CHARACTERIZING THE BENEFITS OF ALFALFA IN ROTATION & COMMUNICATING VALUE OF ENVIRONMENTAL SERVICES TO THE PUBLIC

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ABSTRACT

Alfalfa (Medicago sativa L.) has long been recognized as an important leguminous perennial rotation crop which improves soil 'tilth' and health. However, these benefits are often not well documented. Declining market value and competition with row crops in the Midwest US, and competition from high value crops in the West has contributed to declining alfalfa acreages in the US. A proper valuation of the effects of alfalfa in rotation could incentivize adding alfalfa back into crop rotation for its benefits on soil health, and benefits to subsequent crops. The benefits of alfalfa rotated with high value crops such as tomato have not been widely studied. In this research, we compared a three-year alfalfa crop rotated with tomato, and the effects on soil biological, chemical, and physical soil health indicators at the end of the alfalfa phase, compared to an annual corn "control" rotation. We measured the rotation effects on the following tomato crop under different N fertilizer regimes. Studies were conducted under irrigation at the UC Davis Russell Ranch facility in Davis, CA, a Mediterranean climate. With no N fertilizer applied, residual N following alfalfa increased tomato fruit yields by 17 tons/acre compared to tomato following corn, and were 85% of fruit yields following corn with 250 lb N/acre applied through drip irrigation. Fruit yields following alfalfa with no N fertilizer applied were equivalent to yields following corn with 170 lb. N/acre applied, indicating an N fertilizer credit of approximately 170 lb N/acre should be applied to tomato following alfalfa in rotation. Although the nitrogen remaining after alfalfa benefitted the following tomato crop significantly, replacing significant need for N fertilizer in tomato, alfalfa left little leachable nitrate in the soil at the end of the season, compared to corn (10 vs. 35 micrograms g-1 of soil, respectively). Lower nitrate leaching was observed under alfalfa compared to corn both with and without cover crops. However, the rotation benefit was not only due to N contribution, but likely due also to other soil properties. Soil microbiological biomarkers were nearly 50% greater, and mycorrhizal fungal numbers were 66% greater, at the end of three-year alfalfa compared to corn. In the following tomato crop, tomato yields were positively correlated with the previous year's microbial biomarkers following alfalfa but not corn. On the negative side, alfalfa tended to deplete soil cations, leaving low levels of potassium and calcium fertility for the following tomato crop. However, alfalfa greatly improved soil aggregation, an important indicator of soil structure and health, which was positively correlated with higher tomato yields. In summary, this study alfalfa

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greatly benefitted tomato yields in the subsequent crop, improved biological and physical soil health parameters compared with a corn rotation, and tended to prevent N leaching since most of the soil N was in the organic fraction. This study suggests that, without N fertilizers, yield increases in tomatoes rotated with alfalfa would be worth $1275 more per year, compared with rotation with corn. The economic benefit of alfalfa grown in rotations should not be underestimated.

INTRODUCTION

Alfalfa is the fourth most widely grown crop in the US, covering over 17 million cropland acres in 2017 (USDA-NASS, 2018). However, alfalfa acreages have been declining nationwide, as alfalfa is being replaced in rotation by commodity grains in the Midwestern U.S., and by annual vegetables (and tree crops) in California. For example, in 2018 in California, alfalfa acreages were the lowest in over 100 years (USDA-NASS 2019). Loss of acreage is due in part to stagnation of alfalfa yields in the U.S. in the past 20 to 30 years (USDA-NASS 2019), which has limited profitability of alfalfa.

To achieve yield gains, some have suggested improved optimization of cutting schedules and soil fertility management. However, it is clear that new management innovations are needed to drive alfalfa yield progress. In other crops, new innovations have come from a greater understanding of soil dynamics, including soil biology and nutrient cycling and rotational benefits. It's particularly important to consider crops as components of 'systems' which benefit the economics of the entire farm, in addition to the prevention of diseases and pests and the conservation and health of the soil. Alfalfa is known to form a large number of associations with soil microbes, including fungi, compared with other crops; however, knowledge of how to manage these associations, particularly mycorrhizal associations, has remained largely unexplored in alfalfa. Although there is considerable focus on soil health as a key element for sustaining our food production in the future, alfalfa has largely been omitted from that discussion. Could alfalfa, the third most important economic crop in the US have considerably greater scope for soil contributions than previously thought?

Research on plant-soil-microbe interactions in cropping systems has expanded greatly in the past few decades, and results from this research have helped catalyze the "soil health" movement. New rotations and management practices that enhance soil health are being promoted by food companies, state and federal agencies, and crop advisors to improve long-term agricultural yields and to mitigate yield and economic risks associated with changing climate. Consumers are interested in the 'sustainability' of their food supply, which includes environmental impacts. As a perennial crop, alfalfa has obvious benefits to soil health but this crop has not been the focus of many soil health studies. Quantifying the mechanisms and benefits of alfalfa on soil health indicators has the potential to expand alfalfa acreage nationwide, as growers and conservation groups consider alfalfa as a soil conservation crop.

CROP ROTATION EXPERIMENT

In the U.S., alfalfa is most commonly rotated with corn in the Midwest. In the western U.S., alfalfa is sometimes rotated with annual vegetable crops to break disease cycles, especially in processing tomato rotations; however, this practice has declined recently due to low alfalfa hay market prices compared to other crops. At the UC Davis Russell Ranch Sustainable Agriculture Facility, Davis, CA, which conducts a long-term cropping systems trial (now in its 29th year), a three-year alfalfa-tomato-corn-tomato rotation was added to the long-term systems in 2013 to elucidate the effects of a perennial legume in rotation with tomato on tomato productivity and soil health, compared to conventional tomato production (Figure 1) and other alternative management practices like compost application and cover cropping. Alfalfa was managed conventionally, cut for hay 5 to 6 times per year using common practices, and corn was harvested for grain. This study was conducted to examine the rotation effects and N credit of alfalfa as a rotational crop with corn, compared to an annual rotational crop (in this case corn), in a corn-tomato-corn-tomato rotation compared with an alfalfa-alfalfa-alfalfa-tomato rotation in the tomato rotation year four (Table 1). Corn is commonly rotated with tomato in California's Central Valley, where alfalfa is sometimes but not often rotated with tomato.

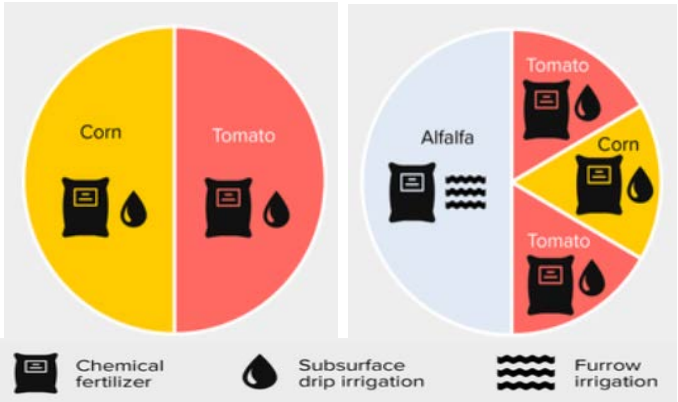

Figure 1. The conventional 2-year corn-tomato (left) and six-year alfalfa-tomato (right) rotations of the long term systems experiment at Russell Ranch. These treatments will continue to examine long-term impacts of crop rotation.

Table 1. Crop rotation treatments for the alfalfa rotation study conducted at Russell Ranch, UC Davis, 2016-2019. N-study on tomato and soil data was conducted in the last year of the 4-year crop rotation.

Crop Rotation	2016	2017	2018	Data Collection 2019
Corn-Tomato	Corn	Tomato	Corn	Tomato
Alfalfa-Tomato	Alfalfa	Alfalfa	Alfalfa	Tomato

YIELD BENEFITS AND ACCOUNTING FOR THE NITROGEN CREDIT

To account for the residual nitrogen effect on tomato yields, we undertook a nitrogen fertilizer response experiment in tomato following alfalfa or corn in the two cropping systems (Figure 1, Table 1). In the 2019 growing season, nitrogen fertilizer rates of 0, 90, 180, and 250 lb N/acre were applied to tomato via subsurface drip irrigation in fertigation throughout the season.

In the absence of N fertilization in tomato, the alfalfa rotation effect increased tomato yield by 17 tons/acre, 75% greater following alfalfa compared to following corn at zero N (Figure 2). Unfertilized tomato following alfalfa even rivaled well-fertilized tomato, yielding 85% of tomato rotated with corn and fertilized with 250 lb N/acre (Figure 2). These data indicated that residual nitrogen was benefiting the tomato crop and explains a considerable part of the yield benefit from rotating with alfalfa. Tomato yields rotated with corn achieved equivalence to unfertilized tomatoes following alfalfa only when 170 lb N/acre were added, indicating that alfalfa's N credit to the tomato to be approximately 170 lb/acre

However, there was also some response to nitrogen fertilizer in the alfalfa system. Tomato yields increased by 4 ton/acre for every 100 lb N/acre added, a rate half that of the yield response following corn, where yields increased by 9 ton/acre for every 100 lb N/acre added following corn (Figure 2).

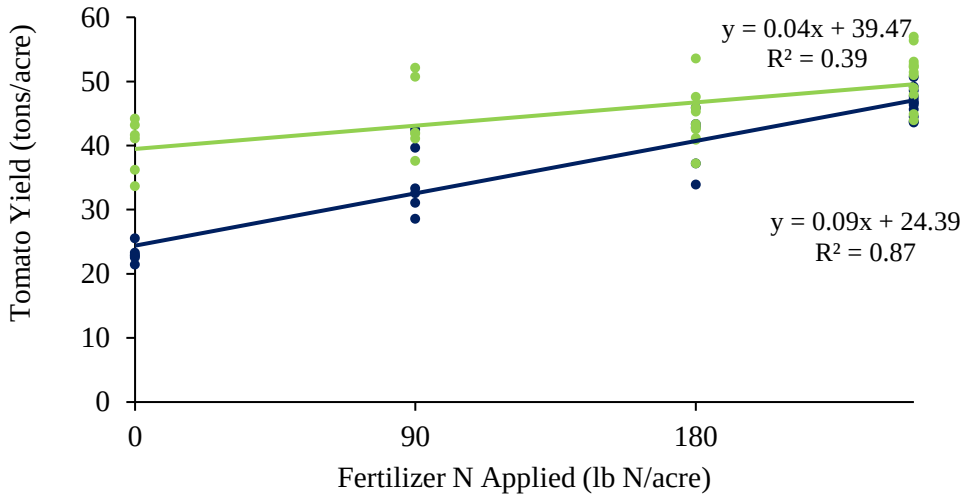

Figure 2. Tomato fruit yield response to synthetic nitrogen fertilizer following alfalfa (green line) compared to following corn (blue line) in 2019 at Russell Ranch near Davis, CA

Economics. The tomato yield boost following alfalfa represents a significant economic benefit to the economics of tomato production. In 2019, the value of the harvested tomato crop was approximately $75/ton of fruit (the price that year, California Tomato Growers Association). Thus, the 'rotational benefit' at zero N could be calculated as $1275/year, since an additional 17 tons/acre were achieved simply by rotation with alfalfa. This is one way of evaluating the economic benefit of crop rotation, but of course, farmers would rarely grow a high-value tomato crop in the complete absence of N fertilization. By rotating with alfalfa, and taking into account the savings of the 170 lb N/acre credit to their N fertilizer program, growers would gain an

additional $878, $497, and $326 in revenue at N fertilizer levels of 90, 180, and 250 lb N/acre, respectively (Figure 3).

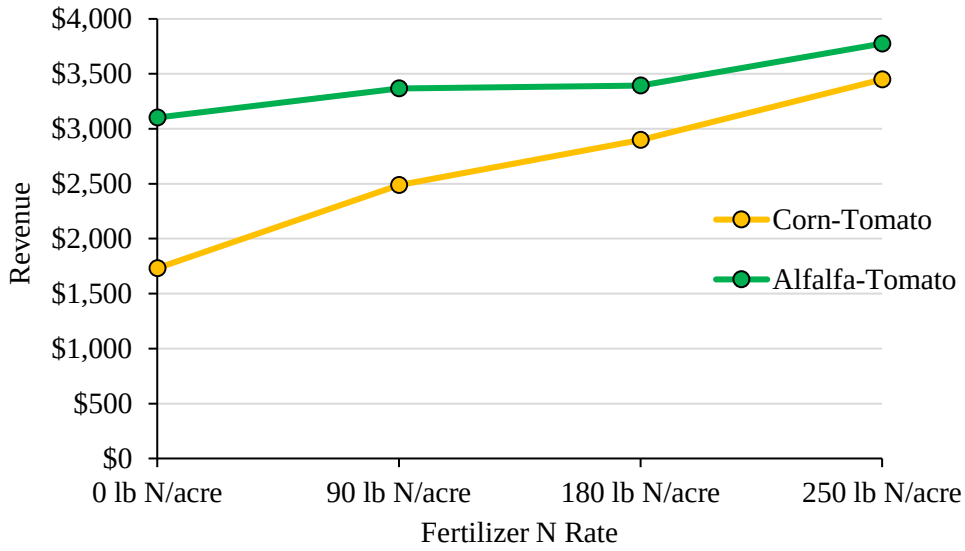

Figure 3. Revenues gained from tomato marketable fruit sales in 2019 following alfalfa and corn crops. Alfalfa system revenues also take into account savings from N fertilizer purchases by an N credit of 170 lb./acre. Assumed price of N fertilizer was $0.60 per unit N, and a tomato fruit price of $75/ton.

SOIL HEALTH INDICATORS AND NITRATE LEACHING FOLLOWING THE ROTATIONAL CROP

Alfalfa enhanced soil microbial biomarkers (a measurement of total microbial biomass) and the nitrogen uptake of the soil microbial pool (microbial N) after three years, compared to corn. Alfalfa fostered higher levels of mycorrhizal fungi in the soil, as mycorrhizal fungi biomarkers were 45% more abundant in alfalfa soils than corn soils (Table 2). Alfalfa likely associates with mycorrhizal fungi in their roots to a greater degree than corn.

Total dissolved nitrogen (representing a pool of potentially leachable nitrogen) in the soil solution was over 2 times greater following corn than following alfalfa (Table 2). Greater potentially leachable nitrate in the fall resulted in greater measured nitrate leaching losses over the winter (measured via ion-exchange resin bags buried at 75 cm in the soil following both alfalfa and corn). Nitrate leached with winter precipitation was lower following alfalfa compared to conventional corn, and was lower than any other conservation measure, including cover cropping and compost replacement of synthetic fertilizer (Figure 2).

Table 2. Microbial three-year alfalfa and corn at Russell Ranch.biomarkers measured with phospholipid fatty acid analysis, following

System	Total Microbial Biomass	Mycorrhizal Fungi Biomarkers	Microbial N	Total Dissolved Nitrogen
	µg/g soil	µg/g soil	µg/g soil	µg/g soil
Alfalfa-Tomato	43.3	1.6	5.0	9.4
Corn-Tomato	31.1	1.1	1.7	23.5

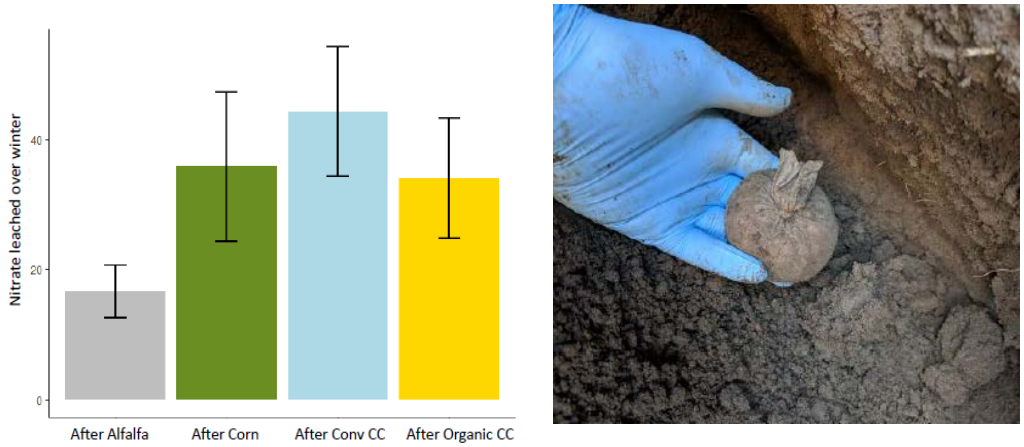

Figure 4. (Left) Nitrate leached over the winter season following three-year alfalfa, conventional corn, cover crops following conventional corn, and cover crops following organic corn with compost over the 2018-19 winter season at Russell Ranch. **(Right)** Ion-exchange resin bag being installed under the alfalfa soil profile.

ARE TOMATO YIELD EFFECTS RELATED TO SOIL HEALTH INDICATORS FROM THE PREVIOUS CROPPING YEAR?

While analysis of the 2019 tomato cropping year is ongoing, there is some evidence that tomato fruit yields were related to microbial community measures from the previous year's rotational crop. Tomato fruit yields in 2019 were 10% greater following alfalfa than corn, and were positively correlated with microbial biomass nitrogen and total microbial biomass measured at the end of the 2018 year following alfalfa and corn. Interestingly, tomato yields were *not* correlated with microbial measures from 2019, suggesting that a more causational relationship may have occurred, with the presence and/or functions of the microbial community in the previous year's rotation crop resulting in carryover conditions that benefited the tomato crop (rather than a correlation being present in 2019 resulting from favorable soil conditions for both microbes and the tomato crop. Soil structure (aggregation) was strongly positively correlated with tomato yields as well, *indicating that a significant benefit of alfalfa in rotations could be improvement of soil structure and tilth*. Improving soil structure in vegetable rotations could also benefit soil water holding capacity and infiltration, important soil health indicators for ensuring the sustainability of alfalfa production in the semiarid West.

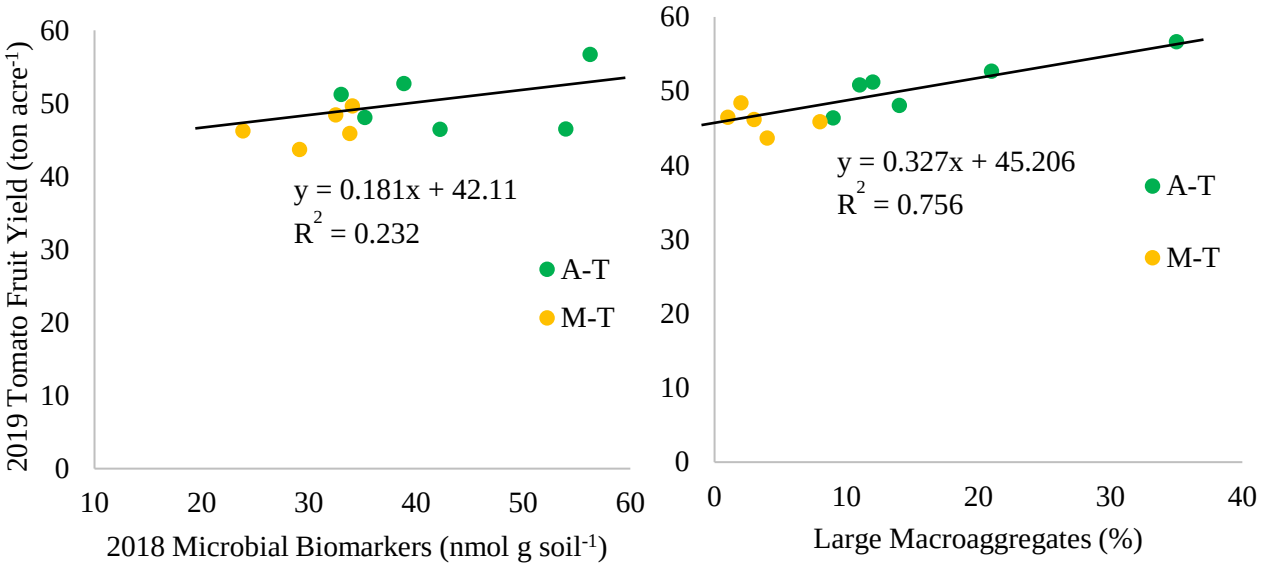

Figure 5. (Left) Linear regression of tomato marketable fruit yields harvested in 2019 vs. the microbial biomass levels measured at the end of the previous rotational crop (alfalfa, A-T; corn, M-T). **(Right)** Linear regression of tomato marketable fruit yields harvested in 2019 vs. the portion of macroaggregates on a w/w basis, measured at the end of the previous rotational crop.

CONCLUSIONS

Production of tomato following alfalfa produces significant benefit to tomato producers, due to yield improvements at all levels of N fertilization as well potential savings in fertilizer costs. This yield benefit is likely a function both residual N contributions from the alfalfa crop as well as improvement in soil properties. Nitrate leaching was also reduced in alfalfa rotations compared with conventional corn, but also compared with cover crops or organic corn systems.