Nutrient Cycling in Organic and Conventional Agricultural Systems with Winter Cover Crops

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ABSTRACT

Agricultural management practices influence nutrient cycling processes such as decomposition, N immobilization, and nutrient release. These are vital to soil quality and therefore agroecosystem productivity. The aim of this study was to investigate the impacts of different management practices combined with the use of winter cover crops (WCC) on soil quality variables in a Mediterranean environment. The soil sampling took place at Russell Ranch in Davis, CA, where 6 samples from an organic + wcc system and 6 from a conventional + wcc system were taken. The results show that soil dissolved nutrients C and N, pH, and moisture were all greater ($p<0.05$) in the organic + wcc system than the conventional + wcc system. Furthermore, the WCC root and shoot yields were both greater in the organic + wcc over the conventional + wcc system. This implies that the fertilizer regime of the organic system created healthier soil over time, and in combination with cover crops, increased nutrient cycling more than the conventional system. Research like this is useful when determining the sustainability of agriculture, and importantly, soil, for the future.

KEYWORDS

Microbial biomass, crop yields, long-term study, fertilizer regime, soil quality

INTRODUCTION

Agricultural land is under intense anthropogenic use today, which has increased detrimental effects on the environment. These include N runoff into water systems, drought stress from excessive water usage, soil erosion, and the greenhouse gas effect (Crews and Peoples 2004). The foundation of this land, and a key component to all of the above negative effects, is soil. Soil acts as a sink for C and N, sequestering these elements in the form of CO_2 or N_2O for a lengthy time period under favorable conditions (Lal 2004). In addition to sequestration, soil is responsible for nutrient cycling between different rounds of crops and the surrounding agroecosystem. Due to alterations by human impact, however, soils lose their ability to efficiently sequester or cycle nutrients through a system (Mazzoncini et al. 2011). This lessens soil's resilience against disturbance and worsens the effects of climate change, while also raising the question of how to ensure the sustainability of soil for the future of agriculture.

Extensive research shows that soil quality differs between organic and conventional agricultural systems. This is because the two systems are managed differently: organic agriculture is aimed at producing food with minimal harm to ecosystems, animals or humans and excludes use of artificial fertilizers, artificial pesticides and herbicides, and genetic engineering (Ponti et al. 2012, Seufert et al. 2012). Conventional agricultural, however, is any system in which chemical inputs are used (Ponti et al. 2012). It is clear from this literature that a key component of each management practice is the type of fertilizer used- mixtures of compost or manure in the organic compared to synthetic N fertilizer in the conventional (Fliebach et al. 2007). This in turn plays a large role in soil quality (Barthes et al. 2004, Pimentel et al. 2005).

One technique is already being implemented to try to improve soil quality, and therefore nutrient cycling in agricultural systems. The use of cover crops is shown to improve soil quality by creating positive feedback loops of crop residue decomposition and soil microbial activity (Barel et al. 2018). Multiple studies found that by improving soil organic matter, cover crops also have the ability to increase microbial C and N biomasses (Drury et al. 1991, Moore et al. 2000, Wells et al. 2000, Freibauer et al. 2004). Leguminous cover crops, in particular, benefit agroecosystems because they fix N and make it available for microbial and plant uptake. Most of the N produced below ground is removed during harvest, whether that be applied N from synthetic fertilizer in a conventional system or N produced by legumes through nitrogen fixation

(Peoples et al. 2009). Nodules on the roots of these legumes form symbiotic relationships with the bacteria of microbial communities surrounding them, and together they release N that becomes available for use (Kong and Six 2012). Soil quality consists of many intertwined factors besides microbial biomass C and N, and they may all present different relationships depending on the management practice and presence of cover crops.

Many agricultural studies focus solely on one or two variables of a system, so more research is needed to understand the effects of management practices on multiple factors of soil quality, such as microbial activity, dissolved nutrients, pH, and moisture. Recent studies show that management practices are strongly correlated with nutrient cycling, C and N inputs, and synthetic uses on microbial communities (Barel et al. 2018, Shennan 1992, Altieri 1999). Furthermore, Drinkwater et al. found that rapid nutrient cycling through soil organic matter creates healthier soil, which suggests that improving this process should be a priority in agricultural research (1998). Research clearly shows that soil quality is affected by management practice, but it is still unclear the extent to which this and cover crops together influence below-ground processes.

I aim to determine how to improve soil quality, and therefore nutrient cycling, in two different agricultural systems with winter cover crops: organic (organic + wcc) and conventional (conventional + wcc). I will evaluate this by answering the following sub-questions: (1) Do soil quality variables microbial biomass C (MBC) and N (MBN), dissolved organic C (DOC) and total dissolved N (TDN), pH, or moisture differ between management practice? (2) Does WCC root and shoot yield differ between management practice? Each sub-question will be answered through multiple tests to draw conclusions about soil quality and nutrient cycling.

METHODS

Study Site

The Century Experiment was established in 1993 to test the long-term impacts of wheat- and tomato-based cash crop rotations common to northern California. The experiment was previously known as the Long-Term Research on Agricultural Systems, (LTRAS). The site is located near Davis, CA (38 32 24″ N, 121 52 12″ W), with an elevation of 16m. The climate is semi-arid, Mediterranean, characterized by wet winters and hot, dry summers. Little or no gravel is present. The site has two soil types: (i) Yolo silt loam (fine-silty, mixed, nonacid, thermic Typic Xerothent) and (ii) Rincon silty clay loam (fine, smectitic, thermic Mollic Haploxeralf).

Researchers at UC Davis designed these systems to utilize various nutrient management and irrigation strategies along a gradient of management intensity and to evaluate outcomes on the basis of productivity, profitability, resource-use efficiency, environmental impacts, and ecosystem services. Both crop phases of each system are represented every year on three 0.4-ha (64 x 64 m) replicate plots in blocks laid out along the soil type gradient present on the site. Throughout the study they restricted discing operations to a depth of 15 to 20 cm and ploughing operation to a maximum depth of 25 cm.

Management practices

UC Davis researchers started tomatoes in a commercial greenhouse and transplanted into 150 cm beds. They then applied and incorporated a preplant herbicide in the conventional + wcc system where tomatoes were planted with 56 kg N ha^{-1} 8-24-6 starter fertilizer. They fertilized conventional tomatoes via sidedressing in one application, or two split applications, with ammonium sulfate to apply a total rate of 112 kg N ha^{-1}. In the organic + wcc system, researchers broadcast and incorporated composted poultry manure in March at an average rate of 4 t ha^{-1}, with tomatoes transplanted in early April. They did not apply herbicides in the organic rotation.

Researchers performed one cultivation between beds in the conventionally managed systems and performed three to four cultivations in the organically managed system, as needed, to control weeds. They mechanically harvested tomatoes in August and incorporated green fruits and vine residues by shallow discing after harvest.

Instead of a traditional winter fallow period following the harvest of the cash crops, researchers applied a WCC mix starting in November. From 1994 to 2001, the WCC mix consisted of field pea (*Pisum sativum* L.) and hairy vetch (*Vicia villosa* Roth). From 2002 through 2012, they replaced field pea with faba bean (*Vicia faba* L.) and added cereal oat (*Avena sativa*L.) to the mix. They terminated the WCC mix by mowing and then incorporated it with two to three discing operations in March.

For the next round in March, researchers applied a preplant herbicide and glyphosate to the conventional + wcc system prior to planting maize. In the organic + wcc system, researchers broadcast and incorporated composted poultry manure in March at an average rate of 4 t ha^{-1}. They planted maize in two rows per bed in both the conventional and organic + wcc systems in early April with 56 kg N ha^{-1} 8-24-6 starter fertilizer. They also fertilized conventional maize via sidedressing in one application, or two split applications, with ammonium sulfate to apply a total rate of 180 kg N ha^{-1}. Researchers performed one cultivation between beds in the conventionally managed systems and three to four cultivations in the organically managed system, as needed, to control weeds. A full-scale combine harvested maize in late September or early October and researchers chopped and diced stalks to incorporate residues. A WCC mix as previously described above followed in November on top of the beds. Researchers terminated them by two dicing operations in March.

Data Collection

Soil sampling

I sampled soil at a depth of 0-15cm from six organic + wcc plots and six conventional + wcc plots. Samples consisted of three subsamples from the west side and three subsamples from the east side of each plot. I bagged and froze all 12 samples at the Scow Soil Microbial Ecology Lab, UC Davis.

Soil quality variables

To determine how microbial communities from different management practices differ in C and N biomass, I performed two different procedures. Firstly, I did chloroform fumigation extractions for C by determining the total dissolved C in a TIC/TOC analyzer (Joergensen et al. n.d.). The difference between C in the fumigated and non-fumigated samples is the chloroform-labile C pool, and is proportional to MBC. Next, I followed the Kjeldahl method for N, in which I determined total dissolved N by digesting 20 ml of extract using Kjeldahl digestion and running the digest in the analyzer for total N ("Kjeldahl method for nitrogen determination." n.d.). The difference between N in the fumigated and non-fumigated samples is the chloroform-labile N pool, and is proportional to MBN. In addition to the MBC and MBN, I acquired dissolved organic C (DOC), total dissolved N (TDN), pH, and gravimetric water content at this time.

Winter cover crop yields

I will use the previously recorded yields of each system for both WCC roots and shoots. These are the harvests of the WCC in March, prior to cash crop planting, that were collected by UCD and Russell Ranch researchers.

Data analysis

I will perform various statistical tests in R to test the hypotheses comprising my sub-questions (R Studio 2009). To determine if nutrient levels (C and N) in soil microbial communities differ between management practices, I will perform paired t-tests and correlation analysis. For water content and pH, I will also perform paired t-tests and correlations. Likewise, to determine if WCC yields differ between management practices, I will perform paired t-tests and correlation analysis.

RESULTS

Soil quality variables

Neither MBC nor MBN significantly differed between the organic + wcc and conventional + wcc systems (Table 1). The DOC was greater in the organic + wcc system ($P=0.045$), as was the TDN ($P=0.029$). Furthermore, my analysis yielded multiple strong correlations between MBC, MBN, DOC, TDN, pH, and water content (Figures 3-6). MBC and TDN were positively correlated ($P=0.0112$), whereas the MBC and DOC ($P=0.0264$) differed between positive and negative associations between both systems. In addition, TDN and DOC were positively correlated ($P=0.0002$), and finally water content and pH ($P=0.0073$).

Table 1. T-test Results for Microbial Biomass, Soil Quality Variables, and WCC Yields. I determined which system had greater levels of each variable by performing paired t-tests.

	CONVENTIONAL + WCC	ORGANIC + WCC	
Variable	**Value**	**Value**	**p-value**
Microbial Biomass C (ug/g)	133.207	169.423	0.07
Microbial Biomass N (ug/g)	12.783	14.233	0.30
Dissolved organic C (ug/g)	51.885	103.312	0.045*
Total dissolved N (ug/g)	30.117	48.877	0.029*
pH	6.96	7.273	0.097
Moisture (%)	12.187	14.048	0.4356
WCC root yield (kg/ha)	2177.142	5738.781	0.03388*
WCC shoot yield (kg/ha)	1284.435	1706.607	0.0008**

*Denotes significance (p<0.05)

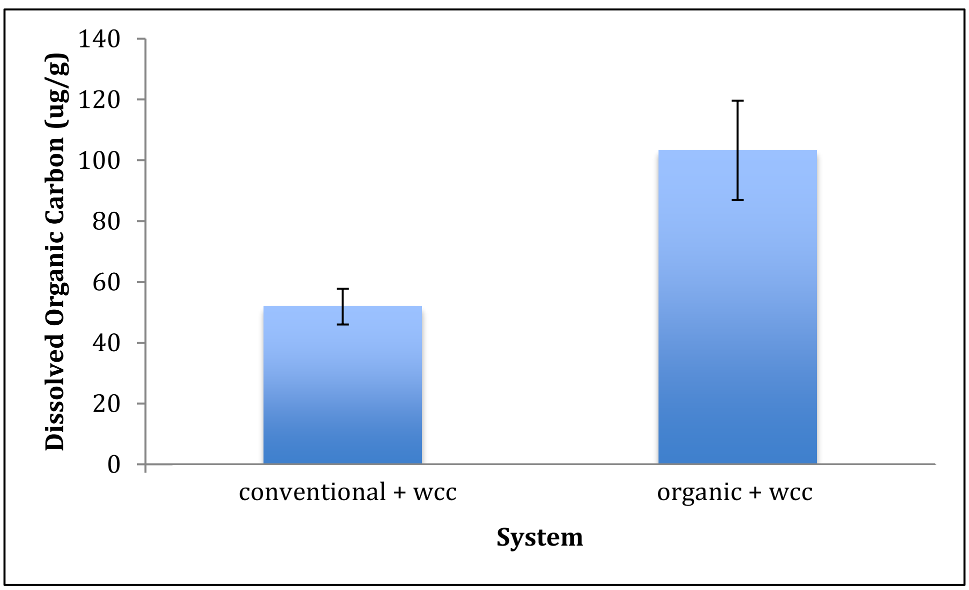

Figure 1. Dissolved organic C against management practice. DOC is greater in organic + wcc system (P=0.045).

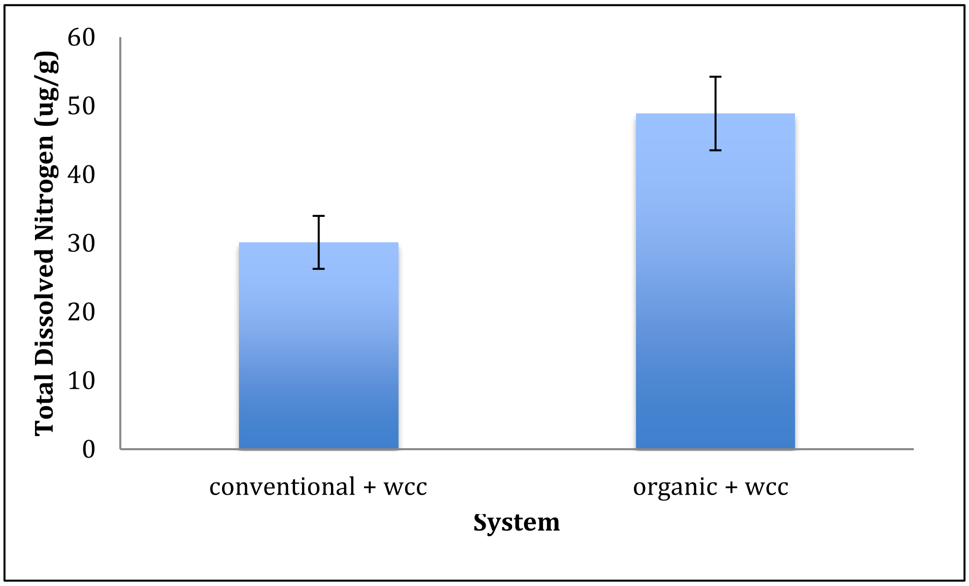

Figure 2. Total dissolved N against management practice. TDN is greater in organic + wcc system (P=0.029).

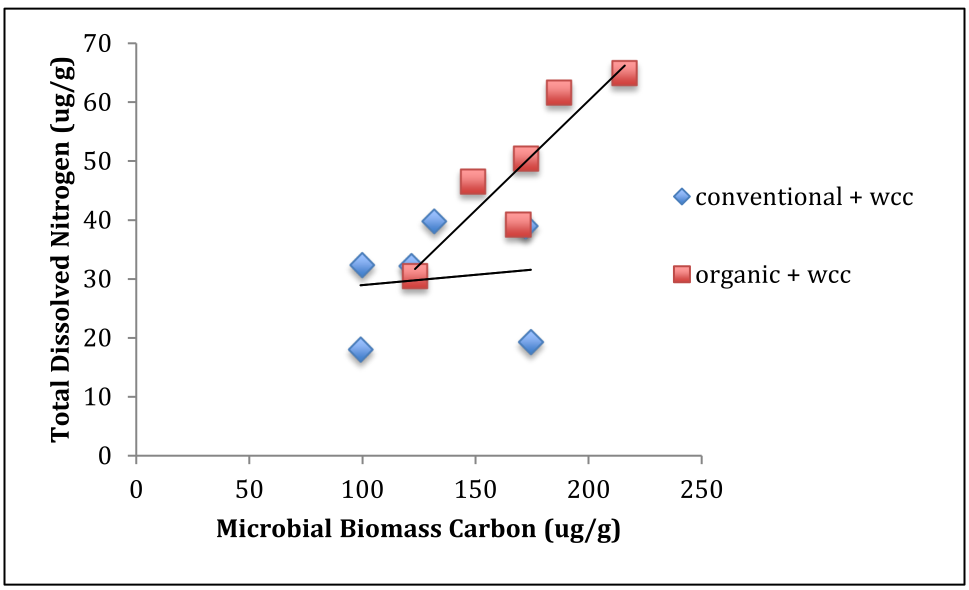

Figure 3. Total dissolved N correlation with microbial biomass C. Across both systems MBC and TDN are related (P=0.0112). There is a stronger positive relationship between the two variables in the organic + wcc system ($R^2 = 0.81307$) compared to the conventional + wcc system ($R^2 = 0.01538$).

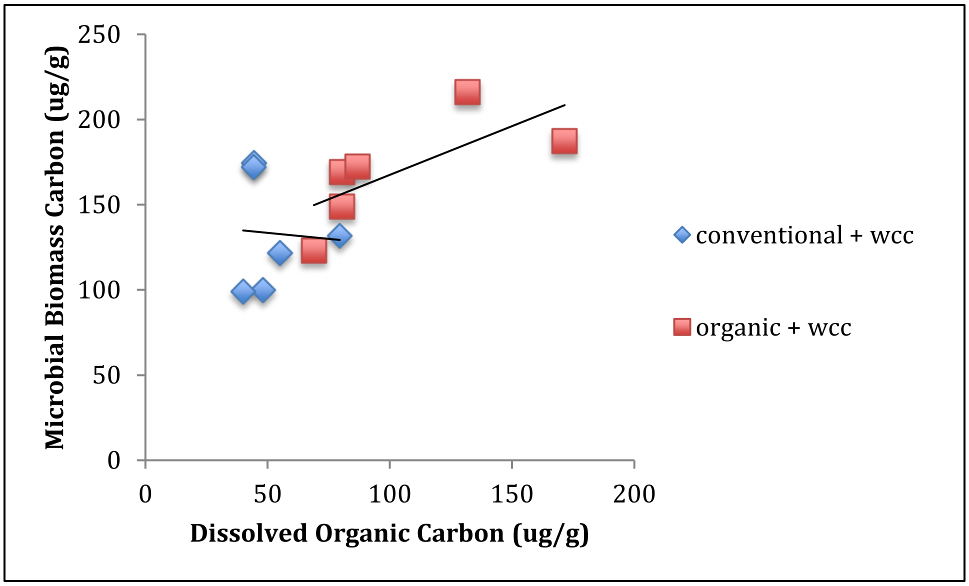

Figure 4. Microbial biomass C correlation with dissolved organic C. Across both systems there is a relationship between the two variables (P=0.0264). In the conventional + wcc system, there is a negative correlation (R^2 = 0.00369), whereas the organic + wcc system demonstrates a stronger, more positive relationship (R^2 = 0.51649).

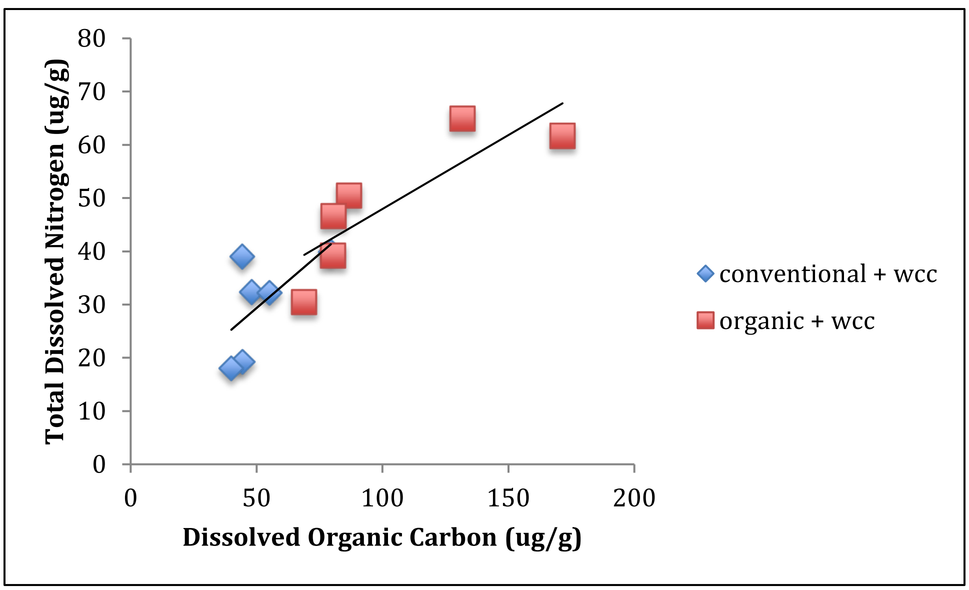

Figure 5. Total dissolved N correlation with dissolved organic C. Across both systems there is a relationship between the two variables (P= 0.0002). In the conventional + wcc system, there is a weak positive relationship (R^2= 0.38536), whereas the organic + wcc system shows a strong positive relationship between the variables (R^2= 0.71323).

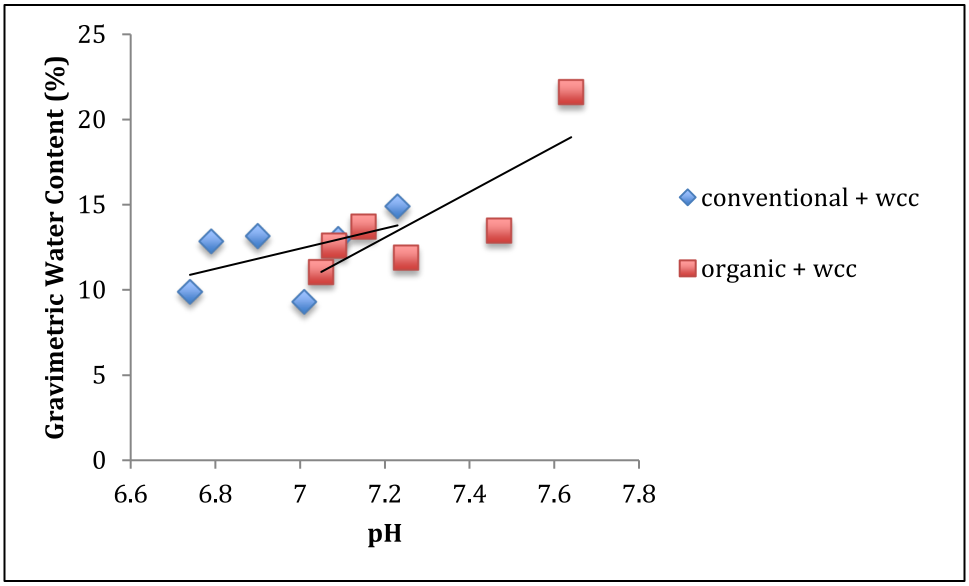

Figure 6. Water content correlation with pH. Across both systems there is a relationship between the two variables (P=0.0073). The conventional + wcc system shows a weak positive relationship (R^2 = 0.26545), and the organic + wcc system shows a strong positive relationship between the variables (R^2 = 0.67704).

Winter cover crop yields

The WCC yields demonstrate a clear favorability of one management practice over the other. The WCC shoot yield was significantly greater in the organic + wcc system (P=0.0008), and the WCC root yield was also greater in this system (P=0.03388, Fig. 7-8).

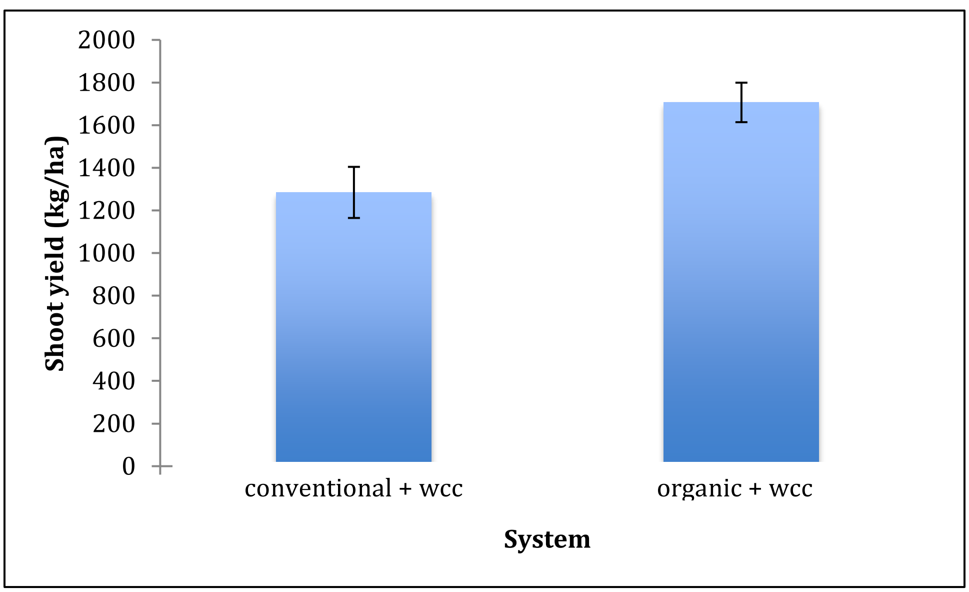

Figure 7. WCC shoot yield against management practice. The organic + wcc system yielded a significantly greater yield of shoots than the conventional + wcc system (P=0.0008).

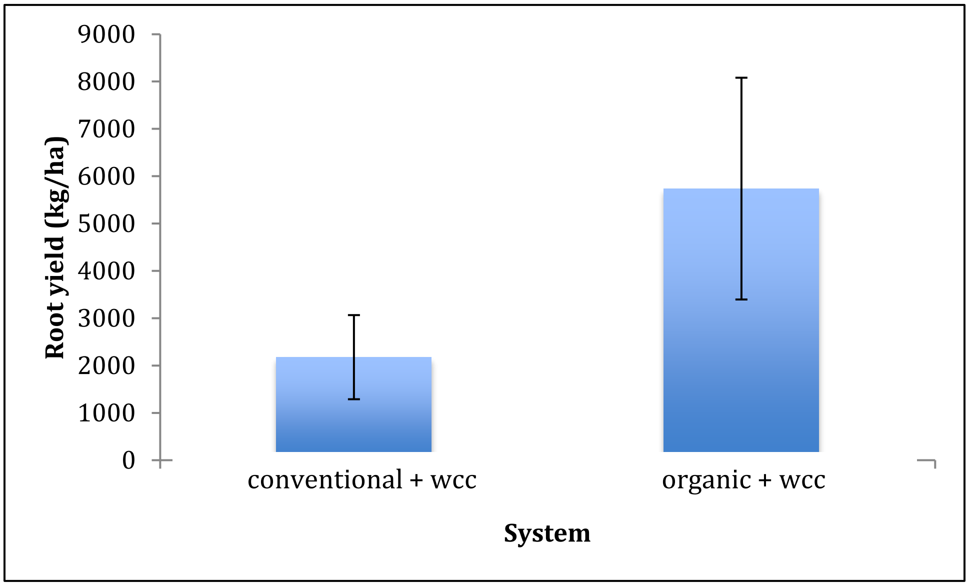

Figure 8. WCC root yield against management practice. The organic + wcc system yielded a significantly greater yield of roots than the conventional + wcc system (P=0.03388).

Soil quality variables and WCC yields together

The MBN and WCC root yield showed a positive correlation (P=0.0243) across both systems (Fig. 9). pH and WCC shoot yield were also correlated (P=0.0094), with the organic + wcc system directed towards a neutral pH and the conventional + wcc system more acidic (Fig. 10). Finally, the water content and WCC root yield are correlated (P=0.0013, Fig. 11).

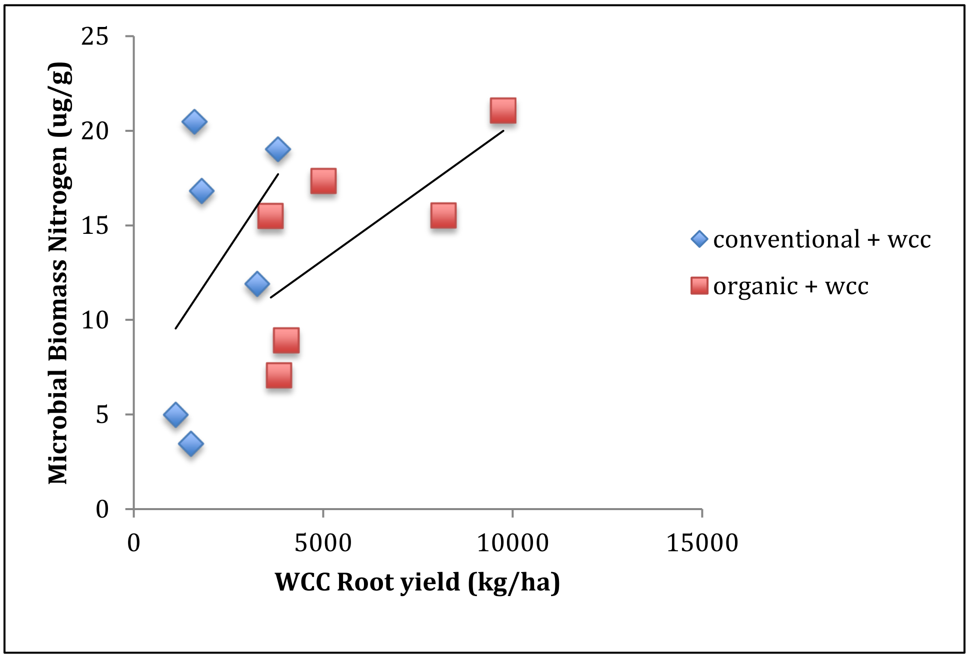

Figure 9. Microbial Biomass N correlation with WCC root yield. Across both systems there is a relationship between the two variables (P=0.0243). In the conventional + wcc system, there is a weaker positive relationship between the variables ($R^2 = 0.2045$) than the organic + wcc system ($R^2 = 0.49804$).

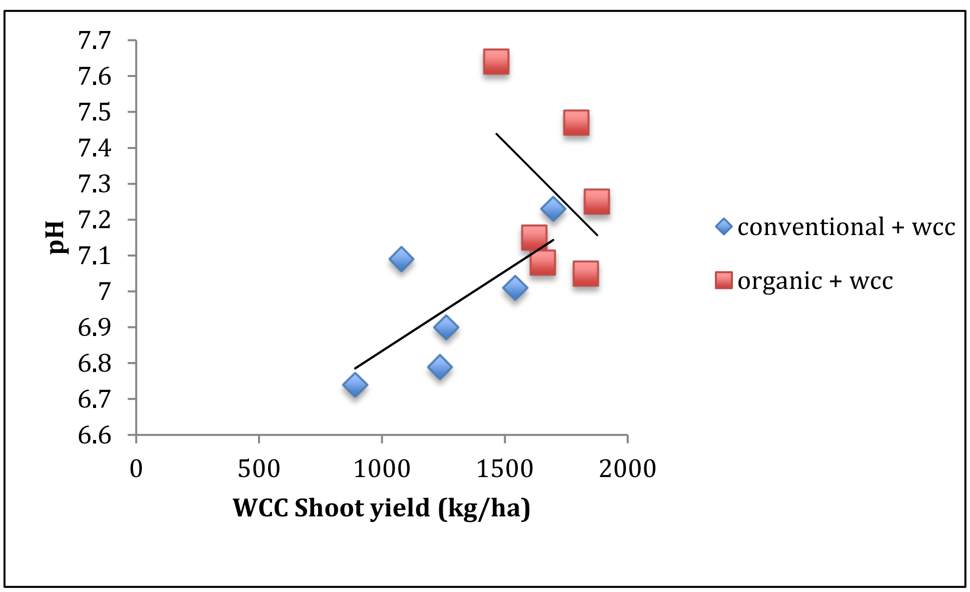

Figure 10. pH correlation with WCC shoot yield. The conventional + wcc system demonstrates a positive relationship ($R^2 = 0.49688$), with more acidic pH, and the organic + wcc system shows a strong negative relationship ($R^2 = 0.2048$) with a more neutral pH.

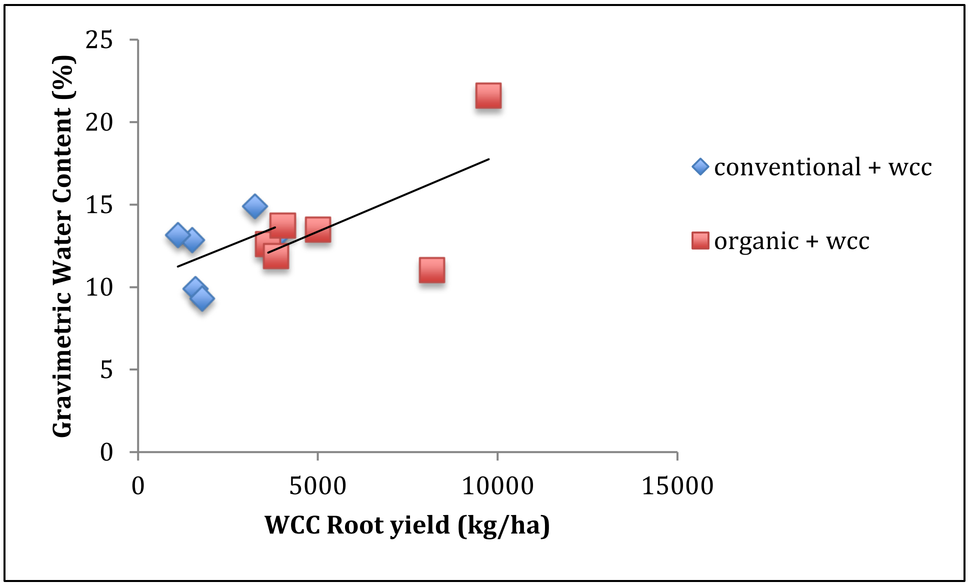

Figure 11. Water content correlation with WCC root yield. Across both systems there is a relationship between the two variables (P=0.0094). In the conventional + wcc system, there is a weaker positive relationship between the variables (R^2 = 0.19881) than the organic + wcc system (R^2 = 0.39161).

DISCUSSION

Soil quality variables

My first objective was to determine if MBC, MBN, DOC, or TDN levels differed between the two systems, organic + wcc and conventional + wcc. Of the four variables, only DOC and TDN were significantly greater in the organic + wcc system over the conventional + wcc system (Table 1). I suggest that because the organic + wcc system has had consistent manure and cover crop N input for an extended period of time, the DOC and TDN that are broken down from crop residues and made available for uptake have steadily increased in concentration (Liu et al. 2014).

This is in accordance with keynote studies such Havlin et al., who found that soil organic matter, and therefore soil productivity, can be increased through the presence of crop residues with each rotation (1990). This is because crop residues are a primary source of organic matter (Moore et al. 2000). The residues are decomposed and taken up via microbial populations in the soil community, which increases the amount of dissolved organic nutrients and improves soil organic matter. Moore et al. additionally state that crop management and fertilizer regime strongly impact nutrient availability by controlling the availability of crop residues for decomposition (2000). Conventional systems may acquire excess nutrients from chemical fertilizers, which then leach out of the system, whereas organic systems tend to be nutrient limited, making them more dependent on soil microbial communities to effectively cycle nutrients (Kuo and Sainju 1998, Wells et al. 2000, Drinkwater and Snapp 2007).

While pH and water content were not statistically significant in one system, they still proved to have influential relationships with WCC yields, and may have biological significance (Table 1). The lower pH of the conventional system follows the results of Goladi and Agbenin, who found through a 45-year study that plots with chemical fertilizer became significantly more acidic than those with manure (1997). This has important implications for the long term, as research shows that decomposition of crop residues happens faster in neutral than acidic soils (Kumar and Goh 1999). Water content is also affected by fertilizer regime, with organic fertilizers of manure and compost creating more stable soil structure and therefore able to hold greater capacity of water (Drury et al. 1991, Liu et al. 2014). Greater water capacity increases microbial activity, which improves residue decomposition and nutrient cycling (Stanford and Epstein 1974, Schomberg et al. 1994).

Winter cover crop yields

Both the WCC root and shoot yields were significantly higher in the organic + wcc system (Table 1). This result suggests that the organic + wcc system provided higher quality soil that in turn made the system more productive, similarly to the below-ground variables studied above. In a study with lettuce cash crops, Liu et al. found that organic fertilizer over chemical fertilizer led to greater shoot yield (2014). This result, along with my own findings, provides a contrast to most studies, which state that synthetic fertilizer is vital to successful cash crop production and increases yield (Peoples et al. 1995, Crews and Peoples 2004, Villalba et al 2019). It is important to note that all of these studies use yields of cash crops, whereas mine used yields of leguminous cover crops, creating a difference. Additionally, my research poses results from complex systems of alternating cash and cover crops and differing fertilizer regimes, which makes it increasingly difficult to compare to those with even slightly altered systems.

Soil quality variables and WCC yields together

Looking at all of the soil quality variables in combination with the yields of the cover crops can provide insight into how these factors work together to create a productive ecosystem, and possibly which management practice is more beneficial. Firstly, the WCC root yield was correlated with MBN (Fig. 9), which is in accordance with Wang et al., who found that soil microbial biomass N was strongly related to the N concentration of their cover crops and of the soil, even suggesting that legumes are more influential than non-legumes because of their higher N concentration (2007). The WCC root yield was also correlated with soil moisture (Fig. 11), which is in accordance with Drury et al. who found that soil moisture impacts the rhizospheric populations through altering the soil structure (1991). Increases in soil moisture can lead to an increase in rhizosphere microbial populations, and therefore the yield of the WCC roots. The symbiotic relationship between the root nodules and microbial communities is apparent with this result, which has implications that leguminous cover crops may function as a substitute for synthetic fertilizer, should they be paired with an organic fertilizer in addition.

Limitations and future directions

While this research provided noteworthy information for the agricultural field, there are certain limitations to be addressed. Firstly, this study took place in a Mediterranean environment, as stated in the Methods. Mediterranean is a distinct climate that occurs in few places around the world, specifically California, central Chile, south and southwest Australia, South Africa, and the Mediterranean basin. It specifically has mild, rainy winters with hot, dry summers, so this research is most applicable to other environments with those conditions. This also influences the type of soil and its structure. In the agricultural systems studied here, it was silty clay loam soil, but soil can vary between sandy, peaty, and chalky as well. Studies show that soil structure itself is influenced by crop type, microbial populations, and water content, all of which were shown to have varying effects in this study (Drury et al. 1991).

Another point to be made is that while my data set was complex, I still was not able to draw the larger, more holistic conclusions of which I was originally hoping. The DOC, MBC, TDN, and MBN data was particularly valuable along with the WCC yields, however the arguably more important values are those of the cash crop yields. I was able to identify how nutrients cycle through systems with cover crops, but it would be more useful for farmers to know how cash crops are impacted by the various factors, as the cash crops provide their revenue and allow them to sustain their livelihoods; the cover crops alone cannot do that. By obtaining the cash crop yields, I would be able to determine how efficiently nutrients cycle through the WCC period into the soil and back into the next round of crops. Therefore, this study provides a strong starting point to gain broader understanding of how these variables work with cash crops under different management practices.

CONCLUSIONS

Compared to the conventional + wcc system, the organic + wcc system had better soil quality and greater WCC yields. MBC and MBN levels were not statistically significant between the two systems, however, combined with the result of significantly greater DOC and TDN in the organic + wcc system, the greater amounts of MBC and MBN in the organic + wcc system have biological implications that the organic management practice is more beneficial. In addition, the organic + wcc system had better water retention and a more neutral pH compared to the conventional practice, and greater WCC yields of both roots and shoots. With this interesting information, we should prioritize management practices that favor all aspects of nutrient cycling- decomposition, N immobilization, and nutrient release- to ensure the stability and sustainability of agricultural soil for the future (Altieri 1999).

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APPENDIX A: Study Site

Figure A1. Aerial view of Russell Ranch. All plots of the Century Experiment, including those of the organic + wcc and conventional + wcc systems shown here.

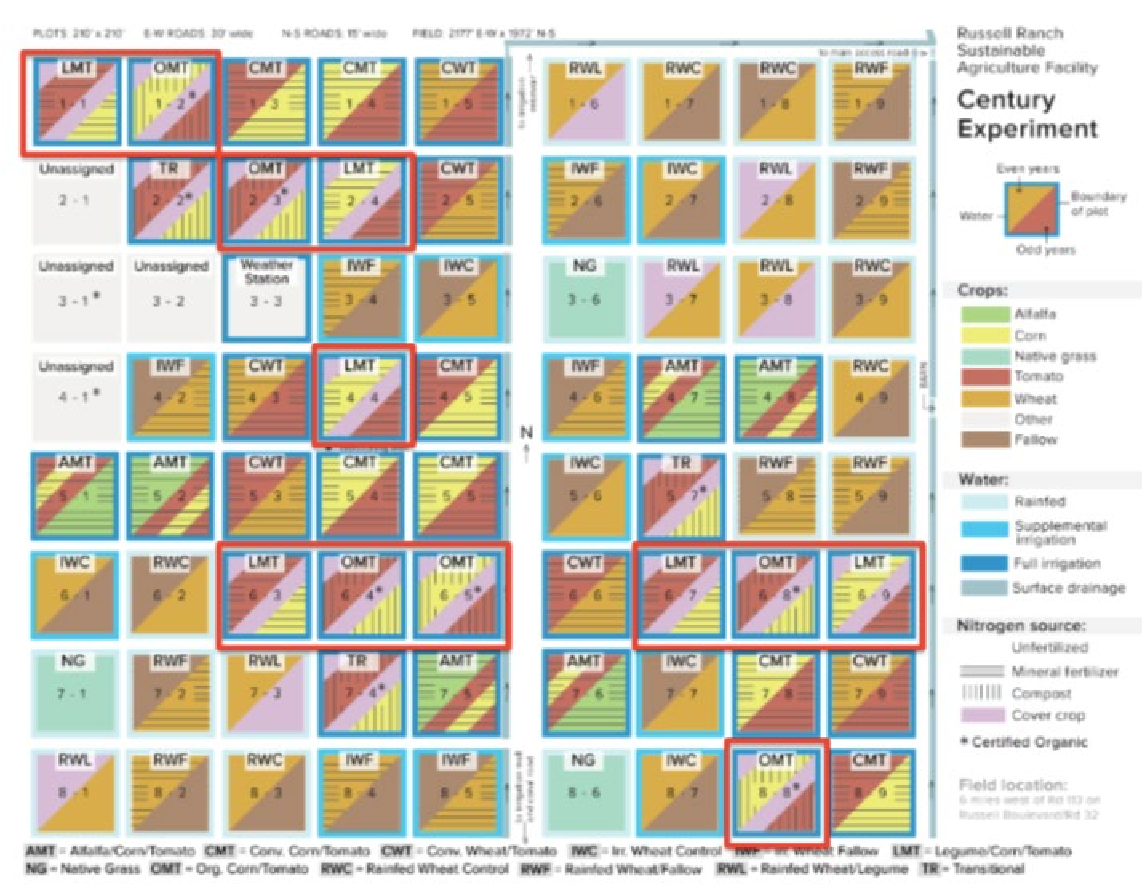

Figure A2. Conventional and organic plots. Outlined in red are the 6 organic and 6 conventional plots of the experiment.