Co-Composted Biochar Improves Dry-Farmed Tomato Productivity in the Santa Clara Valley, CA, with No Change in Soil Microbiology

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CO-COMPOSTED BIOCHAR IMPROVES DRY-FARMED TOMATO PRODUCTIVITY IN THE SANTA CLARA VALLEY, CA, WITH NO CHANGE IN SOIL MICROBIOLOGY

A Thesis

Presented to

The Faculty of the Department of Environmental Studies

San José State University

In Partial Fulfillment

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Master of Science

by

Duncan A. Keller

December 2022
The Designated Thesis Committee Approves the Thesis Titled

CO-COMPOSTED BIOCHAR IMPROVES DRY-FARMED TOMATO PRODUCTIVITY IN THE SANTA CLARA VALLEY, CA, WITH NO CHANGE IN SOIL MICROBIOLOGY

by

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APPROVED FOR THE DEPARTMENT OF ENVIRONMENTAL STUDIES

SAN JOSÉ STATE UNIVERSITY

December 2022

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ABSTRACT

CO-COMPOSTED BIOCHAR IMPROVES DRY-FARMED TOMATO PRODUCTIVITY IN THE SANTA CLARA VALLEY, CA, WITH NO CHANGE IN SOIL MICROBIOLOGY

by Duncan A. Keller

California is a globally important site for agricultural production, but the state is currently suffering from an unprecedented drought. One strategy to conserve water is dry farming, where growers cache moisture in the soil from off-season rain or early-season irrigation for crops to use throughout the growing season. Some California growers have dry-farmed tomatoes for decades. Recently, some have begun adding co-composted biochar (COMBI) to boost productivity and stimulate soil microbiology, particularly arbuscular mycorrhizal fungi. To the best of my knowledge, no field research on dry-farmed tomato systems currently exists, let alone on the effects of COMBI amendments on yield, soil microfauna, or the relative cost of production. This on-farm collaboration between San José State University (SJSU) and an organic grower was thus designed to test the effect of COMBI on dry-farmed tomato yield, soil microbiota, and cost implications. Compost treatments with and without a softwood biochar amendment were applied to a 4-acre dry-farm tomato field at Martial Cottle Park (San José, CA). To estimate productivity two weeks before fruit maturity, I non-destructively measured plant height and per-plant fruit number and size, then harvested and measured fruit and shoot biomass after maturity. I sent soil samples for phospholipid fatty acid analysis to describe the microbial community. COMBI improved tomato productivity enough to outweigh the cost of the amendment. Still, microbial community parameters did not differ between treatments, suggesting that chemical or physical mechanisms may drive the yield effects.
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Finally, I would like to express gratitude to the people of the Santa Clara County Parks Department. Thank you for connecting me with Jacobs Farm and helping me navigate any obstacles throughout the study. And most of all, thank you for preserving the agricultural legacy of the Santa Clara Valley and bringing it to the people.
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Introduction

The past two years were particularly dry for the semi-arid state of California. Not only was the 2021 water year the second driest on record (California Department of Water Resources 2021), but January and February 2022 were record-setting in the lack of expected precipitation, culminating in a severe drought for most of the state (Esquivel and Sobeck 2022). Statewide water deficiencies from irrigation overdrafts and consequent legislative restrictions worsen the strain (Langridge and Schmidt 2020; Kanter et al. 2021). Since almost all California farmers irrigate their vegetable crops, the domestic market has suffered, and vegetable imports are rising (Davis and Lucier 2021). Coupled with projected climate change-related heat waves and less predictable rainfall, these facts make the direness of the water situation difficult to ignore (Pathak et al. 2018).

One priority to ensure quality food production in the face of drought is to optimize adaptive strategies at the farm level. Unfortunately, the typical model where farmers acquire new tools and techniques from academic institutions and extension services is insufficient for addressing problems like this (Lacoste et al. 2022). As agroecosystem engineers, farmers are a rich source of experiential knowledge (Wezel et al. 2020). An alternative to the conventional model is on-Farm Experimentation (OFE), where scientists and farmers jointly explore questions directly relevant to the farmer while co-organizing practically feasible research within the farm system (Lacoste et al. 2022). Local farms are an unrealized resource for stabilizing productivity amidst the uncertainties of climate change (Pathak et al. 2018).

Dry farming is one agricultural practice that is effective under certain local conditions. It is a water-conservation practice that some use in places where growing season precipitation
is limited. Those who practice dry farming force crops to scavenge for moisture deep in the
soil in place of irrigation. Although researchers showed avid interest in the practice more
than a century ago (McOmie et al. 1918; Widtsoe 1911), the subsequent record is lopsided in
favor of specific markets. While in-depth and long-term research on grains in the United
States exists, vegetable crops are virtually absent from the literature. Nevertheless,
commercial-scale dry farming has a legacy of more than three decades in California (Leap et
al. 2017; Rabkin 2010; Reti 2010). Since California generates more than a third of the
nation’s vegetable produce on a small fraction of U.S. arable land (Pathak et al. 2018), it is
worth researching as a drought mitigation strategy wherever practical (Parks et al. 2021).

In organic dry farm systems, effective soil amendment practices are indispensable.
However, compost is not the only organic soil amendment, though ubiquitous in organic
farming (Diacono and Montemurro 2011). Biochar is a form of pyrolyzed biomass used to
improve agricultural soils. It is often physically identical to charcoal but is used to amend the
soil rather than produce fuel (Lehmann and Joseph 2015). Some credit biochar as the key
ingredient in the nutrient-rich Amazonian terra preta soils, or “dark earths,” so-called due to
the dark color from the high carbon content (Glaser and Birk 2012). Those who support this
hypothesis maintain that these soils are from centuries of human contributions of biochar and
other organic matter, such as manures, to the soil. Conceptually linked to terra preta is the
notion of co-composted biochar (COMBI), where biochar is added to compost as it matures.
Recently, scholars began considering whether utilizing COMBI might improve crop systems
versus compost alone (Wang et al. 2019). However, there may be benefits of adding biochar
while composting relating to nutrient availability, moisture retention, and microbial stimulation (Kammann et al. 2015; Ogawa and Okimori et al. 2010; Zhou et al. 2022).

Despite the relevance of soil amendment practices to organic farms, the literature offers no direct guidance for maintaining healthy and productive dry farm soils using organic amendments. More specifically, to the best of my knowledge, no one has investigated whether COMBI is better than non-biochar compost for crop productivity or soil microbial life. If it were, understanding the mechanisms behind any success would be necessary for adaptation across different growing conditions (Wang et al. 2019). A full exploration of possible biotic or abiotic causes would be enlightening but beyond the scope of this study. However, taking a broad look at soil microbial community structure in COMBI-treated crops is one way to begin discussing how COMBI may alter agroecosystems (Buyer et al. 2010).
Literature review

Dry farming

A universal feature of dry farming is that crops are grown in a semi-arid region without irrigation, requiring plants to scavenge for stored soil moisture. The exact meanings of some terms are nuanced from place to place, however. For example, what has been suggested as the minimum annual rainfall threshold in one place (Garrett 2019) was once recommended as the maximum in another (Widtsoe 1911). Moreover, crops in some regions may need initial irrigation to ensure establishment (Leap et al. 2017). Local variables such as annual precipitation distribution (Peterson 2018), evaporation rate (Peterson et al. 2020), and soil type (Hargreaves 1977) accentuate the importance of context. However, there is consensus that rainfed agriculture in regions with adequate precipitation for plant growth is not dry farming, particularly to the East of the Great Plains. On the other hand, dry farms' lack of growing season precipitation is a limiting factor.

The most well-established area of dry farm research is cereal grains. The United States Department of Agriculture (USDA) began sponsoring dry farm research more than a century ago. Early USDA-sanctioned dry farm experimental stations include some in the Great Plains (Campbell 1909), Utah (Widtsoe 1911), and Arizona (McOmie et al. 1918). Dry farming was not a novel concept at the time. Indigenous dry farming techniques informed early USDA research (McOmie et al. 1918; Shaw 1909), and the application itself is ancient (Peterson 2018).

The development, promulgation, and adoption of a science-based dry farming doctrine enormously impacted American agriculture (Libecap and Hansen 2002). Early promoters
claimed that if new homesteaders kept some of their land fallow (out of production) for at least a season and vigilantly tilled the fallowed land to control weeds, enough moisture could be stored in the soil to grow crops successfully in a subsequent growing season (Hargreaves 1977). Settlers moved westward *en masse* leading to a large-scale American dry farm experiment.

Despite widespread optimism about dry farming, there were concrete reasons to be cautious, such as the prescription of dust mulch. To reduce soil moisture loss from evaporation during the summer fallow, promoters advised that growers pulverize the top soil layer into a fine powder. Nevertheless, some contemporary scientists worried that this could exacerbate wind erosion (Granatstein 1992). Another underestimated possibility was long-term drought, which could interfere with caching soil moisture during fallow periods (Libecap and Hansen 2002). In the context of mechanical innovations enabling massive-scale topsoil disruption, the expanses of finely-ground topsoil and sustained drought were primary contributors to the Dustbowl of the 1930s (Peterson et al. 2020). However, as ecological awareness has since changed, dry-farmed research has persisted.

Better soil management was a necessary consequence of the Dust Bowl. To preserve the summer fallow and its application for water storage, agronomists began experimenting with alternative strategies. One key trend was a tillage reduction revolution, both in terms of intensity and the number of passes (Peterson et al. 2020). Over the 20th Century, deep tillage with seven to ten passes gave way to lighter and less frequent tillage. Eventually, strategies to terminate and leave the stubble of previous crops appeared, followed by herbicide programs to kill weeds and phase out tillage altogether in some cases.
No-till agriculture is strongly present in dry farming history. It typically involves herbicides to minimize weed pressure in place of tillage, shifting soil water reserves toward intended crops. The reduced danger of wind erosion is one benefit of no-till dry farming (Schnarr et al. 2022), but there are other advantages. One is the option for crop intensification, where growers can mow the remains of one crop and drill seed for the following crop into the soil (Schillinger et al. 1999). Another is that no-till can reduce soil water loss compared to the summer fallow (McGee et al. 1997) and even lower the amount of herbicide needed (Rosenzweig et al. 2018). Reduced herbicide application is critical because excessive use can result in the evolution of herbicide-resistant populations of weeds (Genna et al. 2021). Although it comes with its problems, there is optimism about fine-tuning no-till dry farming in the future (Peterson et al. 2020).

Unlike dry-farmed grains, scant dry-farmed vegetable publications based on field trials exist in the United States, and none to my knowledge occurred in California. Of the six U.S. studies I could find, four were with pumpkin (*Cucurbita pepo*) in Illinois (Swiader 1985a, 1985b; Swiader et al. 1988; Swiader and Moore 2002), one was with potato (*Solanum tuberosum*) in North Dakota (Nelson and Thoreson 1986) and another was with taro (*Colocasia esculenta*) in Hawaii (Sipes and Arakaki 1997). Parks et al. (2021) recognized that although dry farming vegetable crops is well-established in practice, it is not well reflected in scientific literature due to a predominantly farmer-to-farmer mode of knowledge transfer. However, the authors acknowledge a way forward through locally-driven participatory research among dry farming communities. This contrasts the conventional “top-down” dissemination of academic research into farming systems with the utility of more of
an interactive process where the farmer experience influences experimental design, consistent with the OFE model (Lacoste et al. 2022).

Biochar

BACKGROUND

Char, charcoal, and biochar are all partially combusted biomass produced under oxygen-limited conditions (Lehmann and Joseph 2015; Bruckman and Pumpanen 2019). Char results from natural processes, such as wildfire from a lightning strike. The second two are distinct from the first because of their anthropogenic origin and purpose. Charcoal is produced for fuel, while biochar is added to the soil to improve it, usually for agricultural or environmental reasons (Lehmann and Joseph 2015). However, the time when humans began producing and using biochar is a point of contention (Silva et al. 2021).

Some argue that peculiar pockets of rich dark soils within the agriculturally poor soils of the Amazon Basin are anthropogenic, known as anthrosols. *Terra preta de Índio*, or Amazonian dark earths (ADEs), contain evidence of stable pyrogenic carbon. Some posit that Amazonian residents created ADEs by amending the soil with biochar and other organic matter for more than a millennium (Glaser and Birk 2012; Schellekens et al. 2017). Others argue that it would have taken much longer than the documented period of human occupation for the ADEs to form (Silva et al. 2021). Humans possibly instead encountered the ADE areas, formed through natural processes, and recognized them as agriculturally desirable.

Other possible instances of rich anthropogenic soils exist. From about a thousand to 150 years ago in Germany, peasants discarded charcoal and other organic waste material producing dark soil similar to the Amazon Basin (Kern et al. 2019). West Africa is another
example where soils are enriched with pyrogenic carbon and other discarded materials, and in this case, local farmers still add to the soils. These latter dark earths may be as old as almost 700 years (Solomon et al. 2016). Nevertheless, the extent of biochar use *per se* (i.e., intentionally-amended soils) is not firmly established in these traditional cases.

Before the coinage of “biochar” as a name for pyrogenic carbon used to amend the soil, many studies of the same substance already existed. These publications refer to it as charcoal without assigning a unique name based on its application to the soil. Some explored how adding charcoal may stimulate soil microbiota (Ishii and Kadoya 1994; Pietikäinen et al. 2000). Others observed improved productivity and chemical soil properties (Lehmann et al. 2003; Yamato et al. 2006). Glaser et al. (2002) first reviewed this application, highlighting how charcoal, a cheap and accessible product for farmers, could benefit tropical agricultural soils. Several years later, Chan et al. (2007) described charcoal as biochar, in the context of amending the soil. A fundamental discovery was that, although the biochar did not improve yield alone, it improved nitrogen fertilizer uptake. It also improved soil physical properties, such as cation exchange capacity and organic carbon content. In subsequent years, biochar as a soil amendment has become an increasingly popular area of research. A Web of Science search, containing ‘biochar’ in the title and ‘soil* OR amend*’ in the abstract, renders approximately 6,000 results. More than half these are from 2019, 2020, and 2021.

### CROP PRODUCTIVITY

The influx of biochar research reveals how difficult it is to grasp whether, how, and under what conditions biochar may benefit crops. For example, pyrolysis temperature and feedstock type (e.g., hardwood or peanut shells) can impact the properties of the finished
product (e.g., cation exchange capacity or surface area) or the soil (e.g., beneficial microbiota or water retention) (Tomczyk et al. 2020). Nevertheless, a survey of meta-analyses shows that biochar can render benefits across many criteria, including productivity and yield, soil water, photosynthesis efficiency, soil organic carbon, and remediation of contaminated soils (Schmidt et al. 2021).

A baseline for generalized biochar information about plant productivity is a meta-analysis by Jeffery et al. (2011). The authors confine their discussion to studies comparing treatments with and without biochar. They only included quantitative results to track measurable data regarding the effect of biochar on control treatments. One problem, owing to the diversity of experimental conditions and relatively few studies, was the diversity of results. Nonetheless, biochar, modestly improved overall yield. This was particularly true for acidic soils (Chan et al. 2007), moderate or coarse-textured soils (Major et al. 2010), and some particularly ligneous materials (Yamato et al. 2006). While biochar did seem somewhat effective in tropical and subtropical latitudes, temperate studies were almost absent. The researchers recommended that future study conditions be reported rigorously to update subsequent meta-analyses accurately.

A later meta-analysis considered how well biochar yield results from the tropics and subtropics translate to yield results in temperate areas (Jeffery et al. 2017). While, on average, yield improved by 25% with biochar in the tropics, temperate zones did not show a significant effect. In the often weathered, acidic, and nutrient-poor tropical soils such as the Amazon Basin (Glaser and Birk 2012), biochar's liming and anti-leaching aspects may be uniquely helpful. Jeffery et al. (2017) also distinguish between feedstock types, categorizing
them into “Nutrient” (e.g., manure) and “Structure” (e.g., wood chips). While in tropical zones, Structure improved yields by about 20% and Nutrient enhanced outcomes by 60-80%, neither improved temperate zone yields.

Related to the relative benefits of higher nutrient biochar (Jeffery et al. 2017), Ye et al. (2020) characterized the effect of combining biochar with different types of fertilizer on yield through meta-analysis. This analysis compared a series of factors for each of two general groups: 1) biochar and non-fertilized controls, and 2) biochar and fertilized controls (the same fertilizer treatment was applied to controls). In studies where a biochar soil amendment was used and compared to an unfertilized control, yields almost invariably improved, particularly in tropical and subtropical, sandy, and low pH soils (Ye et al., 2020). Where biochar was compared with fertilized controls, results were more variable. However, adding biochar to control treatments, with or without inorganic fertilizer, was beneficial in both instances. The same was true for biochar from cereal waste feedstocks; compared to fertilized and non-fertilized controls, it improved yield. In contrast, woody feedstocks were marginally beneficial against an unfertilized control and not effective against fertilized controls. An enlightening limitation was evident in the relationship between soil pH and pyrolysis temperature. Low pyrolysis temperature was associated with a higher yield, but many of these studies had soils with a low pH. A similar problem appeared with climate. Since studies in temperate zones generally used more ligneous biochar feedstock than tropical areas, it is difficult to compare the two based on region directly. The authors suggest that factors such as biochar characteristics and mode of fertilizer application are at least as relevant as climate.
They accordingly emphasize the usefulness of basing future comparisons on biochar feedstock and the delivery of nutrients.

**CO-COMPOSTED BIOCHAR**

Biochar literature often focuses exclusively on applying unmodified biochar to agricultural systems, with or without other amendments or fertilizers. On the other hand, co-composted biochar (COMBI) research, where biochar and compost feedstocks are combined before composting, has distinct characteristics (Wang et al. 2019). The concept behind COMBI is not new, appearing conceptually in centuries-old agricultural manuals advising farmers to combine organic waste and charcoal (Ogawa and Okimori 2010). Agricultural experts then recognized and disseminated the practical benefits of co-composting.

Despite the literature endorsing the potential benefit of COMBI for agroecosystems, there are limited original studies of its effect on crop productivity. In contrast with biochar alone (Jeffery et al. 2017), COMBI has a unique potential for improving crop productivity in temperate soils (Kammann et al. 2015). Yet, a recent meta-analysis found only eighteen COMBI publications (Wang et al. 2019). The authors acknowledged that the variation in many factors across studies (e.g., biochar and compost feedstock types, pyrolysis temperature and duration, plant type, COMBI application rate, soil type, and soil pH) makes general inferences unreliable. They did suggest, however, that the effects of COMBI and compost alone did not seem to differ much and that perhaps compost, instead of biochar, might explain yield differences.
ARBUSCULAR MYCORRHIZAL FUNGI
AND BIOCHAR

Before the conventional adoption of the term ‘biochar,’ many studies investigated the effect of charcoal on arbuscular mycorrhizal fungi (AMF) (Ishii and Kadoya 1994; Ogawa and Okimori 2010; Saito 1990). Comprising the phylum Glomeromycota, AMF naturally forms obligate mutualisms with most terrestrial plants (Smith and Read 2008; van der Heijden et al. 2016). To initiate symbiosis, plants exude chemicals to attract AMF symbionts, and viable fungal spores germinate and send filaments called hyphae in the direction of plants (Lanfranco 2018; Waters et al. 2017). The fungus penetrates the plant root tissue, forming branched nutrient exchange structures called arbuscules (Smith and Read 2008). Here, plants deliver photosynthetic sugars in exchange for essential nutrients such as phosphorus and nitrogen. A complex network of fungal hyphae, called mycelium, scavenge from places the plant roots cannot access (Wang et al. 2017). AMF associations are significant for plants under environmental stress, such as drought or nutrient deficiency, and plants tend to send biochemical signals to AMF in response to such pressures (Lanfranco 2018; Ruiz-Lozano et al. 2016). AMF colonization is often reduced when soil moisture (Augé et al. 2015) and phosphorus (Balzergue et al. 2013; Bonneau et al. 2013) are abundant.

As biochar research began to gain more widespread academic attention, Warnock et al. (2007) suggested several mechanisms by which biochar might promote AMF soil communities, including increased available nutrients, better conditions for AMF-supporting bacteria, improved plant-fungus communication, and protection from predators. One mechanism of increased nutrients could be pH modulation since the liming character of biochar can bring acidic soils closer to a pH value between 5.5 and 7.0, which is optimal for
plant-accessible nutrients (Warnock et al. 2007). Conversely, adding biochar to alkaline soils may not affect or even reduce AMF root colonization (Warnock 2010). However, some research in acidic soils has also found a reduction of AMF biomass in the soil (Birk et al. 2009). Another study observed, across 34 different types of biochar under various pyrolysis conditions, that biochar tended to increase AMF root colonization, contingent on P content in the biochar and the soil (Solaiman et al. 2019).

**PLFA analysis of the soil community**

There are many ways to study AMF in the agroecosystem, each with certain advantages. For example, the microscopic quantification of root arbuscules gives visual evidence of the amount of active AMF directly associated with plants (Giovanetti and Mosse 1980; McGonigle et al. 1990). Genetic sequencing, on the other hand, allows scientists to capture the diversity of **Glomeromycota** taxonomic units in a given rhizosphere (Öpik et al. 2014). Another tool, sometimes used in concert with microscopic (Sharma and Buyer 2015) or genetic (Malik et al. 2016) methods, can simultaneously estimate living AMF biomass and other major microbial groups. One such method is phospholipid fatty acid (PLFA) analysis, which quantifies living microbial biomass based on biochemical signatures, allowing researchers to capture a “fingerprint” of a living microbial community at a moment in time (Buyer and Sasser 2012; Quideau et al. 2016).

Phospholipids are the essential components of cellular membranes, some of which contain fatty acids corresponding to certain microbial groups and taxa (Buyer et al. 2010). For soil microbial communities, the process involves collecting soil samples, separating phospholipids from other fatty acids in solution, converting them into fatty acid methyl
esters, and analyzing these with gas chromatography to detect levels of different signatures corresponding to different microbial groups (Willers et al. 2015). Because the fatty acids quickly degrade after an organism dies, this method provides a snapshot of the living microbiota in the soil based on the panel of PLFA biomarkers (Zhang et al. 2019). Thus, PLFA data associated with certain groups, like gram-positive bacteria, gram-negative bacteria, or AMF, is a good indicator of living biomass.

Beyond estimating the biomass of different microorganisms based on PLFA signatures, knowing the relative proportion of certain broad microbial groups can provide ecological clues about environmental conditions (Willers et al. 2015). For example, two commonly used ratios to describe soil health are fungal/bacterial and gram+/gram- bacteria (Willers et al. 2015). For example, some describe the fungal/bacterial ratio to help compare till and no-till systems (Zhang et al. 2012), and others used the ratio of gram+/gram- bacteria to compare organic with conventional farming systems (Romaniuk et al. 2011). Although PLFA analysis renders a relatively low taxonomic resolution compared to genetic methods, it is a valuable tool for broadly gauging the composition of living microbial groups in the soil (Buyer et al. 2010).
Objectives and research questions

This study explored whether co-composting 10% softwood biochar with green waste and manure would affect dry-farmed tomato productivity and soil microbial community composition. To quantify productivity, I measured plant height, fruit quantity, diameter, shoot mass, and fruit mass. I ordered a soil phospholipid fatty acid (PLFA) analysis to quantify whether COMBI would affect soil microbial community composition. Based on the productivity results, I also determined whether the cost of adding biochar to produce COMBI was economically worthwhile. I integrated the study into a working commercial farm to match actual production settings. The results of this study are intended to inform future farming practices at the study site.

To address the objectives, I tested whether supplanting compost-only (Compost) with co-composted biochar (COMBI) affects the following:

RQ1 Dry-farmed tomato productivity, as measured by:

RQ1_A: Early-season plant height
RQ1_B: Early-season per-plant fruit quantity
RQ1_C: Early-season fruit diameter
RQ1_D: Mid-season fruit mass
RQ1_E: Mid-season shoot mass

RQ2 Microbial community structure, as measured by:

RQ2_A: Total PLFA biomass
RQ2_B: AMF PLFA biomass
RQ2_C: The ratio of fungi to bacteria
RQ2₀: The ratio of gram-positive to gram-negative bacteria

RQ2₁: The ratio of protozoa to bacteria

RQ2₂: The ratio of saturated to unsaturated fatty acids

RQ2₃: The ratio of monounsaturated to polyunsaturated fatty acids

RQ3 Net financial return on crop investment
Introduction

California is amidst a multi-year drought with no foreseeable end (Esquivel and Sobeck 2022). Because California is the top source of agricultural support for the United States (Cooley et al. 2015), there is a need to innovate locally-effective solutions. Increasingly severe water restrictions (Langridge and Schmidt 2020), a looming threat of saltwater intrusion into aquifers (Goebel et al. 2019), and the prospect of increased temperatures jeopardizing specialty produce (Kerr et al. 2018) are only a few related obstacles. The Cooperative Extension Service, designed to communicate agricultural research outcomes and technologies into rural areas, has heavily influenced the transfer of agricultural information for more than a century (Prokopy et al. 2015). While this model has many tangible benefits, it is inadequate for addressing many nuanced local concerns (Lacoste et al. 2022). Farming is an iterative process, and those who farm for decades often conduct informal experiments of their own, driven by contextual challenges. On-Farm Experimentation (OFE) challenges the traditional Cooperative Extension Service model by establishing practically-gained farmer knowledge as the basis of research that addresses relevant questions to farmers in a way that adapts to their farming practices (Lacoste et al. 2022).

One practice heavily dependent on local variables is dry farming, whereby growers in semi-arid climates strategically trap off-season moisture in the soil for crops to access during the dry growing season without irrigation (Garrett 2019; Granatstein 1992; Leap et al. 2017). Staple crops such as dry-farmed cereals have motivated agricultural research at experimental stations since the inception of the Cooperative Extension Service (Campbell 1909; McOmie
et al. 1918; Widtsoe 1911). Yet, dry-farmed vegetable crop research is practically absent from the literature.

Dry-farmed tomatoes are an established commercial crop in some areas of the West Coast of the United States (Garrett 2019; Leap et al. 2017; Parks et al. 2021). Yet, publications supporting the optimization and adaptability of dry farm methods are lacking. This is likely partly because the techniques are mostly an accumulation of farmer-to-farmer transmission over the years (Parks et al. 2021). However, for a substantial shift toward climate resiliency (Morris and Bucini 2016), it is incumbent upon researchers to partner with farmers to study the effects, ecology, and underlying mechanisms of dry farming vegetables (Parks et al. 2021). California is the biggest producer of U.S. tomatoes (*Solanum lycopersicum*) by a large margin (Cooley et al. 2015), and tomatoes are particularly well-suited for dry farming in California (Leap et al. 2017; Rabkin 2010; Reti 2010). Given the agricultural prominence of tomatoes amidst tightened groundwater restrictions (Esquivel and Sobeck 2022), the dry-farmed tomato market thus deserves rigorous academic attention.

An important starting point for improving dry-farmed tomato strategies is soil amendment practices, particularly for organic systems (Scotti et al. 2015). Compost is central to organic agriculture, providing slow-release fertility, improving soil structure, and encouraging healthy soil biology (Diacono and Montemurro 2011). Composts co-aged with biochar (COMBI) may boost crop productivity, soil fertility, moisture retention, and soil microbiota, particularly arbuscular mycorrhizal fungi (AMF), under the right conditions (Kammann et al. 2015; Ogawa and Okimori 2010; Wang et al. 2019). Yet, no one, to the best of my knowledge, has explored whether COMBI can make a difference for dry-farmed crops.
I conducted an OFE, under the guidance of an organic farmer, to address three questions – whether switching from compost to COMBI improves dry-farmed tomato productivity, whether it affects the soil microbial community, and whether it would be financially worthwhile for the farm to make the change. Aside from some farmer-approved modifications to ensure a robust study design, normal operations proceeded as usual.
Materials and methods

Study site

The trial occurred at Martial Cottle Park (MCP), in the South San José region of California’s Santa Clara Valley, at 37°15'48.1"N 121°50'26.4"W. Now better known as Silicon Valley, Santa Clara Valley was the once epicenter of fruit production in the United States (Grossinger et al. 2007; Matthews 1999). However, urban sprawl led to the disappearance of vast expanses of orchards and farmland (Matthews 1999). The 287-acre (116 ha) MCP is a rare exception, rendering the park in stark relief from the surrounding urban development (Fig. 1). Walter Cottle Lester was the last property owner, which his family held from 1854 to 2003. Lester donated 120 acres (48.6 ha) to Santa Clara County, sold 136.5 acres (55.4 ha) to the State of California, and left a small remainder under private ownership (Design, Community, and Environment 2010). After Lester died in 2014, The County of Santa Clara and The State of California opened MCP to the public. It now offers its local community a wide range of educational, volunteer, and recreational benefits. The lessee on most of the land is Jacobs Farm / Del Cabo Inc. (JFDC), an organic producer whose co-founders began dry-farming vegetable crops in the 1980s (Reti 2010).
Between 2006 and 2020, MCP has received approximately 11.9 inches (30.2 cm) of precipitation annually. It has a Mediterranean climate, characterized by cool wet winters and hot dry summers. The hottest month of summer is July, with an average high temperature of 81.5 °F (27.5 °C) (National Oceanic and Atmospheric Administration, 2023). The topography is flat, except for the Canoas Creek cement canal passing through the southwest region of the park. The channel constrains and directs seasonal precipitation that would historically form temporary marshes and wetlands on what is now the western side of the park (Design, Community, and Environment et al. 2009). This area has hydric clay soils.
(Beller et al. 2010), but all MCP soil types are classified as suitable for growing row crops (U.C. Davis et al. 2020).

Alluvial deposits, full of organic matter, accumulated in this valley basin, providing three distinct types of deep, fertile soil (Fig. 2). The eastern region is 90% Newpark silty clay loam, a moderately well-drained Mollisol well-suited for growing row crops (U.C. Davis et al. 2020). To the southwest, the composition is 90% Clear Lake silty clay, a particularly rich but hydric Vertisol, currently used for vegetable crops (G. Rawlings, personal communication; U.C. Davis et al. 2020). The central part of the park (northwest to south-central) is 90% Hangerone clay loam series, also a hydric soil from the seasonal wetlands (Beller et al. 2010). The area furthest to the northwest is moderately alkaline and historically prone to ponding (Beller et al. 2010). In January 2021, before the study began, a broad soil sample of the experimental area reflected a pH of 7.3 and 8.3% organic matter (Control Soil Lab 2021).
JFDC has commercially dry-farmed tomatoes at MCP for several years. The research plots I used for this work were distributed within a 4.3-acre (1.7 ha) parcel of farmland in the park's northwestern Hangerone clay loam region (Figure 2). The area had been in commercial vegetable and herb rotations for five years before this study (D. Rawlings, personal communication). The westernmost portion of the study area was fallow in 2019 and used to grow dill and cilantro in 2020. The easternmost part of the study area had a garlic crop in 2019 and was fallow in 2020.

**Study design**

This field study, spanning from January to September of 2021, contrasted the effects of two soil treatments on tomato plant productivity and microbial community composition (Fig. 3). Compost (n=14) was one treatment derived from green waste and cow manure as
feedstock. The other was COMBI (n=14), where the same feedstock was mixed with 10% biochar by mass at the beginning of the composting process. To assess tomato plant productivity, I measured pre-harvest plant height, fruit quantity per plant, and fruit diameter on July 5, 2021 and mid-season fruit and shoot mass on August 2 and 9, 2021. To document the effects of COMBI on soil microbial abundance and community structure, I obtained late-season rhizosphere soil samples, which I sent to a laboratory for PLFA analysis on September 6, 2021. In addition to raw peak fatty acid biomass data, the laboratory sent information about key proportions of soil microbiota that can indicate aspects of soil health (PLFA Sample Data Sheet). After sampling, I compared Compost and COMBI data in yield per acre to assess whether the biochar addition might have been financially worthwhile.

**FIG 3.** Study design. I collected samples to compare the effect of the experimental Compost treatment and COMBI treatment on pre-harvest productivity, mid-season productivity, and PLFA biomass.
Field layout

In January 2021, the JFDC field crew amended four alternating 95-ft-wide (~30 m) strips of soil east-west across the study plots, either with Compost or with COMBI (Fig. 4). In late April, they planted approximately 14,000 seedlings of Early Girl tomatoes in seven three-row planting blocks [80 in (~200 cm) x ~380 ft (~120 m); totaling 1.2 acres] that ran north-south, perpendicular to the amendment strips. The interplant distance was approximately 6 in (~15 cm), and trellis netting, held up by stakes spaced about 9 ft (~3 m) apart, supported the vines as they matured. The crew left approximately 60 ft (~18 m) of space between planting blocks, where they grew commercial spaghetti squash and left a path for harvest access. Each planting block contained four 27-ft (8.2 m) long sample plots to collect data, totaling 14 Compost and 14 COMBI sample plots. For sampling, I divided each

FIG 4. Depiction of the experimental layout. The background is a satellite image of the study site. Elements not to scale to present all relevant aspects.
plot into row segments, representing the three adjacent 27-foot lengths of tomato row in each plot. To reduce the risk of inaccuracy from edge effects, I did not collect samples from the planting block lengths' outer 18-36 ft (5.5-11m) depending on row length variability. I also reduced the chance of cross-contamination between treatments by leaving a buffer of 72 ft (22 m) between alternating treatments.

**Field preparation**

Pacific Biochar (Santa Rosa, CA) produced the biochar for the COMBI treatment, derived from softwood timber mill waste (Humboldt County, CA) and pyrolyzed at 700 °C for less than 10 minutes. Central Coast Compost (Gonzalez, CA) used green waste and cow manure for the Compost treatment and co-composted the same feedstock with 10% biochar, by initial mass, for COMBI. Both mixes were composted over approximately one month, then mixed with gypsum at 2.6-2.8 tons/acre. The finished product was delivered to MCP. Before field application, the JFDC crew mixed the amendments with True® dry pelleted organic fertilizer (12-3-0 x 0.3 tons/acre; 7.5-5-7.5 x 0.3 tons/acre).

On January 22, Central Coast Compost used a truck-mounted compost spreader to distribute each amendment at 8.4 (Compost) and 8.1 (COMBI) tons per acre. The slight difference in application rate resulted from practical limitations of existing mixing and spreading methods at MCP (G. Rawlings, personal communication). The crew disced the amendments into the soil's top 6-7 inches (~15-18 cm). There were no additional modifications for the remainder of the study. Despite an exceptionally dry 2021 water year, the following week was remarkably wet. Precipitation in the San Jose area was far below average at 5.32 inches (13.51 cm) from October 2020 through September 2021, but more
than half of that fell between January 22 and January 29 (NOAA). This was optimal timing; the soil was still workable while relatively dry, but immediate precipitation after application reduces the potential for wind erosion and helps with moisture capture. Following the April planting, the crew irrigated the transplants with overhead sprinklers. Then, when the fruits had begun to mature, they ceased irrigation on June 14.

**Sampling**

**PRE-HARVEST PRODUCTIVITY**

On July 5, 2021, I gathered early data for pre-harvest productivity nondestructively with the help of three field assistants. It had been approximately two months since transplanting the seedlings, three weeks since irrigation was cut off, and the fruits had begun to mature on the vine. To avoid inter-sampler bias, to determine which seven plots we would each sample, my assistants and I selected seven random numbers out of an opaque container corresponding to the 28 total sample plots and independent of amendment treatment. Samplers then used a random number generator smartphone application (Pretty Random, Steven Burnett, Version 4.2, Updated June 29, 2021) to select one of the three 27-foot (8.2 m) row segments in each sample plot. Samplers counted the number of plants in the row segment, randomly generating three sub-sample plants (84 in total) with the same software.

We measured the height of each sub-sample plant by following the distance from the plant base to the tallest leading shoot tip (Zhang et al. 2020) using a retractable vinyl tape measure. We measured the diameters of all fruits that appeared to be successfully pollinated, which I defined as those attached to the vine when we arrived and with a diameter of at least 0.5 in (1.3 cm). We took measurements by viewing each fruit from above where the pedicel
meets the fruit, with the tape measure extended parallel along the bottom of the fruit (perpendicular to the base of the tomato).

**MID-SEASON PRODUCTIVITY**

As part of normal commercial activity, JFDC workers collected a preliminary harvest of all tomato rows between July 17 and 19, 2021. I was then permitted to collect destructive plant and fruit samples on August 2, 2021. Two field assistants and I selected sample plots and three sub-sample plants from each plot using almost the same methodology I had at pre-harvest. An exception was that one sub-sample plant was selected per 27-ft (8.2 m) row segment rather than three from one randomly selected row segment. We removed and bagged aboveground plant biomass, fruits and shoots from each selected plant, for sample collection to weigh offsite. We cut each plant at the base and carefully separated it from neighboring vines. We collected tomatoes if they were either still attached to the vine or witnessed falling from the vine as it was removed. We placed shoots and fruits into identical paper grocery bags, labeling bags based on the sample plot and row segment the plant came from, and I obtained the fresh weight of all material within 48 hours of collection.

On August 9, 2021, I collected destructive biomass samples from all sample plots without the help of field assistants, using the same sub-sample selection and data collection methods as for August 2, again obtaining fresh fruit weights within 48 hours of harvest. However, I dried the shoots for shoot mass to get dry weights. Access to drying facilities was limited due to COVID-19 closures, so the process took about three weeks. I first staged the 84 bags in a greenhouse by rolling them up to efficiently use space. I then placed batches of approximately eight bags at a time in an oven for 24 hours at 221°F (105 °C). To avoid loss
of fragile plant biomass, I weighed the shoots while they were still in the bag (I had employed identical new mass-produced paper bags to ensure that variation in bag mass would be negligible).

**MICROBIAL BIOMASS AND COMMUNITY STRUCTURE**

I gathered microbial community structure data from a phospholipid fatty acid (PLFA) analysis (Buyer and Sasser 2012). This method captures a “fingerprint” of the soil microbial community based on signature biomarkers corresponding to different microbial groups. Since these fatty acids degrade quickly after an organism dies, PLFA analysis is a reliable proxy for living organisms (Zhang et al. 2019). PLFA analysis requires a costly multi-day process to extract fatty acids from fewer than 100 samples in solution at a time, followed by gas chromatography to detect and quantify biochemical peaks corresponding to microbial groups (Quideau et al. 2016). Given the complicated and costly methods, I sent the soil samples to a laboratory specializing in PLFA analysis [MIDI Labs (Newark, DE)]. Coding the samples and sending them to a third party also helped mitigate observer bias.

On September 6, 2021, approximately four months after transplant and 12 weeks after discontinuing irrigation, I collected 28 soil samples for PLFA from beneath three randomly selected sub-sample plants in the middle row segment of each sample plot, using an auger made from a 1.25-inch (3.17 cm) diameter PVC tube tapered at the end. Approximately 4 inches (~10 cm) from each plant base, I pulled away a couple of inches of mounded dust mulch and pounded the auger in with a rubber mallet to a depth of 6 inches (~15 cm). I angled the probe, carefully lifted it, and deposited the contents into a plastic freezer bag with the soil sub-samples from the other two plants in the sample plot. I nested this bag in another
(labeled) plastic freezer bag, then placed it into a portable cooler of dry ice. The same day, I sieved the 10 g of soil (Microbial ID, Domestic Soil Packaging and Shipping Instructions, June 2, 2021) from each sample into a tared plastic container on a digital kitchen scale. I emptied each batch into a new bag, which I rolled up and placed in another labeled freezer bag. After collecting the samples, I sent the 28 packs in a well-insulated box with fresh dry ice via two-day shipping to MIDI Labs for PLFA analysis. After following the protocols detailed in Buyer and Sasser (2012) to extract PLFA and quantify biomass, MIDI Labs provided a digital spreadsheet with raw PLFA data for each sample, including the total biomass of 43 peak fatty acid biomarkers representing the microbial community (including AMF); percentages of fatty acid biomarkers that coming from broad microbial groups; and ratios of certain broad microbial groups fatty acids, with general interpretive guidelines about soil health (PLFA Report 2021).

**COMBI COST VERSUS BENEFIT**

Based on the soil amendment market costs (US$ 2021) and the average value of tomato sales (US$ 2021) between the August 2 and 9 mean fruit mass data, I estimated net revenue differences between COMBI and Compost for dry-farmed tomato production at MCP. I estimated tomato sales by multiplying the number of plants per acre, mean fruit mass per plant (ounces), and price per ounce to determine revenue per acre. Price per ounce was determined based on Central California USDA shipping point price records from August 9, 2021. No organic tomato data was available, so I used the lowest price for conventionally grown 25-lb boxes of loose tomatoes to make a conservative estimate (USDA Agricultural Marketing Service, August 9, 2021). Since replacing some of the compost feedstock with
biochar was more expensive, I calculated the cost per acre of COMBI based on the relative proportions of biochar (10%) and compost feedstock (90%). I factored in the application rates to obtain a cost per acre of the soil amendment. I subtracted the differences in revenue between treatments from the differences in amendment cost for a net revenue difference.

Data analysis

For all plant productivity parameters, I averaged data across the three plant subsamples in each sample plot, resulting in 14 samples for each treatment. PLFA data had the same number of samples since I combined the three soil subsamples from each sample plot in the field. Every statistical test [IBM SPSS (Version 28)] compared two independent treatment variables – COMBI and Compost. I first analyzed normality for inferential tests, evaluating plant height, fruit quantity, fruit diameter, fruit biomass, shoot biomass, and PLFA biomass data using the Shapiro-Wilk and Kolmogorov-Smirnov tests.

I used an unpaired t-test to determine whether pre-harvest plant height, fruit quantity or diameter, or mid-season fresh (August 2) or dry (August 9) shoot weight differed across treatments (Fig. 5). Since I collected fruit yield data in the same way on August 2 and August 9, I used a repeated measures ANOVA to compare mean fruit mass between the two treatments, looking at change over time, the interaction of time and treatment, and the effect of treatment on fruit mass. To broadly compare PLFA biomass values to characterize soil microbial community composition, I used an unpaired t-test for total biomass, AMF biomass, fungi/bacteria, protozoa/bacteria, gram+/gram-, saturated/unsaturated fatty acids, and monounsaturated/polyunsaturated fatty acids. Differences in significant PLFA data, such as fungi/bacteria or gram+/gram- bacterial, would suggest some impact of co-composted
biochar on the soil microbial community (Romaniuk et al. 2011; Willers et al. 2015; Zhang et al. 2012). In contrast, a complete absence across all parameters would be a good indication of no effect. Moreover, if COMBI did affect tomato productivity without a microbial effect, this would suggest an alternate cause or causes for the difference.

**FIG 5.** Statistical tests used for each portion of the study.

The financial analysis drew from the August 2 and August 9 fruit data. However, although the repeated measures ANOVA results provided the context, the economic analysis relied on arithmetic calculations instead of inferential statistical tests. After the soil treatment costs had been subtracted from the fruit revenues, I compared the resulting net revenues to see whether the extra cost of biochar was financially worthwhile.
Results

Productivity

Across both treatments on July 5, plants had a mean height of 35.2 in (89.4 cm) and a mean of 10 fruits per plant, and the mean fruit diameter was 1.4 in (3.6 cm). The mean fresh fruit weight per plant on August 2 was 24.5 oz (694.2 g) and on August 9 was 19.6 oz (556.8 g), and the mean fresh shoot weight from August 2 was 10.9 oz (308.8 g). Overall mean dry shoot weight from August 9 was 2.6 oz (72.5 g).

On July 5, productivity did not differ between Compost and COMBI treatments. Mean plant heights did not differ detectably, $t(26) = 0.20, P = 0.84$, and not only did the mean fruit diameters not differ statistically, $t(26) = 0.19, P = 0.90$, but the total number of tomatoes observed from each treatment was exactly the same. Of the 42 plants sampled from each treatment, the total number of tomatoes counted in both Compost and COMBI treatments was 421, a mean of just over ten fruits per plant.

Across both mid-season sample dates, COMBI resulted in greater fruit yield than Compost, $F(1, 26) = 9.22, P = 0.005$, and mean fruit mass tended to decrease through time in both treatments, although not significantly, across the two mid-season dates, $F(1, 26) = 3.91, P = 0.06$; treatment x time $F(1, 26) = 0.10, P = 0.76$. (Fig. 6).
On August 2, fresh shoot weight was higher for the COMBI treatment $M = 12.7$ oz (360.0 g), $SD = 5.1$ oz (144.6 g) than the Compost, $M = 9.1$ oz (258.0 g), $SD = 5.6$ oz (158.8 g); $t(26) = 2.04, P = 0.05$ (Fig. 7), but dry weight of shoots collected on August 9 did not differ detectably between COMBI an Compost treatments $t(26) = 1.23, P = 0.23$. 

**FIG 6.** Mean fruit mass per tomato plant in COMBI and Compost sample plots across two dates.
Microbial biomass and community structure

Microbial community structure did not differ discernably between the COMBI and Compost-amended soils. In addition to having the same total PLFA biomass overall, $t(26) = 0.000$, $P = 0.84$, and AMF biomass, $t(26) = 0.140$, $P = 0.89$, no key ratios differed:
fungi/bacteria, $t(26) = 0.091$, $P = 0.96$; protozoa/bacteria $t(25) = 4.739$, $P = 0.18$; gram+/gram- bacteria, $t(26) = 1.085$, $P = 0.60$; saturated/unsaturated fatty acids, $t(26) = 1.131$, $P = 0.48$; and monounsaturated fatty acids to polyunsaturated fatty acids $t(26) = 2.988$, $P = 0.32$.

Financial analysis

The combined August 2 and August 9 mean fruit mass was 17.1 ounces per-plant for Compost, and 27.0 ounces per plant for COMBI, a 58% increase. According to 2021 US$ values, a conservative market price per ounce estimate from August 9 USDA shipping point
data is $0.013. There were approximately 7,000 plants across 0.64 acres for each treatment, equaling 10,938 plants per acre, so the total difference in revenue was $1,408. Biochar cost $270 per ton (2021 US$) and compost cost $50 per ton ($2021 US$). Thus, the 10% biochar COMBI cost approximately $72 per ton, approximately $22 more than biochar. Based on the prescribed application rates, COMBI cost $583 per acre, and compost cost $420 per acre, a difference of $163 per acre between treatments, making the net difference in revenue per acre between treatments $1,245 (Table 1).

Table 1. After factoring in soil amendment cost, the estimated net difference in revenue per acre from COMBI plots and Compost plots

<table>
<thead>
<tr>
<th></th>
<th>Compost</th>
<th>COMBI</th>
<th>Net</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean fruit mass (ounces / plant):</td>
<td>17.1</td>
<td>27.0</td>
<td>9.9</td>
</tr>
<tr>
<td>Fresh tomato value(^1) (US(^2) / ounce):</td>
<td>$0.013</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tomato (# plants / acre):</td>
<td></td>
<td></td>
<td>10,938</td>
</tr>
<tr>
<td><strong>Total difference in value COMBI vs compost (US(^3) / acre)</strong></td>
<td></td>
<td></td>
<td>$1,408</td>
</tr>
<tr>
<td>Amount of soil amendment applied (tons / acre):</td>
<td>8.4</td>
<td>8.1</td>
<td></td>
</tr>
<tr>
<td>Soil amendment cost (US(^3)) / ton:</td>
<td>($50.00)</td>
<td>($72.00)</td>
<td></td>
</tr>
<tr>
<td>Soil amendment cost (US(^3)) / acre:</td>
<td>($420.00)</td>
<td>($583.00)</td>
<td>($163)</td>
</tr>
<tr>
<td><strong>Net difference in revenue:</strong></td>
<td></td>
<td></td>
<td>$1,245</td>
</tr>
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Note: \(^1\)Market price on August 09, 2021. *USDA Agricultural Marketing Service*
Note: \(^2\)US$ 2021
Discussion

The first research question sought to determine whether adding biochar to compost feedstock would be better for tomato productivity, than compost without biochar. Earlier in the season (July 5), there was no evidence that COMBI and Compost treatments differed in productivity. However, the COMBI treatment yielded significantly more fruit by mass than Compost at mid-season (August 2 and August 9). An explanation for the delay in detectable effect may be that the COMBI was higher in N before application, that it better resisted leaching during early season precipitation and irrigation, or both. Since the field crew only added fertility once at the beginning of the season, finite N stocks may therefore have depleted more quickly under the Compost treatment. Nitrogen is an essential plant nutrient, and tomato yield is generally linked to amounts of soil N (Cheng et al. 2021). A meta-analysis by Zhou et al. (2022) shows that adding biochar to compost feedstock has consistently resulted in COMBI with higher nitrate levels than non-biochar compost. Others highlight how the composting process can oxidize biochar, allowing for the sorption of N and other essential nutrients, such as calcium, potassium, and magnesium (Osman et al. 2022). One study found that COMBI consistently increased potted *Chenopodium quinoa* biomass, whether it was compared against pure biochar, compost alone, or compost and pure biochar, at two different nitrogen fertilizer levels (Kammann et al. 2015). In the same study, leaf-tissue N positively increased with higher plant biomass, and the isolated co-composted biochar particles more effectively resisted N leaching than pure biochar particles.

In Research Question 2, I asked whether COMBI would have different microbial community structures in dry-farmed tomato soils, when compared with Compost. None of
the PLFA signatures measurably differed between the two treatments, including total PLFA, AMF, fungi/bacteria, protozoa/bacteria, gram+/gram- bacteria, or saturated/unsaturated and monounsaturated/polyunsaturated fatty acids. This raises a question as to why microbial community structure did not discernably differ, despite an increase in yield. First, timing may have been a factor. For example, PLFA results from a viticultural experiment comparing compost and COMBI showed a difference between bacterial PLFA in April and not in August (Mackie et al. 2015). Moreover, the relatively low taxonomic resolution of PLFA (Palansooriya et al. 2019) might render the test not sensitive enough. A study that quantified soil bacteria by genetically-sequenced operational taxonomic units (OTU), a higher resolution than PLFA signature groupings, revealed that COMBI-amended soil had higher OTU richness than compost, biochar, and control (Wu et al. 2016). The authors discuss that this richness may impact nutrient cycling. While broader measurements of bacterial biomass did not differ at MCP on September 6, 2021, more granular bacterial taxonomic distinctions might have.

Research Question 3 had the practical objective of estimating whether the cost of incorporating biochar into the composting process would be financially worth any possible added revenue. While COMBI was only marginally more expensive per acre than Compost, mid-season yields were approximately 58% higher. For approximately $163 more per acre (US$ 2021), the dry-farmed plants amended with COMBI generated an estimated $1,408 more in revenue than Compost. Moreover, the numbers used in the analysis to estimate the USDA shipping point market price were conservative because I used the lowest price from the conventionally-grown tomato range. Since JFDC sells only organic tomatoes, and organic
produce typically sells for higher prices than conventional produce, these crop yields would have fetched a higher price than estimated. Thus, the respective increase in revenue for organically-grown COMBI and Compost tomatoes would mean a higher cost-effectiveness for COMBI given the same price of amendments. Very few studies about biochar cost-effectiveness exist and none, to my knowledge, about COMBI exist. However, a multiyear study of biochar in U.S. corn fields determined that while biochar conferred certain public benefits, such as reduced nitrate leaching and CO₂ emissions, it was not financially worthwhile for farmers (Aller et al. 2018). This is unsurprising since plain biochar is not usually effective at improving yields in non-tropical climates (Jeffery et al. 2017). In contrast, incorporating biochar into the composting process has been shown to uniquely alter the end product's physical, chemical, and biological properties (Hagemann et al. 2017; Kammann et al. 2015; Zhou et al. 2022). Moreover, while Aller et al. (2018) cited a rate of 9.1 biochar tons per acre, the present study only required a fraction of this to be combined with organic waste before applying the composted product at 8.1 tons per acre. Thus, while biochar alone may have not been cost-effective for some farmers, COMBI merits its own consideration.

The 2021 MCP study, while demonstrating support for COMBI use in dry-farmed tomato systems, had some limitations. Since the study only occurred over one season, it remains to be seen whether repeated biochar application at the same site may have differing effects. Also, as mentioned previously, I was only able to collect microbial data at a single point in time, using the PLFA method. It may be beneficial to use multiple methods in future research (Malik et al. 2016; Sharma and Buyer 2015) at different points in the season (Mackie et al.
Since this study also may be the first to experiment with co-composted biochar in a dry-farmed system, there are many questions following from the results. Would the outcome be similar for other farms with different soil types, if the same soil amendment feedstocks and application rates are used? Or, how would different rates and feedstock types at the same site affect productivity? This is not to mention other factors like different crops, biochar pyrolysis temperature, or degrees of early season irrigation allowance. The multivalent nature of agriculture combined with a sheer lack of scientific research on the subject of dry farmed vegetables thus presents agricultural science with a sea of questions.

Dry farming is an intrinsically water-conserving approach worth investigating as one solution to the water crisis facing California. Despite the daunting task of coherently and usefully addressing many looming questions, there is a way forward. Meta-analysis is an indispensable tool for detecting patterns among many varied studies (Cheng et al. 2021; Jeffery et al. 2017; Wang et al. 2019; Zhou et al. 2022). In order to draw practical conclusions about dry farming in California more broadly, a high volume of on-farm studies under a variety of conditions is vital. To achieve this, it may be useful to have an interface between farmers, researchers, and the general public. There already is a model for driving and documenting dry farm participatory research in Oregon, called the Dry Farming Collaborative (Parks et al. 2021). A similar organization may be beneficial for fighting water shortages in California, particularly if OFE is emphasized (LaCoste et al. 2022). The On-Farm Experimentation at MCP closely tracked actual production conditions, because the study was integrated into existing farm operations. While this study may be one drop in the
drought resilience bucket, coordinated efforts to promote a culture of dry farming in California may help fill it.
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