Residue and Nitrogen Management Effects on Carbon Cycling in Irrigated Conservation Tillage Systems

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Summary

One of the major challenges within California's irrigated conservation tillage systems is the rational management of residues from an operational and soil fertility standpoint. Only very few field experiments on conservation tillage have been established in California and none of them are > 10 years and/or have different residue management options. We capitalized on the existence of a unique long-term experiment in Northwest Mexico, established under similar climatic conditions as in the Central Valley. The conventional tilled bed planting (CTB) system is compared with permanent bed (PB) systems with different residue management (burning, partly removed, and retained) and N fertilizer treatments (0, 150 and 300 kg N ha^{-1} applied at planting, and 300 kg N ha^{-1} applied around 1^{st} node stage). Wheat is the main crop, with maize planted in the summer of most years. We measured crop performance, above- and belowground biomass, soil C and N stocks, microbial biomass C and N, stable aggregate fractions, and aggregate-associated C fractions to establish the link between residue and N fertilization management, soil C inputs, soil structure and C dynamics in PB with different residue management versus CTB systems.

Tillage/residue management effects on yields were small. Except, PB with residues burned (PB burned) resulted in a significant yield decline over time. No significant effects of management on root biomass were found. A clear decrease in macroaggregation was observed for CTB, compared to the PB with residue retention. Burning of residues had a detrimental effect on soil aggregation, compared to PB with residue retention, although to a lesser extent than tillage. Results indicate that total biomass inputs are not a major factor determining stable macroaggregation in those systems. PB burned showed the highest stabilization of soil C, although at the cost of yield decline and soil degradation. No significant differences in total soil C and N stocks due to tillage or residue retention levels were found. Any observed differences in C stocks could not be related to differences in macroaggregate stability or macroaggregate-within-macroaggregate formation.

The results suggest the existence of two largely separated decomposition phases: The residue layer shows relatively low decomposition, while belowground C contents remain low and largely unchanged by management. From a standpoint of rational residue management, not only the C sequestration should be taken into account but also the effects on soil quality and economic profitability. Burning of residues should therefore be discouraged. Partial residue retention may be the best option from a practical, soil quality and economic standpoint.

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Objectives

The overall objective of this project was to elucidate how residue and fertilizer management of PB systems affect soil C dynamics and stabilization compared to conventionally tilled system

The specific objectives were to determine the effects of tillage/residue and N management on:

1. Grain yields and above- and belowground biomass inputs.
2. Stable macroaggregation and microaggregate formation within stable macroaggregates.
3. The stabilization of total soil C and aggregate associated C and N.
4. Soil microbial biomass C and N.

Approach and Procedures

Research location and trial description

The research was carried out at the CIANO/CIMMYT experimental station, located near Ciudad Obregón in the state of Sonora, NW Mexico (lat. 27.33^0 N, long. 109.09^0 W, 38 m above sea level). The soil type is classified as coarse, sandy, mixed montmorillonitic typic Calciorthid containing 50% clay, 30% sand and 20% silt (homogeneous from 0-30 cm depth). The mean annual rainfall and mean daily temperature are 407 mm and 25.8^{0}C, respectively. The long-term trial was initiated in 1992 and involves a two-crop, annual rotation with wheat planted in late November and harvested in early May. Either maize (most years) or soybeans are planted in late May-early June and harvested in October, but in some years the land was left fallow in the summer. The experiment includes three replicates of different tillage/residue × N treatments arranged in a randomized complete block design with a split plot treatment.

The tillage/residue management treatments are:

1. Conventional tillage with reformation of new beds for each crop; all crop residues are incorporated (**CTB**)
2. Permanent beds; all residues are burned (**PB; burned**)
3. Permanent beds; crop residues are baled off for fodder, leaving only the standing stubble in the field, corresponding to ca. 30% of total residues (**PB; partial 1**)
4. Permanent beds; maize residues are baled off for fodder and wheat residues are retained in the field (**PB; partial 2**)
5. Permanent beds, all crop residues retained (**PB; allres**).

Superimposed on the tillage/residue treatments are different levels and timing of N fertilizer:

1. 0 N (0N)
2. 150 N ha^{-1} basal (150N)
3. 300 N ha^{-1} basal (300Nb)
4. 300 N ha^{-1} near 1st node (300Nf)

A homogeneous amount of 75 (until 2001) or 150 (after 2001) kg N ha^{-1} was applied at planting when maize was grown in summer. No N fertilizer was applied when soybean was grown.

General chemical soil characteristics for the different treatments are given in table 1.

Table 1. *Chemical soil properties as affected by management. Values are averaged across N treatments (tillage/residue effect) and tillage/residue treatment (N fertilizer effect). No significant interactions between tillage/residue and N management were found.*

Depth	Tillage/ Residue	pH_CaCl2 mean	ste		CEC (meq/100g) mean	ste		EC (mmhos/cm) mean	ste		SAR mean	ste		ESP mean	ste		P-Olsen (ppm) mean	ste	
0-15 cm	CTB	7.7	(0.0)	b	38.2	(0.5)	b	1.5	(0.0)	b	4.6	(0.2)	bc	10.8	(0.3)	b	6.7	(0.6)	ns
	PB burned	7.8	(0.0)	a	40.1	(0.6)	ab	2.7	(0.2)	a	6.4	(0.3)	a	14.6	(0.5)	a	6.9	(1.3)	
	PB partial 1	7.7	(0.0)	ab	39.3	(0.6)	ab	1.4	(0.1)	b	4.8	(0.2)	b	11.2	(0.4)	b	5.2	(0.8)	
	PB partial 2	7.7	(0.0)	b	39.8	(0.4)	ab	1.2	(0.1)	b	4.6	(0.1)	bc	10.7	(0.2)	bc	4.9	(0.5)	
	PB allres	7.7	(0.0)	b	40.6	(0.3)	a	1.1	(0.0)	b	4.1	(0.2)	c	9.5	(0.3)	c	6.3	(0.7)	
15-30 cm	CTB	7.7	(0.0)	c	35.5	(1.0)	ns	1.9	(0.1)	b	5.0	(0.3)	ab	12.3	(0.7)	ab	3.1	(0.3)	ns
	PB burned	7.8	(0.0)	b	38.0	(1.1)		2.6	(0.2)	a	6.6	(0.3)	a	15.4	(0.7)	a	3.1	(0.4)	
	PB partial 1	7.8	(0.0)	ab	38.9	(1.3)		1.9	(0.1)	b	6.1	(0.2)	ab	14.2	(0.4)	ab	2.1	(0.3)	
	PB partial 2	7.8	(0.0)	ab	40.0	(1.2)		1.7	(0.1)	b	5.8	(0.5)	ab	13.1	(1.0)	ab	2.3	(0.3)	
	PB allres	7.8	(0.0)	a	34.7	(1.3)		1.5	(0.1)	b	4.8	(0.4)	b	11.9	(0.9)	b	2.0	(0.4)	

Depth	N fertilizer	pH_CaCl2 mean	ste		CEC (meq/100g) mean	ste		EC (mmhos/cm) mean	ste		SAR mean	ste		ESP mean	ste		P-Olsen (ppm) mean	ste	
0-15 cm	0N	7.7	(0.0)	ab	39.3	(0.5)	ns	1.6	(0.2)	ns	5.1	(0.3)	a	11.7	(0.7)	a	9.2	(0.9)	a
	150N	7.7	(0.0)	a	39.7	(0.4)		1.7	(0.2)		5.1	(0.3)	a	11.9	(0.5)	a	4.8	(0.4)	b
	300Np	7.7	(0.0)	ab	39.7	(0.5)		1.5	(0.2)		4.5	(0.2)	b	10.5	(0.4)	b	5.1	(0.4)	b
	300Nf	7.7	(0.0)	b	39.6	(0.5)		1.6	(0.2)		4.8	(0.3)	ab	11.3	(0.5)	ab	4.8	(0.5)	b
15-30 cm	0N	7.8	(0.0)	ns	36.9	(1.1)	ns	1.9	(0.1)	ns	5.6	(0.4)	ns	13.4	(0.8)	ns	3.2	(0.4)	ns
	150N	7.8	(0.0)		36.6	(1.2)		2.0	(0.2)		5.7	(0.4)		13.7	(0.8)		2.0	(0.2)	
	300Np	7.8	(0.0)		38.3	(1.2)		1.8	(0.1)		5.3	(0.4)		12.5	(0.8)		2.6	(0.3)	
	300Nf	7.8	(0.0)		37.9	(1.2)		2.0	(0.1)		5.9	(0.3)		14.0	(0.6)		2.3	(0.3)	

Determination of grain yields, aboveground biomass inputs and residue cover

Available data on cropping history since the start of the trial, maize and wheat grain yield and harvest index were used to estimate the aboveground maize and wheat biomass inputs for each management treatment in each year. The fraction of residue retained for each of the different residue treatments was estimated as follows:

- CTB+res and PB+res: $f_{(\text{wheat residues})} = 1$; $f_{(\text{maize residues})} = 1$
- PB burned: $f_{(\text{wheat residue})} = 0$; $f_{(\text{maize residue})} = 0.05$
- PB wht stubble = $f_{(\text{wheat stubble})} = 0.30$; $f_{(\text{maize})} = 0.1$
- PB +wht/-mz = $f_{(\text{wheat stubble})} = 1$; $f_{(\text{maize})} = 0.1$

Residue cover was measured for the PB treatments only (since residues were incorporated in case of the CTB system) before wheat planting in November. Residues were collected in three 40 cm × 80 cm subplots per plot, covering the area from the bottom of a furrow to the bottom of the next furrow, across the bed. Residues were oven-dried for 48 hours at 70°C and weighed.

Determination of belowground biomass inputs (wheat roots)

Soil samples (0-30 cm) were collected in March 2006, along four transects perpendicular to the direction of the beds, to account for the spatial variability in root density with distance from the plants. The soil cores were divided into 0-15 cm and 15-30 cm depth increments. Once in the laboratory, root washing and biomass determination was done as described in detail by Barzegar et al. (2004).

Stable aggregate fractions, C and N concentrations and microbial biomass

Four intact soil cores (5.5 cm diameter) per plot were collected in May 2006, between wheat harvest and maize planting. Before sampling, the litter layer was removed and the 30 cm soil cores were divided into two depth increments: 0-15 cm and 15-30 cm. Once in the laboratory, the field moist samples were gently broken apart along their planes of weakness, air dried, combined per treatment replicate and depth layer and stored at room temperature.

Aggregate fractionation procedure and isolation of aggregate-associated POM fractions

An overview of the complete fractionation scheme is shown in figure 1. The procedure was as follows: 35 grams of air-dried soil samples were separated into three different aggregate size fractions by a wet-sieving method adapted from Elliott (1986): (1) > 250 µm (macroaggregates); (2) 53-250 µm (microaggregates); and (3) < 53 µm (silt and clay fraction). During sieving, water-stable aggregates were separated by manually moving the sieve up and down 3 cm with 50 repetitions during a period of 2 minutes. Water-stable aggregates were oven-dried (70°C) for 24 h, weighed and stored at room temperature. Microaggregates protected within macroaggregates (mM) were isolated according to Six et al. (2000). Macroaggregate (M) subsamples of 15 g were immersed in de-ionized water on top of a 250-µm-mesh screen inside a cylinder and shaken with glass beads until the complete disruption of all macroaggregates. Minimal break up of mM is ensured by continuous water flow flushing the < 250-µm sized material immediately to a 53-µm sieve. After macroaggregate disruption, coarse POM (> 250 µm) is retained on the 250-µm mesh screen. The material on the 53-µm sieve was wet-sieved (Elliott 1986) to separate water-stable microaggregates from the silt plus clay fraction (mineral-M). The fraction on top of the 53-µm sieve (53-250 µm) consists of microaggregates, fine POM that is not protected by microaggregates (inter-mM-POM), and fine sand. From a subsample of this 53-250-µm fraction, inter-mM-POM was isolated by density flotation (1.85 g cm^{-3} sodium polytunstate) and subsequently microaggregate-protected POM (intra-mM-POM) by dispersion of the heavy fraction (Six et al. 1998).

C, δ^{13}C and N contents and calculation of maize derived C

Straw, root, whole soil, soil aggregates, and POM fractions were finely ground to powder and analyzed for C and N content, and ^{13}C isotopic composition by a continuous flow design integrated with on-line sample combustion (ANCA-IRMS) at the Stable Isotope Facility at the University of California, Davis (UC Davis). Because the soil is calcareous, the calcium was first removed by HCl-fumigation according to Harris et al. (2001).

The fraction (f) of C derived from maize in the whole soil was calculated as:

$$f = \frac{\delta_{sample} - \delta_{initial}}{\delta_{maize} - \delta_{initial}}$$

where: δ_{sample} is delta PDB of the fraction; $\delta_{initial}$ is the delta PDB of soil samples taken from a neighboring continuous wheat field; and δ_{maize} is the delta PDB of the maize.

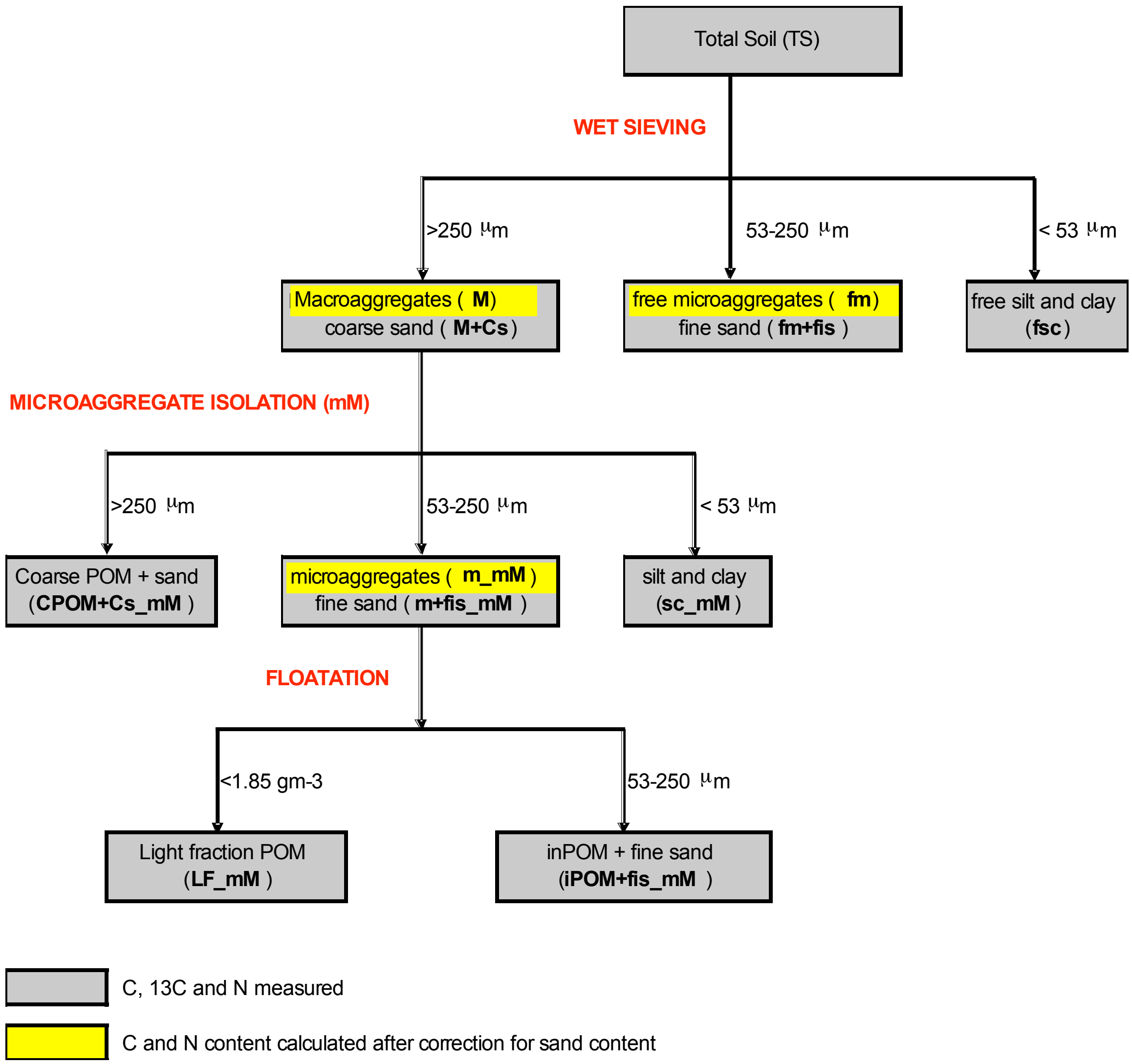

Figure 1. Soil fractionation scheme.

Determination of microbial biomass C and N

Soil samples for microbial biomass measurements were pre-incubated at 25°C for 10 days. After incubation, half of the samples were fumigated with chloroform for 24 h. After fumigation the fumigated soil samples were extracted by 0.5 M K_2SO_4 in a ratio of 4:1 liquid:solid. The other half of the subsamples were extracted at the time the fumigation started. The C concentrations and isotopic signature of extracts were determined with a TOC analyzer at the Stable Isotope Facility of UC Davis. N concentrations were determined colorometrically with an auto analyzer. Microbial biomass C and N contents were calculated from the difference between fumigated and non-fumigated control using k factors derived from Vance et al. (1987) and Moore et al. (2000).

Results

Aboveground biomass inputs

Wheat grain yield (averaged across tillage/residue treatments) increased with increasing amounts of N fertilizer added, but timing of N application in case of 300 kg N ha^{-1} did not significantly affect yields when averaged across tillage/residue treatments (*table 2*). However, a significant yield decrease was observed for PB burned when N application was delayed until first node stage. The PB allres led to the highest grain yields, irrespective of N fertilizer treatment, although closely followed by, and not significantly different from CTB. Within the PB treatments, PB burned led to a significant yield decrease compared to PB with at least some level of residue retention. PB with partial residue retention had intermediate yields. Maize yields did not show any significant differences between management systems (*table 3*) but it should be noted that yield differences for both wheat and maize are diverging with time.

Table 2. *Average wheat grain yields as affected by tillage/residue management and N fertilizer treatment. Standard errors are given between parentheses. Values followed by different letters are significantly different (p<0.05).*

Tillage/residue management	0N			150N basal			300N basal			300N at 1st node			All N treatments		
CTB	3394	(142)	ab	6180	(31)	a	6745	(11)	abc	6876	(131)	ab	5914	(345)	ab
PB allres	3759	(98)	a	6293	(114)	a	7098	(63)	a	7091	(36)	a	6146	(332)	a
PB burned	3153	(151)	b	6000	(181)	a	6683	(63)	bc	6192	(45)	c	5639	(342)	c
PB partial 1	3465	(85)	ab	6170	(103)	a	7005	(90)	ab	6888	(59)	ab	5927	(345)	b
PB partial 2	3747	(83)	a	6259	(123)	a	6550	(153)	c	6628	(153)	bc	5897	(293)	b
All tillage/res treatments	3504	(75)	C	6180	(53)	B	6816	(64)	A	6735	(90)	A	5905	(146)	

Table 3. *Average maize grain yields as affected by tillage/residue management. No significant differences were found between N treatments, since those are only applied to the wheat crop. Values followed by different letters are significantly different (p<0.05).*

Tillage/residue management	All N treatments		
CTB	3213	(83)	ns
PB allres	3149	(79)	
PB burned	3289	(97)	
PB partial 1	3215	(111)	
PB partial 2	3294	(104)	

Residue cover

In November 2006 (after maize harvest and before wheat planting), residue cover was considerably greater than the total amount of maize residues produced during the maize cycle (± 172% irrespective of N fertilizer treatment; *table 4*), indicating that residues produced during the preceding wheat cycle had not yet been decomposed completely.

Table 4. *Residue cover in November 2006, as compared to residue production in 2006 cropping season.*

Till/ Res	N	November residue cover (kg ha -1)	Maize straw produced in 2006 (kg ha-1)	Residues retained (as % of maize residue production)	Wheat straw produced in 2006 (kg ha-1)	Residues retained (as % of wheat + maize residue production)
PB burned	0N	2917	3232	91	5799	32
	150N	2938	1991	154	6226	36
	300Nb	2476	2876	88	7022	25
	300Nf	2813	3092	91	7007	28
	All N treatments	**2786**	**2798**	**106**	**6514**	**30**
PB partial 1	0N	3424	5204	66	6986	28
	150N	4781	7091	68	4972	40
	300Nb	3434	5526	65	4968	33
	300Nf	3854	7201	57	5428	31
	All N treatments	**3873**	**6256**	**64**	**5588**	**33**
PB partial 2	0N	5104	6255	81	5679	42
	150N	3667	5759	65	4984	34
	300Nb	3993	6143	64	5028	35
	300Nf	5358	4544	119	5161	55
	All N treatments	**4530**	**5675**	**82**	**5213**	**42**
PB allres	0N	10451	6170	170	6196	84
	150N	11257	6385	176	6693	86
	300Nb	10090	5903	174	6493	81
	300Nf	8788	5291	169	6046	78
	All N treatments	**10147**	**5937**	**172**	**6357**	**82**

Below ground biomass inputs

There were no significant differences in wheat root biomass in the top 30 cm of the different tillage/residue or fertilization treatments (*figs. 2 and 3*). However, a trend can be observed that is repeated in both depths. First, there is trend of lowest root biomass in burned plots versus greatest root biomass in PB with full residue retention. Second, root biomass tends to be greatest when fertilizer N is applied at basal whereas it tends to be lower when the N application was at 1st node stage.

Aggregate fractionations and C and N concentrations

The percentage of water-stable macroaggregates was significantly lower in CTB than in the PB allres at both depths (*fig. 4*). Within the PB systems, PB burned had significantly less water stable macroaggregates than the PB with partial or, especially, with full residue retention. The differences were more pronounced at 0-15 cm depth than at 15-30 cm depth. The percentage of microaggregates-within-macroaggregates did not show any significant differences between management systems (data not shown) and as a consequence the amount of micros-within-macroaggregates expressed on a total soil weight basis followed a similar pattern in response to management as the stable macroaggregate fraction (*fig. 4*).

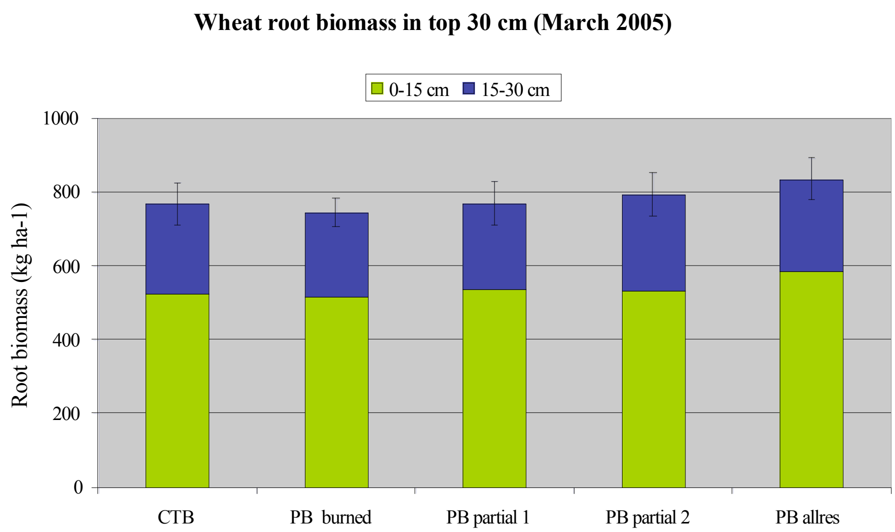

Figure 2. Wheat root biomass stocks (0-15 and 15-30 cm depth) in the different tillage/residue treatments averaged across fertilization treatments.

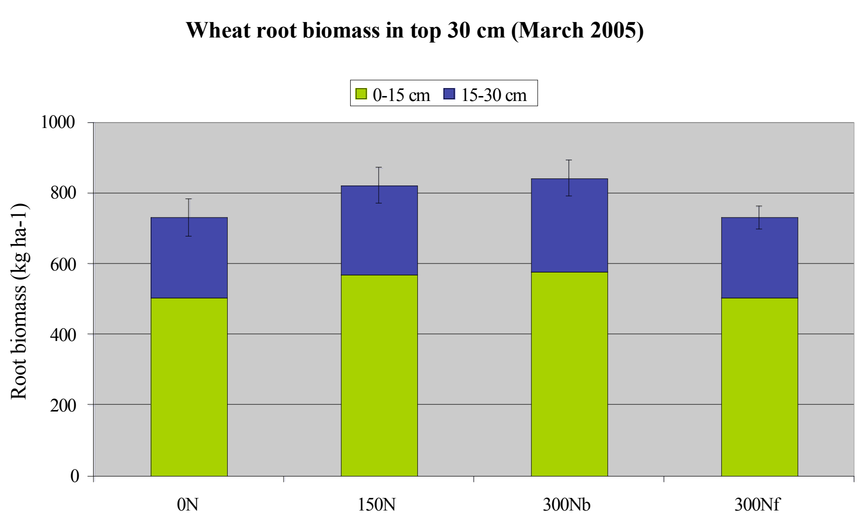

Figure 3. Wheat root biomass stocks (0-15 and 15-30 cm depth) in the different fertilization treatments averaged across tillage/residue treatments.

The same pattern was observed for the C distribution across macroaggregates and micro-within macroaggregates (*fig. 4*), because no differences in C percentages of those fractions, nor in total soil C contents were found between tillage/residue treatments. No significant differences in POM distribution across fractions was found (data not shown).

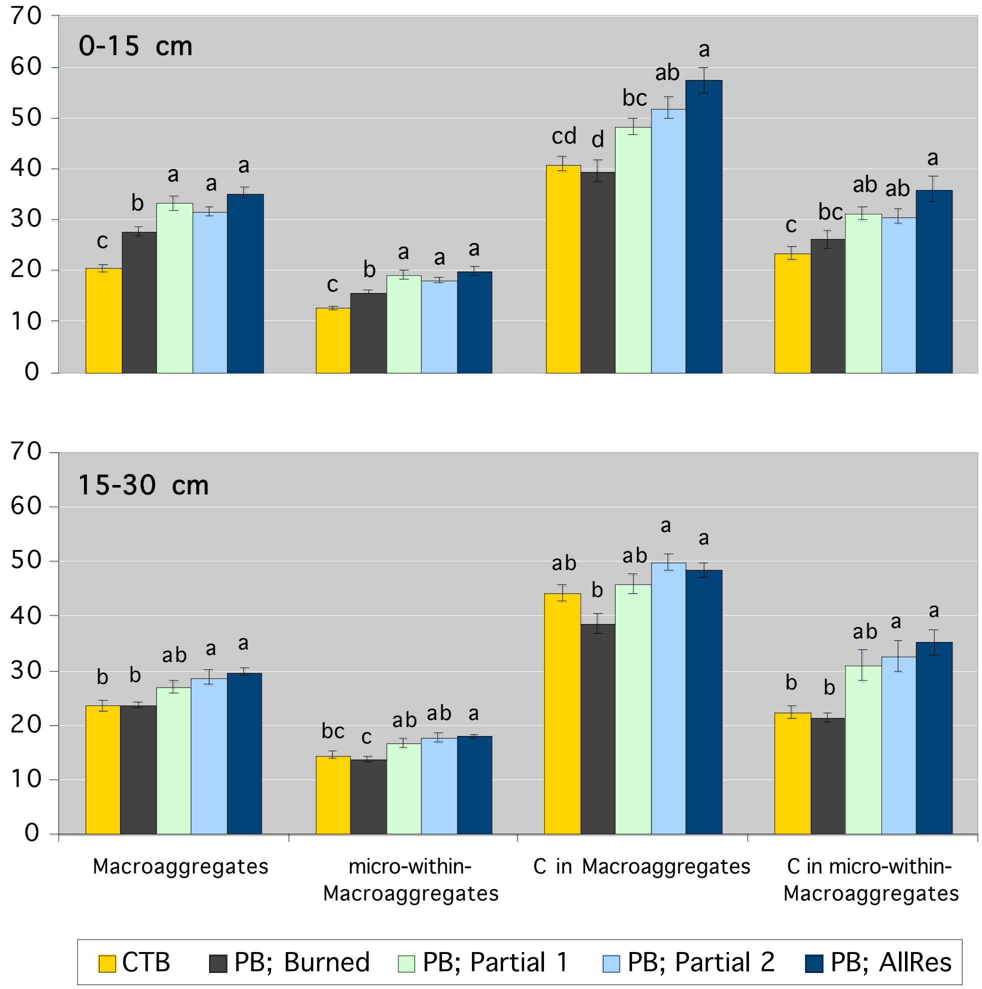

Figure 4. Stable macroaggregate and microaggregate-within-macroaggregate mass percentages (sand corrected) and their relative contribution to total soil C contents. Error bars indicate standard errors and different letters indicate that values are significantly different between tillage/residue management treatments.

No significant differences of N fertilizer management on water stable macroaggregation or microaggregates-within-macroaggregates were found and no interaction between tillage/residue system and N treatment occurred.

Total soil C and N stocks and maize-derived C

In addition to C concentrations comparisons, comparisons were made between C stocks (Mg ha^{-1}) based on an equivalent soil mass (Ellert and Bettany 1995). At 0-15 cm depth, no significant differences in soil C concentrations, except for the PB partial 1 system had a lower soil C concentration. At 15-30 cm depth the C concentration was highest in the CTB system. The same trend was observed in the soil N concentrations. However, C stocks of the top 15 cm were highest in the PB allres and PB burned systems. At 15-30 cm depth, the largest C stocks were again found in the CTB system with residue incorporation. A similar pattern was found for N.

Carbon and N concentrations tended to increase with increasing N inputs at both depths, although these differences are not significant anymore when corrected for bulk density differences.

Highest total C stocks (*table 6*) were found in the PB burned system. No significant differences occurred due to tillage or due to different residue retention levels in PB systems. Soil N stocks followed the same pattern but did not show any significant differences due to tillage/residue system. With respect to N fertilizer application rate, both C and N stocks were highest in the 300N treatment, when applied at first node, and lowest in the 0N treatment.

Table 5. *Total soil C and N concentrations as affected by tillage/residue management and N fertilizer treatment. Standard errors are given between parentheses. Values followed by different letters are significantly different ($p<0.05$).*

Tillage/res system	N treatment	Soil C (g kg-1) 0-15cm			Soil C_Eq soi mass (Mg ha-1) 0-15cm			Soil N (g kg-1) 0-15cm			Soil N_Eq soi mass (Mg ha-1) 0-15cm		
CTB		7.01	(0.14)	a	1054	(33)	c	0.56	(0.02)	ab	84.9	(4.0)	b
PB burned		7.24	(0.20)	a	1329	(41)	a	0.53	(0.02)	ab	97.5	(3.4)	ab
PB partial 1		6.17	(0.10)	b	1119	(25)	c	0.49	(0.02)	b	89.0	(3.3)	b
PB partial 2		6.73	(0.12)	a	1220	(30)	abc	0.54	(0.02)	ab	97.4	(3.1)	ab
PB allres		7.11	(0.12)	a	1270	(29)	a	0.57	(0.01)	a	102.3	(2.6)	a
	0N	6.50	(0.13)	b	1140	(38)	ns	0.50	(0.01)	b	87.1	(3.3)	ns
	150N	6.95	(0.18)	ab	1215	(44)		0.54	(0.01)	ab	94.4	(3.2)	
	300Nb	7.05	(0.14)	a	1199	(26)		0.56	(0.02)	a	95.2	(2.3)	
	300Nf	6.92	(0.14)	ab	1239	(40)		0.56	(0.02)	a	100.1	(3.7)	

Tillage/res system	N treatment	Soil C (g kg-1) 15-30 cm			Soil C_Eq soi mass (Mg ha-1) 15-30 cm			Soil N (g kg-1) 15-30 cm			Soil N_Eq soi mass (Mg ha-1) 15-30 cm		
CTB		5.46	(0.13)	a	1052	(31)	a	0.40	(0.02)	a	77.5	(3.5)	ns
PB burned		4.73	(0.11)	b	1003	(31)	ab	0.38	(0.01)	ab	80.4	(2.1)	
PB partial 1		4.44	(0.10)	b	885	(29)	b	0.36	(0.01)	b	71.3	(3.3)	
PB partial 2		4.48	(0.12)	b	916	(23)	b	0.37	(0.01)	ab	75.3	(2.4)	
PB allres		4.55	(0.09)	b	917	(19)	b	0.36	(0.01)	b	72.3	(2.3)	
	0N	4.50	(0.10)	b	909	(19)	ns	0.35	(0.01)	b	70.2	(1.8)	ns
	150N	4.71	(0.17)	ab	971	(29)		0.36	(0.01)	ab	75.4	(2.0)	
	300Nb	4.78	(0.14)	ab	947	(35)		0.38	(0.01)	ab	75.4	(2.7)	
	300Nf	4.95	(0.11)	a	989	(26)		0.40	(0.01)	a	80.1	(3.0)	

Table 6. *Total soil C and N stocks in the top soil as affected by tillage/residue management and N fertilizer treatment. Standard errors are given between parentheses. Values followed by different letters are significantly different (p<0.05).*

Tillage/res system	N treatment	Soil C_Eq soi mass (Mg ha-1) 0-30 cm			N_Eq soi mass (Mg ha-1) 0-30 cm		
CTB		2105	(45)	b	162.4	(6.5)	ns
PB burned		2324	(62)	a	177.2	(4.0)	
PB partial 1		2010	(43)	b	160.7	(5.3)	
PB partial 2		2136	(31)	b	172.7	(4.1)	
PB allres		2186	(45)	ab	174.6	(3.8)	
	0N	2052	(33)	b	157.7	(3.5)	b
	150N	2186	(50)	ab	169.8	(4.3)	ab
	300Nb	2144	(43)	ab	170.4	(3.3)	ab
	300Nf	2228	(55)	a	180.2	(5.3)	a

Table 7 shows preliminary data estimating the fraction (f) of maize derived vs. wheat derived C in soils of the different management systems and N fertilizer treatments. Data are preliminary because δPDB values of maize inputs are not yet available. We used values derived from the literature (-12 ‰ ; Dignac et al. 2005). The results show that the soil in the CTB system contains relatively more wheat derived C than the PB allres system. No significant differences were found between the PB systems with different residue management. There was no significant effect of N management, although the maize derived C fraction was slightly higher in the 0N treatment at both depths.

Microbial biomass C and N

Microbial biomass C and N responded significantly to residue/tillage system and N management in the 0-15 cm, but not in the 15-30 cm (*table 8*). The MBC was about twice as high at 0-15 cm depth than at 15-30 cm depth. No significant interactions between tillage/residue system and N treatment were found.

The highest microbial biomass C was found in the CTB system. The MBC was lower, though not significantly ($p<0.05$) in the PB allres system. The lowest values were found in the PB burned system and the two PB systems with partial residue retention had an intermediate MBC. C:N ratios and isotopic signature were similar in all systems apart from the PB burned, that was characterized by a higher C:N ratio and δPDB value. There is a lower MBC, accompanied by a higher δPDB in the 0N treatment compared to the other N treatments. No significant differences in MB C:N ratio was found across N treatments.

The MBC as a fraction of TSC was greater in the CTB system compared to the PB systems with residue retention (Table 8). The PB burned has a considerably lower MBC, also when expressed as a fraction of TSC.

Table 7. *Preliminary data estimating the fraction (f) of maize-derived vs. wheat-derived C in soils and residue layer of the different management systems and N fertilizer treatments. Values followed by different letters are significantly different (p<0.05).*

	depth	treatment	dsample	f (maize derived)	
TSC	0-15	1 CTB	-21.0	0.18	b
		2 PB-burned	-20.6	0.21	ab
		3 PB-partial1	-20.5	0.22	ab
		4 PB-partial2	-20.5	0.22	ab
		5 PB-allress	-20.5	0.22	a
TSC	0-15	0N	-20.3	0.24	NS
		150N	-20.7	0.20	
		300Nb	-20.7	0.20	
		300Nf	-20.7	0.20	
TSC	15-30	1 CTB	-20.4	0.19	NS
		2 PB-burned	-20.6	0.18	
		3 PB-partial1	-20.9	0.15	
		4 PB-partial2	-20.8	0.16	
		5 PB-allress	-20.6	0.17	
TSC	15-30	0N	-20.3	0.24	NS
		150N	-20.7	0.20	
		300Nb	-20.7	0.20	
		300Nf	-20.8	0.19	

Table 8. *Microbial biomass C, C:N ratio and δPDB of the microbial biomass as affected by tillage/residue management and N fertilizer treatment. Standard errors are given between parentheses. Values followed by different letters are significantly different (p<0.05).*

Tillage/res system	N treatment	MBC (mg kg-1)			C:N_MB			Delta_PDB_MBC			MBC (as % of TSC)		
CTB		421	(121)	a	7.4	(0.2)	b	-19.9	(0.2)	b	6.1	(0.2)	a
PB burned		300	(87)	d	8.6	(0.4)	a	-18.1	(0.2)	a	4.2	(0.1)	c
PB partial 1		338	(98)	cd	7.6	(0.2)	b	-19.4	(0.2)	b	5.5	(0.2)	b
PB partial 2		356	(103)	bc	7.5	(0.2)	b	-19.4	(0.3)	b	5.3	(0.1)	b
PB allres		383	(110)	ab	7.0	(0.2)	b	-19.5	(0.2)	b	5.4	(0.2)	b
	0N	314	(81)	b	7.4	(0.2)	ns	-18.5	(0.3)	a	4.9	(0.1)	b
	150N	383	(99)	a	7.6	(0.3)		-19.3	(0.2)	b	5.6	(0.3)	a
	300Nb	370	(95)	a	7.9	(0.4)		-19.7	(0.2)	b	5.3	(0.2)	ab
	300Nf	372	(96)	a	7.6	(0.2)		-19.5	(0.2)	b	5.4	(0.2)	ab

Discussion

Our overall hypothesis was that the combination of conservation tillage, residue retention, and rational fertilization results in a greater soil C sequestration and N retention. We rationalized this hypothesis further by postulating that the enhanced C and N stabilization would be attributable to an increase in above- and belowground biomass inputs, microbial biomass, stable aggregation, free particulate organic matter and, especially, micro-within macroaggregate-associated soil organic matter.

We furthermore outlined the following specific hypotheses:

- The combination of conservation tillage and increasing levels of residue retention and N fertilization enhances water and N availability and consequently microbial biomass and plant growth, resulting in increased above- and belowground C and N inputs into the soil (H1).
- The combination of conservation tillage and increasing levels of residue retention and N fertilization enhances stable macroaggregation and decreases macroaggregate turnover resulting in the formation of microaggregates within stable macroaggregates (H2a).
- In conservation tillage systems, removal of residues, especially by burning, will decrease stable macroaggregation, thereby increasing macroaggregate turnover, allowing less formation of microaggregates within stable macroaggregates (H2b).
- Consequently, stabilization of soil C and N, and preferentially C and N stabilized in microaggregates within macroaggregates, will increase in the order: permanent bed-burned ≤ conventional tillage, residues incorporated < permanent bed; only wheat stubble < permanent bed; residues partly removed ≤ permanent bed; full residue retention (H3).

H1 management effects on crop performance and biomass inputs

Tillage/residue management effects on long-term wheat and maize yield were relatively small, especially when compared to results from other tillage trials in rain-fed conditions (Sayre and Hobbs 2003). This can be explained by the fact that any physical soil degradations due to mismanagement can be (partly) overcome by high irrigation intensity. The only exception is the PB system with residues burned, which has resulted in a significant yield decline over time, and is still declining further. The yield decline was highest when the application of N fertilizer was delayed until first node stage, which suggests that PB burned has less buffering capacity to retain N and/or release it at the start of the wheat growing season. Soil chemical analyses indicated that differences between management systems are mainly found in salinity and sodicity related parameters. Especially when the soil under PB burned showed high values of EC and exchangeable sodium. Except for possible direct effects on crop performance, this may well be indicative of a decline in physical soil properties and water availability (through less infiltration and/or higher evaporation). Irrespective of the tillage/residue management system, increasing amounts of N fertilizer from 0 to 150 to 300 kg N ha^{-1} increased wheat yields. However, no carry-over effect on the subsequent maize crop was observed.

The wheat root biomass data are in line with Barzegar et al. (2004), who found a wheat root biomass at anthesis (for flood-irrigated system in Iran wheat with yields around 4 t and total biomass around 10 t ha) around 0.2 mg cm^{-3} in the top 30 cm. When we express our average root biomass in the same units, the values are 0.26 mg cm^{-3} with a production of around 7 t ha^{-1} grain yield. Data on the same location for wheat systems under conventional tillage indicate that root biomass in the top 30 cm is around 60% of total root biomass between 0-120 cm depth (M. Reynolds, personal communication). No significant effects of management on belowground biomass of wheat were found although both depths showed a general, but less pronounced, trend corresponding with differences in yield. This suggests that any differences in crop performance due to N limitations or burning of crop residues are accompanied by a higher investment of the plant in belowground functions, probably to overcome water and/or nutrient limitations. It is thus suggested that any differences in aboveground inputs are partly negated by belowground inputs. However, estimating absolute amounts of belowground biomass or C inputs is not straightforward, since the rate of turnover of root biomass is not known.

In conclusion, differences in biomass input between tillage/residue systems are largely determined by residue retention level and less by crop performance. The N treatments, however, did represent differences in yield-related biomass inputs, especially when considering aboveground inputs.

H2a & b management effects on stable macroaggregation and microaggregate formation

A clear decrease in stable macroaggregation was observed for CTB, compared to the permanent bed plots with full or partial residue retention, which is in line with previous studies indicating a less well structured soil in plowed systems (e.g., Six et al. 2000). Moreover, burning of residues in permanent bed systems was shown to have a detrimental effect on soil aggregation, compared to permanent beds with residue retention, although to a lesser extent than tillage. It has been suggested that not only the direct effect of increased disturbance, but also the general observed reduction in microbial biomass/activity (e.g., Frey et al. 1999; Simpson et al. 2004) leads to a reduction in aggregation because the microbial biomass produces binding agents holding together aggregates (Tisdall and Oades 1982). However, our results do not support this. The conventional system does not have a lower microbial biomass, compared to the permanent bed systems with full or partial residue retention. The C inputs and soil C content were at least equally high as in the PB systems. All this indicates that the disturbance by tillage itself plays a major role in the reduction of soil structure. However, the PB-burned system also has a significantly lower percentage of water-stable macroaggregates in the top 15 cm, compared to the other PB systems, though not as low as the CTB system. Two factors may explain these observations: less availability of reactive soil organic matter due to the charring (as indicated by the low microbial biomass), and high exchangeable sodium compared to the other PB systems (*table 1*). The observation that total biomass inputs are not a major factor determining stable macroaggregation in those systems is also supported by the fact that N fertilizer application levels had no effect on stable macroaggregation.

H3 management effects on C and N stabilization in total soil and aggregates

Our hypothesis that stabilization of soil C and N, and preferentially C and N stabilized in microaggregates within macroaggregates, would increase in the order PB burned ≤ CTB < PB partial 1 < PB partial 2 ≤ PB allres was not confirmed by our results. Therefore, any observed differences in C stocks could not be related to differences in macroaggregate stability or macroaggregate-within-macroaggregate formation. No differences in C contents of aggregate fractions were observed. However, the PB burned showed the highest stabilization of soil C, especially when corrected for the relatively high bulk density of the soil under this system. CTB had a different C distribution with depth than the PB systems, due to residue incorporation. A relatively larger part of TSC was present below 15 cm, thus stressing the importance of taking soil samples of at least the whole plow layer when comparing C sequestration potential between systems. Another important consideration is the differences in soil mass sampled, depending on differences in bulk density between tilled and no-till systems since this can significantly affect calculations of total C stocks (Ellert and Bettany 1995). When C stocks in the whole top soil (0-30 cm depth) were expressed on an equivalent soil mass basis, C and N stabilization of soil C and N increased in the order PB partial 1 ≤ CTB ≤ PB partial 2 ≤ PB allres < PB burned. That burning did lead to higher C (not N) stocks despite lower input levels – probably due to the greater recalcitrance of the charred materials and a lower overall decomposition rate (as indicated by the low microbial biomass).

Regarding the effect of N fertilizer management: there is a small, but significant increase in C and N stocks when comparing the 0N treatment with the 300Nf treatment, which may be explained by both differences in C inputs and N availability which influences residue decomposition.

When determining total soil sequestration, the residue layer may have to be taken into account. In our case, we calculated that the C held in the residue layer of the PB allres system represented about 10%-15% of total soil C stocks, and about 66% of this survived at least one crop cycle. From the point of view of rational residue management, this may mean that the residue cover may become too thick over time when all residues are retained. From a scientific point of view, it raises the question why residue decomposition seems to be rather low, despite high temperatures, solar radiation and frequent irrigation, while soil C contents remain relatively low and largely unchanged by management. One explanation could be that there is little exchange of organic matter between the aboveground and the belowground phase in the PB systems and that belowground conditions are largely determined by root inputs. Although the systems are characterized by low soil faunal activity and diversity, the vertic properties of the soil cause some natural incorporation of organic matter into the soil.

Conclusions

Our **overall hypothesis** that the combination of reduced tillage, residue retention, and rational fertilization results in a greater soil C sequestration and N retention was not confirmed by our data. Despite clear negative effects of tillage and, to a lesser extent, residue burning on stable macroaggregation, no relation between soil aggregation and C and N stocks was observed. The practice that did lead to C sequestration was PB burned, but at the cost of yield decline and soil degradation (as expressed by decreased aggregation and microbial biomass and increased salinity and sodicity) as compared to the other PB systems. When defining rational residue management practices for California systems under highly productive irrigated cropping systems, not only the C sequestration should be taken into account but also the effects on soil quality as well as economic profitability. Burning of residues should be discouraged. However, partial residue retention may be the best option from a practical, soil quality and economic standpoint. No significant decline in chemical soil parameters, stable soil aggregation, and microbial biomass C and N were detected after 14 years, as compared to PB allres, while the yield decline is small (<3%) and part of the residues can be sold or used as fodder.

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