Aggregate Dynamics Control on Carbon Sequestration and Resource Use Efficiency

Johan Six[1] and Chris van Kessel[1]

Summary

During the two-year funding period of this project, we accomplished our two major project goals. First, we quantified the relationship between C input, SOC sequestration, and aggregate stability, and determined the underlying mechanisms for C stabilization in Mediterranean cropping systems at the LTRAS/SAFS site. Results from this first study indicate that the long-term crop management practices, which increase residue-C returned to the soil through differences in N input rates and irrigation regimes, result in greater aggregate stability and aggregate-associated SOC levels and, ultimately, in enabling agricultural soils to sequester C in the long term. However, we found that not only the quantity but also the quality of above- plus belowground crop residue returned to the soil are influential in determining the rates of soil C sequestration. Second, we examined the role of aggregate dynamics on the relationship between C input/fertilizer quality and SOC sequestration plus N synchronization, under conventional and minimum tillage practices. This study was conducted on the systems with high C input levels but differing in forms of resource inputs (i.e., organic versus mineral resource). We found greater aggregate stability and aggregate-C and –N levels in the organic-maize-tomato (OMT) cropping system, which received the greater C and N inputs than the legume-maize-tomato (LMT) and conventional-maize-tomato (CMT) cropping systems, in the form of organic amendments. Using stable isotope techniques, we were able to calculate greater C and N turnover in the CMT cropping system, where only mineral fertilizers were applied, while C and N turnover was slowest in the OMT cropping system. Results from both the first and second studies indicated that the microaggregate-within-macroaggregate fraction (mM) can explain a majority of the accumulation of SOC, due to additional C inputs and different resource inputs. Findings from this project will serve as a valuable description of the functional relationships between aggregate dynamics, resource input, and C and N cycling in agroecosystems. The latter will aid in identifying soil C and N management strategies and policy options with the ultimate goals of optimizing resource utilization, mitigating rising CO_2 levels via C sequestration, improving N synchronization to increase plant productivity and attenuate N losses, and promoting long-term soil fertility.

Objectives

The global objectives of the project are to elucidate 1) the linkage between organic plus mineral fertilizer additions, tillage, aggregate dynamics and C sequestration, and 2) how this linkage controls both organic and mineral fertilizer use efficiency.

Within this global objective, we designed two studies with laboratory and field components, which took place at the experimental site (LTRAS/SAFS; Davis, CA). For the first study, we collected soil samples from all 10 LTRAS/SAFS cropping systems to address the following

[1] Department of Plant Sciences, University of California, Davis

specific objectives: 1) to quantify the relationship between C input and SOC sequestration in whole soil and SOM fractions, as governed by irrigation and organic plus mineral fertilizer additions, and 2) to identify mechanisms of long-term soil C stabilization across a range of C input levels. The second study of our project focused on the three cropping systems at the LTRAS/SAFS site with the highest C input levels and different nutrient management regimes to address the following specific objectives: 1) to assess how conventional tillage (CT) versus minimum tillage (MT) practices influence the link between the quantity and quality of fertilizer additions and SOC sequestration plus N synchronization, and 2) to elucidate the mechanisms of short-term C stabilization and N synchronization in these cropping systems.

Approach and Procedures

For the first study of the project, soil samples (4cm dia.; 0-15 cm) were taken from the 10 different cropping systems at the LTRAS/SAFS experimental site in April 2003. Since 1993, the LTRAS/SAFS site has been the location for testing the sustainability of conventional and alternative cropping management practices. The 10 different cropping systems (*table 1*) vary in crop, irrigation, N levels, and N sources and are represented by three 0.4 ha replicate plots, with both phases of each two-year rotation represented each year. Subsamples of archived LTRAS/SAFS soils, which were taken in September 1993 (time-zero of the LTRAS/SAFS experiment) from the 0-15cm layer, were obtained for plots corresponding to those that were sampled in April 2003.

Physical Fractionation

Air-dried 2003 soil samples were separated into four aggregate size classes by wet sieving through a series of three sieves (2,000, 250, and 53μm) according to Elliott (1986). Water-stable aggregates were separated by moving the sieve in an up-and-down motion with 50 repetitions, over a period of two minutes. Consequently, four aggregates size fractions were isolated: 1) large macroaggregates (>2,000μm; LM), 2) small macroaggregates (250-2,000μm; sM), 3) microaggregates (53-250μm; m), and 4) silt-and-clay (<53μm) fractions. Subsamples of approximately 10g from both the large and small macroaggregate fractions were further separated into coarse particulate organic matter (cPOM), microaggregates (mM) and silt-and-clayM (<53μm) SOM fractions according to the methodology outlined in Six et al. (2000).

Carbon Sequestration

Subsamples from 1993 and 2003 whole soil and all 2003 extracted fractions (i.e., LM, sM, m, silt and clay, cPOM, mM, and silt-and-clayM) were ground and analyzed for C concentrations using a Carlo-Erba NA 1500 elemental analyzer (Milan, Italy). The SOC sequestered in each plot after 10 years of the respective cropping management practices was taken to be the difference between 1993 and 2003 SOC values.

Carbon Input

Carbon input values were derived from nine years (1994-2002) of harvest yield data and added compost estimates (Denison et al. 2004). Equations converting corn and wheat yields to corn stover and wheat straw (aboveground biomass), respectively, originated from literature-derived data (S. Williams, personal comm.). Carbon concentrations of corn, wheat, and tomato residue were on average 43% C, while C concentrations of compost and cover crop were 23% and 42.5 %C, respectively.

Table 1. *The 10 cropping systems at the Long-term Research on Agricultural Systems (Davis, CA, USA) site. Abbreviated codes for the names of the cropping systems are in parentheses.*

Cropping System	Even Years of Cropping	Odd Years of Cropping
Rainfed-wheat-control (RWC)	unfertilized rainfed wheat	fallow
Rainfed-wheat-legume (RWL)	unfertilized rainfed wheat	rainfed legume cover crop
Rainfed-wheat-fallow (RWF)	fertilized rainfed wheat	fallow
Irrigated-wheat-control (IWC)	unfertilized irrigated wheat	fallow
Irrigated-wheat-legume (IWL)	unfertilized irrigated wheat	rainfed legume cover crop
Irrigated-wheat-fallow (IWF)	fertilized irrigated wheat	fallow
Conventional-wheat-tomato (CWT)	fertilized irrigated wheat	fertilized irrigated tomato
Conventional-maize-tomato (CMT)	fertilized irrigated maize	fertilized irrigated tomato
Legume-maize-tomato (LMT)	winter legume then irrigated maize	fertilized irrigated tomato
Organic-maize-tomato (OMT)	winter legume then irrigated maize with compost and no pesticides	winter legume then irrigated tomato with compost and no pesticides

For the second study of the project, vetch (*Vicia dasycarpai*) and pea (*Pisum sativum*) plants were ^{13}C- (~1700‰) and ^{15}N-labeled (~67 atom%) according to (Bird et al. 2001). Labeled material were added to microplots within the CMT, LMT, and OMT treatments. Pre-addition soil samples (4cm dia.; 0-15cm) were taken in March 2004 to establish all necessary baseline data (i.e., SOC and SON content, and natural abundance ^{13}C and ^{15}N levels within treatments). Under both CT and MT regimes, the ^{13}C- and ^{15}N-labeled WLCC (vetch/pea mix) were incorporated into the LMT plus OMT in April 2004, while the CMT plots received ^{15}N-labeled urea and NH_4NO_3 (~67 atom%) mineral fertilizers, both at the end of April and mid-May. Soil samples were taken three more times over the course of the maize season. Grain and maize biomass samples were collected during the September maize harvest from each of the cropping systems, under both tillage regimes.

Physical Fractionation

Physical soil fractionation methods used in the second study of the project were similar to those of the first study.

Total and Isotopic C and N Chemical Analyses

Subsamples from whole soil and all extracted fractions (i.e., macroaggregates, microaggregates, silt and clay, cPOM, mM, and silt-and-clayM) for the four sampling periods were ground and analyzed for TOC, TON, $\delta^{13}C$ and ^{15}N-atom% values were measured using a Carlo-Erba 1500 elemental analyzer (Milan, Italy) interfaced with a PDZ Europa Geo 20-20 isotope ratio mass spectrometer (IRMS).

Results

Study #1: C input levels, SOC sequestration, and aggregate stability

Estimates of cumulative C input levels for each of the cropping systems after 10 years of continuous cropping management ranged from a low of 8.3 Mg C ha^{-1} in the rainfed-wheat-control (RWC) system to a high of 89.6 Mg C ha^{-1} in the OMT system. Average C input values calculated for the maize-tomato systems, between 45.9 Mg C ha^{-1} to 89.6 Mg C ha^{-1}, were significantly higher than the other seven cropping systems.

Table 2. *Soil organic carbon (SOC), sequestered SOC, cumulative C input, and aggregate stability values for the 10 Long-term Research on Agricultural Systems (Davis, CA, USA) cropping systems. Values followed by a different lowercase letter within one column are significantly different ($p<0.05$) between cropping systems.*

Cropping System	1993 SOC (Mg C ha^{-1})	2003 SOC (Mg C ha^{-1})	Annual SOC sequestered (Mg C ha^{-1} yr^{-1})	Cumulative C input (Mg C ha^{-1})	Mean weight diameter (MWD; mm)
RWC	20.4^{a}	16.9^{c}	-0.35^{c}	8.3^{g}	0.33^{a}
IWC	17.7^{b}	15.9^{c}	-0.19^{bc}	9.1^{fg}	0.31^{a}
RWF	18.4^{b}	17.9^{bc}	-0.05^{bc}	10.3^{ef}	0.37^{ab}
IWF	15.8^{b}	16.1^{c}	0.04^{b}	11.8^{e}	0.30^{a}
IWL	17.2^{b}	17.8^{bc}	0.06^{b}	30.4^{d}	0.80^{c}
RWL	18.9^{b}	19.6^{b}	0.06^{b}	30.5^{d}	0.95^{cd}
CWT	17.7^{b}	17.1^{c}	-0.06^{bc}	42.0^{c}	0.45^{b}
LMT	17.0^{b}	16.9^{c}	-0.01^{b}	45.9^{c}	0.88^{c}
CMT	17.3^{b}	17.7^{bc}	0.04^{b}	51.8^{b}	0.85^{c}
OMT	17.2^{b}	22.8^{a}	0.56^{a}	89.6^{a}	1.2^{d}

Slight variability around a mean SOC value of 17.8 Mg C ha^{-1} (SE=0.6) was found for the 1993 archived soils. After 10 years of continuous cropping management, the RWC, irrigated-wheat-control (IWC), rainfed-wheat-fallow (RWF), conventional-wheat-tomato (CWT), and LMT systems lost SOC, whereas the irrigated-wheat-fallow (IWF), irrigated-wheat-legume (IWL), rainfed-wheat-legume (RWL), CMT, and OMT systems sequestered SOC (*table 2*). Soil organic C losses were greatest in the wheat control systems, RWC and IWC, with SOC losses of 3.5 and 1.9 Mg C ha^{-1}, respectively. A significantly higher accumulation of SOC was seen in the OMT system than in the other cropping systems (*table 2*). Annual C sequestration rates at LTRAS ranged from –0.35 Mg C ha^{-1} yr^{-1} in the low C input RWC system to 0.56 Mg C ha^{-1} yr^{-1} in the high C input OMT system (*table 2*). Irrigated and rainfed legume cover cropped wheat systems (IWL and RWL, respectively) demonstrated identical yearly C sequestration rates (*table 2*).

Aggregate stability was low for the control (RWC and IWC) and wheat fallow (RWF and IWF) cropping systems, with mean plot MWD values in the range of 0.30mm to 0.37mm (*table 2*). Approximately 50 to 70% of the soil in the RWC, IWC, RWF, IWF, and CWT cropping systems was recovered as microaggregates, while less than 2% of the soil in these systems was comprised of macroaggregates. However, up to 21% of the soil from the OMT, CMT, IWL, RWL, and LMT cropping systems was found in the macroaggregate fraction.

Table 3. *Preferential carbon stabilization factors (PCSF) of the microaggregate-within-large and within-small-macroaggregate fractions.*

Cropping System	Fraction	PCSF	SE
IWL	LM	0.46	0.04
RWL	LM	0.53	0.05
LCT	LM	0.59	0.04
CCT	LM	0.60	0.01
OCT	LM	0.58	0.01
RWC	sM	0.48	0.03
IWC	sM	0.42	0.01
RWF	sM	0.54	0.02
IWF	sM	0.48	0.02
IWL	sM	0.49	0.05
RWL	sM	0.55	0.04
CWT	sM	0.54	0.03
LCT	sM	0.56	0.03
CCT	sM	0.61	0.02
OCT	sM	0.57	0.06

Significant positive linear relationships were found between SOC sequestered and aggregate stability (r^2=0.63, p=0.006), aggregate stability and C input levels (r^2=0.75, p=0.001), as well as between SOC and C input levels (r^2=0.70, p=0.003; Figure 1). The relationship between SOC sequestered (*Y*: Mg C ha^{-1}) and cumulative C input (*X*: Mg C ha^{-1}) was described by the following linear equation: $Y = 0.076X - 2.39$. Multiple linear regressions indicated a significant (p=0.006) relationship across the cropping systems between SOC sequestered, MWD, and the cumulative C input:

$$MWD = 0.35 + 0.03(SOC\,sequestered) + 0.009(C\,input)\ (r^2 = 0.77;\ data\ not\ shown)$$

We found an increase in macroaggregate-C with increasing C input and a decrease in microaggregate-C with increasing C additions (*fig. 2*). While a significant positive interaction was observed between cumulative C inputs levels and both the large macroaggregate-associated C (r^2=0.71, p=0.002) and small macroaggregate-associated C (r^2=0.80, p=0.0005) (*fig. 2*), the microaggregate-associated C was found to decrease with increasing C inputs (r^2=0.33, p=NS) (*fig. 2*). Carbon concentrations of the aggregate fractions isolated from the large and small macroaggregates were evaluated based on their preferential C stabilization factor (PCSF) across the C input gradient. The PCSF is a measurement of the C contribution from the isolated fraction to the total C of the aggregate fraction from which it was isolated. Therefore, a PCSF value of zero indicates that macroaggregate-associated C has not been preferentially stabilized within the particular fraction, while a PCSF value of 1.0 indicates that C from the macroaggregate fraction has been completely sequestered in the isolated fraction. In the >250μm aggregate-within-large and small-macroaggregate fractions (cPOM-within-LM and cPOM-within-sM), low PCSF values were obtained, 0.07 – 0.31 and 0.06 – 0.44, respectively. No significant interaction between increasing C input levels and the PCSF values of the cPOM was observed (data not shown). Similarly low PCSF values were found for the silt-and-clayM fractions. On the other hand, the highest PCSF values were found for the microaggregate-within-macroaggregate fractions (mM) (*table 3*). In both the LM and sM fractions, the mM fraction accounted for 40% to 68% of the C stabilized within the macroaggregate fractions.

Table 4. *Total C, C_{new}, Total N, and N_{new} for bulk soils under conventional tillage practices. Values with different letters, within one sampling period and C or N component, are significantly different (p<0.05). Total C and N values shown with '*' indicate a significant difference from pre-plant samples, while '**' shows a significant difference between either mid-season's and harvest samples. Values with '***' indicate a significant difference between pre-plant and harvest (p<0.05).*

		Cropping System					
Sampling Period		CMT		LMT		OMT	
		C (Mg·ha^{-1})	N (Mg·ha^{-1})	C (Mg·ha^{-1})	N (Mg·ha^{-1})	C (Mg·ha^{-1})	N (Mg·ha^{-1})
Pre-Plant							
	Total	15.6^{a}	1.49^{a}	15.3^{a}	1.49^{a}	20.3^{b}	2.15^{b}
	New						
Mid-Season$_{irrigated}$							
	Total	$17.7^{a,b}$	$1.98^{a,b,*}$	14.5^{a}	1.54^{a}	20.8^{b}	2.41^{b}
	New		0.12^{a}	0.55^{a}	0.06^{a}	0.53^{a}	0.16^{a}
Mid-Season$_{end\ of\ irrigation}$							
	Total	$18.7^{a,b,*}$	$1.97^{a,b,*}$	16.8^{a}	1.68^{a}	20.9^{b}	2.25^{b}
	New		0.10^{a}	0.50^{a}	0.05^{a}	0.29^{a}	0.08^{a}
Harvest							
	Total	$18.6^{a,b,*}$	$2.07^{a,*}$	18.2^{a}	1.89^{a}	23.6^{b}	2.65^{b}
	New		0.16^{a}	0.30^{a}	$0.08^{b,*}$	0.73^{a}	0.05^{b}

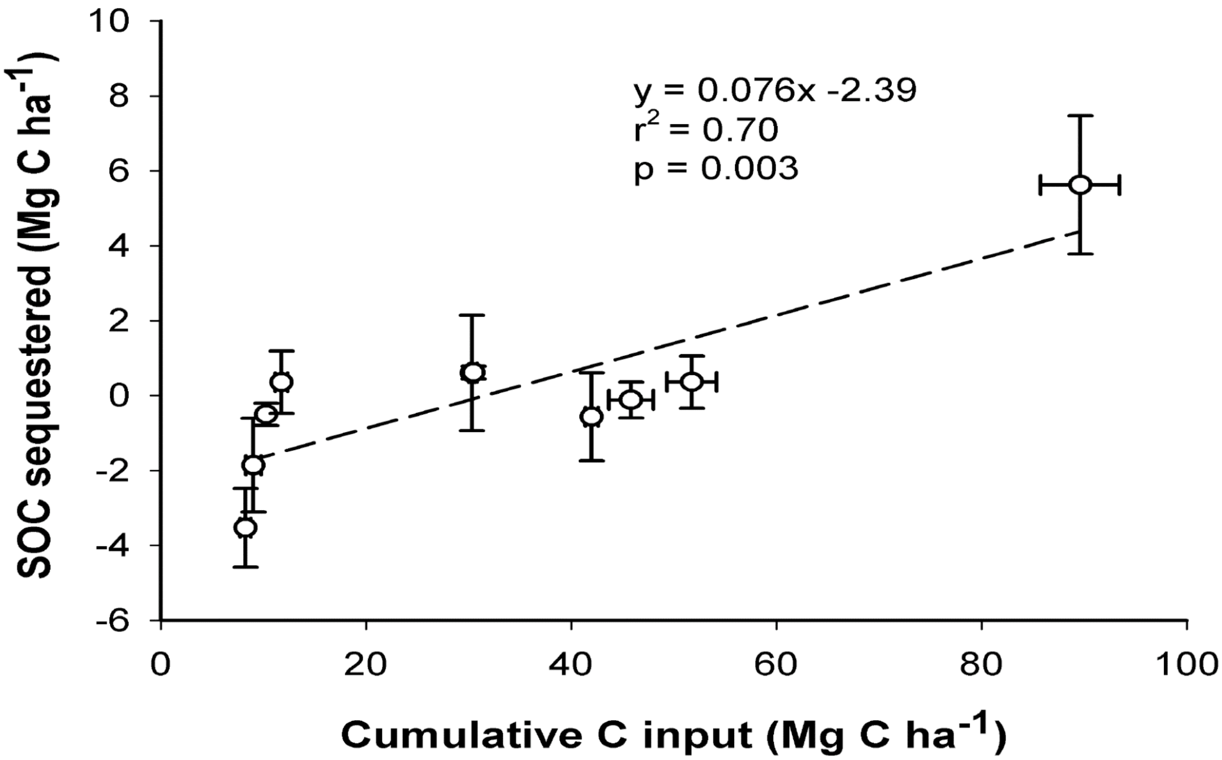

Figure 1. Relationship between sequestered soil organic carbon (SOC) and cumulative carbon (C) input across the 10 different cropping systems at the LTRAS (Long-term Research on Agricultural Systems, Davis, CA, USA) site. Vertical and horizontal error bars indicate standard errors from the means of the SOC sequestered and cumulative C input level, respectively.

Study #2: Seasonal trends in SOC, SON, aggregate dynamics, and nutrient turnover

We found no effects of tillage within the three cropping systems for any of the variables measured (SOC, SON, aggregate-associated C and N, C_{new}, N_{new}, etc.). Therefore, we only report data for the CT treatment.

Both SOC and SON for bulk soil samples increased significantly over the season for all cropping systems ($p<0.05$; *table 4*). The OMT cropping system showed the highest SOC and SON levels (~17.6 Mg C ha^{-1} and ~1.9 Mg N ha^{-1}) at all sampling periods, while SOC and SON levels for the CMT and LMT were lower than the OMT across the whole maize season and were not significantly different from each other at the beginning and the end of the season (*table 4*). Of the SOC and SON in the bulk soil, the fraction of $^{13}C/^{15}N$-labeled fertilizer (OR or MF) recovered in the soil, f_C and f_N, respectively, was not different between the LMT and OMT cropping systems (data not shown). However, f_N of the bulk CMT was significantly higher than both the LMT and OMT cropping systems after the first mid-season sampling period until the harvest (data not shown).

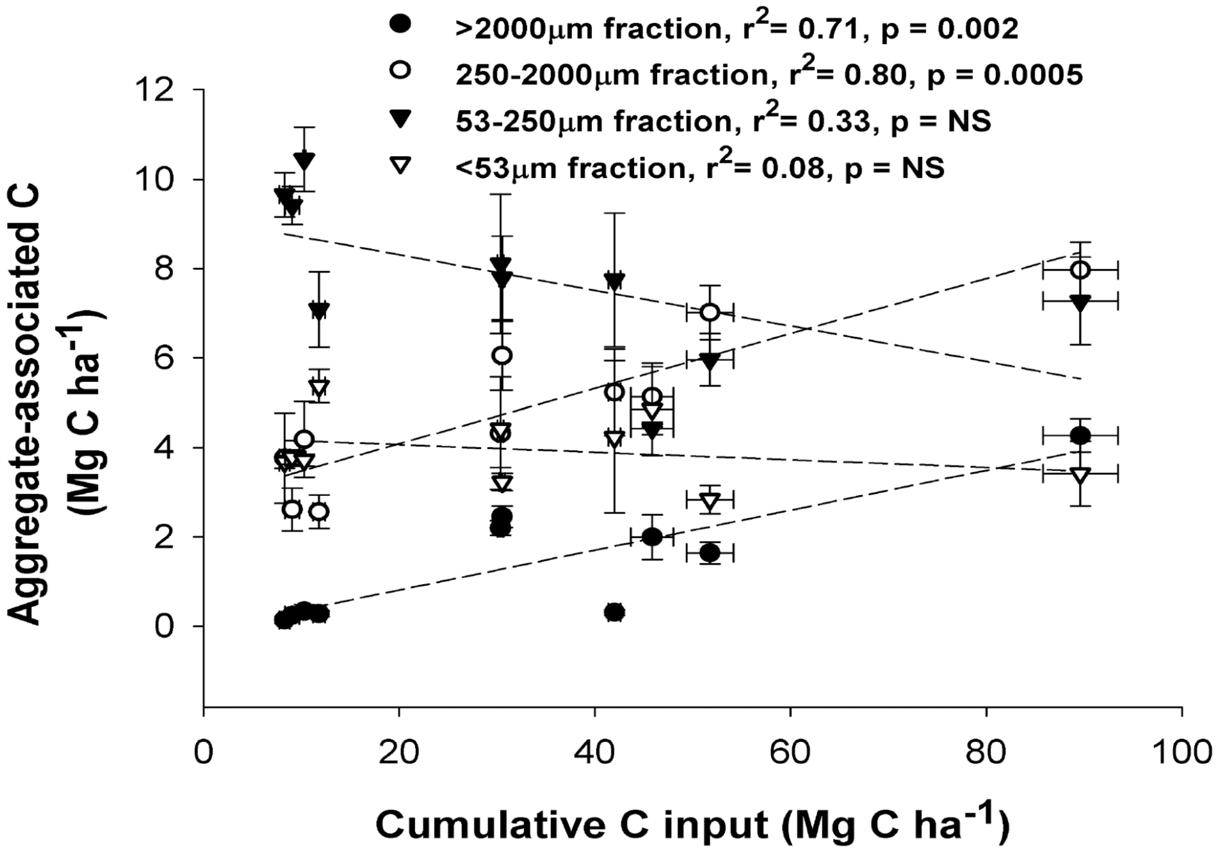

Figure 2. Trends in aggregate-associated carbon (C) across the C input gradient determined for the 10 cropping systems at the LTRAS (Long-term Research on Agricultural Systems, Davis, CA, USA) site. Vertical and horizontal error bars indicate standard errors from the means of the aggregate-associated C and cumulative C input level, respectively.

Aggregate stability, measured as mean weight diameter (MWD), increased in following sequence among the three systems, after fertilizer treatments: LMT < CMT < OMT, with seasonal MWD values in the range of 1.09mm to 1.40mm for the LMT cropping systems, and seasonal MWD values in the range of 1.40mm to 1.77mm for the OMT cropping system. Approximately 41-53% of the soil in CMT, LMT, and OMT cropping systems was recovered as microaggregates, while 24-43% of the soil in these systems was comprised of macroaggregates. Bulk soil of the OMT plots consisted of a higher percentage (~40%) of macroaggregates than that observed in the LMT and CMT plots (data not shown).

Aggregate-C and –N of the OMT system were significantly higher than aggregate-associated C and N in both the LMT and CMT cropping systems (*figs. 4 and 5*, respectively). We found a decrease in macroaggregate-associated C and N concomitant with an increase in microaggregate-C and N for the LMT and CMT cropping systems, across the maize growing season, yet no changes in aggregate-associated C were measured in the OMT cropping systems (*figs. 4 and 5*, respectively). The increases in C and N in the microaggregate fractions of the cropping systems were accompanied by decreases in C_{new} and N_{new} from the macroaggregate fractions and increases in C_{new} and N_{new} in the microaggregate fraction. Total C and N concentrations in the isolated SOM fractions were also highest for the OMT cropping system, with the mM fraction showing higher C and N (4.5 – 6.6 Mg C ha^{-1}) levels than the cPOM and the silt-and-clayM fractions (0.9 – 3.4 Mg C ha^{-1}). Preferential C and N stabilization factor (PNSF) values for the three treatments revealed results similar to that reported for the first study. In the OMT cropping system, which receives the highest C input of the three maize-tomato cropping systems, we see that the mM fraction holds the majority of the macroaggregate-associated C and N and that mM-C increases significantly over time (*fig. 6*). A similar trend of increasing mM-associated C and N across the cropping season is seen in the LMT and CMT cropping systems, however, this trend is not significant (*figs. 6 and 7*, respectively).

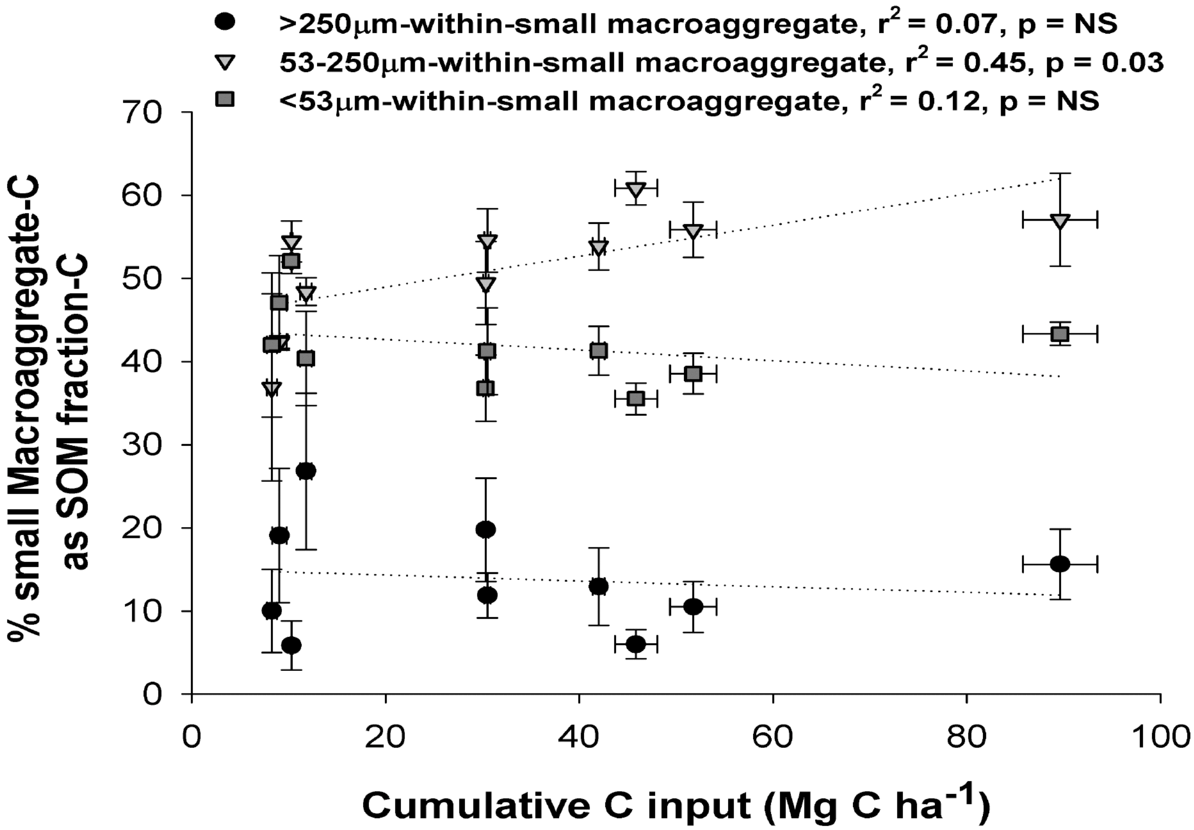

Figure 3. Cumulative carbon (C) input levels for the 10 cropping systems at the LTRAS (Long-term Research on Agricultural Systems, Davis, CA, USA) site regressed against percentages of small macroaggregate-C derived from soil organic matter fractions that were isolated from the small macroaggregates. Vertical and horizontal error bars indicate standard errors from the means of the percentage of small macroaggregate-C as SOM fraction-C and the mean cumulative C input level, respectively.

Of the measured C_{new} and N_{new} in the aggregate fractions, we see equally substantial stabilization of the N_{new} in the CMT systems into the mM and silt-and-clayM fractions ($PN_{new}SF$ value range: 0.27 - 0.41), yet preferential stabilization of the ^{15}N-labeled fertilizer-derived N occurred only in the mM for the LMT and OMT cropping systems (data not shown). No clear trends of preferential stabilization were observed for the C_{new} in the isolated SOM fractions of the LMT and OMT systems.

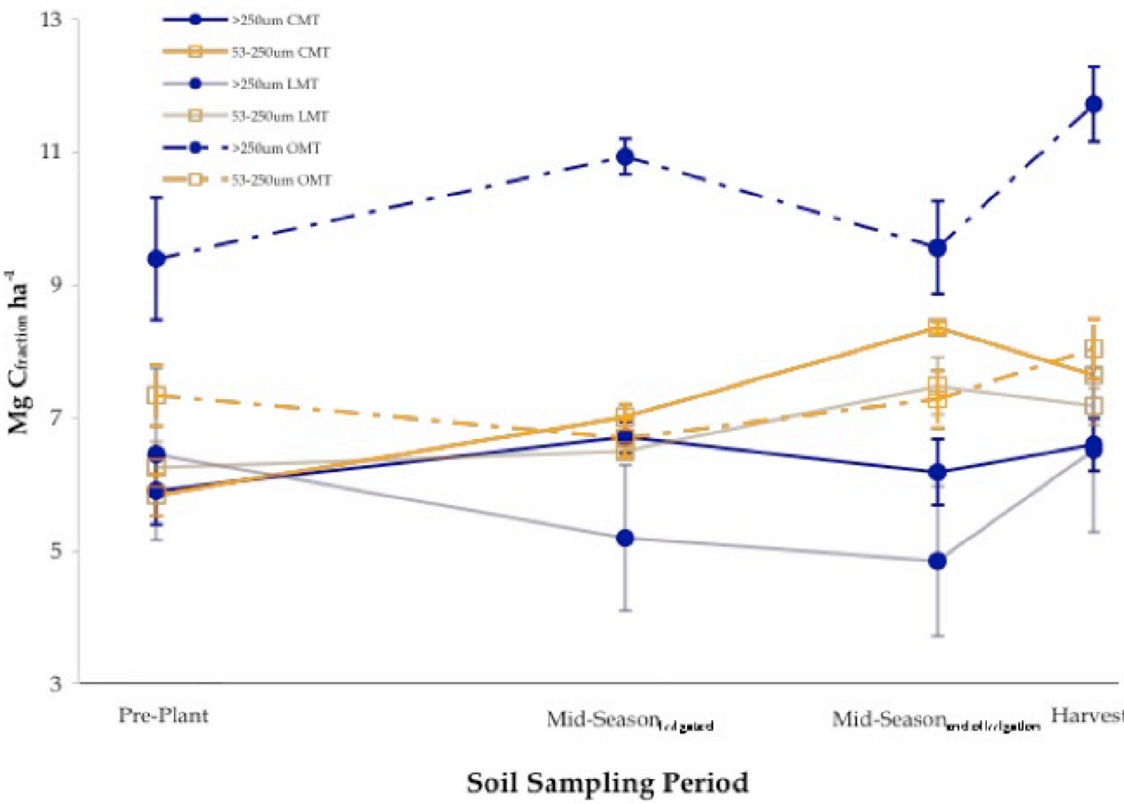

Figure 4. Aggregate-associated carbon (C) across the maize growing season at the LTRAS/SAFS site. Vertical bars indicate standard errors from the means of the aggregate-associated C.

Discussion

Study #1: Relationship between C input, SOC sequestration, and aggregate stability

C input, soil organic carbon, aggregate stability, and rate of C sequestration

Soil organic C usually changes only slowly with time following a change in cropping management. Long-term experiments are necessary to detect differences of SOC against the background SOC as well as against analytical variability. Rasmussen and Parton (1994) and others (Cole et al. 1993; Horner et al. 1960; Larson et al. 1972) have shown that SOC responds linearly to increasing rates of residue or C additions in both short and long-term experiments. The strong, linear relationship between SOC and C input shown at the LTRAS/SAFS site after 10 years of continuous cropping corroborates these findings.

While it has been suggested that the type of residue applied only weakly relates to SOC (Larson et al. 1972), our results suggest that residue or C quality might be directly linked to the amount of SOC sequestered in the cropping systems. We observed trends among cropping systems where a particular cropping system disproportionately accumulated SOC relative to its C input level. For example, the OMT cropping system received 1.7 times more C additions in the form of crop residues, winter legume cover crops, and compost, on a yearly-basis, than the CMT cropping system. However, the OMT system had an annual C sequestration rate 14 times greater than the CMT system, where the C inputs consisted only of crop residues. Comparison of the two rainfed wheat systems (RWF and RWL) also revealed a disproportionate rate of SOC sequestration relative to the difference in C input between the two systems. Although the RWL system received three times higher annual C inputs (wheat residue and legume cover crop) than its wheat-fallow counterpart (RWF), the net annual SOC sequestration in RWL system was more than three times larger than the net SOC accumulation in the RWF system, which actually lost SOC. Moreover, in a comparison of the CWT and the two wheat-legume systems (IWL and RWL), where 1.4 times more C inputs were added annually to the CWT system than to either the IWL and RWL systems, annual C sequestration rates for both wheat-legume systems were found to be close to three times higher than that of the CWT system. Hence, it appears that the growth of winter legume cover crops in the IWL and RWL systems enhanced the rate of C sequestration, irrespective of irrigation. Our data imply that C quality, as governed by legume and compost addition, is as influential on soil C sequestration as the quantity of C added to the system.

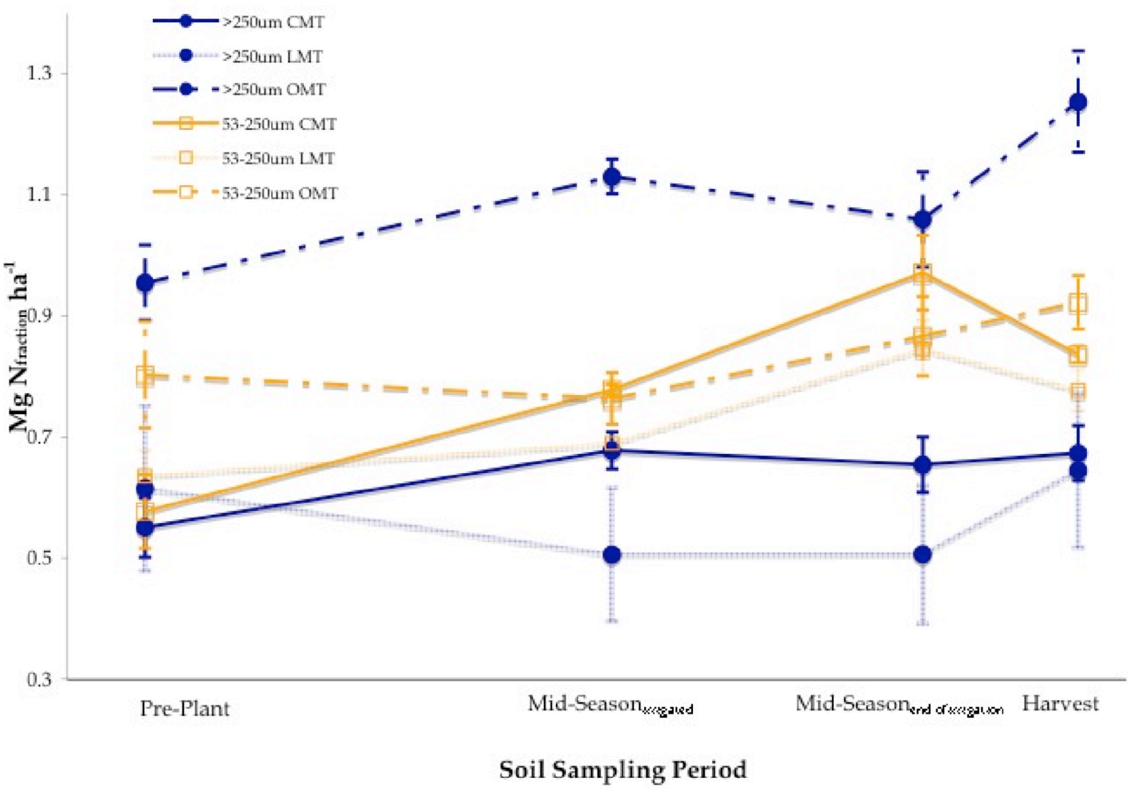

Figure 5. Aggregate-associated nitrogen (N) across the maize growing season at the LTRAS/SAFS site. Vertical bars indicate standard errors from the means of the aggregate-associated N.

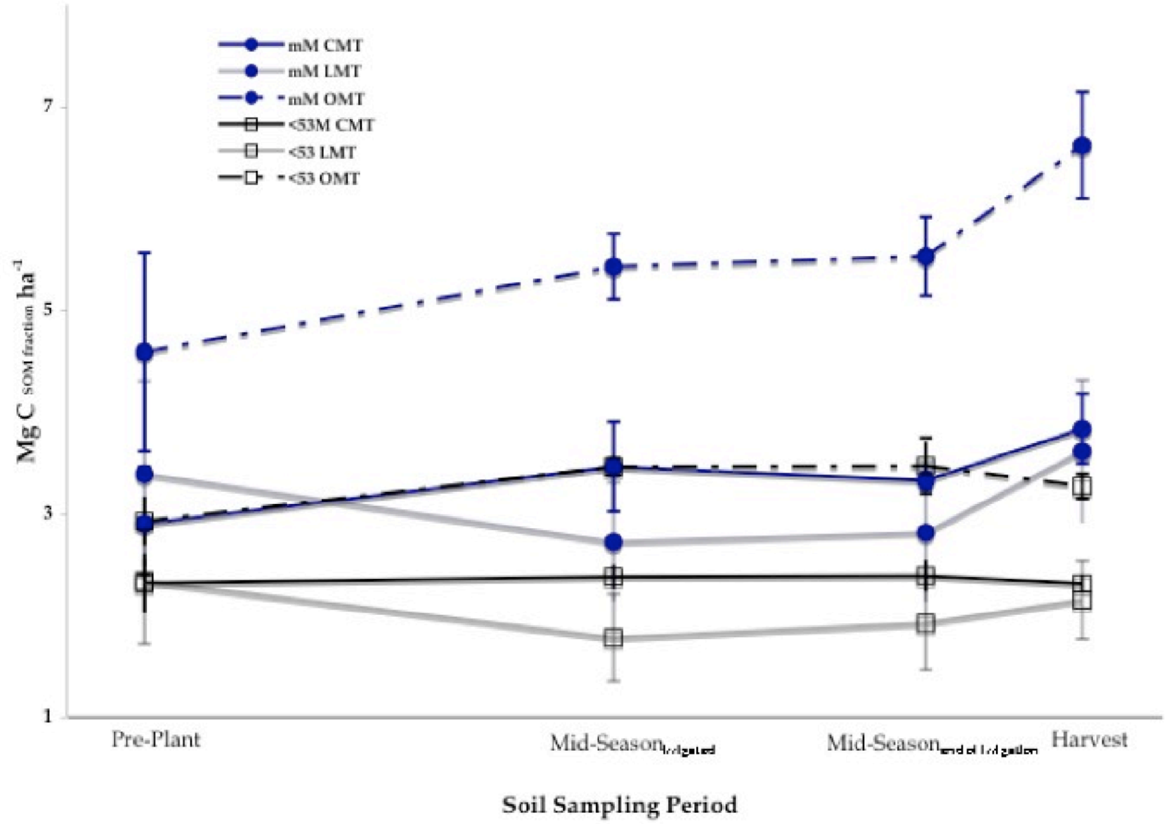

Figure 6. Carbon levels in soil organic matter (SOM) fractions isolated from macroaggregates across the maize growing season at the LTRAS/SAFS site. Values of C associated with the >250μm SOM fraction were low (<1.5 Mg C ha^{-1}) and were not included. Vertical bars indicate standard errors from the means of the SOM fraction-associated C.

Comparison of our data with that of other long-term agricultural experiment sites suggests that cropping systems in California have a lower efficiency in sequestering C from added C inputs. The slope of the relationship between SOC sequestered and cumulative C input corresponds to the residue-C conversion to SOC rate. It follows that 7.6% of each additional Mg C input per hectare is sequestered as SOC at the LTRAS site. This estimate of the residue-C conversion to SOC rate at the LTRAS site was similar to the rate Horner et al. (1960) found for a continuous wheat system in Pullman, Washington, where 8.7% of organic residue was ultimately retained as SOC. However, Rasmussen and Smiley (1997) found a residue-C conversion to SOC rate of 14.8% for a wheat-fallow system in Pendleton, Oregon. Moreover, under a variety of climatic conditions, Rasmussen and Collins (1991) found that the residue-C conversion to SOC rates ranged between 0.14 and 0.21, which were two to three times greater than that found for the LTRAS cropping systems.

Preferential stabilization of C in fractions

According to the hierarchical model of soil aggregation (Tisdall and Oades 1982), there are different levels of soil structural organization, each stabilized by materials of different nature and, perhaps, in different locations. Our results show that the relationship between C input and SOC sequestration was dominated by the increase in SOC associated with the macroaggregate fractions (LM and sM) (*fig. 2*) and that SOC stabilization is associated with greater macroaggregation. Oades (1984) was the first to conceptualize the formation of microaggregates taking place at the center of macroaggregates, and subsequent studies by several investigators (e.g., Golchin et al. 1994; Angers et al. 1997; Six et al. 1998) have corroborated the notion of microaggregate formation within macroaggregates (mM fraction). Recent findings by Bossuyt et al. (2002) and Six et al. (1998 and 2000) have revealed the importance of microaggregates formed within macroaggregates to C sequestration in soils.

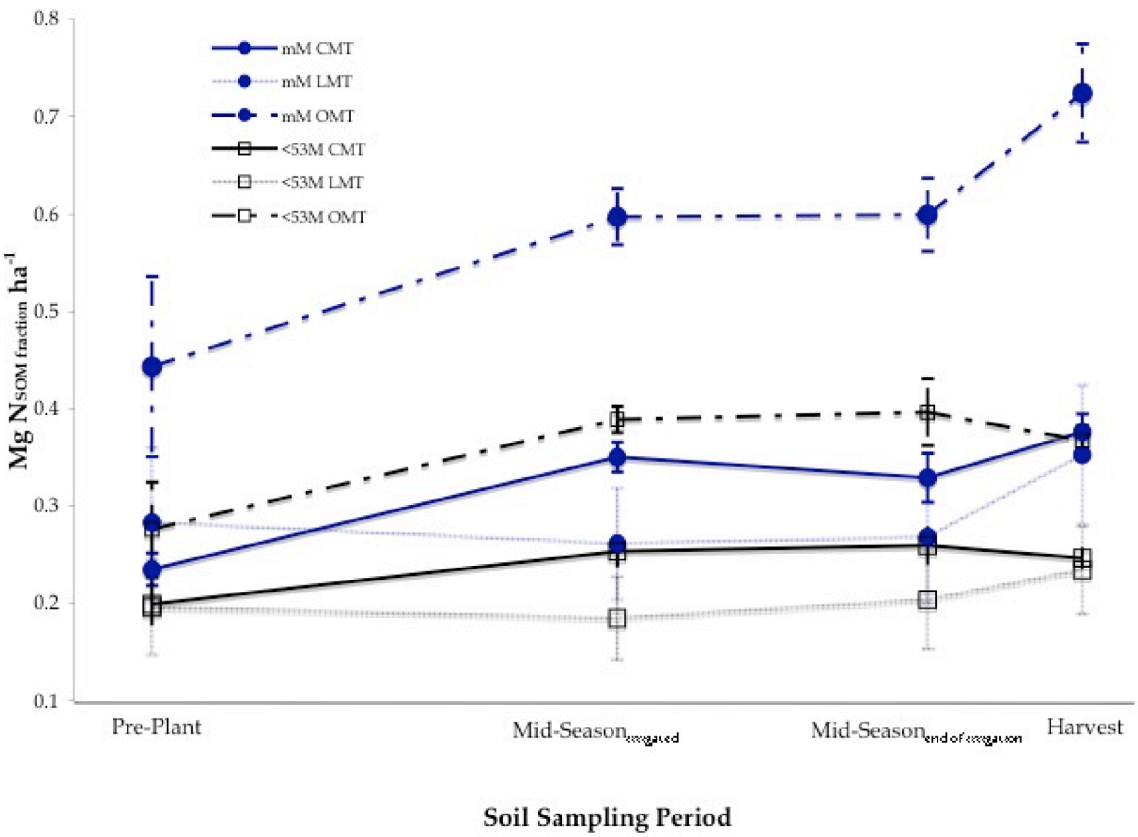

Figure 7. Nitrogen levels in soil organic matter (SOM) fractions isolated from macroaggregates across the maize-growing season at the LTRAS/SAFS site. Values of N associated with the >250μm SOM fraction were low (<0.10 Mg N ha^{-1}) and were not included. Vertical bars indicate standard errors from the means of the SOM fraction-associated N.

After 10 years of continuous cropping management, the LTRAS soils also demonstrated higher microaggregate-within-macroaggregate-C in the higher C input cropping systems (data not shown). Although PCSF values of 0.42 -0.61 were associated with the microaggregates-within-small-macroaggregates, no significant relationship was found between the C input levels and the microaggregates-within-large-macroaggregates. Lack of a significant correlation between the PCSF in the mM fraction isolated from the LM aggregate fraction and the lower rate of C stabilization found in the LM fraction versus the sM fraction were likely the result of the fact that the LM fraction comprised a very small portion of the entire soil and did not contribute a significant amount of C to the total SOC pool. Compared to the sM and m fractions, which represented 13 to 50% of the total SOC, the LM fraction consisted of an insignificant part of the total SOC (0.6 – 14.9% of total SOC). The increase in SOC across the increasing C input gradient could not be attributed to either the C associated with the cPOM (>250μm) or silt-and-clay fractions isolated from the LM fraction (data not shown). Hence, preferential stabilization of SOC in the mM fraction explains a majority of the increase in SOC across the C input gradient. This is in accordance with similar recent studies in afforested and no-tillage systems. Therefore, preferential C stabilization in the mM fraction seems to be a mechanism for soil C sequestration in terrestrial ecosystems.

Study #2: Linking aggregate dynamics, SOC sequestration, and N use efficiency

At the time of this study, the MT practices at the LTRAS/SAFS site had only been in place for two years. Tillage operations for the MT regime were still changing from the inaugural year and had yet to be finalized. We surmise that tillage effects within the cropping systems, across the maize-growing season, and for all the variables measured were insignificant due to either the lack of sufficient time after establishment of the new tillage regime to generate dramatic changes in soil structural and chemical properties or because of minimal operational differences between the CT and MT. We report data only for the CT treatment because this tillage regime is typical for these cropping systems and has been in place longer than the MT regime (11 years).

The increase in SOC and SON in the bulk soils of the three cropping systems, across the maize-growing season is reasonable since these plots receive both external fertilizer (C and N) additions as well as root exudates and residue C input over a six month period. However, the distribution of the added C and N inputs into soil aggregates was not equivalent for the three cropping systems, despite similar aggregate-size distribution, and is likely related to interactions between resource input differences among the cropping systems and aggregate dynamics. The shift in aggregate-associated C and N from the macroaggregates to the microaggregates in the LMT and CMT systems, across the maize-growing season compared to the lack of change in aggregate-associated C and N seen in the OMT cropping systems, show that C and N in the LMT and CMT are not as stabilized as in the OMT system. Moreover, the increase in the OMT system of C_{new} in the microaggregate fraction, where SOM protection is greatest, further suggests that the OMT cropping system has greater capacity to stabilize and store cover crop-derived C in the long term.

Similar to results in other agroecosystem studies and to our first study, the mM is also responsible for the sequestration of a majority of the C accumulation in the macroaggregate fraction of the CMT, LMT, and OMT cropping systems, across the season. However, resource input differences seem to play a role in determining the preferential stabilization of N within SOM fractions, among the cropping systems. We see that two months after the topical application of the MF to the CMT plots (1st Mid-season sampling period), the macroaggregate-associated N_{new} is primarily distributed between the mM and the silt-and-clayM fractions, indicating that the MF was rapidly leached through the soil matrix. The preferential stabilization of N_{new} in the mM fractions of the LMT and OMT systems suggests that the ^{15}N from the cover crop (OR) was not rapidly turned over among the soil aggregates.

Greater overall C and N levels, slower C and N turnover among the soil pools, and higher preferential C and N stabilization factors than the LMT and CMT cropping systems, suggest that the OMT crop management practices are optimal for C sequestration. However, the reduced yields of the OMT cropping system in comparison to the CMT cropping system bring into question the N synchronization potential of organic management practices.

References

Angers, D.A., S. Recous, and C. Aita. 1997. Fate of carbon and nitrogen in water-stable aggregates during decomposition of $^{13}C^{15}N$-labelled wheat straw *in situ*. *European Journal of Soil Science* 48 :295-300.

Bossuyt, H., J. Six, and P.F. Hendrix. 2002. Aggregate protected carbon in no-tillage and conventional tillage agroecosystems using ^{14}C labeled plant residue. *Soil Science Society of America Journal* 66 :1965-1973.

Cole, C.V., K. Flach, J. Lee, D. Sauerbeck, and B. Stewart. 1993. Agricultural sources and sinks of carbon. *Water, Air and Soil Pollution* 70 :111-122.

Del Galdo, I., J. Six, A. Peressotti, and M.F. Cotrufo. 2003. Assessing the impact of land-use change on soil C sequestration in agricultural soils by means of organic matter fractionation and stable isotopes. *Global Change Biology* 9 :1204-1213.

Denison, R.F., D.C. Bryant, and T.E. Kearney. 2004. Crop yields over the first nine years of LTRAS, a long-term comparison of field crop systems in a Mediterranean climate. *Field Crops Research* 86 :267-277.

Golchin, A., J.M. Oades, J.O. Skjemstadt, and P. Clarke. 1994. Study of free and occluded particulate organic matter in soils by solid state ^{13}C CP/MAS NMR spectroscopy and scanning electron microscopy. *Australian Journal of Soil Research* 32 :285-309.

Horner, G.M., M.M. Oveson, G.O. Baker, and W.W. Pawson. 1960. Washington, Oregon and Idaho Agricultural Experiment Station and USDA-ARS. *Bull No.* 1.

Kuo, S., U.M. Sainju, and E.J. Jellum. 1997. Winter cover crops effects on soil organic carbon and carbohydrate in soil. *Soil Science Society of America Journal* 61 :145-152.

Rasmussen, P.E., and W.J. Parton. 1994. Long-term effects of residue management in wheat-fallow: I. Inputs, yield, and soil organic matter. *Soil Science Society of America Journal* 58 :523-530.

Six, J., E.T. Elliot, K. Paustian, and J. Doran. 1998. Aggregation and soil organic matter accumulation in cultivated and native grassland soils. *Soil Science Society of America Journal* 62 :1367-1377.

Six, J., E.T. Elliot, K. Paustian. 2000. Soil macroaggregate turnover and microaggregate formation: A mechanism for C sequestration under no-tillage agriculture. *Soil Biology and Biochemistry* 32 :2099-2103.

Tisdall, J.M., and J.M. Oades. 1982. Organic matter and water-stable aggregates in soils. *Journal of Soil Science* 62 :141-163.

This research was funded by the Kearney Foundation of Soil Science: Soil Carbon and California's Terrestrial Ecosystems, 2001-2006 Mission (http://kearney.ucdavis.edu). The Kearney Foundation is an endowed research program created to encourage and support research in the fields of soil, plant nutrition, and water science within the Division of Agriculture and Natural Resources of the University of California.