800).

The specific surface area was determined by Micromeritics' Particle Testing Authority (https://www.particletesting.com/) from CO_2 adsorption isotherms according to the Brunauer, Emmet, Teller (BET) method.[60] Fourier transform infrared (FTIR) spectra of AS500, AS800, and SW500 biochars were collected using diffuse reflectance infrared Fourier transform spectroscopy (DRIFT; PIKE Technologies EasiDiff) with air-dried samples diluted to 3% with potassium bromide. All FTIR spectra were collected using a Thermo Nicolet 6700 FTIR spectrometer (Thermo Scientific) using 256 scans, 4 cm^{-1} resolution, and a DTGS detector. FTIR bands were assigned as in Parikh et al. (2014). Gross morphological differences among AS500, AS800, and SW500 were visualized by X-ray micro-computed tomography (X-ray microCT) at the Lawrence Berkeley National Laboratory Advance Light Source on beamline 8.3.2, using a beam energy of 21 KeV. Biochars were sieved to 2mm and mounted in syringes of 8.3mm diameter for imaging. A total of 1025 projections were acquired using continuous tomography mode with a 4x objective for a final pixel size of 1.7 µm. Images were reconstructed using Gridrec methods via TomoPy and Xi-CAM.[62,63] Image analysis was completed in Dragonfly, a 3D image analysis software free for non-commercial use (Object Research Systems, Canada).

E.2 Soil characterization

Hanford sandy loam (HSL) and Yolo silt loam (YSiL) soils were chosen for continuity between laboratory experiments and ongoing field trials. Collectively, these soils represent over 260,000 hectares of arable land in California and offer textural distinctions within a range of soils commonly farmed in the Central Valley of California.[64] Soils were located via Web Soil Survey (http://websoilsurvey.sc.egov.usda.gov/) and collected from the top 30 cm in fallowed agricultural fields in Parlier, California (HSL) and Davis, California (YSiL). Soils were homogenized and sieved to 2 mm for characterization and column experiments. Colorimetric NO_3^- and NH_4^+ measurements were made according to Doane and Horwath (2003) and Verdouw et al. (1978) (Shimadzu UV-1280). Extractable P was measured using the Olsen sodium bicarbonate extraction.[67] Concentrations of potassium, calcium, magnesium, and sodium were measured by extracting 4 g of soil with 40 ml of 1 M ammonium acetate on a shaker for 30 minutes. Nutrient concentrations of filtered extracts were determined through atomic absorption spectroscopy (Perkin Elmer AAnalyst 800). Total porosity was calculated as the pore volume divided by the total soil volume in representative cores. Pore volume was determined as the difference in weight between saturated and oven-dried (105 °C for 24 h) cores. The pH and EC of soils with and without biochar were measured via 1:2 soil to 18.2 MΩ-cm water (w:v) dilution, after 15 minutes on the shaker and 60 minutes at rest.[68] Soil texture analysis was performed by the Analytical Lab at the University of California, Davis (Davis, CA, USA) using the hydrometer method.[69]

E.3 Sorption experiments

To investigate the ability of biochar to adsorb ammonium and nitrate, 0.1 g of biochar was added to 40 ml of solution containing either 0, 50, 100, 200, 400, or 600 mg L^{-1} of NO_3^- (as KNO_3) or NH_4^+ (as NH_4Cl), along with method blanks. All solutions were prepared in 5.84 mg L^{-1} NaCl and, as in Hale et al. (2013a), spiked at 1% volume with a stock solution of 20 g L^{-1} of the bactericide sodium azide. All sorption experiments were performed in triplicate at 22 ± 1 °C. Tubes were placed on an end-over shaker at 8 rpm for 24 h. Supernatants were passed through a 0.45 µm filter and analyzed for colorimetric NO_3^- and NH_4^+ (Shimadzu UV-1280).[65,66] Single-point sorbed ion concentration was determined at initial concentrations of 100 mg NO_3^- or NH_4^+ g^{-1} biochar using Eq. (1).

$$q = \frac{C_0V_0 - C_fV_f}{m} \qquad (1)$$

Here, q is the sorbed ion concentration (mg g^{-1}), C_0 and C_f are the initial and final sorbate concentrations, respectively (mg L^{-1}), V_0 and V_f are the initial and final solution volumes, respectively (L), and m is the mass of biochar (g). Multiple equations were tested to model the adsorption isotherms, with the Freundlich equation (Eq. (2)) demonstrating the best fit based on r^2 values.

$$q = K_f C_f^{\frac{1}{n}} \qquad (2)$$

Here, q and C_f are the same as in equation 1, K_f is the Freundlich constant (mg g^{-1}), and $1/n$ is the degree of nonlinearity of the isotherm. Excel was used to determine the parameters for the equations. Using batch sorption results, AS500, AS800, and SW500 were selected for further experimentation.

E.4 Column experiments

To investigate the influence of biochar on saturated hydraulic conductivity (K_{sat}), constant head column experiments were performed in five replicates using the 5 station Chameleon Kit (Soilmoisture Equipment Corporation (SEC) 2816GX). SEC tempe cells were packed with soils amended with 0 and 2% (w/w) AS500, AS800, or SW500 biochars, to a bulk density of 1.34 ± 0.02 g cm^{-3}. An application rate of 2% was chosen as the midrange of those represented in similar experiments.[9] Columns were saturated for 24 h before the start of each experiment. Each column was gravity-fed a solution of 11.1 mg L^{-1} $CaCl_2$ at a pressure head of 34 cm for 10 pore volumes. K_{sat} was calculated using data produced by SEC pressure transducers and PressureLogger software, which monitored head and flow over time. Columns were also used to investigate the nutrient retention and leaching in HSL amended with 0 and 2% biochar. Native soil nitrogen was flushed for 10 pore volumes with 11.1 mg L^{-1} $CaCl_2$, after which 50 mg L^{-1} of both NO_3^- and NH_4^+ (as NH_4Cl and KNO_3) was gravity-fed through columns for 15 pore volumes. Leachate was collected every 0.5 pore volumes and analyzed for colorimetric NO_3^- and NH_4^+ as in sorption experiments.[65,66]

E.5 Growth chamber trials

To screen biochars for their effect on plant growth, romaine lettuce (*Lactuca sativa*) was grown in 4.5 kg of Hanford Sandy Loam (HSL) completely mixed with 2% (w/w) AS500, AS800, CS650, SW500, SW500-I, SW650, SW800, a raw, unpyrolyzed almond shell (AS), or a soil-only control (NO), in four replicates. Romaine was chosen for its short growing period and its small size. HSL was chosen for continuity between growth chamber and field trials. The pH and EC of each soil and biochar mixture were taken at time 0, using a 1:2 soil to water ratio (w/v) after 15 minutes on the shaker and 60 minutes equilibration.[68] The growth chamber was illuminated for 12 h per day and kept at 22 ± 1 °C. Lettuce was transplanted into pots 20 days after seeding. In three separate fertilizing events, each pot received 400 mg N kg^{-1} (as NH_4NO_3), 100 mg P kg^{-1} (as KH_2PO_4), and 200 mg K kg^{-1} (as KH_2PO_4 and K_2SO_4). Pots were watered to 50% of water holding capacity every 2-3 days. All aboveground biomass was harvested 45 days after transplanting. Plants were weighed, oven dried at 60 °C, and ground to a fine powder. Milled lettuce samples were analyzed for total C and N using a dry combustion-elemental analyzer (Costech ECS4010).

E.6 Field site and management

Identically designed trials, approximately 0.5 hectares each, were established in two California locations: (1) Davis (Yolo County), in a Yolo Silt Loam (YSiL): Fine-silty, mixed, superactive, nonacid, thermic Mollic Xerofluvent,[71] and (2) Parlier (Fresno County), in a Hanford sandy loam (HSL): Coarse-loamy, mixed, superactive, nonacid, thermic Typic Xerorthent.[72] Field sites were chosen within the heavily-farmed Central Valley to provide agricultural soils with contrasting textures. Collectively, these soils represent over 260,000 hectares of arable land in California.[64] Each trial was designed as a randomized complete block, with three blocks and one replicate per block of the following combinations of treatments, in plots measuring 4.6 m wide (3 beds) and 6.1 m long: One of seven biochars (AS500, AS800, CS650, SW500, SW500-I, SW650, SW800), a raw, unpyrolyzed almond shell (AS), or a soil-only control (NO). Treatments were subsurface banded at one of two rates (low: 2.3 t ha^{-1} or high: 4.6 t ha^{-1}), in conjunction with one of two fertilizer rates in split plots (low: 168 kg N ha^{-1} or high: 252 kg N ha^{-1}). Biochars were amended to soils in a single application event in October 2017, by hand application into trenches 25-30 cm in depth. Trenches were created and left open following the installation of subsurface drip tape. One subsurface drip line was buried at the center of each bed and remained in place for the duration of the three-year trials. Biochar-filled trenches were immediately closed, burying the concentrated biochar at the center of the bed. This application technique places the biochar directly above the drip tape and within the rooting zone of the plant, in order to collocate it with irrigation and fertigation. It also allows the simulation of high application rates in the rooting zone (approximately 22.8 and 45.6 t ha^{-1}) while using less biochar in the field overall. A visual schematic of this application method is provided in Santos-Medellin et al. (2021).[73]

Fields were managed under processing tomato (*Solanum lycopersicum*) production using common practices[74] for three consecutive growing seasons from 2018 to 2020. Tomatoes were transplanted in late April or early May each year, except in 2018 in Parlier, where planting was delayed until early June due to challenges in field preparation. Tomatoes were transplanted in one row per 1.5 m wide bed. Tomatoes were irrigated to 100% of evapotranspiration demand as determined by a Tule Evapotranspiration Tower (www.tuletechnologies.com/). Urea-ammonium-nitrate 32 (UAN-32) was fertigated through the drip tape in five different events throughout the growing season, to a total of 168 or 252 kg N ha^{-1}. Fertilizer rates were selected at the low and high ends of the recommended range for processing tomatoes.[74] Potassium thiosulfate was applied at a rate of 39.2 kg K ha^{-1} 83 days after planting. Broadly, Dual Magnum, Treflan, and/or Round-Up were used to treat weeds. Advise 4, Coragen, Platinum, and/or Admire were used for pest control. The quantity and timing of pesticide application varied by season and location, following common regional practices.[74]

E.7 Plant sampling and analysis

Plants were harvested at the end of August, except in 2018 in Parlier, when the harvest was delayed until October due to late planting. All aboveground biomass was harvested from three plants in the center of each plot. Red fruit, green fruit, and vines were separated and weighed, and a subsample of each was kept for analysis. The fruit was blended, freeze-dried, and ground, while vines were oven dried at 60 °C and ground. All powdered plant tissues were analyzed for total C and N using a dry combustion-elemental analyzer (Costech ECS4010). Tomato yields are reported in terms of fresh weight, with red fruit weight reported as marketable yield, and red + green fruit reported as total yield.

E.8 Soil sampling and analysis

Before establishing field trials, baseline soil samples were taken from each location down to 30 cm in September 2017. Samples were kept on ice until they could be transferred to a 4 °C refrigerator, after which they were sieved to 4 mm and analyzed within one week. NO_3^- and NH_4^+ were extracted with a 1:5 soil to 0.5 M potassium sulfate solution dilution (w/v) and measured colorimetrically according to Doane and Horwath (2003) and Verdouw et al. (1978), respectively, on a spectrophotometer (Shimadzu UV-1280). The following analyses were performed on air-dried soils. Total C was measured using a dry combustion-elemental analyzer (Costech ECS4010). Extractable P was measured using the Olsen sodium bicarbonate extraction.[67] Concentrations of K^+, Ca^{2+}, Mg^{2+}, and Na^+ were measured by extracting 4 g of soil with 40 ml of 1 M ammonium acetate on a shaker for 30 minutes. Nutrient concentrations of filtered extracts were determined through atomic absorption spectroscopy (Perkin Elmer AAnalyst 800). The pH and EC of soils with and without biochar were measured via 1:2 soil to 18.2 MΩ-cm water (Barnstead nanopore, Thermo Fisher) dilution (w:v), after 15 minutes on the shaker and 60 minutes at rest [68]. Soil texture analysis was performed by the Analytical Lab at the University of California, Davis (Davis, CA, USA) using the hydrometer method.[69] Soil moisture content was reported as the difference in soil weight before and after 24 h in a 105 °C oven.

During the three-year field trials, soil sampling was performed directly after harvest each fall. Because the drip tape remained buried 25-30 cm below the soil surface for the duration of the experiment, probes were taken 13-18 cm on either side of the bed's center. Each sample was composited from three Giddings probe samples taken to 90 cm and subsequently separated into three depths: 0-30, 30-60, and 60-90 cm. A total depth of 90 cm was chosen to investigate the effects of biochar deeper into the soil profile than is conventionally explored. For ease of discussion, and because biochar had the greatest effect from 0-30 cm, only that depth is presented here. Samples were kept on ice until they could be transferred to a 4 °C refrigerator, after which they were sieved to 4 mm and analyzed within one week as described above.

E.9 Statistical analyses

The trials at Davis and Parlier were analyzed separately to detect the effect of biochar within each location. All data were analyzed as a randomized complete block design with split plots using mixed models and four-way analysis of variance (ANOVA) in the lme4 and Tidyverse packages in R.[75–77] Blocks, split plots, and subplots were considered random effects, with all treatment factors (biochar type, biochar rate, fertilizer rate, and year) considered fixed effects. Two separate models were built for each response variable. The first included each biochar as well as the unamended control. The second averaged all biochar treatments together, to test the overall effect of adding biochar compared to the unamended control. Both sets of models tested treatment factors individually and the interactions between them. All effects with p-values < 0.05 were considered statistically significant. P-values were generated using the emmeans package in R and corrected for multiple comparisons using Tukey's honestly significant difference (HSD) method.[78] Scatter plots were generated in R using the ggplot2 package.[79] and are visualized as the mean, with error bars representing the 95% confidence interval of the mean.

All data for the column experiments were analyzed with mixed models and two-way analysis of variance (ANOVA) in the stats and Tidyverse packages in R.[75,76] If a significant interaction between the fixed effects (biochar and soil type) was found, the effect of biochar within each soil type was analyzed separately. For analysis of results, all effects with p-values < 0.05 were considered significant. P-values were generated using the emmeans package in R[78] and corrected for multiple comparisons using Tukey's honestly significant difference (HSD) method. Plots were generated in R using the ggplot2 package[79] and visualized as the mean plus or minus the standard error of the means.

E.9 Literature review approach for study on biochar dust emissions

Web of Science was searched using "biochar AND dust OR toxicity OR health." Studies regarding materials similar to biochar, such as hydrochar, soot, and carbon nanotubes, were excluded, as were studies concerning aquatic environments and waste water treatment systems. There are few studies regarding biochar-induced dust emissions due to the emerging nature of this field, though all available publications concerning this topic were included. Publications regarding biochar polycyclic aromatic hydrocarbons (PAHs), the ability of biochar to bind to soil contaminants, and the ecotoxicological effect of biochar, however, are increasingly available. While the authors were careful to include a representative sample of these works, with an emphasis on review papers, recent publications, and studies that investigated multiple biochar production parameters and multiple contaminants, the list of studies included here is not exhaustive. The purpose of this review is not to provide a quantitative assessment, but rather to highlight an emerging environmental concern. As such, a selection of publications was included which contribute to the overall objectives of summarizing the current state of knowledge and highlighting areas for future study.

F. Results

Objective #: 1, Task 1: Produce and characterize biochar
Tasks activities and accomplishments: Biochar production was completed in August 2017. These seven biochars were produced by working with commercial biochar companies to obtain local CA feedstocks and produce biochar at specified temperatures. Feedstocks include softwood, almond shell, and coconut shell. One biochar with a microbial inoculant was also obtained. Biochar characterization was completed in 2020 (Table 2), with FTIR analysis and microCT imaging added in 2021 (Figure 1).
Results for each task: Biochars exhibited a broad range of chemical and physical properties depending on their production temperature and feedstock (Table 2, Figure 1). Generally, increased production temperature was associated with higher ash content, pH, electrical conductivity (EC), and surface area, as well as decreased carbon, hydrogen, and dissolved organic carbon. These trends are consistent with those of a recent meta-analysis on temperature and biochar properties. Softwood biochars produced at 500 and 800 °C had substantially higher surface areas than almond shell biochars produced at the same temperatures. All biochars contained less than 1% nitrogen, spanning from SW800 at 0.13% to CS650 at 0.79%. Almond shell biochars contained 4-6x more nitrogen than softwood biochars produced at the same temperature. Overall, AS800

possessed the most unique properties, with the lowest carbon content at 35.3%, the highest ash content at 55.4%, the highest EC at 27.2 mS cm^{-1}, and a basic pH of 10.13. Contrary to trends observed in the literature regarding high-temperature biochars, AS800 had the highest O/C ratio at 0.56, and the second highest cation exchange capacity (CEC) at 53.77 cmol$_c$ kg^{-1}. The IR spectra of AS500 and SW500 were notably similar, with carboxyl and aromatic functional groups present at 1697 and 1703 cm^{-1} (C=O) and 1410 and 1418 (COO$^-$); aromatic bands around 1580 cm^{-1}; C=C skeletal vibrations; out of plane C-H bending vibrations (700 to 900 cm^{-1}) associated with adjacent aromatic hydrogen bonds; and aromatic C=C and C=O stretching vibrations (1581 and 1589 cm^{-1}) (Figure 1a). The similarity between these biochars was expected, as each was produced at the same temperature by the same company via fractional hydropyrolysis. Additionally, the AS500 biochar included 25% softwood chips to aid the pyrolysis process. By contrast, AS800 was produced via gasification. AS800 spectra contained a strong band at 1405 cm^{-1} representing substantial contributions of COO$^-$, and multiple sharp IR peaks from ~1000 to 700 cm^{-1} arising from metal oxide vibrations (Figure 1a). The high contribution of O-rich functional groups and metal oxide vibrations is consistent with the elemental analysis of AS800, which showed high oxygen and ash content (Table 2). Each biochar was visually distinct at the macroscale (Figure 1b). The macro-pores (>50 μm) of SW500 were more uniform in size compared to those of AS500 and AS800 (Figure 1b). The softwood chips added to the AS500 feedstock matrix are visible in the background and contrast sharply with the almond shells (Figure 1b). The macro-pores of AS800 appeared to increase in size (most visible in the bottom right of AS800 Figure 1b) due to the collapse of the lacy carbon pores that were visible in AS500. The increase in production temperature resulted in more binomial pore size distribution in AS800, with larger macropores as well as an increased quantity of micro-pores, leading to an overall increase in surface area as confirmed by BET (Table 2, Figure 1b).

Objective #: 2+3, Task 2: Field trials in Yolo and Fresno Counties

Tasks activities and accomplishments:

In the Winter of 2017, one acre was amended with seven biochars in two locations: UC Davis Campbell Tract (Yolo County) and at the Kearney Agriculture Research and Extension Center (Fresno County). The two soils, a Yolo silt loam (YSiL) and a Hanford sandy loam (HSL) (Table 3), respectively, represent over 500,000 acres of CA soils. The experimental design is a randomized complete block design (RCBD) with three blocks and one treatment replicate per block. Biochars were banded, applied in concentrated trenches directly above the drip tape to maximize contact with irrigation and fertigation and to minimize application costs. Biochars were applied in two or three rates. Each treatment was combined with a low (150 lbs N) and high (225 lbs N) NPK fertilizer rate.

Field sites were planted with processing tomatoes each spring in 2018, 2019, and 2020, and harvested each fall. Soil samples were taken from 0-30 cm, 30-60 cm, and 60-90 cm and analyzed for mineral nitrogen, total carbon and nitrogen, pH, EC, and moisture content. Plant samples were collected and analyzed for yield as well as total carbon and nitrogen. A manuscript containing experimental results was completed and submitted to Agriculture, Ecosystem, and the Environment in June 2021, where it remains under review.

A smaller subset of soil samples was taken for a study on the impact of biochar on soil microbial communities and soil health for 2.5 years in the soil. Samples from the high N fertilizer rate at the high biochar application rate of the following treatments were chosen: NO, AS500, AS800, and SW500 (n=3). Microbial community structure was measured using phospholipid fatty acid (PLFA) analysis at MicrobialID (Newark, Delaware), and a complete soil health assessment was conducted by Oregon State University Soil Health Lab (Corvalis, Oregon). A manuscript with these results is currently under production.

Results for each task:

Agronomic study: Biochar did not have a significant effect on marketable yield (Figure 2), the percentage of tomatoes determined marketable (ripe yield divided by total yield), or aboveground biomass N (Figure 3) in either location, at either application rate, in any year. This was true when biochars were averaged together and when analyzed separately. Fertilizer rate did not result in differences in marketable yield or ratio in any year in either location. The primary controls on marketable yield were year and location. When sites were analyzed together, yields were higher in Davis than in Parlier in years 2 ($p = 0.009$) and year 3 ($p = 0.008$). Yields were substantially lower in 2020 in both locations (each $p < 0.001$). When averaged across all biochars, there was an increase in the concentration of soil mineral N (NH_4^+-N and NO_3^--N combined) in Davis in year 3, from 42.9 to 59.1 kg N ha^{-1} ($p = 0.012$) (Figure 4). When averaged across biochar rate and fertilizer rate, the following treatments increased mineral N in Davis in year 3: AS to 72.6 kg N ha^{-1} ($p= 0.004$), AS800 to 70.6 kg N ha^{-1} ($p = 0.009$), and SW650 to 70.1 kg N ha^{-1} ($p = 0.011$). In Parlier, when averaged across all biochars at both rates and fertilizer rates, there was a trend towards increased N in year 3 from 63.3 to 73.7 kg N ha^{-1}, though the effect was not significant ($p = 0.075$). No other effects of biochar on mineral N were detected in Parlier in any year. In both locations, in all years at both rates, biochar had no effect on postharvest soil moisture content. In Davis, there was no detected effect of biochar on soil pH in any year (Figure 5). In Parlier, there was a main effect of biochar and year. The effect of biochar in Parlier was greatest in year 2, when biochars (averaged together) raised the soil pH from the control at 7.35 to 7.50 ($p = 0.044$). AS800 had the largest impact in year 2, raising pH to 7.79 ($p < 0.001$). By year 3, the effect of AS800 and all biochars averaged together had diminished and were not significant at $p = 0.09$ and 0.106, respectively.

Soil health study: YSiL in Davis had more than 3x the total C than HSL in Parlier (1.06% compared to 0.28% ($p = 0.001$)) (Table 3). Biochar had a marginally significant effect on total C in Davis two and a half years after amendment to the soil ($p = 0.079$) (Figure 6). When each biochar was compared to the control, only AS500 increased total C in Davis, from 1.06 to 1.20% ($p = 0.063$). Similar increases in total C were not observed in Parlier. There was no effect of biochar in either location on DOC or PMC at 24 or 96 h. In Davis, adding biochar increased POXC from the control at 65.0 mg kg^{-1} as follows: AS500 to 89.4 mg kg^{-1} (not significant at $p = 0.533$), AS800 to 122.9 mg kg^{-1} ($p = 0.054$)

and SW500 to 122.1 mg kg^{-1} ($p = 0.056$) (Figure 6). Averaged across all biochars, biochar significantly increased POXC by 46.5 mg kg^{-1} or a total of 71.5% ($p = 0.022$). In Parlier, POXC was increased from the control at 76.6 mg kg^{-1} as follows: AS500 to 90.2 mg kg^{-1} ($p = 0.018$), AS800 to 86.9 mg kg^{-1} ($p = 0.059$), and SW500 to 93.3 mg kg^{-1} ($p = 0.007$). Averaged across all biochars, POXC was significantly increased in Parlier by 13.6 mg kg^{-1}, or 17.8% ($p = 0.002$). Davis had more than 3x the total soil N than Parlier, at 0.103% compared to 0.03%. There was no effect of biochar on total N or PMN in either location. There was a main effect of biochar on water stable aggregation (WSA) in Parlier ($p = 0.035$) though, due to variation within each treatment, the effects of individual biochars were not significant. AS500 appeared to increase WSA in Parlier from 28.1 to 42.0% ($p = 0.1$) and AS800 to 40.4% ($p = 0.151$). While increases in WSA were observed across biochars and locations, no statistically significant effects were detected (Figure 7). YSiL in Davis contained nearly double the PLFA biomass than Parlier, or 67.5 compared to 34.6 nmol g^{-1} (Figure 8). Biochar had no effect on PLFA biomass in Davis, and a marginally significant effect in Parlier ($p = 0.095$). Due to variation within treatments, no individual biochar raised PLFA biomass compared to the control. Averaged across biochars, however, there was a marginally significant increase in PLFA biomass of 6.23 nmol g^{-1} in Parlier ($p = 0.078$). Biochar had no effect on select PLFA ratios in Davis (Figure 9). In Parlier, AS500 and AS800 reduced cy17/pre, cy19/pre, and S/U. AS500 and AS800 appeared to reduce G+/G- and increase F/B, though the effects were not significant ($p = 0.236$ and 0.121, respectively). The effect of SW500 on PLFA ratios was minor and not statistically significant for any ratio in either location.

Objective #: 2+3, Task 3: Lab Trials

Tasks activities and accomplishments:

Sorption trials, column studies, and X-ray micro-computed tomography (micro-CT) imaging of biochar-amended soils are complete. A manuscript with these experimental results was prepared and submitted to SOIL in June of 2021, where it remains under review.

Results for each task:

Sorption: All biochars exhibited the capacity to remove ammonium from solution (Figure 10), though K_f values were low. Single point concentration tests at a C_0 of 100 mg L^{-1} revealed the following hierarchy of sorption capacities, in order of lowest to highest: SW650 < SW500 < CS650 < SW500-I < AS500 < SW800 < AS800. These q values spanned 0.70 (SW650) to 7.15 (AS800) mg g^{-1}, or removal efficiencies of 0.70 and 7.15%. AS800 exhibited the greatest K_f value at 0.16 mg NH_4^+ g^{-1}. Isotherms for nitrate and biochar are not provided, as only AS500 exhibited the capacity to remove nitrate from solution. The other six biochars released, rather than removed, nitrate. For AS500, the single point concentration test at a C_0 of 100 mg L^{-1} revealed a removal efficiency of 1.74% or a q of 1.74 mg g^{-1}.

Soil columns: There was a main effect of biochar and soil texture, as well as a significant interaction between biochar and soil texture, on saturated hydraulic conductivity ($p = 0.001$, < 0.001, and 0.006, respectively). In HSL soil, AS500 and

SW500 each decreased K_{sat} by 75%, from the control at 1.2 cm s^{-1} to 0.3 cm s^{-1} ($p = 0.023$) (Figure 11). AS800 caused a 12.5% decrease in K_{sat} to 1.05 cm s^{-1}, though the effect was not significant ($p = 0.939$). In YSiL soil, AS500 decreased K_{sat} by 63.6%, from the control at 0.044 cm s^{-1} to 0.016 ($p < 0.001$). SW500 caused a decrease of 79.5%, to 0.009 cm s^{-1} ($p < 0.001$). In contrast to its effect on HSL, AS800 increased K_{sat} in YSiL by 97.7%, to 0.087 cm s^{-1} ($p < 0.001$). Figure 12 illustrates the ammonium and nitrate breakthrough curves for HSL amended with 0 and 2% AS500, AS800, and SW500. Biochar affected the timing and quantity of ammonium (introduced in pore volumes 11-25 at 50 mg L^{-1}) leached from the soil column (Figure 11a). The estimated breakthrough point, or the pore volume at which the concentration of the leachate equals 0.5x the concentration of the incoming solution ($C/C_0 = 0.5$), was reached as follows, in order of fastest to slowest for ammonium: HSL at pore volume 14.3, SW500 at 15.5, AS500 at 16.2, and AS800 at 18.1. Biochar also significantly decreased the total amount of ammonium in the leachate at all pore volumes, as follows, in order of least to most retention: HSL < SW500 < AS500 < AS800 (Fig. 13). At pore volume 15, AS500 decreased the ammonium concentration of the leachate compared to the control (HSL = 37.33 mg L^{-1}) by 30.5% ($p < 0.001$), AS800 by 78.1% ($p < 0.001$), and SW500 by 24.4% ($p = 0.002$). This effect was diminished by pore volume 25, where differences from the control (HSL= 41.69 mg L^{-1}) were decreased to 21.8% by AS500 ($p < 0.001$), 28.9% by AS800 ($p < 0.001$), and 8.5% by SW500 (not statistically significant at $p = 0.463$).

Estimated nitrate breakthrough points for biochar amended soils were each within 0.5 pore volumes of the control (pore volume 11.4), indicating that biochar had little to no effect on the timing of nitrate release from HSL. The effect of biochar on the total quantity of nitrate released was also less substantial than for ammonium (Figure 12). Only SW500 significantly decreased the concentration of nitrate in the leachate compared to the control. At pore volume 15, SW500 inhibited nitrate transport by 35.01% ($p = 0.002$) (Figure 13). This effect was not present at pore volume 20 and was slightly lessened to 26.5% by pore volume 25 (marginally significant at $p = 0.098$).

Objective #: 3, Task 4: Economic analysis of biochar amendments in CA

Tasks activities and accomplishments:

In the winter of 2018, a review of literature related to life cycle assessments (LCAs) of biochar and gasification/pyrolysis systems was conducted. In collaboration with Dr. Alissa Kendall at the University of California. This work is ongoing, to be completed by a graduate student in the Kendall Industrial Ecology Lab.

Results for each task:

NA

Objective #: 4, Task 5: Conduct an outreach program

Tasks activities and accomplishments:

Details of all outreach activities are highlighted in Section J below.

G. Discussions and Conclusions

Scientists, policymakers, and growers are increasingly interested in the use of biochar, or pyrolyzed biomass, as an agricultural soil amendment. The number of published biochar studies has increased at a near-exponential rate, from one publication per annum in the early 2000s, to over 4,100 in 2020. Policymakers have also taken notice, resulting in biochar being included as a leading natural climate solution in the 2018 International Panel on Climate Change (IPCC) Special Report, and in California, the creation of the Biochar Research Advisory Group by the Governor's Office of Planning and Research. As scientific and policy interest in biochar grows, so does the biochar market's size. Since 2009, 920 patent applications mentioning biochar have been submitted to the United States Patent and Trademark Office. While interest in biochar is evident, many questions remain about the efficacy of biochar as a soil amendment.

Due to its high surface area, low bulk density, reactive surface functional groups, and recalcitrant carbon, the material is purported to deliver many agronomic and environmental benefits when added to the soil. These benefits include increased water-holding capacity, nutrient retention, crop yield, soil carbon stocks, enhanced microbial activity, and the promotion of soil health. Despite the proliferation of biochar studies, research shows inconsistent results on the ability of biochar to deliver these benefits due to differences in biochar feedstock, production methods, soil properties, climate, and cropping systems. It is especially difficult to interpret results for the fertile agricultural soils of California's Mediterranean climate, as biochar has been shown to have the greatest impact in more acidic, nutrient-limited soils. Furthermore, results from the scientific literature have limited relevance to production agriculture, as biochar studies are dominated by short-term laboratory experiments that are difficult to extrapolate to field-scale. To inform the use and regulation of biochar in California, farmers and policymakers must have access to reliable, location-based data that evaluates biochar across scales. This project fills a gap in the literature by providing mechanistic laboratory studies that are linked to pot trials and long-term, field-scale data about the agronomic and soil health potential of biochar as a soil amendment in California.

Seven biochars were produced by commercial companies at multiple production temperatures from various feedstocks. The potential for these biochars to impact soil physical, chemical, and microbial environment was investigated across scales. In the laboratory, biochars were tested for their ability to physically or chemically retain nitrate and ammonium. Nearly every biochar tested exhibited a strong chemical affinity for ammonium, likely due to the attraction between their negatively charged surfaces and the positively charged ammonium ion. This was evident in that ammonium retention was strongest in biochars with high cation exchange capacity (CEC), oxygen-containing functional groups, and high oxygen to carbon ratios. Biochars exhibited little to no chemical affinity for nitrate, though one biochar reduced nitrate leaching in soil column studies to a small extent. This result was linked to the biochar's high surface area and low CEC. The ability of biochar to alter the soil physical environment was most evident in its effect on saturated hydraulic conductivity (K_{sat}). Broadly, biochars increased K_{sat} in a silt loam but had a mixed effect in a sandy loam. An additional small-scale study was carried out in a growth chamber, in which biochar-amended soil was observed to substantially increase the yield of romaine lettuce (*Lactuca sativa*) when compared to the unamended control. This study's short-term laboratory experiments demonstrated that these biochars could improve ammonium retention, water conductivity, and crop yield when added to the soil. However, these benefits were not observed in three-year field trials with the same biochars in the same soils.

For the field trials, seven biochars were amended to soils at two rates, combined with two synthetic nitrogen (N) fertilizer rates, in two California locations. Processing tomatoes (*Solanum lycopersicum*) were grown for three years, and data was collected on the influence of biochar on plant and soil properties. Biochar had minor effects on soil pH, EC, and N content, though the effects varied by biochar, location, and year, and were not substantial enough to impact plant yield or quality parameters. Under no combination of experimental conditions was biochar observed to increase processing tomato yield, plant nitrogen uptake, or soil moisture. Field trial results are consistent with those from other studies, which indicate biochar may confer limited benefits in soils that do not require conditioning for the successful growth of crops. Furthermore, the discrepancy between results from experiments at different scales demonstrates that short-term laboratory trials are not sufficient to make conclusions about field-scale agriculture.

While biochar did not deliver tangible agricultural benefits in field trials, further investigation was made into its influence on parameters that constitute current notions of soil health. Soils were sampled 2.5 years after amendment with almond shell biochars produced at 500 or 800 °C, or softwood biochar produced at 500 °C, for a comprehensive soil health assessment. To varying effects, biochars were observed to increase labile carbon, water stable aggregates, pH, and EC in both the silt loam and sandy loam. The results were not substantial enough to influence the microbial community in the finer textured silt loam, which had higher fertility and organic matter concentration. Phospholipid fatty acid (PLFA) analysis from the silt loam revealed that biochar had no effect on community composition or on the PLFA ratios typically interpreted to denote microbial stress. In the coarser, more nutrient-limited sandy loam, however, a canonical correspondence analysis (CCA) revealed microbial communities responded to the increase in water stable aggregates, pH, and potassium conferred by the addition of biochar. This resulted in both a distinct community composition, as well as reduced indicators of microbial stress. Results were greatest in plots amended with almond shell biochars, likely due to the high potassium content of almond shells, and the high pH and ash concentration of these biochars. The soil health assessment indicates that, while biochar may not deliver agronomic improvements in fertile agricultural soils, it may confer other ecological or environmental benefits, or have the potential to deliver agronomic benefits across a longer time horizon. Importantly, results from multiple scales indicate biochar may be added to agricultural soils with few negative consequences for cropping systems. However, a growing body of research suggests some biochars may contain potentially toxic properties that threaten human health when airborne biochar is inhaled.

To optimize the ecological benefits of adding biochar to soils, care should be taken to select biochars that conform to quality standards established by the International Biochar Initiative or the European Biochar Certificate. Care should also be taken to amend biochars to soils under conditions that minimize dust emissions. Together, data from this project can assist policymakers and land managers in California in making decisions about amending biochar to working lands. Realistic expectations should be established for the agronomic benefits of adding biochar to California cropping systems. Meanwhile, carbon sequestration or soil health projects may be pursued with minimal consequence, given the safe and appropriate selection of biochars. As a financial incentive for California growers to add biochar to their soils may be limited, cost-share and incentive programs should be considered.

H. Challenges

Challenge	Corrective Action and/or Project Change/lessons learned
Due to the widespread impacts of COVID-19, all 2020 pre-plant soil sampling activities were canceled on UC recommendation, and due to stay at home orders and the closure of campus laboratories and Kearney ARE dormitories. This cancelation will result in a missing dataset of 720 soil samples	To salvage the spring 2020 season, a smaller subset of soil samples was taken for an unplanned but important study on the impact of biochar on soil microbial communities and carbon storage after three years. Samples from the high N fertilizer rate at the high biochar application rate of the following treatments were chosen: NO, AS, AS500, AS800, SW500 (n=3)
Images of biochar amended soils were taken via x-ray microcomputed tomography at the LBLN Advanced Lightsource beamline 8.3.2. We have encountered several issues with processing and quantifying these images, largely due to their large size and high resolution. Initially, we ran out of computing power and ran through several different options to increase RAM. We also moved from using ImageJ to using Dragonfly to process images.	Object Research Systems, or the company that produces the Dragonfly software, assisted in developing a segmenting/quantification workflow for our project. Although not fully successful some images were processed and are included in one published journal article.

I. Project Impacts

a) Through our outreach activities regarding biochar use, we directly reached over 2,200 people. Additionally, one of the activities was posted to YouTube and has over 29,000 views. The dissemination of this information is critical for educating the public about biochar and its potential use. Growers, industry, and other stakeholders can use this information to inform their practices and decisions.

b) Additional dissemination of information has occurred via six peer-reviewed journal publications, a USDA Fact Sheet, and a Ph.D. dissertation. These publications provide the results of the project efforts to an international audience.

c) Project results demonstrate that considering the seven evaluated, biochars can retain ammonium but have little impact on nitrate retention in soils. This is critical information as nitrate contamination of California's groundwater is a major concern. Based on the findings, unmodified biochars will not increase nitrate leaching but will have little impact on reducing it. However, modified biochars can be produced to bind nitrate and reduce leaching.

d) Biochar amendment to two fertile California soils did not significantly impact tomato yield. This is consistent with much of the published literature that demonstrates biochar is typically most effective when used to improve marginal or low-fertility soils. This information is important for developing decision-making processes for the use of biochar in agriculture.

e) No evidence was observed indicating that biochar application is harmful to agronomic practice. However, due to its low density and small size, care should be taken when applying biochar through the use of personal protective equipment and applying at a high moisture content under low wind conditions.

f) Data the results of this study suggest that biochar may increase the residence time of water in sandy soils and increase drainage in fine-textured soils, though soil- and biochar-specific investigation is required. Due to the continued drought in California, this finding could be important as part of a land management strategy for sandy soils.

g) Results from this project indicate that biochar may deliver soil health benefits in agricultural soils in a Mediterranean climate, though increased soil health may not confer increased agricultural production within the first few years of application.

h) Biochar soil amendments were added as a management strategy for the CDFA Healthy Soils Program. A white paper that was written as part of this project was submitted to the CDFA and was cited as a key proposal to determine whether to include biochar as an amendment in the program.

J. Outreach Activities Summary

A wide range of outreach activities reached a diverse audience: growers, industry, policymakers, government scientists, and university faculty and students. These activities were directed at the state, national, and international communities. A total of 28 presentations were given, directly reaching over 2,200 people. One of these outreach activities is available on YouTube and has been viewed 29,215 times (10/25/2022). Along with the oral presentations, there have eight publications. These include six peer-reviewed journal articles, one USDA Fact Sheet, and one Ph.D. dissertation. At least two more peer-reviewed journal articles are expected to be published. The outreach activities are listed below.

Event Name (1)	Capitol Corridor Growers, Organic Lunch Series
Presentation title	Evaluation of biochar for agricultural soil management in California
Location and date	January 27th, 2021 Zoom *https://www.youtube.com/watch?v=JhIHMwyZ75o*

Attendee demographics	Mostly growers and a few attendees from UCCE		
CCA/Grower Continuing Education Units	NA	**Number of participants**	40 participants 29,215 YouTube views

Event Name (2)	European Geological Union (EGU) Annual Meeting		
Presentation title	Biochar inhibits nutrient leaching and alters hydraulic conductivity in two agricultural soils		
Location and date	February 21st, 2021 Zoom		
Attendee demographics	Academics and researchers from around the globe		
CCA/Grower Continuing Education Units	NA	**Number of participants**	40

Event Name (3)	Natural Resource and Conservation Society (NRCS), Conversations in Soil Health: Biochar		
Presentation title	Safe Use of Biochar		
Location and date	May 27, 2021 Webinar		
Attendee demographics	NRCS staff and other scientists		
CCA/Grower Continuing Education Units		**Number of participants**	100

Event Name (4)	PhD Exit Seminar		
Presentation title	Multiscale evaluation of biochar for the delivery of agronomic and soil health benefits in California		
Location and date	June 23rd, 2021 Zoom		
Attendee demographics	A mix of researchers, the public, and staff from FREP, Almond Board, and the Washington State Department of Agriculture		
CCA/Grower Continuing Education Units		**Number of participants**	35

Event Name (5)	Presentation to El Dorado County Master Gardeners
Presentation title	Evaluating Biochar use in Agriculture
Location and date	Zoom, July 23, 2020.
Attendee demographics (CCAs, PCAs, growers,	Master Gardeners

consultants, researchers, etc.)			
CCA/Grower Continuing Education Units		**Number of participants**	~45

Event Name (6)	Presentation at ASA-CSSA-SSSA Annual Meeting		
Presentation title	The Influence of Biochar on Nutrient Leaching and Hydraulic Conductivity in Agricultural Soils		
Location and date	Zoom, November 9th, 2020		
Attendee demographics			
CCA/Grower Continuing Education Units		**Number of participants**	N/A. This was a recorded seminar with no live participants

Event Name (7)	Submissions to CDFA RFPs: (1) Healthy Soils Program submission: Recommendations for biochar management practices to promote soil health in California. S.J. Parikh, D.L. Gelardi, J. Hunt, K. Trippe. (2) Alternative Manure Management Program submission: Composting with biochar: A recommended practice for manure management. S.J. Parikh, J. Hunt, D.L. Gelardi, K. Trippe.		
Presentation title	See above		
Location and date	August 31st, 2020		
Attendee demographics			
CCA/Grower Continuing Education Units		**Number of participants**	N/A

Event Name (8)	ASA-CSSA-SSSA Annual Meeting, San Diego, CA
Presentation title	The chemical and physical retention of nitrate and ammonium by biochar across laboratory and field scales
Location and date	1/7/2019
Attendee demographics	Mostly soil scientists from academia and the government

CCA/Grower Continuing Education Units		**Number of participants**	~75

Event Name (9)	ASA-CSSA-SSSA Annual Meeting, San Diego, CA
Presentation title	Crop yield and nitrogen retention in the presence of biochar across laboratory and field scales
Location and date	1/7/2019
Attendee demographics	Mostly soil scientists from academia and the government

CCA/Grower Continuing Education Units		**Number of participants**	~250

Event Name (10)	Academic Seminar
Presentation title	Wake up and smell the biochar: A potential new source of PM10 emissions and other airborne pollutants
Location and date	5/14/2019
Attendee demographics	UC Davis Faculty and Students

CCA/Grower Continuing Education Units		**Number of participants**	~25

Event Name (11)	Farm Foundation Round Table Meeting, Lincoln, NE
Presentation title	Crop yield and nitrogen retention in the presence of biochar across laboratory and field scales
Location and date	6/6/2019
Attendee demographics	Industry and government employees

CCA/Grower Continuing Education Units		**Number of participants**	~150

Event Name (12)	Russell Ranch Field Day, UC Davis
Presentation title	Beyond yield: Evaluation of biochar for on-farm soil management
Location and date	6/12/2019
Attendee demographics	Growers, academics, and industry

CCA/Grower Continuing Education Units		**Number of participants**	~150

Event Name (13)	Soil Health Institute Annual Meeting, Sacramento CA		
Presentation title	Crop yield and nitrogen retention in the presence of biochar across laboratory and field scale		
Location and date	7/6/2019		
Attendee demographics	Growers, policy makers, scientists, and NGOs		
CCA/Grower Continuing Education Units		**Number of participants**	~200

Event Name (14)	Academic Seminar, China Agricultural University, Beijing, China		
Presentation title	Evaluating Biochar for Agriculture and Environmental Applications		
Location and date	9/9/2019		
Attendee demographics	Academics and students		
CCA/Grower Continuing Education Units		**Number of participants**	~60

Event Name (15)	Joint International Symposium on Plant-Soil-Microbe Interactions. Zhejiang University, Hangzhou, China		
Presentation title	Wake up and smell the biochar: A potential new source of PM10 emissions and other airborne pollutants		
Location and date	9/14/2019		
Attendee demographics	Academics and students		
CCA/Grower Continuing Education Units		**Number of participants**	~100

Event Name (16)	Soil Science Society of America Annual Meeting, San Antonio, TX		
Presentation title	Wake up and smell the biochar: A potential new source of PM10 emissions and other airborne pollutants		
Location and date	11/11//2019		
Attendee demographics	Academics and students		
CCA/Grower Continuing Education Units		**Number of participants**	~40

Event Name (17)	Almond Board of California Meeting, Sacramento, CA

Presentation title	What do we know about biochar after two years of field trials in CA soils?		
Location and date	12/10/2019		
Attendee demographics	Growers, policymakers, and scientists		
CCA/Grower Continuing Education Units		**Number of participants**	~40

Event Name (18)	Almond Board of California, Leadership Class on Utilization of Biomass		
Presentation title	Evaluating the Potential for Soil Biochar Amendments		
Location and date	3/2/2018		
Attendee demographics	Almond Board leadership class		
CCA/Grower Continuing Education Units		**Number of participants**	~30

Event Name (19)	Environmental Studies Departmental Seminar. University of Santa Cruz, Santa Cruz, CA		
Presentation title	Explorations into the Biochar Frontier		
Location and date	4/2/2018		
Attendee demographics	Faculty and students		
CCA/Grower Continuing Education Units		**Number of participants**	~45

Event Name (20)	FREP-UCD Biochar Field Day, Russell Ranch Sustainable Agriculture Facility, Winters, CA		
Presentation title	What is Biochar?		
Location and date	6/6/2018		
Attendee demographics	Growers, industry, and scientists		
CCA/Grower Continuing Education Units		**Number of participants**	~100

Event Name (21)	FREP-UCD Biochar Field Day, Russell Ranch Sustainable Agriculture Facility, Winters, CA

Presentation title	Evaluation of Biochar for On-Farm Soil Management in California		
Location and date	6/6/2018		
Attendee demographics	Growers, industry, and scientists		
CCA/Grower Continuing Education Units		**Number of participants**	~100

Event Name (22)	American Society for Agronomy Annual Meeting, Madison, WI		
Presentation title	Deciphering Biochars for Agronomic and Environmental Applications		
Location and date	11/4/2018		
Attendee demographics	Scientists		
CCA/Grower Continuing Education Units		**Number of participants**	~100

Event Name (23)	Almond Board Annual Conference, Sacramento, CA		
Presentation title	The chemical and physical retention of nitrate and ammonium by biochar across laboratory and field scales		
Location and date	12/5/2018		
Attendee demographics	Scientists		
CCA/Grower Continuing Education Units		**Number of participants**	~150

Event Name (24)	American Geophysical Union Annual Conference, Washington, D.C.		
Presentation title	Soil viral ecology in natural and agricultural ecosystems		
Location and date	12/10/2018		
Attendee demographics	Scientists		
CCA/Grower Continuing Education Units		**Number of participants**	~125

Event Name (25)	Soil Security and Planetary Health Conference. Sydney, Australia		
Presentation title	Evaluating the potential for human exposure to dust emissions from biochar amended soils		
Location and date	12/5/2018		
Attendee demographics	Scientists		
CCA/Grower Continuing Education Units		**Number of participants**	~150

Event Name (26)	FREP/WPHA Annual Conference, Modesto, CA		
Presentation title	Can Amending Soils with Biochar Improve Fertilizer Use Efficiency?		
Location and date	11/1/2017		
Attendee demographics	Growers, scientists, policymakers		
CCA/Grower Continuing Education Units		**Number of participants**	~40

Event Name (27)	Almond Board of California Annual Conference, Sacramento, CA		
Presentation title	Can Amending Soils with Biochar Improve Fertilizer Use Efficiency?		
Location and date	12/6/2017		
Attendee demographics	Growers, scientists, policymakers		
CCA/Grower Continuing Education Units		**Number of participants**	~50

Event Name (28)	Radio interview on biochar and agriculture, “The Local Dirt,” KDVS		
Presentation title	Biochar and agriculture		
Location and date	12/18/2017		
Attendee demographics	General public		
CCA/Grower Continuing Education Units		**Number of participants**	unknown

Publications:

1. Gelardi, D.L. Multiscale evaluation of biochar for the delivery of agronomic and soil health benefits in California. 2021. *Published dissertation*. Journal publication pending.

2. Gelardi, D.L.; Ainuddin, I.; Rippner, D.A.; Najm, M.A.; Parikh, S.J. Biochar alters hydraulic conductivity and inhibits nutrient leaching in two agricultural soils. 2021. SOIL. DOI: 10.5194/soil-2021-45

3. Gelardi, D.L.; Lazicki, P.; Leinfelder-Miles M.; Geisseler, D.J.; Parikh, S.J.; Parikh, S.J. Three-year field trials with seven biochars reveal minor changes in chemical properties of two agricultural soils but no impact on yield. 2021. *Published dissertation*. Journal publication pending.

4. Gelardi, D.L., S.J. Parikh. 2021. Soil and Beyond: Optimizing Sustainability Opportunities for biochar. Sustainability. 13:10079.

5. Winfield, E. and S.J. Parikh. 2020. Climate-Smart Agriculture: Biochar Amendments. California Climate Hub, U.S. Department of Agriculture. Climate-Smart Agriculture Fact Sheet Series: 4.

6. Gelardi, D.L., C. Li, and S.J. Parikh. 2019. An emerging environmental concern: Biochar-induced dust emissions and their potentially toxic properties. Sci. Total Environ. *678:813-820.*

7. Hassan, M., Y. Liu, R. Naidu, S.J. Parikh, J. Du, F. Qi, I.R. Willett. 2020. Influences of feedstock sources and pyrolysis temperature on the properties of biochar and functionality as adsorbents: A meta-analysis. Sci. Tot. Environ. 744:140714.

8. Santos-Medellin, C., L. Zinke, A. ter Horst, D.L. Gelardi, S.J. Parikh, and J. Emerson. 2021. Viromes outperform total metagenomes in revealing the spatiotemporal patterns of agricultural soil viral communities. ISME Journal. 15:1956-1970.

9. Zhang, M., G. Song, D.L. Gelardi, L. Huang, E. Khan, O. Mašek, S.J. Parikh, Y.S. Ok. 2020. Evaluating biochar and its modifications for the removal of ammonium, nitrate, and phosphate in water. Water Research. 186:116303.

K. References

(1) Web of Science. Core Collection Database, “Biochar.” **2020**.

(2) US Patent and Trademark Office. Patent Application Full Text and Image Database.

(3) International Biochar Initiative (IBI). Standardized Product Definition and Product Testing Guidelines for Biochar That Is Used in Soil. *Int. Biochar Initiat.* **2015**, No. November, 23. https://doi.org/http://www.biochar-international.org/characterizationstandard. 22.

(4) Sparrevik, M.; Field, J. L.; Martinsen, V.; Breedveld, G. D.; Cornelissen, G. Life Cycle Assessment to Evaluate the Environmental Impact of Biochar Implementation in Conservation Agriculture in Zambia. *Environ. Sci. Technol.* **2013**, *47* (3), 1206–1215. https://doi.org/10.1021/es302720k.

(5) Dutta, B.; Raghavan, V. A Life Cycle Assessment of Environmental and Economic Balance of Biochar Systems in Quebec. *Int. J. Energy Environ. Eng.* **2014**, *5* (2–3), 1–11. https://doi.org/10.1007/s40095-014-0106-4.

(6) Ibarrola, R.; Shackley, S.; Hammond, J. Pyrolysis Biochar Systems for Recovering Biodegradable Materials: A Life Cycle Carbon Assessment. *Waste Manag.* **2012**, *32* (5), 859–868. https://doi.org/10.1016/j.wasman.2011.10.005.

(7) Downie, A.; Crosky, A.; Munroe, P. Characteristics of Biochar – Physical and Structural Properties. *Biochar Environ. Manag. - Sci. Technol.* **2009**, 89–108. https://doi.org/10.4324/9780203762264.

(8) Sadowska, U.; Domagała-Świątkiewicz, I.; Żabiński, A. Biochar and Its Effects on Plant–Soil Macronutrient Cycling during a Three-Year Field Trial on Sandy Soil with Peppermint (Mentha Piperita L.). Part I: Yield and Macro Element Content in Soil and Plant Biomass. *Agronomy* **2020**, *10* (12), 1950. https://doi.org/10.3390/agronomy10121950.

(9) Blanco-Canqui, H. Biochar and Soil Physical Properties. *Soil Sci. Soc. Am. J.* **2017**, *81* (4), 687–711. https://doi.org/10.2136/sssaj2017.01.0017.

(10) Nan, Q.; Wang, C.; Wang, H.; Yi, Q.; Liang, B.; Xu, J.; Wu, W. Biochar Drives Microbially-Mediated Rice Production by Increasing Soil Carbon. *J. Hazard. Mater.* **2020**, *387*. https://doi.org/10.1016/j.jhazmat.2019.121680.

(11) Oladele, S. O. Changes in Physicochemical Properties and Quality Index of an Alfisol after Three Years of Rice Husk Biochar Amendment in Rainfed Rice – Maize Cropping Sequence. *Geoderma* **2019**, *353* (June), 359–371. https://doi.org/10.1016/j.geoderma.2019.06.038.

(12) Solaiman, Z. M.; Shafi, M. I.; Beamont, E.; Anawar, H. M. Poultry Litter Biochar Increases Mycorrhizal Colonisation, Soil Fertility and Cucumber Yield in a Fertigation System on Sandy Soil. *Agric.* **2020**, *10* (10), 1–14. https://doi.org/10.3390/agriculture10100480.

(13) MacCarthy, D. S.; Darko, E.; Nartey, E. K.; Adiku, S. G. K.; Tettey, A. Integrating Biochar and Inorganic Fertilizer Improves Productivity and Profitability of Irrigated Rice in Ghana, West Africa. *Agronomy* **2020**, *10* (6), 1–23. https://doi.org/10.3390/agronomy10060904.

(14) Jones, D. L.; Rousk, J.; Edwards-jones, G.; Deluca, T. H.; Murphy, D. V. Biochar-

Mediated Changes in Soil Quality and Plant Growth in a Three Year Fi Eld Trial. *Soil Biol. Biochem.* **2012**, *45*, 113–124. https://doi.org/10.1016/j.soilbio.2011.10.012.

(15) McDonald, M. R.; Bakker, C.; Motior, M. R. Evaluation of Wood Biochar and Compost Soil Amendment on Cabbage Yield and Quality. *Can. J. Plant Sci.* **2019**, *99* (5), 624–638. https://doi.org/10.1139/cjps-2018-0122.

(16) Griffin, D. E.; Wang, D.; Parikh, S. J.; Scow, K. M. Short-Lived Effects of Walnut Shell Biochar on Soils and Crop Yields in a Long-Term Field Experiment. *Agric. Ecosyst. Environ.* **2017**. https://doi.org/10.1016/j.agee.2016.11.002.

(17) Gajić, A.; Koch, H.-J. Sugar Beet (Beta Vulgaris L.) Growth Reduction Caused by Hydrochar Is Related to Nitrogen Supply . *J. Environ. Qual.* **2012**, *41* (4), 1067–1075. https://doi.org/10.2134/jeq2011.0237.

(18) Glaser, B.; Lehmann, J.; Zech, W. Ameliorating Physical and Chemical Properties of Highly Weathered Soils in the Tropics with Charcoal - A Review. *Biol. Fertil. Soils* **2002**, *35* (4), 219–230. https://doi.org/10.1007/s00374-002-0466-4.

(19) Hestrin, R.; Torres-Rojas, D.; Dynes, J. J.; Hook, J. M.; Regier, T. Z.; Gillespie, A. W.; Smernik, R. J.; Lehmann, J. Fire-Derived Organic Matter Retains Ammonia through Covalent Bond Formation. *Nat. Commun.* **2019**, *10* (1), 1–8. https://doi.org/10.1038/s41467-019-08401-z.

(20) Glaser, B.; Lehr, V. I. Biochar Effects on Phosphorus Availability in Agricultural Soils: A Meta-Analysis. *Sci. Rep.* **2019**, *9* (1), 1–9. https://doi.org/10.1038/s41598-019-45693-z.

(21) Haider, G.; Joseph, S.; Steffens, D.; Müller, C.; Taherymoosavi, S.; Mitchell, D.; Kammann, C. I. Mineral Nitrogen Captured in Field-Aged Biochar Is Plant-Available. *Sci. Rep.* **2020**, *10* (1), 1–12. https://doi.org/10.1038/s41598-020-70586-x.

(22) Glaser, B.; Wiedner, K.; Seelig, S.; Schmidt, H. P.; Gerber, H. Biochar Organic Fertilizers from Natural Resources as Substitute for Mineral Fertilizers. *Agron. Sustain. Dev.* **2015**, *35* (2), 667–678. https://doi.org/10.1007/s13593-014-0251-4.

(23) Martos, S.; Mattana, S.; Ribas, A.; Albanell, E.; Domene, X. Biochar Application as a Win-Win Strategy to Mitigate Soil Nitrate Pollution without Compromising Crop Yields: A Case Study in a Mediterranean Calcareous Soil. *J. Soils Sediments* **2020**, *20* (1), 220–233. https://doi.org/10.1007/s11368-019-02400-9.

(24) Zhang, D.; Yan, M.; Niu, Y.; Liu, X.; van Zwieten, L.; Chen, D.; Bian, R.; Cheng, K.; Li, L.; Joseph, S.; Zheng, J.; Zhang, X.; Zheng, J.; Crowley, D.; Filley, T. R.; Pan, G. Is Current Biochar Research Addressing Global Soil Constraints for Sustainable Agriculture? *Agric. Ecosyst. Environ.* **2016**, *226*, 25–32. https://doi.org/10.1016/j.agee.2016.04.010.

(25) Jeffery, S.; Verheijen, F. G. A.; van der Velde, M.; Bastos, A. C. A Quantitative Review of the Effects of Biochar Application to Soils on Crop Productivity Using

Meta-Analysis. *Agric. Ecosyst. Environ.* **2011**, *144* (1), 175–187. https://doi.org/10.1016/j.agee.2011.08.015.

(26) Hassan, M.; Liu, Y.; Naidu, R.; Parikh, S. J.; Du, J.; Qi, F.; Willett, I. R. Influences of Feedstock Sources and Pyrolysis Temperature on the Properties of Biochar and Functionality as Adsorbents: A Meta-Analysis. *Sci. Total Environ.* **2020**, *744*, 140714. https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.140714.

(27) Atkinson, C. J.; Fitzgerald, J. D.; Hipps, N. A. Potential Mechanisms for Achieving Agricultural Benefits from Biochar Application to Temperate Soils: A Review. *Plant Soil* **2010**, *337* (1), 1–18. https://doi.org/10.1007/s11104-010-0464-5.

(28) Ye, L.; Camps-Arbestain, M.; Shen, Q.; Lehmann, J.; Singh, B.; Sabir, M. Biochar Effects on Crop Yields with and without Fertilizer: A Meta-Analysis of Field Studies Using Separate Controls. *Soil Use Manag.* **2020**, *36* (1), 2–18. https://doi.org/10.1111/sum.12546.

(29) Sanchez-Monedero, M. A.; Cayuela, M. L.; Roig, A.; Jindo, K.; Mondini, C.; Bolan, N. Role of Biochar as an Additive in Organic Waste Composting. *Bioresour. Technol.* **2018**, *247* (July 2017), 1155–1164. https://doi.org/10.1016/j.biortech.2017.09.193.

(30) Hagemann, N.; Kammann, C. I.; Schmidt, H. P.; Kappler, A.; Behrens, S. Nitrate Capture and Slow Release in Biochar Amended Compost and Soil. *PLoS One* **2017**, *12* (2), 1–16. https://doi.org/10.1371/journal.pone.0171214.

(31) Kammann, C. I.; Schmidt, H. P.; Messerschmidt, N.; Linsel, S.; Steffens, D.; Müller, C.; Koyro, H. W.; Conte, P.; Stephen, J. Plant Growth Improvement Mediated by Nitrate Capture in Co-Composted Biochar. *Sci. Rep.* **2015**, *5*, 1–13. https://doi.org/10.1038/srep11080.

(32) Pandit, N. R.; Mulder, J.; Hale, S. E.; Zimmerman, A. R.; Pandit, B. H.; Cornelissen, G. Multi-Year Double Cropping Biochar Field Trials in Nepal: Finding the Optimal Biochar Dose through Agronomic Trials and Cost-Benefit Analysis. *Sci. Total Environ.* **2018**, *637–638*, 1333–1341. https://doi.org/10.1016/j.scitotenv.2018.05.107.

(33) Cornelissen, G.; Martinsen, V.; Shitumbanuma, V.; Alling, V.; Breedveld, G.; Rutherford, D.; Sparrevik, M.; Hale, S.; Obia, A.; Mulder, J. Biochar Effect on Maize Yield and Soil Characteristics in Five Conservation Farming Sites in Zambia. *Agronomy* **2013**, *3* (2), 256–274. https://doi.org/10.3390/agronomy3020256.

(34) Zhang, M.; Song, G.; Gelardi, D. L.; Huang, L.; Khan, E.; Mašek, O.; Parikh, S. J.; Ok, Y. S. Evaluating Biochar and Its Modifications for the Removal of Ammonium, Nitrate, and Phosphate in Water. *Water Res.* **2020**, *186*, 116303. https://doi.org/10.1016/j.watres.2020.116303.

(35) Haider, G.; Steffens, D.; Müller, C.; Kammann, C. I. Standard Extraction Methods May Underestimate Nitrate Stocks Captured by Field-Aged Biochar. *J. Environ. Qual.* **2016**, *45* (4), 1196–1204. https://doi.org/10.2134/jeq2015.10.0529.

(36) Hale, S. E.; Nurida, N. L.; Jubaedah; Mulder, J.; Sørmo, E.; Silvani, L.; Abiven, S.; Joseph, S.; Taherymoosavi, S.; Cornelissen, G. The Effect of Biochar, Lime and Ash on Maize Yield in a Long-Term Field Trial in a Ultisol in the Humid Tropics. *Sci. Total Environ.* **2020**, *719*, 137455. https://doi.org/10.1016/j.scitotenv.2020.137455.

(37) Liu, X.; Zhou, J.; Chi, Z.; Zheng, J.; Li, L.; Zhang, X.; Zheng, J.; Cheng, K.; Bian, R.; Pan, G. Biochar Provided Limited Benefits for Rice Yield and Greenhouse Gas Mitigation Six Years Following an Amendment in a Fertile Rice Paddy. *Catena* **2019**, *179* (March), 20–28. https://doi.org/10.1016/j.catena.2019.03.033.

(38) Backer, R. G. M.; Schwinghamer, T. D.; Whalen, J. K.; Seguin, P.; Smith, D. L. Crop Yield and SOC Responses to Biochar Application Were Dependent on Soil Texture and Crop Type in Southern Quebec, Canada. *J. Plant Nutr. Soil Sci.* **2016**, *179* (3), 399–408. https://doi.org/10.1002/jpln.201500520.

(39) Omara, P.; Aula, L.; Oyebiyi, F. B.; Eickhof, E. M.; Carpenter, J.; Raun, W. R. Biochar Application in Combination with Inorganic Nitrogen Improves Maize Grain Yield, Nitrogen Uptake, and Use Efficiency in Temperate Soils. *Agronomy* **2020**, *10* (9). https://doi.org/10.3390/agronomy10091241.

(40) Marks, E. A. N.; Mattana, S.; Alcañiz, J. M.; Pérez-Herrero, E.; Domene, X. Gasifier Biochar Effects on Nutrient Availability, Organic Matter Mineralization, and Soil Fauna Activity in a Multi-Year Mediterranean Trial. *Agric. Ecosyst. Environ.* **2016**, *215*, 30–39. https://doi.org/10.1016/j.agee.2015.09.004.

(41) Nelissen, V.; Ruysschaert, G.; Manka'Abusi, D.; D'Hose, T.; De Beuf, K.; Al-Barri, B.; Cornelis, W.; Boeckx, P. Impact of a Woody Biochar on Properties of a Sandy Loam Soil and Spring Barley during a Two-Year Field Experiment. *Eur. J. Agron.* **2015**, *62*, 65–78. https://doi.org/10.1016/j.eja.2014.09.006.

(42) Ramlow, M.; Foster, E. J.; Del Grosso, S. J.; Cotrufo, M. F. Broadcast Woody Biochar Provides Limited Benefits to Deficit Irrigation Maize in Colorado. *Agric. Ecosyst. Environ.* **2019**, *269* (August 2018), 71–81. https://doi.org/10.1016/j.agee.2018.09.017.

(43) Razzaghi, F.; Obour, P. B.; Arthur, E. Does Biochar Improve Soil Water Retention? A Systematic Review and Meta-Analysis. *Geoderma* **2020**, *361* (October). https://doi.org/10.1016/j.geoderma.2019.114055.

(44) Kerré, B.; Willaert, B.; Cornelis, Y.; Smolders, E. Long-Term Presence of Charcoal Increases Maize Yield in Belgium Due to Increased Soil Water Availability. *Eur. J. Agron.* **2017**, *91* (September), 10–15. https://doi.org/10.1016/j.eja.2017.09.003.

(45) Madari, B. E.; Silva, M. A. S.; Carvalho, M. T. M.; Maia, A. H. N.; Petter, F. A.; Santos, J. L. S.; Tsai, S. M.; Leal, W. G. O.; Zeviani, W. M. Properties of a Sandy Clay Loam Haplic Ferralsol and Soybean Grain Yield in a Five-Year Field Trial as Affected by Biochar Amendment. *Geoderma* **2017**, *305* (June 2016), 100–112. https://doi.org/10.1016/j.geoderma.2017.05.029.

(46) Nawaz, H.; Hussain, N.; … M. A.-I.; 2019, U. Biochar Application Improves the Wheat Productivity under Different Irrigation Water-Regimes. *Intl. J. Agric. Biol* **2019**, *21* (April), 936–942. https://doi.org/10.17957/IJAB/15.0978.

(47) Jin, Z.; Chen, C.; Chen, X.; Jiang, F.; Hopkins, I.; Zhang, X.; Han, Z.; Billy, G.; Benavides, J. Soil Acidity, Available Phosphorus Content, and Optimal Biochar and Nitrogen Fertilizer Application Rates: A Five-Year Field Trial in Upland Red Soil, China. *F. Crop. Res.* **2019**, *232* (September 2018), 77–87. https://doi.org/10.1016/j.fcr.2018.12.013.

(48) Jeffery, S.; Abalos, D.; Prodana, M.; Bastos, A. C.; van Groenigen, J. W.; Hungate, B. A.; Verheijen, F. Biochar Boosts Tropical but Not Temperate Crop Yields. *Environ. Res. Lett.* **2017**, *12* (5), 053001. https://doi.org/10.1088/1748-9326/aa67bd.

(49) Raboin, L. M.; Razafimahafaly, A. H. D.; Rabenjarisoa, M. B.; Rabary, B.; Dusserre, J.; Becquer, T. Improving the Fertility of Tropical Acid Soils: Liming versus Biochar Application? A Long Term Comparison in the Highlands of Madagascar. *F. Crop. Res.* **2016**, *199* (April 2013), 99–108. https://doi.org/10.1016/j.fcr.2016.09.005.

(50) Sun, Y. peng; Yang, J. song; Yao, R. jiang; Chen, X. bing; Wang, X. ping. Biochar and Fulvic Acid Amendments Mitigate Negative Effects of Coastal Saline Soil and Improve Crop Yields in a Three Year Field Trial. *Sci. Rep.* **2020**, *10* (1), 1–12. https://doi.org/10.1038/s41598-020-65730-6.

(51) Akhtar, S. S.; Andersen, M. N.; Liu, F. Biochar Mitigates Salinity Stress in Potato. *J. Agron. Crop Sci.* **2015**, *201* (5), 368–378. https://doi.org/10.1111/jac.12132.

(52) Mahmoud, E.; El-Beshbeshy, T.; El-Kader, N. A.; El Shal, R.; Khalafallah, N. Impacts of Biochar Application on Soil Fertility, Plant Nutrients Uptake and Maize (Zea Mays L.) Yield in Saline Sodic Soil. *Arab. J. Geosci.* **2019**, *12* (23). https://doi.org/10.1007/s12517-019-4937-4.

(53) Beesley, L.; Moreno-Jiménez, E.; Gomez-Eyles, J. L. Effects of Biochar and Greenwaste Compost Amendments on Mobility, Bioavailability and Toxicity of Inorganic and Organic Contaminants in a Multi-Element Polluted Soil. *Environ. Pollut.* **2010**. https://doi.org/10.1016/j.envpol.2010.02.003.

(54) Almaroai, Y. A.; Eissa, M. A. Effect of Biochar on Yield and Quality of Tomato Grown on a Metal-Contaminated Soil. *Sci. Hortic. (Amsterdam).* **2020**, *265* (August 2019), 109210. https://doi.org/10.1016/j.scienta.2020.109210.

(55) Kätterer, T.; Roobroeck, D.; Andrén, O.; Kimutai, G.; Karltun, E.; Kirchmann, H.; Nyberg, G.; Vanlauwe, B.; Röing de Nowina, K. Biochar Addition Persistently Increased Soil Fertility and Yields in Maize-Soybean Rotations over 10 Years in Sub-Humid Regions of Kenya. *F. Crop. Res.* **2019**, *235* (March), 18–26. https://doi.org/10.1016/j.fcr.2019.02.015.

(56) Sánchez-Monedero, M. A.; Cayuela, M. L.; Sánchez-García, M.; Vandecasteele, B.; D'Hose, T.; López, G.; Martínez-Gaitán, C.; Kuikman, P. J.; Sinicco, T.;

Mondini, C. Agronomic Evaluation of Biochar, Compost and Biochar-Blended Compost across Different Cropping Systems: Perspective from the European Project FERTIPLUS. *Agronomy* **2019**, *9* (5). https://doi.org/10.3390/agronomy9050225.

(57) Gaskin, J. W.; Steiner, C.; Harris, K.; Das, K. C.; Bibens, B. Effect of Low-Temperature Pyrolysis Conditions on Biochar for Agricultural Use. *Trans. ASABE* **2008**, *51* (6), 2061–2069. https://doi.org/10.13031/2013.25409.

(58) Mulvaney, R. L.; Yaremych, S. A.; Khan, S. A.; Swiader, J. M.; Horgan, B. P. Use of Diffusion to Determine Soil Cation-Exchange Capacity by Ammonium Saturation. *Commun. Soil Sci. Plant Anal.* **2004**, *35* (1–2), 51–67. https://doi.org/10.1081/CSS-120027634.

(59) Mukome, F. N. D.; Zhang, X.; Silva, L. C. R.; Six, J.; Parikh, S. J. Use of Chemical and Physical Characteristics to Investigate Trends in Biochar Feedstocks. *J. Agric. Food Chem.* **2013**. https://doi.org/10.1021/jf3049142.

(60) ISO [International Organization for Standardization]. Determination of the Specific Surface Area of Solids by Gas Adsorption - BET Method (ISO 9277:2010(E)). *Ref. number ISO* **2010**. https://doi.org/10.1007/s11367-011-0297-3.

(61) Parikh, S. J.; Goyne, K. W.; Margenot, A. J.; Mukome, F. N. D.; Calderón, F. J. *Soil Chemical Insights Provided through Vibrational Spectroscopy*; 2014; Vol. 126. https://doi.org/10.1016/B978-0-12-800132-5.00001-8.

(62) Gürsoy, D.; De Carlo, F.; Xiao, X.; Jacobsen, C. TomoPy: A Framework for the Analysis of Synchrotron Tomographic Data. *J. Synchrotron Radiat.* **2014**, *21* (5), 1188–1193. https://doi.org/10.1107/S1600577514013939.

(63) Pandolfi, R. J.; Allan, D. B.; Arenholz, E.; Barroso-Luque, L.; Campbell, S. I.; Caswell, T. A.; Blair, A.; De Carlo, F.; Fackler, S.; Fournier, A. P.; Freychet, G.; Fukuto, M.; Gürsoy, D.; Jiang, Z.; Krishnan, H.; Kumar, D.; Kline, R. J.; Li, R.; Liman, C.; Marchesini, S.; Mehta, A.; N'Diaye, A. T.; Parkinson, D. Y.; Parks, H.; Pellouchoud, L. A.; Perciano, T.; Ren, F.; Sahoo, S.; Strzalka, J.; Sunday, D.; Tassone, C. J.; Ushizima, D.; Venkatakrishnan, S.; Yager, K. G.; Zwart, P.; Sethian, J. A.; Hexemer, A. Xi-Cam: A Versatile Interface for Data Visualization and Analysis. *J. Synchrotron Radiat.* **2018**, *25* (4), 1261–1270. https://doi.org/10.1107/S1600577518005787.

(64) Soil Survey Staff. Web Soil Survey, Natural Resources Conservation Service, United States Department of Agriculture.

(65) Doane, T. A.; Horwath, W. R. Spectrophotometric Determination of Nitrate with a Single Reagent. *Anal. Lett.* **2003**. https://doi.org/10.1081/AL-120024647.

(66) Verdouw, H.; Van Echteld, C. J. A.; Dekkers, E. M. J. Ammonia Determination Based on Indophenol Formation with Sodium Salicylate. *Water Res.* **1978**. https://doi.org/10.1016/0043-1354(78)90107-0.

(67) Watanabe, F. S.; Olsen, S. R. Test of an Ascorbic Acid Method for Determining

Phosphorus in Water and NaHCO 3 Extracts from Soil . *Soil Sci. Soc. Am. J.* **1965**, *29* (6). https://doi.org/10.2136/sssaj1965.03615995002900060025x.

(68) Thomas, C. W. *Soil PH and Soil Activity in Methods of Soil Analysis: Part 3 Chemical Methods*; Sparks, D. L., Page, A. L., Helmke, P. A., Loeppert, R. H., Soltanpour, P. N., Tabatabai, M. A., Johnston, C. T., Summer, M. E., Eds.; American Society of Agronomy Inc.; Soil Science Society of America: Madison, WI, 1996.

(69) Sheldrick, B. H.; Wang, C. *Particle Size Distribution*; Lewis Publications/CRC Press: Boca Raton, FL, 1993.

(70) Hale, S. E.; Alling, V.; Martinsen, V.; Mulder, J.; Breedveld, G. D.; Cornelissen, G. The Sorption and Desorption of Phosphate-P, Ammonium-N and Nitrate-N in Cacao Shell and Corn Cob Biochars. *Chemosphere* **2013**, *91* (11), 1612–1619. https://doi.org/10.1016/j.chemosphere.2012.12.057.

(71) USDA National Resource Conservation Service. Yolo Series.

(72) USDA National Resource Conservation Service. Hanford Series.

(73) Santos-Medellin, C.; Zinke, L. A.; ter Horst, A. M.; Gelardi, D. L.; Parikh, S. J.; Emerson, J. B. Viromes Outperform Total Metagenomes in Revealing the Spatiotemporal Patterns of Agricultural Soil Viral Communities. *ISME J.* **2021**. https://doi.org/10.1038/s41396-021-00897-y.

(74) Hartz, T.; Miyao, G.; Mickler, J.; Lestrange, M.; Stoddard, S.; Nuñez, J.; Aegerter, B. Processing Tomato Production in California. *Process. Tomato Prod. Calif.* **2008**. https://doi.org/10.3733/ucanr.7228.

(75) Wickham, H.; Averick, M.; Bryan, J.; Chang, W.; McGowan, L.; François, R.; Grolemund, G.; Hayes, A.; Henry, L.; Hester, J.; Kuhn, M.; Pedersen, T.; Miller, E.; Bache, S.; Müller, K.; Ooms, J.; Robinson, D.; Seidel, D.; Spinu, V.; Takahashi, K.; Vaughan, D.; Wilke, C.; Woo, K.; Yutani, H. Welcome to the Tidyverse. *J. Open Source Softw.* **2019**, *4* (43), 1686. https://doi.org/10.21105/joss.01686.

(76) R Core Team. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing: Vienna, Austria 2020.

(77) Bates, D.; Mächler, M.; Bolker, B. M.; Walker, S. C. Fitting Linear Mixed-Effects Models Using Lme4. *J. Stat. Softw.* **2015**, *67* (1). https://doi.org/10.18637/jss.v067.i01.

(78) Lenth, R. Emmeans: Estimated Marginal Means. *Aka Least-Squares Means.* **2019**, https://cran.r-project.org/package=emmeans. https://doi.org/https://CRAN.R-project.org/package=emmeans.

(79) Wickham, H. Ggplot2: Elegant Graphics for Data Analysis. *Springer-Verlag New York* **2016**.

L. Appendix - Figures, tables, and supporting documents

Table 2. Select chemical and physical biochar properties (n=3) ± standard error of the means

	AS500	AS800	CS650	SW500	SW500-I	SW650	SW800
Carbon (%)	65.8 ± 0.45	35.33 ± 0.25	71.23 ± 0.73	70.89 ± 0.25	63.49 ± 0.33	78.32 ± 0.41	41.76 ± 0.47
Nitrogen (%)	0.76 ± 0.01	0.55 ± 0.02	0.79 ± 0.04	0.13 ± 0.03	0.69 ± 0.01	0.29 ± 0.01	0.13 ± 0.03
Oxygen (%)	17.11 ± 0.75	26.44 ± 0.75	13.66 ± 0.64	17.07 ± 0.58	20.11 ± 0.23	10.18 ± 0.16	15.3 ± 0.88
Hydrogen (%)	3.05 ± 0.04	1.83 ± 0.02	3.23 ± 0.06	3.76 ± 0.01	3.79 ± 0.03	2.92 ± 0.07	1.48 ± 0.05
Molar O/C ratio	0.19 ± 0.01	0.56 ± 0.01	0.15 ± 0.01	0.18 ± 0.01	0.24 ± 0	0.1 ± 0	0.27 ± 0.01
Molar H/C ratio	0.55 ± 0.01	0.62 ± 0.01	0.54 ± 0.01	0.63 ± 0	0.71 ± 0.01	0.44 ± 0.01	0.42 ± 0.02
Volatile (%)	30.74 ± 2.67	28.17 ± 0.5	32.14 ± 0.36	37.99 ± 0.86	38.83 ± 1.21	26.87 ± 0.29	21.67 ± 0.17
Ash (%)	19.01 ± 0.99	55.35 ± 0.78	5.28 ± 0.15	4.48 ± 0.06	9.21 ± 0.53	4.45 ± 0.29	31.45 ± 1.21
pH	9.34 ± 0.02	10.13 ± 0.01	7.77 ± 0.02	7.85 ± 0.02	10.43 ± 0.01	8.03 ± 0.03	10.29 ± 0.01
EC (mS cm^{-1})	3.17 ± 0.01	27.2 ± 0.12	0.28 ± 0	2.54 ± 0.02	2.05 ± 0.02	0.12 ± 0	2.71 ± 0.01
DOC (mg kg^{-1})	38322.1 ± 1776.6	1055.9 ± 52.9	644.5 ± 77.1	43776.2 ± 1103.8	32171.2 ± 934.8	423.4 ± 50.6	475.2 ± 66.9
CEC (cmolc kg^{-1})	24.02 ± 0.57	52.74 ± 0.81	26.82 ± 1.06	16.46 ± 0.39	34.13 ± 0.18	21.65 ± 0.43	60.83 ± 0.75
Mean particle size (μm)	464	269.8	609.1	493.6	241.1	212.3	139.4
Median particle size (μm)	590.6	334.8	931.2	763.5	312.8	446.3	171.2
Surface Area (m^2 g^{-1})	54.7	188.2	233.6	93.5	152.6	305.6	363.6

EC = electrical conductivity; DOC = dissolved organic carbon; CEC = cation exchange capacity

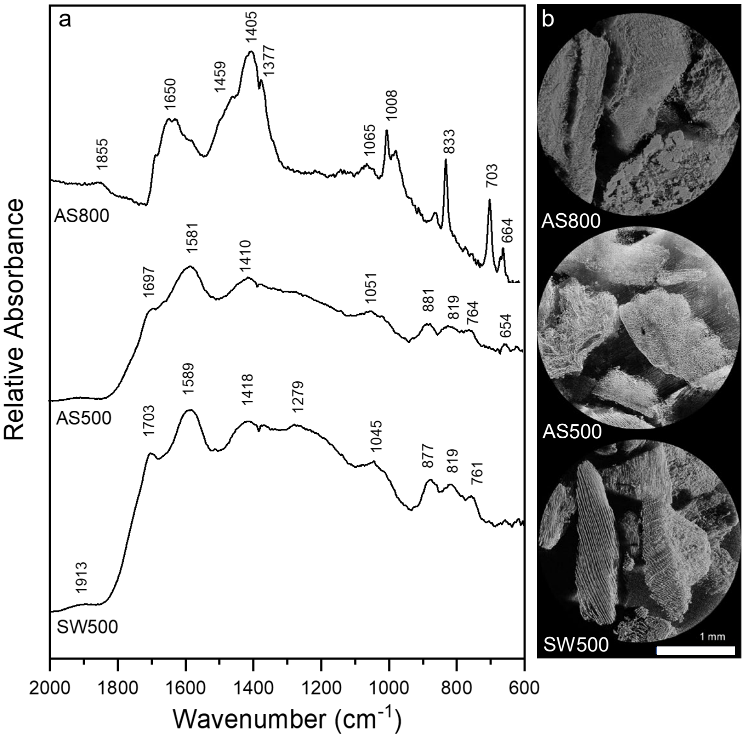

Figure 1. a) DRIFT spectra of AS800, AS500, and SW500 biochars. Samples diluted with potassium bromide to 3% sample, and collected with 256 cm^{-1} scans with a 4 cm^{-1} resolution; b) X-ray microCT images of AS800, AS500, and SW500 biochars.

Table 3. Select physical and chemical properties of Hanford Sandy Loam (HSL) and Yolo Silt Loam (YSiL) from 0 to 30 cm (n = 3) ± standard error of the means. Samples were taken before the establishment of the field trial in September 2017 to measure baseline fertility

	HSL	YSiL
Total C (%)	0.37 ± 0.009	1 ± 0.02
NH_4^+-N (mg kg^{-1})	0.74 ± 0.1	1.02 ± 0.1
NO_3^--N (mg kg^{-1})	34.5 ± 0.5	40.4 ± 1.1
Ca^{2+} (mg kg^{-1})	943.4 ± 11.6	2191.3 ± 7.2
Mg^{2+} (mg kg^{-1})	58.1 ± 1.6	508.5 ± 11.6
K^+ (mg kg^{-1})	55.9 ± 1.0	360.1 ± 0.7
Na^+ (mg kg^{-1})	118.1 ± 2.3	146.6 ± 0.7
Olsen P (mg kg^{-1})	9.2 ± 0.1	9.8 ± 0.2
pH	7.30 ± 0.1	7.31 ± 0.1

EC (μS cm^{-1})	427.3 ± 2.8	269.3 ± 1.9
Sand (%)	58.7 ± 1.4	24.0 ± 0.9
Clay (%)	12.0 ± 0.9	32.7 ± 0.5

EC = electrical conductivity

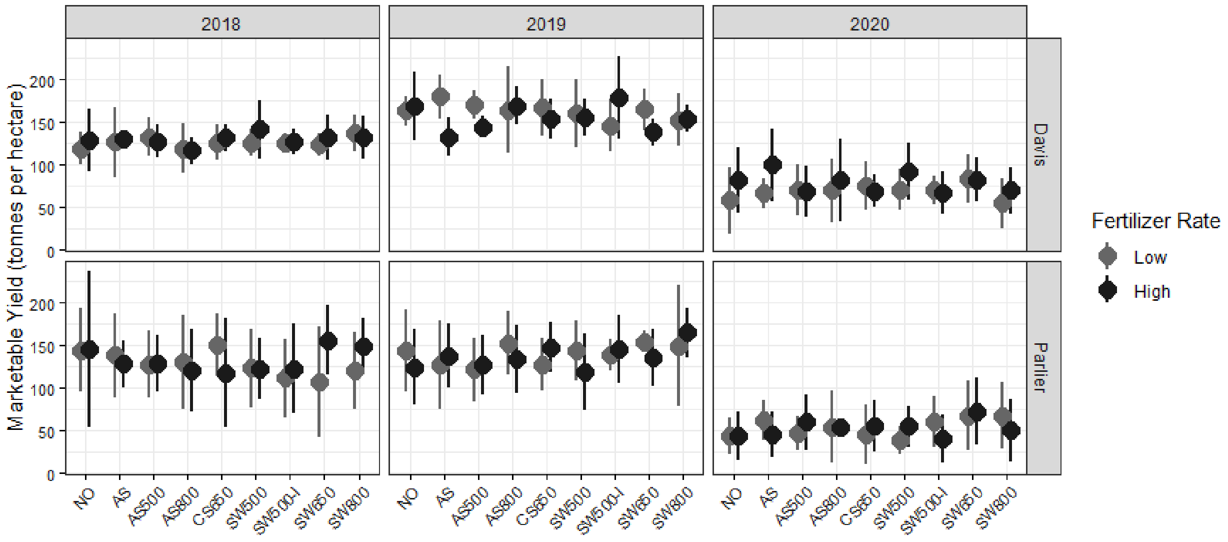

Figure 2. Marketable yield in a three-year processing tomato field trial by biochar, year, location, and fertilizer rate (Low = 168 kg N ha^{-1}; H = 252 kg N ha^{-1}). Results are averaged over the level of biochar rate (n = 3 per rate) as it was not significant in any models tested. Error bars represent the 95% confidence intervals of the means (n = 6).

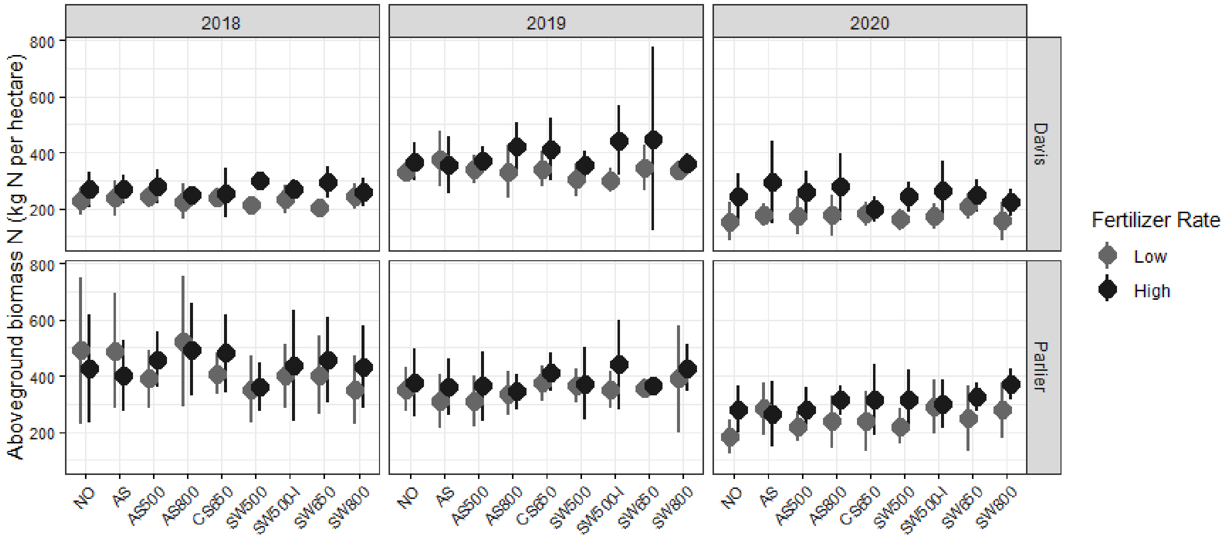

Figure 3. Aboveground biomass (fruit + vine) nitrogen (N) in a three-year processing tomato field trial by biochar, year, location, and fertilizer rate (Low = 168 kg N ha^{-1}; H = 252 kg N ha^{-1}). Results are averaged over the level of biochar rate (n=3 per rate) as it

was not significant in any models tested. Error bars represent the 95% confidence intervals of the means (n = 6).

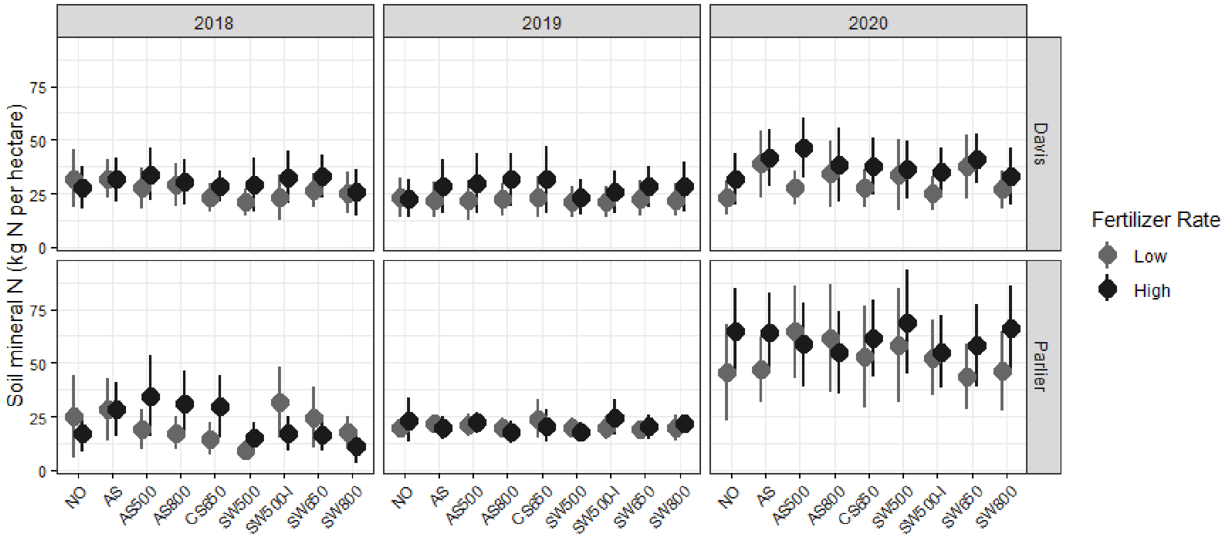

Figure 4. Soil mineral nitrogen (NH_4^+-N and NO_3^--N combined) in a three-year processing tomato field trial by biochar, year, location, and fertilizer rate (L= low, or 168 kg N ha^{-1}; H = high, or 252 kg N ha^{-1}). Results are averaged over the level of biochar rate (n = 3 per rate) as it was not significant in any models tested. Error bars represent the 95% confidence intervals of the means (n = 6).

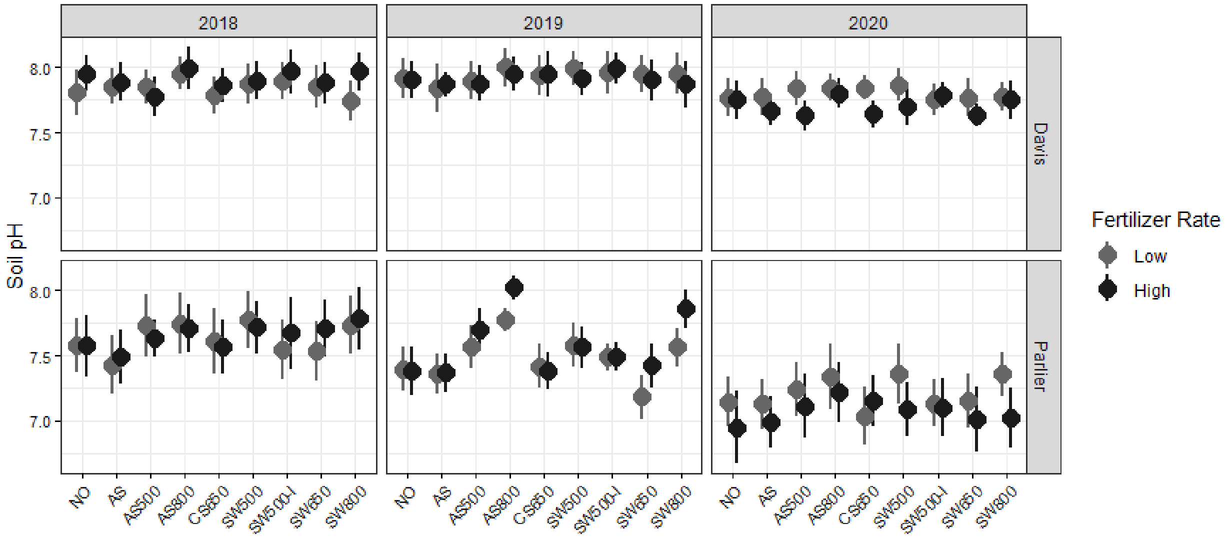

Figure 5. Soil pH in a three-year processing tomato field trial by biochar, year, location, and fertilizer rate (Low = 168 kg N ha^{-1}; High = 252 kg N ha^{-1}). Results are averaged over the level of biochar rate (n = 3 per rate) as it was not significant in any models tested. Error bars represent the 95% confidence intervals of the means (n = 6).

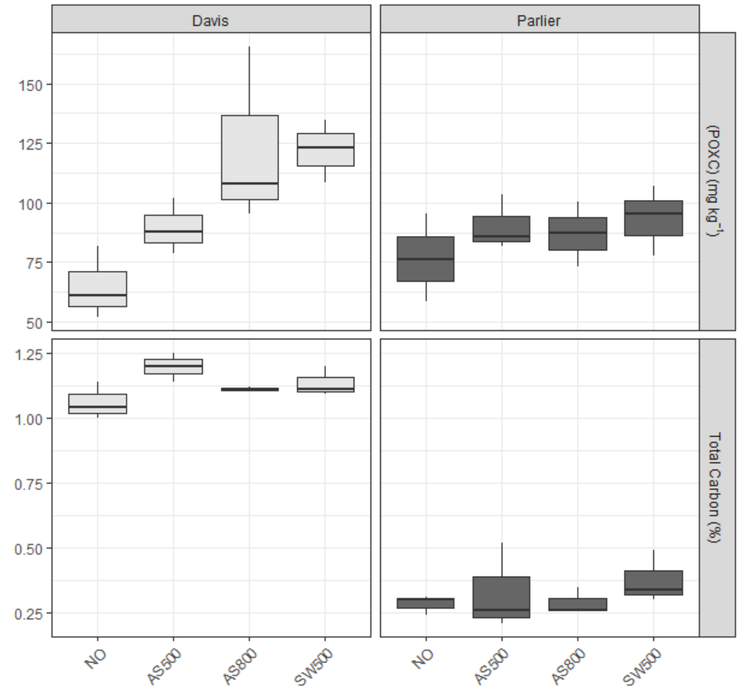

Figure 6. Permanganate oxidizable carbon (POXC) and total carbon in soils 2.5 years after biochar amendment, from a three-year processing tomato field trial, by biochar and location. Box plots show medians with the middle bars and the first and third quartiles with the boxes' lower and upper limits, respectively. The ends of each whisker represent the highest and lowest values within 1.5 times the inter-quartile range (n = 3).

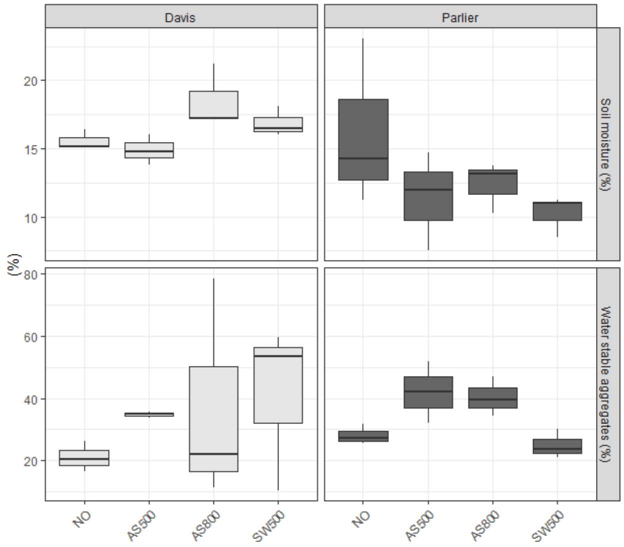

Figure 7. Moisture and water stable aggregates from soils 2.5 years after biochar amendment, from a three-year processing tomato field trial, by biochar and location. Box plots show medians with the middle bars and the first and third quartiles with the boxes' lower and upper limits, respectively. The ends of each whisker represent the highest and lowest values within 1.5 times the inter-quartile range (n = 3).

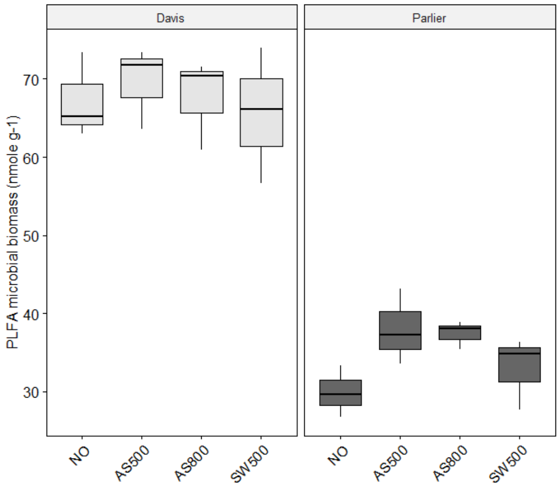

Figure 8. Phospholipid fatty acid (PLFA) biomass from soils 2.5 years after biochar amendment, in a three-year processing tomato field trial, by biochar and location. Box plots show medians with the middle bars and the first and third quartiles with the boxes' lower and upper limits, respectively. The ends of each whisker represent the highest and lowest values within 1.5 times the inter-quartile range (n = 3).

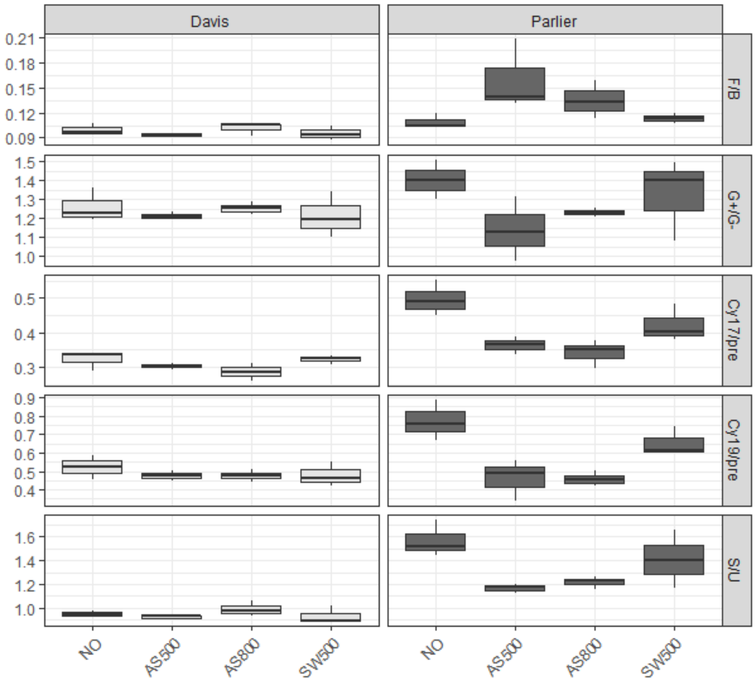

Figure 9. Ratios of select phospholipid fatty acids (PLFAs) from soils 2.5 years after biochar amendment, from a three-year processing tomato field trial, by biochar and location. Box plots show medians with the middle bars and the first and third quartiles with the boxes' lower and upper limits, respectively. The ends of each whisker represent the highest and lowest values within 1.5 times the inter-quartile range (n = 3). F/B = fungal to bacterial; Cy17/pre = cyclopropyl 17:0 to precursors; Cy19/pre = cyclopropyl 19:0 to precursors; G+/G- = gram-positive to gram-negative bacteria; S/U = saturated to monounsaturated

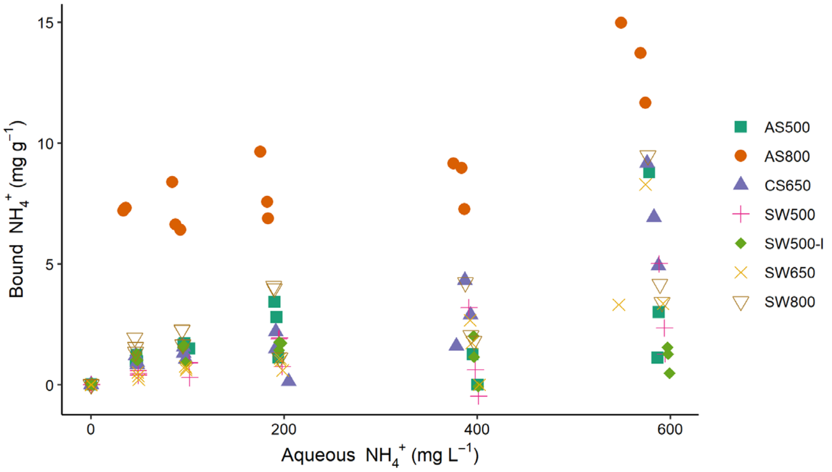

Figure 10. Sorption isotherms for ammonium and biochars, performed at 22 ± 1 °C. All solutions were prepared in 5.84 mg L^{-1} NaCl and spiked at 1% volume with a stock solution of 20 g L^{-1} of the bactericide sodium azide.

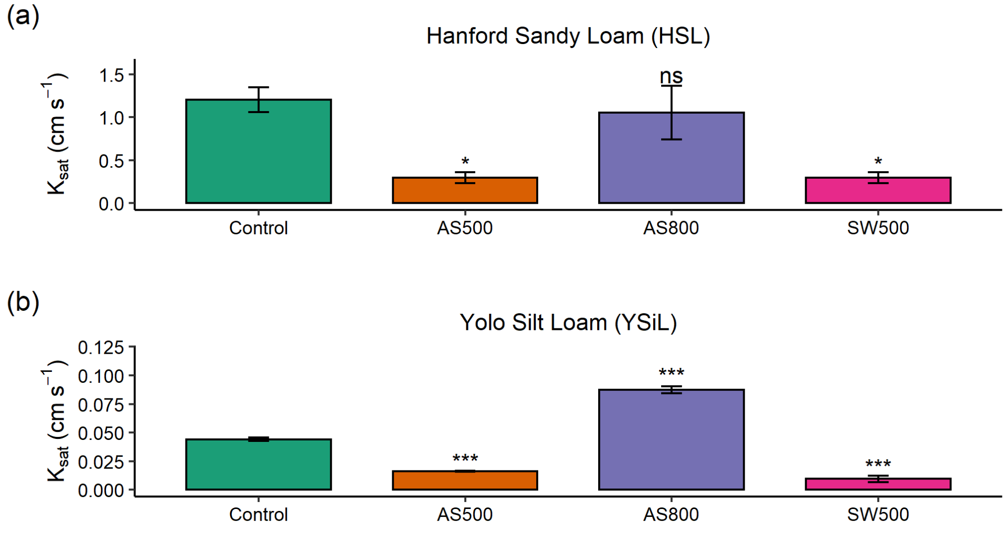

Figure 11: Impact of 0 and 2% addition of AS500, AS800, and SW500 biochars on saturated hydraulic conductivity (K_{sat}) in a) a Hanford Sandy Loam (HSL) soil and b) a Yolo Silt Loam (YSiL) soil (n=5). Symbols denote significance levels as follows: ns = not significant, $*p<0.05$, $**p<0.01$, $***p<0.001$. P-values refer to comparisons between

treatments and the control within each pore volume and were corrected for multiple comparisons using Tukey's honestly significant difference method.

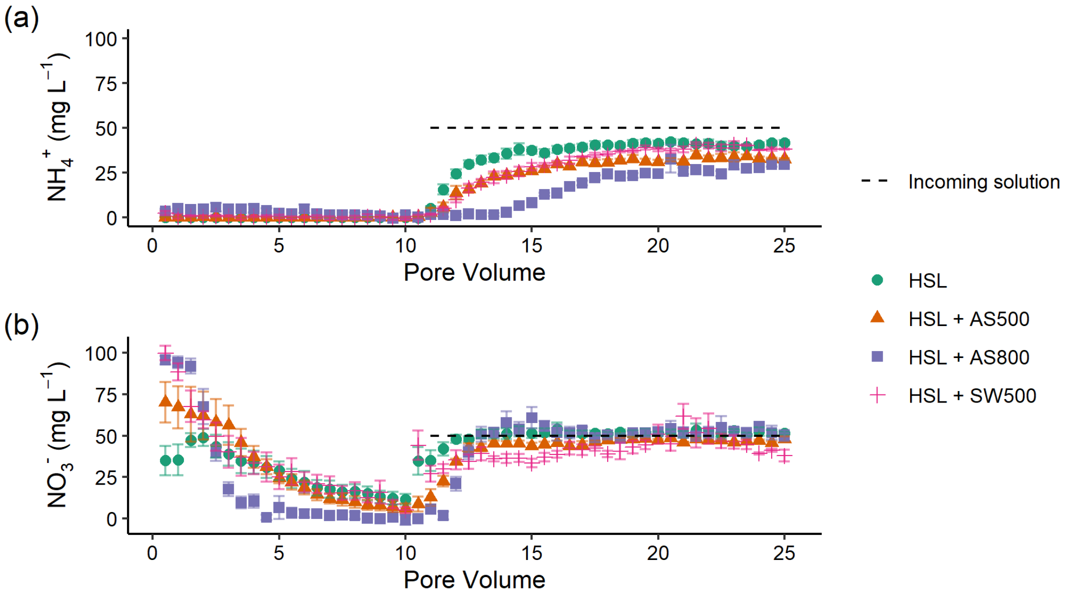

Figure 12: Breakthrough curves for a) ammonium and b) nitrate in a Handford Sandy Loam (HSL) soil with 0 and 2% additions of AS500, AS800, and SW500 biochars. Native soil nitrogen was flushed in pore volumes 0-10 with an 11.1 mg L^{-1} $CaCl_2$ solution, after which 50 mg L^{-1} solutions of NH_4^+ and NO_3^- were gravity-fed through soil columns (n=5). Error bars represent the standard error of the means.

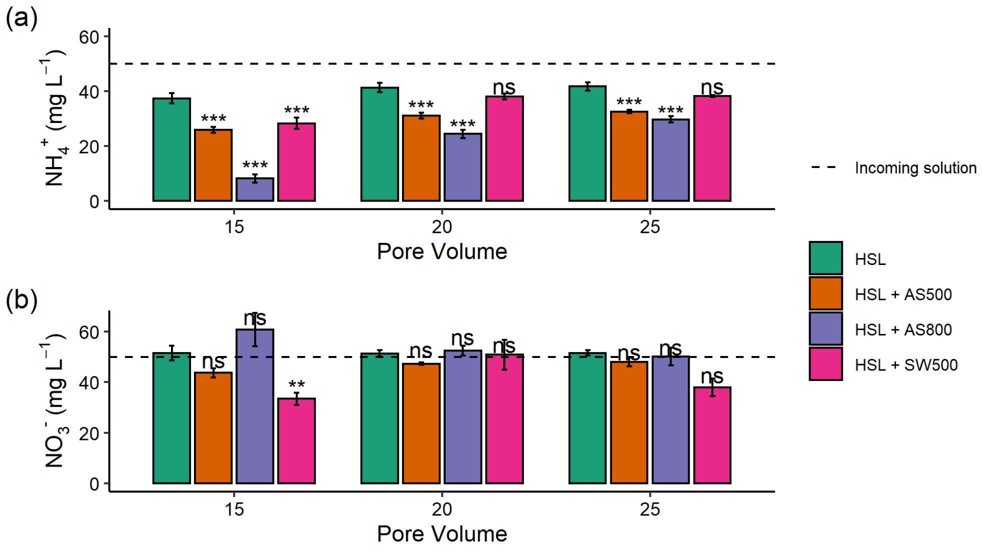

Figure 13: Quantity of a) ammonium and b) nitrate in Hanford Sandy Loam (HSL) soil columns with 0 and 2% additions of AS500, AS800, and SW500 biochars in pore volumes 15, 20, and 25 (n=5). Error bars represent the standard error of the means. Symbols

denote significance levels as follows: ns = not significant, *p<0.05, **p<0.01, ***p<0.001. P-values refer to comparisons between treatments and the control within each pore volume and were corrected for multiple comparisons using Tukey’s honestly significant difference method.

M. Factsheet/Database Template:

1. **Title:** *Evaluation of Biochar for On-Farm Soil Management in California*
2. **Grant Agreement Number:** 16-0662-SA-0
3. **Project Leaders:**

Danielle L. Gelardi[1], Graduate Student Researcher
Sanjai J. Parikh[1], Associate Professor of Soil Chemistry
William R. Horwath[1], Prof. Soil Biogeochemistry
Daniel Geissler[1], Assoc. Coop. Ext. Specialist
Milt McGiffen[2], Veg. Crops Spec. & Vice Chair for Coop. Ex.
Michelle Leinfelder-Miles[3], Coop. Ex. Farm Adv.
Toby A. O'Geen[1], Soil Resource Specialist
Kate M. Scow[1], Professor of Soil Microbiology
[1] Department of Land, Air and Water Resources, University of California, Davis, One Shields Avenue, Davis, CA 95618.
[2] Department of Botany and Plant Science, University of California, Riverside, 4101 Bachelor Hall, Riverside, CA 92521
[3] Cooperative Extension San Joaquin County, 2101 East Earhart Ave., Stockton, CA 95206

4. **Star Year/End Year:** 2017/2021
5. **Location:** Davis, CA and Parlier, CA
6. **Counties:** Yolo and Fresno Counties
7. **Highlights:**
   - No chemical binding between the unmodified biochars (n=7) and nitrate was observed, and biochar did not reduce nitrate leaching.
   - Biochar amendment (n=7) to two fertile California soils did not have a significant impact on tomato yield
   - Biochar (n=3) may increase water residence time in sandy soils and enhance drainage in fine-textured soils.
   - Biochar (n=3) may deliver soil health benefits in course-textured agricultural soils in a Mediterranean climate.
8. **Introduction:** Farmers, researchers, and policymakers are increasingly interested in the use of biochar, a carbon-rich material created from the thermochemical conversion of biomass in an oxygen-limited environment, as a soil amendment. Due to biochar's unique chemical and physical structure, the material offers many potential solutions to pressing agricultural issues. These issues include nitrate leaching, low nutrient use efficiency, vulnerability of soils to drought conditions, and depleted soil carbon stocks. Previous research shows inconsistent results on the ability of biochar to address these issues due to differences in biochar feedstock, production methods, soil properties, climate, and cropping systems. To inform the use and regulation of biochar, farmers and policymakers must have access to reliable, place-based data. This study fills a gap in the literature by providing long-term, field-scale data about the potential of biochar for CA agriculture.

9. **Methods/Management**

   Seven biochars were produced by using mostly CA feedstocks at specified temperatures. Feedstocks include softwood, almond shell, and coconut shell. The biochars were analyzed for total carbon, nitrogen, oxygen, hydrogen, surface area, cation exchange capacity, pH, electrical conductivity, ash content, dissolved organic carbon, and particle size distribution._In fall 2017, one-acre plots were amended with biochar in UC Davis Campbell Tract and the Kearney Agriculture Research and Extension Center in Parlier. The two soils, a Yolo silt loam (YSiL) and a Hanford sandy loam (HSL), represent over 500,000 acres of CA soils. Biochars were subsurface banded directly above the drip tape to maximize contact with irrigation and fertigation, and to minimize application costs. Biochars were applied in two or three rates and combined with a low (150 lbs. N) and high (225 lbs. N) UAN-32 fertilizer rate. Field sites were planted each spring with processing tomatoes and harvested each fall. Plant samples were collected and analyzed for yield and total carbon and nitrogen. To examine microbial communities, soil was analyzed for mineral nitrogen, total carbon and nitrogen, pH, moisture content, and PLFA. Growth chamber and Laboratory studies were conducted to observe plant-soil-biochar interactions concerning yield, nutrition, soil water dynamics, and nitrate and ammonium retention. Studies include sorption experiments, soil columns, micro-CT scans, and lettuce pot trials with 0 and 2% biochar.

10. **Findings**

    Biochars tested exhibited a strong chemical affinity for ammonium, likely due to the attraction between their negatively charged surfaces and the positively charged ammonium ion. Biochars exhibited little to no chemical affinity for nitrate, though one biochar reduced nitrate leaching in soil column studies to a small extent via physical mechanisms. The ability of biochar to alter the soil physical environment was most evident in its effect on saturated hydraulic conductivity (K_{sat}). Broadly, biochars increased K_{sat} in a silt loam but had a mixed impact in a sandy loam. The short-term laboratory experiments in this study demonstrate that biochars could improve ammonium retention and water conductivity.

    For the three-year field trials, no combination of experimental conditions was biochar observed to increase processing tomato yield, plant nitrogen uptake, or soil moisture. While biochar did not deliver tangible agricultural benefits in field trials, the soil health assessment indicates that it may confer other ecological or environmental benefits. Importantly, results from multiple scales indicate biochar can be added to agricultural soils with few negative consequences for cropping systems.