EFFECT OF BIOENERGY CROP RESIDUE REMOVAL ON SECONDARY AND MICRONUTRIENTS IN MINNESOTA SOILS

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FINAL REPORT

Summary of two years of research: 2010 to 2011

INTRODUCTION

Over the past 150 years, atmospheric CO_2 has increased due to fossil fuel combustion, deforestation, and land use change (Lal, 2004). Several near- and long-term strategies have been discussed to reduce CO_2 emissions. Some of the near-term options include changes in land management practices, including improved agricultural and energy use efficiency (Calderia et al., 2004). Long-term options include C storage in geologic reservoirs, large-scale development of non-C based or renewable energy sources, cessation of deforestation, development of energy-efficient transportation systems, and development of highly efficient coal technologies (Caldeira et al., 2004).

Development of bioenergy products is one proposed solution to reduce U.S. dependence on foreign oil, which accounts for 60% of present consumption (Dhugga et al. 2007). The use of cellulosic biomass for fuel production has been presented as one alternative, and researchers have actively sought to develop new organisms or enzymes that can convert cellulosic biomass to ethanol for motor vehicle fuel (Wilhelm et al. 2004). There are several sources of cellulosic biomass such as woody biomass crops, lumber industry wastes, forage crops, industrial and municipal wastes, animal manure and crop residue, but very few of the sources are perceived to be available in sufficient quantity and quality to support the processing facilities, except for crop residues (DiPardo, 2000, cited by Wilhelm et al. 2004).

The use of corn stover appears to be a potential alternative feedstock for bioenergy and bio-based products in the near future. Among crops, corn has greater residue production (45%) than soybeans (24%), wheat (16%) and other cereals (8%) (Wright et al. 2006, cited by Dhugga, 2007). One of the advantages of corn as a feedstock is that is already used for grain production and does not require dedicated land like switchgrass or miscanthus (Dhugga, 2007). However, there is concern about how much residue can be removed and still maintain the sustainability of the cropping system.

Production of biofuels can alter nutrient removal by changes in the crop species and plant part harvested, and the amount of residue removed. On average, nutrient removal rates for corn grain in Minnesota are 1.0, 0.35, 0.25 and 0.07 lb bu^{-1} for N, P_2O_5, K_2O and S respectively (Rehm, 2004). For corn stover these values are 0.5, 0.25, 1.05 and 0.09 lb bu^{-1} for N, P_2O_5, K_2O and S respectively (Rehm, 2004), which represents an important loss of nutrients from the soil if all the stover is removed as feedstock. Although secondary and micronutrients do not typically need to be applied in most Minnesota soils, the accelerated rate of soil removal if residues are harvested warrants this investigation. Measuring amounts of secondary nutrients (Ca, Mg, and S) and micronutrients in the soil when residues are removed at different rates can help determine amounts of fertilizer that will be required to maintain productivity.

Wilhelm et al. (2006) estimated that total stover production for the four states with the greatest corn grain production (Iowa, Illinois, Nebraska and Minnesota) represents 54% of the estimated total U.S residue production and that Minnesota would contribute approximately 9.6 % if all the residue produced were used for ethanol production. This significant share of feedstock suggests that if cellulosic ethanol becomes a feasible economic alternative in Minnesota, farmers will start harvesting corn stover as feedstock, leading to potential effects on soil quality and nutrient availability. More research on effects of corn biomass removal is needed to mitigate these potential negative effects.

The objectives of this research under continuous corn with different rates of residue removal were to:

1) evaluate the plant removal rate of secondary nutrients, Ca, Mg, and S, and micronutrients (B, Zn, Cu, and Mn);

2) evaluate the availability of the secondary nutrients Ca, Mg, and S and micronutrients (B, Zn, Cu, and Mn) in the soil; and

3) estimate the effect of residue removal on soil quality indicators such as potentially mineralizable nitrogen and carbon (PMN and PMC) and particulate organic matter carbon and nitrogen (POM-C and POM-N).

MATERIALS AND METHODS

Experimental sites

Data were collected during the 2010 and 2011 corn growing seasons at three locations where experiments with different residue removal rates have been established under continuous corn. The experiments are located at Rosemount (Waukegan silt-loam) and Southwest (at Lamberton; Normania Ves silt loam) Research and Outreach Centers; and in a farm field in Northfield (Rice County; (Waukegan silt-loam). Tillage comparisons for conventional-till (CT) vs. strip-till (ST) were evaluated at the three sites. At Lamberton and Rosemount the conventional-till was chisel plow, and at Northfield CT was moldboard plow.

The experiment in Lamberton, MN tests two tillage systems: CT (chisel) and ST and 3 residue removal rates: 0, 50 and 100% removal. Residue removal rate treatments were established at the end of the 2007 corn growing season. The experimental design is a split-plot design with 4 replications, where tillage is the main plot and residue management is the split-plot. Plot size is 30 ft x 65 ft.

In Northfield, MN, the experiment includes two tillage systems, CT (moldboard) and ST, and 3 residue removal rates (0, 50 and 100% removal). Residue removal rate treatments were established at the end of the 2008 corn growing season. The experimental design is a split-plot design with 3 replications, where tillage is the main plot and residue management the split-plot. Plot sizes are 20 ft. x 150 ft. for the 50% and 100% removal treatments, and 40 ft. x 150 ft. for the 0% removal treatments.

The experiment in Rosemount, MN is part of another study where we sampled CT (chisel) and ST systems and 3 residue removal rates (0, 50 and 100% removal). Residue removal rate treatments were established at the end of the 2008 corn growing season. The experimental design was considered a split-plot design with 2 replications, where tillage is the main plot and residue management the sub-plot. Plot sizes are 30 ft. x 200 ft. for the 0, 50 and 100% removal treatments.

Soil and plant sampling

Soil sampling was performed at the beginning of each growing season at the three experimental locations: Rosemount, Northfield and Lamberton. Soil samples were taken a few days after corn was planted (corn had either not yet emerged or had only one leaf) in May 2010, and at the 4-leaf stage in June 2011.

Soil sampling was performed at 0-5, 5-15, 15-30, 30-60 and 60-90 cm soil depth using a truck with a mounted Giddings probe. For each treatment 2-3 cores were taken, with additional hand-probe sampling for the surface depths (0-5 cm). Composited soil samples were divided into two bags, one for nutrient analysis and the other for soil quality indicators (PMN, PMC and POM-C and N).

For the secondary nutrients and micronutrient analysis, soil samples at each depth were air-dried and sent to AGVISE Laboratory (Benson, MN) to determine soil availability. Calcium (Ca) and magnesium (Mg) were extracted with ammonium acetate in a 1:10 ratio, and the micronutrients Zn, B, Cu, Mn were extracted with DTPA using a 10:20 ratio. Elemental analyses were performed using inductively coupled plasma atomic emission spectroscopy (ICP). Sulfur concentration was determined by extraction with KCl (5:12.5 ratio) and analysis with a flow injection turbidometric method.

Plant and grain biomass was collected at harvest (Fall) in 2010 and 2011. Plant samples were sent to the Research Analytical Laboratory at University of Minnesota for the analysis of secondary and micronutrients. Nutrient concentrations were determined using a dry ashing method (485ºC ashing temperature) and elemental analysis was conducted by ICP. Total sulfur concentration was determined using a LECO SC-132 S Determinator.

Soil quality indicator measurements

As measures of active organic matter pools and soil quality, we determined potentially mineralizable N and C with 28 day incubations that were modified from the aerobic incubation method described by Drinkwater et al. (1996). Soil samples were sieved, air-dried and placed in beakers in 1-L Mason jars for incubation at 25ºC). Carbon dioxide was trapped and measured after 10 (flush) and 28 (basal respiration) days, and KCl extractions for inorganic N were compared for pre- and post-incubated soils. Mineralizable C was determined as the sum of the flush C mineralization and basal soil respiration.

Particulate organic matter was fractionated as SOM >53 µM using the Turbo POM methodology (Marriot and Wander, 2006). Briefly, soil samples were placed in 30mL plastic bottles covered with 53 µm mesh, then sealed with caps that had holes drilled in them, allowing all materials < 53 µm to pass through the mesh fabric. The 30 mL bottles were placed in 250 mL centrifuge bottles with a sodium hexametaphosphate solution and shaken for 1 h on a reciprocal shaker, then shaken twice with tap water. The remaining POM was rinsed and dried to determined C and N. For both sets of measurements, C and N were measured using a a Vario Max C/N analyzer.

Results

Plant secondary nutrients and micronutrients removal

The distribution of corn biomass in the 2010 and 2011 growing seasons is presented in Table 1. Plant nutrient removal during the 2010 growing season represents the second year after establishment of residue removal rate treatments for the Northfield and Rosemount sites, and the third year for the Lamberton site. The 2011 growing season represents the third year after treatments were imposed for Northfield and Rosemount, and the fourth year for Lamberton.

At Northfield and Lamberton, there were no significant differences between tillage systems in the amounts of plant nutrients removed either in the 2010 or 2011 growing seasons (Table 2). At Rosemount, the conventional-till treatment removed significantly greater amounts of Ca and Mg in both years, and more S and B than strip-till in 2010 (Table 2). Greater removal rates were at least partially explained by greater yields in the conventional-till system.

For all three sites, different residue removal rates resulted in significant differences in the amount of plant nutrients lost from the site. As expected, the amount of plant nutrient removal was significantly greater in the 100% than the 50% removal rate treatments for all locations in both evaluated years (2010-2011) (Tables 3, 4, and 5). At Lamberton, where 50% of all combined plant parts was removed rather than just the top half and cobs, the nutrient removal rate was about half that of the 100% removal rate, with some variation due to differences among the plots (Table 4). However, in Northfield and Rosemount, where only the top half of the plants and the cobs were removed in the 50% treatment, more than twice the nutrients were lost in the 100% removal treatments compared to the 50% removal rate (Tables 3 and 5). This resulted from the fact that a greater proportion of the corn biomass, and hence more of the nutrients (data not shown), are located in the bottom half of the corn crop than in the top half and cobs (Table 1).

For some of the sites and nutrients, there were significant interactions between effects of residue removal rates and tillage treatment on amounts of biomass and plant nutrients removed, as shown in Table 6. In many cases, these interactions reflected the fact that the CT treatments had higher yields and hence greater amounts of biomass and nutrients were removed from the 100% removal plots than from the strip-till 100% removal plots, while amounts of nutrients and biomass removed from the 50% plots did not differ between the two tillage treatments. This situation was the case for Northfield in 2010 (Cu) and 2011 (S), and Rosemount in 2010 (Biomass, Ca, and B) and 2011 (Biomass, Ca and Mg). This same pattern was observed for S at Rosemount in

2010, but with a small, detectable difference between S removal for the two tillage treatments at the 50% rate.

Soil nutrient availability

Soil nutrient availability from 0-15 cm (0-6 inches) did not differ between tillage systems in Spring 2011 (Table 8). In 2010, only B and Cu levels differed at Rosemount (higher in CT) and Mg levels differed at Northfield (higher in ST; Table 7). The ST plots had higher pH than the CT plots at Rosemount. When calculated for the whole soil profile (0-90 cm, or the top 3 feet), there were no differences between tillage systems in either year (data not shown). For most of the nutrients, there were likewise no detectable differences in soil nutrient availability for any of the residue removal rates either in the 0-15 cm depth (Tables 9 and 10) or in the top 90 cm (Tables 11 and 12). Levels of S and micronutrients tended to be higher at Northfield than at Lamberton and Rosemount, where organic matter levels were lower. For the 0-15 cm depth, only at Lamberton (for Cu in 2010 and Cu and Zn in 2011) was soil availability lower in the 100% removal than the 0% removal treatment; in all other cases, nutrients were equal or greater at the 100% removal rate (Table 9 and 10). For 0-90 cm, only Cu at Lamberton (2011) and Mg at Rosemount (2011) were lower for the 100% removal rate (Table 12).

Although some interactions between effects of removal rate and tillage treatment were significant, there were no consistent patterns (Fig 1 and 2). It appears that more than 2-3 years of treatment are required to see significant losses of available soil nutrients in the top 15 cm due to corn residue removal. Interestingly, when averaged across all treatments, there were lower concentrations of available soil nutrients in 2011 than 2010 at Northfield (S, B, Zn, Mn and Cu), Lamberton (all) and Rosemount (Ca, Mg, S, B, Zn), but these differences could not be explained by tillage or residue removal treatment (Table 13). This table also shows that nutrients in most cases were well above critical levels, except for Zn at Lamberton and B at Rosemount.

Soil quality indicators

As indicators of soil quality, we measured “active” fractions of organic matter. Potentially mineralizable N (PMN) and carbon (PMC) were determined for each site sampled in Spring 2010 (Fig. 3A and B). Neither tillage treatment nor residue removal rate affected concentrations of PMN and PMC at any location when averaged across soil depths (0-30 cm, data not shown). At Rosemount and Lamberton, both indicators were significantly greater at the shallow depth (0-15 cm) compared to the lower depth (15-30 cm), but for Northfield, only PMC showed differences with depth (Fig. 3A and B). At both Rosemount (PMN and PMC) and Northfield (PMC) there was a significant tillage x depth interaction, where concentrations of PMN and/or PMC were similar at 0-15 and 15-30 cm for conventional-till, but were significantly greater for the 0-15 cm depth than for the 15-30 cm depth in the strip-till system (Fig 3A and B). This result is expected because of the accumulation of residue in the surface layer of the strip-till system, compared to the mixing that occurs under conventional tillage. At Northfield, there was also a rate by depth interaction, where PMC was similar at 0-15 and 15-30 cm for the 0 and 100% removal rate, but at the 50% removal rate PMC was significantly greater at 0-15 cm than 15-30 cm (Fig. 3B).

In 2011, particulate organic matter N (POMN) and particulate organic matter C (POMC) were analyzed for each location (Figs 4A and B). Similar to PMN and PMC, no differences between tillage systems were detected at any of the sites when averaged across the top 30 cm. However, concentrations of POMN and POMC at 0-15 cm were higher than 15-30 cm for both Lamberton and Rosemount (Fig. 4A and B).

At Rosemount, a significant tillage x depth interaction was detected, where the concentrations of POMN and POMC were similar at 0-15 and 15-30 cm for conventional-till, but were significantly greater for the 0-15 cm depth than for the 15-30 cm depth in the strip-till system (Fig 4A and B).

At Lamberton, significant interactions for tillage by depth (P=0.089) and removal rate by depth (P=0.014) were observed for POM-C (Fig 4B). Both tillage treatments had greater concentrations of POM-C at 0-15 cm than 15-30 cm, but POM-C in the CT treatment tended to be greater than ST for the shallow depth and less than ST at 15-30 cm. Differences between the depths were also greater for the 0% removal rate than for the 50 or 100 % (Fig 4B) .

At Northfield, rate of residue removal treatment affected POM-C. The concentration of POM-C in the top 30 cm was similar for the 50% removal rate (3.66 mg g^{-1}) and 0% removal rate (2.84 mg g^{-1}), and both were significantly greater than the 100% removal rate (2.53 mg g^{-1}).

Correlations among organic C and N fractions measured at 0-30 cm soil depth are presented in Figure 5. PMN was significantly correlated with PMC (r=0.87) and with POMN (r=0.68). POMC was correlated with POMN (r=0.99) and PMC (r=0.74). The best correlations occurred with similar measurement techniques (soil incubations for PMN and PMC, and collection of coarse organic matter for POMN and POMC) but both measures of active SOM fractions were also well correlated with each other.

Summary

The amount of secondary and micronutrient plant removal was similar between tillage systems, except at Rosemount where greater Ca, Mg, S and B were removed under CT than ST systems, because of the higher yields and therefore greater biomass removal under CT systems. In addition, the amount of secondary nutrient and micronutrient removal was significantly greater in the 100% than 50% residue removal rate. Despite the higher rate of nutrient removal under 100% treatments, there were almost no changes observed in soil availability of secondary and micronutrients by 2-3 years after establishment of the treatments.

During this same time period, soil quality indicators reflected differences between tillage treatments due to stratification under strip-till systems compared with conventional-till systems, but no differences were detected due to residue removal rates, except in Northfield where POMC tended to be greater in the 0 and 50% than in the 100% residue removal rate. It appears that longer time periods are required to detect effects of residue removal on soil properties, including availability of secondary and micronutrients and amounts of active C and N in these soils.

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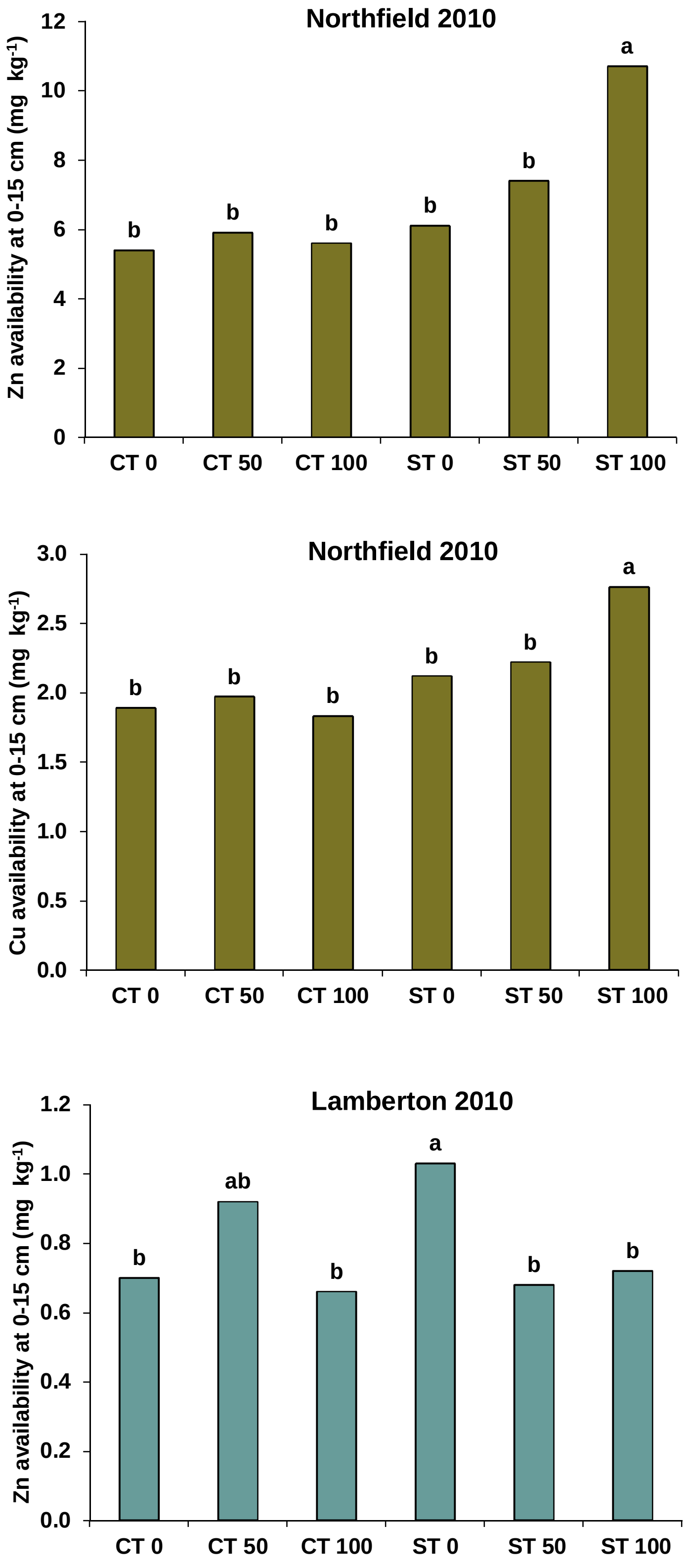

Figure 1. Effect of residue removal rate by tillage interaction on soil nutrient availability for 2010 growing season at Northfield and Lamberton.

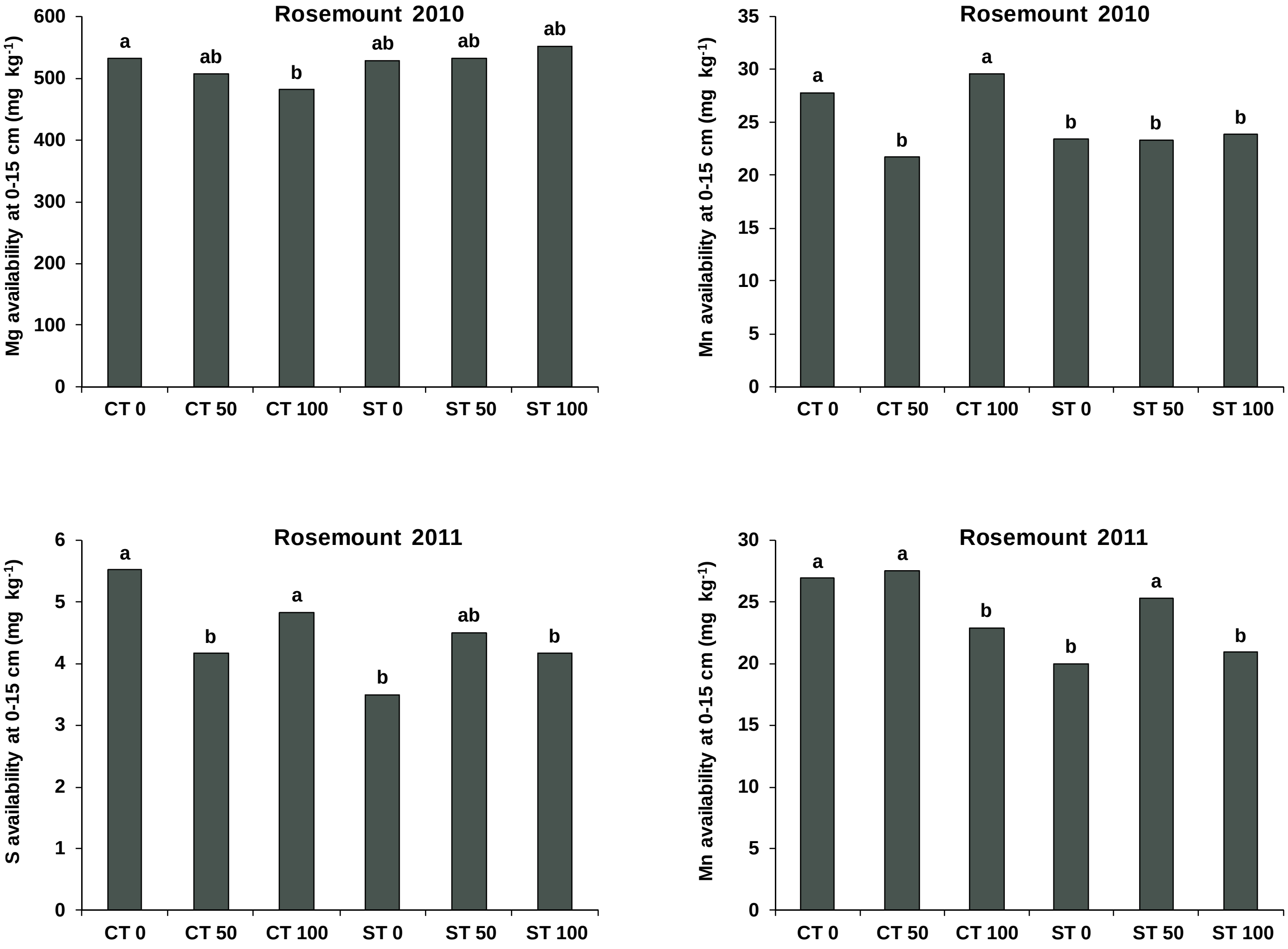

Figure 2. Effect of residue removal rate by tillage interaction on soil nutrient availability for 2010 and 2011 growing season at Rosemount.

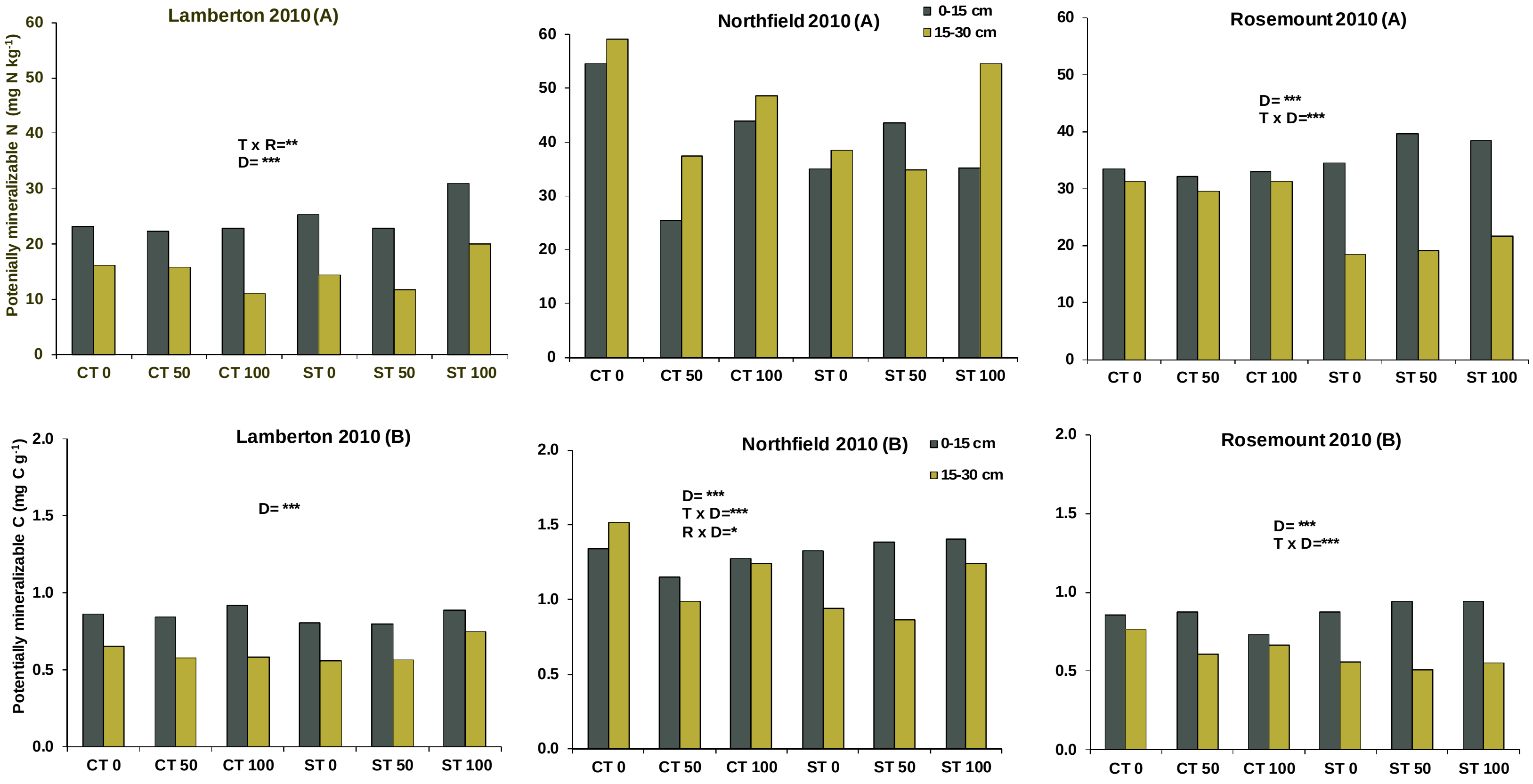

Figure 3. Effect of tillage systems and residue removal rate on Potentially mineralizable N (PMN) and C (PMC) at 0-15 and 15-30 cm measured at Lamberton, Northfield and Rosemount. Statistical results for analysis of effects of tillage (T), residue removal and depth of sampling (D) on soil organic matter fractions are shown. *P<0.10, ** P<0.05, *** P<0.01.

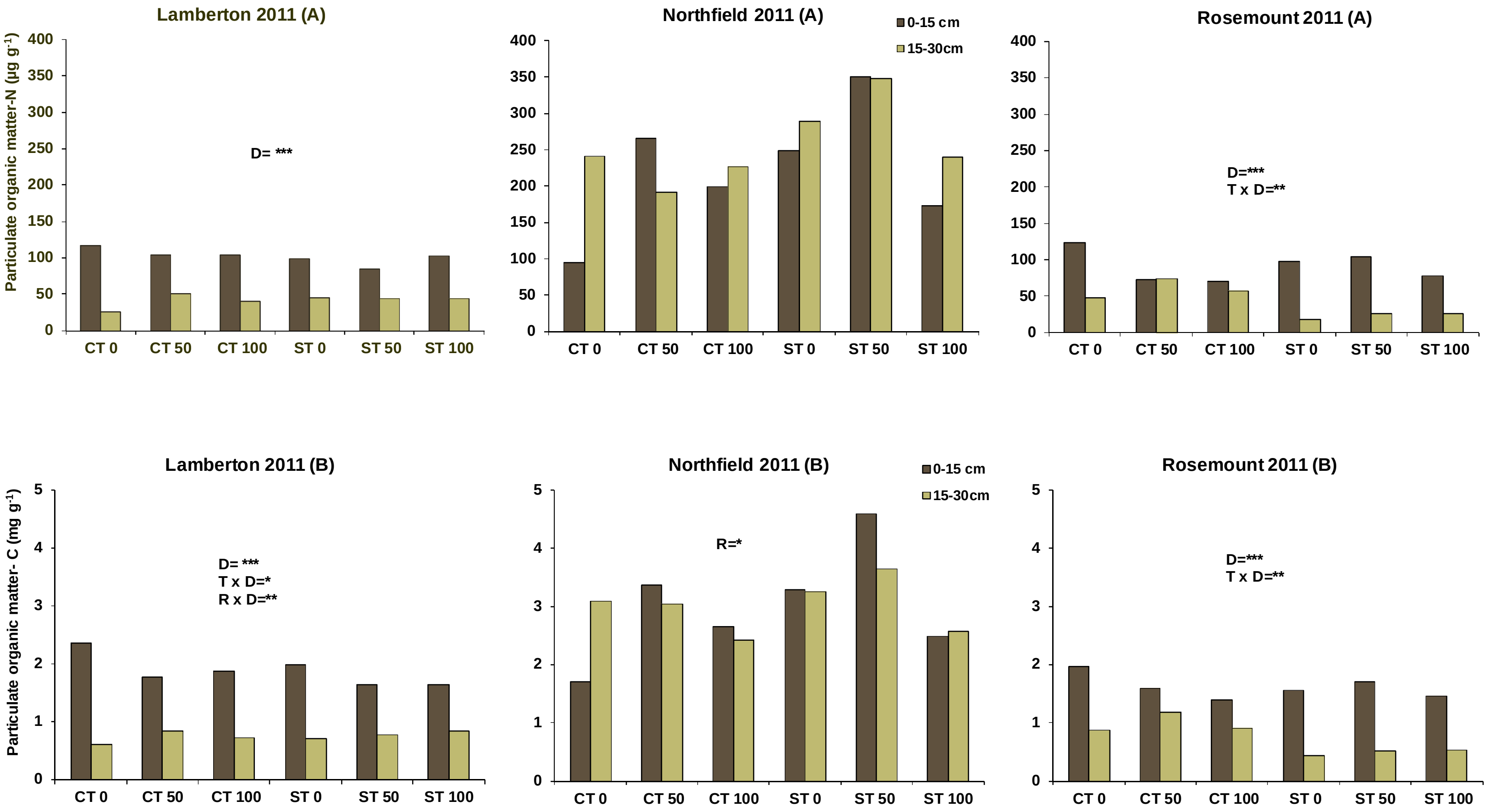

Figure 4. Effect of tillage systems and residue removal rate on Particulate organic matter carbon (POMC) and N (POMN) at 0-15 and 15-30 cm measured at Lamberton, Northfield and Rosemount. Statistical results for analysis of effects of tillage (T), residue removal and depth of sampling (D) on soil organic matter fractions are shown. *P<0.10, ** P<0.05, *** P<0.01.

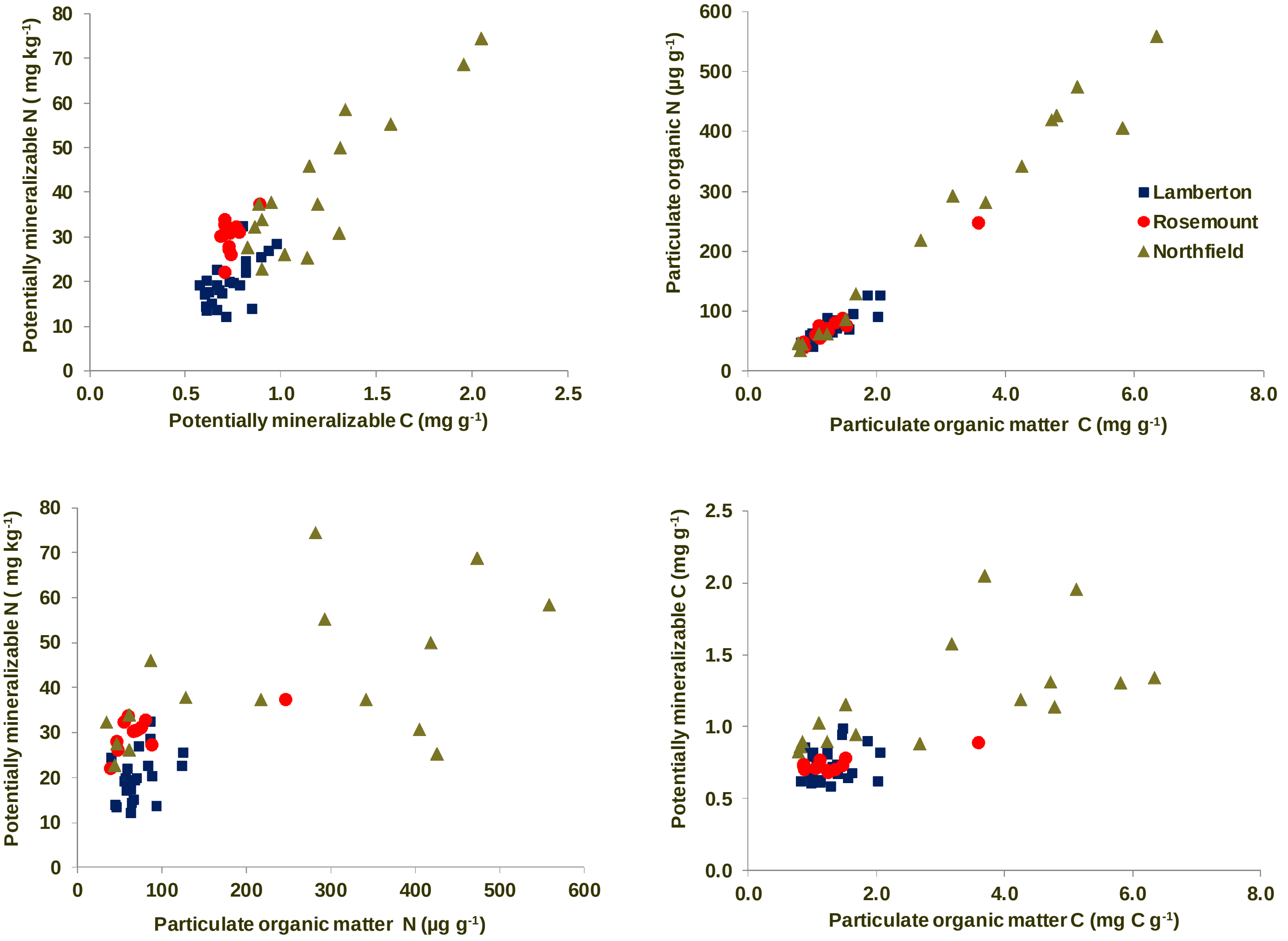

Figure 5. Correlations between selected organic matter fractions for all evaluated sites at 0-30 cm soil depth.

Table 1. Distribution of the corn biomass (ton ac^{-1}) in 2010 and 2011 growing season.

	Northfield		Lamberton		Rosemount	
	2010	2011	2010	2011	2010	2011
	…………….Ton ac^{-1}………………					
Stover						
Bottom Half	1.79	1.66	1.33	0.92	1.92	1.30
Top Half	1.24	1.18	1.03	1.09	0.82	0.51
Cobs	0.56	0.57	0.44	0.55	0.44	0.46
Grain	5.80	5.07	4.57	4.34	4.09	4.38
Total biomass	**9.38**	**8.48**	**7.37**	**6.9**	**7.27**	**6.65**

Table 2. Effect of tillage management on biomass and plant nutrient removal during 2010 and 2011 corn growing season.

		Tillage	Biomass removal[†]	Plant nutrient removal						
				Ca[†]	Mg[‡]	S[†]	B[†]	Zn	Mn	Cu
			Ton ac^{-1}	…lbs nutrient ac^{-1}…			…….g nutrient ac^{-1}……			
Northfield										
	2010	**CT**	2.7	16.7	5.1	3.7	9.1	36.8	53.0	10.2
		ST	2.6	16.5	5.1	3.5	9.4	33.0	59.5	9.5
	2011	**CT**	2.6	15.0	5.9	3.8	10.5	46.6	41.7	9.7
		ST	2.7	16.6	5.9	3.6	11.9	42.1	74.0	10.6
Lamberton										
	2010	**CT**	2.1	15.9	6.9	2.4	8.6	20.8	67.3	5.8
		ST	2.1	14.1	6.8	2.6	8.4	23.9	60.7	5.7
	2011	**CT**	2.0	14.3	7.6	2.8	13.0	28.1	76.0	6.5
		ST	1.9	14.2	8.1	2.7	11.3	32.5	64.7	6.3
Rosemount										
	2010	**CT**	2.5 **a**	10.5 **a**	8.3 **a**	3.7 **a**	8.9 **a**	60.4	60.7	12.5
		ST	2.0 **b**	7.5 **b**	4.9 **b**	2.4 **b**	6.1 **b**	54.7	43.9	8.8
	2011	**CT**	1.7 **a**	11.3 **a**	8.3 **a**	1.8	5.2	30.1	27.0	4.8
		ST	1.5 **b**	8.3 **b**	4.9 **b**	1.8	5.1	32.9	23.3	5.5

[†] Different letters indicates significant differences at P<0.05.

[‡] Different letters indicates significant differences at P<0.10.

Table 3. Effect of residue removal rates on plant nutrient removal at Northfield site in 2010 and 2011 growing season

				Plant nutrient removal						
	Residue removal rate		Biomass removal	Ca	Mg	S	B	Zn	Mn	Cu
Northfield	%		**Ton ac^{-1}**	**……..lbs nutrient ac^{-}**			**……..g nutrient ac^{-1}……….**			
2010	**50**	Top half	1.2	10.3	2.4	1.8	4.8	18.8	32.2	6.0
	50	Cobs	0.6	0.2	0.3	0.6	1.4	9.5	2.5	1.6
		Amount removed[†]	**1.8**	**10.4**	**2.7**	**2.4**	**6.2**	**28.2**	**34.7**	**7.5**
	100	Top half	1.3	11.6	2.6	1.7	5.2	19.1	39.0	5.7
	100	cobs	0.5	0.1	0.3	0.6	1.3	8.5	2.4	1.5
	100	Bottom Half	1.7	11.1	4.5	2.3	5.7	13.9	36.4	5.0
		Amount removed[‡]	**3.5**	**22.8**	**7.4**	**4.7**	**12.3**	**41.6**	**77.9**	**12.1**
2011	**50**	Top half	1.2	9.5	2.4	2.0	6.4	26.8	35.5	4.9
	50	Cobs	0.6	0.1	0.2	0.5	1.0	11.3	2.6	2.4
		Amount removed[†]	**1.8**	**9.5**	**2.6**	**2.5**	**7.4**	**38.1**	**38.2**	**7.3**
	100	Top half	1.2	8.9	2.7	1.8	6.5	24.0	34.5	5.4
	100	cobs	0.6	0.1	0.2	0.6	0.9	10.4	2.6	2.3
	100	Bottom Half	1.7	13.0	6.2	2.5	7.7	16.2	40.5	5.2
		Amount removed[‡]	**3.5**	**22.1**	**9.2**	**4.9**	**15.0**	**50.6**	**77.6**	**13.0**

[†] 50% plots: Sum of top half + cobs biomass is removed.
[‡] 100% plots: Total plant biomass (sum of top half, bottom half and cobs biomass) is removed.

Table 4. Effect of residue removal rates on plant nutrient removal at Lamberton site during 2010 and 2011 growing season

				Plant nutrient removal						
	Residue removal rate		**Biomass removal**	**Ca**	**Mg**	**S**	**B**	**Zn**	**Mn**	**Cu**
Lamberton	%		**Ton ac^{-1}**	**……..lbs nutrient ac^{-}**			**……..g nutrient ac^{-1}……….**			
2010	**50**	Top half	1.0	8.3	3.4	1.4	4.5	15.5	38.4	3.0
	50	Cobs	0.5	0.2	0.4	0.5	1.1	9.0	2.0	1.0
	50	Bottom half	1.3	10.7	6.0	1.4	5.7	11.2	54.3	3.6
		Amount removed[†]	**1.4**	**9.6**	**4.9**	**1.7**	**5.7**	**17.8**	**47.3**	**3.8**
	100	Top half	1.0	8.8	3.3	1.4	4.5	11.6	31.6	3.4
	100	Cobs	0.5	0.2	0.4	0.5	1.2	7.0	2.1	1.0
	100	Bottom Half	1.3	11.4	5.1	1.5	5.7	8.2	47.0	3.3
		Amount removed[‡]	**2.7**	**20.4**	**8.8**	**3.4**	**11.4**	**26.8**	**80.6**	**7.7**
2011	**50**	Top half	1.1	12.2	6.1	1.6	10.5	25.6	61.2	5.2
	50	Cobs	0.5	0.1	0.5	0.7	1.1	9.4	3.8	2.3
	50	Bottom Half	0.9	6.3	4.5	0.8	3.6	5.5	29.1	1.5
		Amount removed[†]	**1.3**	**9.3**	**5.5**	**1.6**	**7.7**	**20.2**	**47.0**	**4.5**
	100	Top half	1.1	11.9	5.3	1.9	11.2	21.8	59.0	4.3
	100	cobs	0.6	0.2	0.5	0.8	1.3	12.3	4.3	2.5
	100	Bottom Half	1.0	7.1	4.4	1.3	4.2	6.3	30.3	1.5
		Amount removed[‡]	**2.7**	**19.2**	**10.2**	**3.9**	**16.7**	**40.4**	**93.6**	**8.3**

[†] 50% plots: 50% of total biomass (mixture of top half, bottom half and cobs biomass) is removed.

[‡] 100% plots: Total plant biomass (mixture of top half, bottom half and cobs biomass) is removed.

Table 5. Effect of residue removal rates on plant nutrient removal at Rosemount during 2010 and 2011 growing season

				Plant nutrient removal						
	Residue removal rate		**Biomass removal**	**Ca**	**Mg**	**S**	**B**	**Zn**	**Mn**	**Cu**
Rosemount	%		**Ton ac^{-1}**	**……..lbs nutrient ac^{-}**			**……..g nutrient ac^{-1}……….**			
2010	**50**	Top half	0.7	4.3	2.7	1.3	2.6	25.3	20.4	4.4
	50	Cobs	0.5	0.1	0.4	0.6	0.8	14.5	2.7	2.0
		Amount removed[†]	**1.2**	**4.4**	**3.1**	**1.8**	**3.4**	**39.9**	**23.1**	**6.5**
	100	Top half	1.0	5.9	3.8	1.7	3.7	39.2	27.9	5.5
	100	cobs	0.4	0.1	0.3	0.5	0.7	13.3	2.3	1.8
	100	Bottom Half	1.9	7.5	5.9	2.1	7.2	22.7	51.3	7.5
		Amount removed[‡]	**3.3**	**13.6**	**10.1**	**4.3**	**11.7**	**75.2**	**81.5**	**14.9**
2011	**50**	Top half	0.5	4.9	2.8	0.6	2.1	14.1	11.7	2.3
	50	Cobs	0.4	0.1	0.2	0.4	0.8	5.9	1.4	1.0
		Amount removed[†]	**0.9**	**4.9**	**3.0**	**1.0**	**2.9**	**20.0**	**13.1**	**3.3**
	100	Top half	0.5	5.1	2.9	0.7	2.4	16.7	12.4	2.4
	100	cobs	0.5	0.1	0.2	0.4	0.9	8.0	1.6	0.8
	100	Bottom Half	1.3	9.4	7.1	1.5	4.2	18.3	23.3	3.9
		Amount removed[‡]	**2.3**	**14.6**	**10.2**	**2.6**	**7.5**	**43.0**	**37.3**	**7.0**

[†] 50% plots: Sum of top half + cobs biomass is removed.
[‡] 100% plots: Total plant biomass (sum of top half, bottom half and cobs biomass) is removed.

Table 6. Effect of residue removal rates and tillage interaction on the amounts of biomass and plant nutrient removed during 2010 and 2011 growing seasons at three experimental sites.

		Conv-till		**Strip-till**	
		50%	**100%**	**50%**	**100%**
		……………mg kg^{-1}………………			
Northfield 2010	**Cu (g ac^{-1})†**	7.3 c	13 a	7.8 c	11 b
Northfield 2011	**S (lb ac^{-1})†**	2.4 c	5.3 a	2.6 c	4.5 b
	Mn (g ac^{-1})†	28 c	56 b	48 b	100 a
	Zn (g ac^{-1})†	37 b	57 a	45 b	40 ab
Lamberton 2011	**Cu (g ac^{-1})†**	5.2 b	7.9 a	3.8 c	8.8 a
Rosemount 2010	**Biomass (ton ac^{-1})†**	1.2 c	3.8 a	1.1 c	2.8 b
	Ca (lb ac^{-1})‡	4.8 c	16.2 a	4.0 c	11 b
	S (lb ac^{-1})†	2.1 c	5.3 a	1.5 d	3.3 b
	B (g ac^{-1})‡	3.7 c	14.1 a	3.0 c	9.3 b
	Zn (g ac^{-1})†	51 b	70 a	29 c	80 a
Rosemount 2010	**Biomass (ton ac^{-1})†**	0.9 c	2.6 a	0.9 c	2.1 b
	Ca (lb ac^{-1})†	5.4 c	17.2 a	4.5 c	12 b
	Mg (lb ac^{-1})†	3.8 c	12.8 a	2.1 c	7.6 b

† Different letters indicates significant differences at $P<0.05$

‡ Different letters indicates significant differences at $P<0.10$

Table 7. Soil nutrient availability at 0-15 cm in Spring 2010. Average across residue removal rates

	Soil nutrient availability at 0-15 cm- Spring 2010										
	Tillage	**Ca**	**Mg** †	**S**	**B**‡	**Zn**	**Mn**	**Cu**†	**pH**‡	**TOC**	**TN**
		………………………...……….mg kg^{-1} (ppm)………………………………………								%	%
Northfield											
	Conv-till	3474	305 **b**	19.3	0.98	5.61	35.9	1.90	6.3	3.5	0.30
	Strip-till	3355	330 **a**	22.2	0.88	8.08	40.2	2.37	5.9	3.6	0.33
Lamberton											
	Conv-till	4020	432	11.2	0.93	0.76	30.4	1.19	6.2	2.1	0.19
	Strip-till	3490	481	10.4	0.73	0.81	35.2	1.26	5.9	2.1	0.18
Rosemount											
	Conv-till	2260	507	8.7	0.33 **a**	1.43	26.37	0.75 **a**	6.2 **b**	2.2	0.18
	Strip-till	2300	538	9.8	0.31 **b**	1.30	23.52	0.62 **b**	6.6 **a**	2.1	0.18

† Different letters indicates significant differences at P<0.05

‡ Different letters indicates significant differences at P<0.10

Table 8. Soil nutrient availability at 0-15 cm in Spring 2011. Average across residue removal rates

	Soil nutrient availability at 0-15 cm- Spring 2011									
Tillage	**Ca**	**Mg**	**S**	**B**	**Zn**	**Mn**	**Cu**	**pH**	**TOC**	**TN**
	……………………...……….mg kg^{-1} (ppm)……………………………………								**%**	**%**
Northfield										
Conv-till	3599	311	7.0	0.76	4.57	27.3	1.78	6.3	3.3	0.28
Strip-till	2981	304	7.7	0.62	6.37	27.9	1.99	5.9	3.5	0.31
Lamberton										
Conv-till	3318	388	5.2	0.67	0.51	28.7	1.10	5.9	2.2	0.18
Strip-till	2870	416	5.6	0.52	0.50	24.4	1.13	5.7	2.1	0.17
Rosemount										
Conv-till	2006	426	4.8	0.27	1.20	25.77	0.68	6.2	2.2	0.17
Strip-till	2038	441	4.1	0.28	1.07	22.09	0.64	6.6	2.1	0.17

Table 9. Soil nutrient availability at 0-15 cm in Spring 2010. Average across tillage systems

	Residue removal rate	Soil nutrient availability at 0-15 cm- Spring 2010									
		Ca	**Mg †**	**S**	**B**	**Zn‡**	**Mn†**	**Cu†**	**pH**	**TOC†**	**TN†**
	%	**……………………….....…mg kg^{-1} (ppm)………...…..…..………….**								**%**	**%**
Northfield											
	0	3389	301. **b**	20.7	0.9	5.7 **b**	40.5	2.0	6.1	3.5	0.3
	50	3232	339 **a**	20.4	0.9	6.7 **ab**	36.0	2.1	6.0	3.3	0.3
	100	3444	313 **b**	21.2	1.0	8.1 **a**	37.8	2.3	6.1	3.9	0.3
Lamberton											
	0	3584	480	10.4	0.73	0.87	32.5	1.26 **a**	6.0	2.1	0.18
	50	3688	477	9.3	0.73	0.80	34.1	1.30 **a**	5.8	2.1	0.18
	100	3993	413	12.6	1.03	0.69	31.7	1.12 **b**	6.4	2.2	0.19
Rosemount											
	0	2288	531	8.6	0.32	1.28	25.6 **a**	0.67	6.4	2.2	0.18
	50	2302	520	9.6	0.31	1.36	22.5 **b**	0.68	6.4	2.2	0.18
	100	2250	517	9.7	0.32	1.46	26.7 **a**	0.70	6.3	2.2	0.18

† Different letters indicates significant differences at $P<0.05$

‡ Different letters indicates significant differences at $P<0.10$

Table 10. Soil nutrient availability at 0-15 cm in Spring 2011. Average across tillage systems

	Soil nutrient availability at 0-15 cm- Spring 2011									
Residue removal rate	**Ca**	**Mg [†]**	**S[‡]**	**B**	**Zn**	**Mn[†]**	**Cu[‡]**	**pH**	**TOC[†]**	**TN[†]**
%	**……………………….…..mg kg^{-1} (ppm)………….…….………..**								**%**	**%**
Northfield										
0	3414	315	8.8	0.7	4.5	27.2	1.7	6.2	3.1 **b**	0.3
50	3353	290	5.7	0.7	5.6	27.9	1.9	6.1	3.7 **a**	0.3
100	3104	317	7.4	0.7	6.3	27.6	2.0	6.0	3.5 **ab**	0.3
Lamberton										
0	2890	422	4.9	0.5	0.6 **a**	27.5	1.2 **a**	5.7	2.1	0.17
50	3097	410	5.2	0.54	0.5 **a**	28.3	1.2 **a**	5.7	2.1	0.17
100	3295	373	6.2	0.77	0.4 **b**	23.8	1.0 **b**	6.1	2.1	0.17
Rosemount										
0	2035 **ab**	440 **a**	4.5	0.27	1.07	23.5 **b**	0.64	6.5 **a**	2.2	0.16
50	1899 **b**	408 **b**	4.3	0.27	1.12	26.4 **a**	0.66	6.3 **b**	2.2	0.17
100	2132 **a**	452 **a**	4.5	0.29	1.21	21.9 **b**	0.68	6.4 **a**	2.1	0.16

Table 11. Soil nutrient availability at 0-90 cm in Spring 2010. Average across tillage systems

	Residue removal rate	**Soil nutrient availability at 0-90 cm- Spring 2010**							
		Ca[‡]	**Mg**	**S[†]**	**B[‡]**	**Zn[†]**	**Mn[†]**	**Cu[†]**	**pH**
	%	**……………………………......…mg kg^{-1} (ppm)…………..……..……..…………….**							
Northfield									
	0	4695	611	14.2	0.63 **ab**	2.11 **b**	17.5	1.91	6.8
	50	4304	617	13.9	0.56 **b**	2.22 **b**	14.3	1.89	6.7
	100	4669	580	15.1	0.69 **a**	2.72 **a**	15.3	2.01	6.8
Lamberton									
	0	5098 **ab**	475	7.4 **b**	0.77	0.44	9.0	1.18 **ab**	7.3
	50	4190 **b**	518	8.1 **b**	0.70	0.44	11.6	1.21 **a**	7.1
	100	6520 **a**	437	10.6 **a**	0.81	0.39	9.4	1.08 **b**	7.3
Rosemount									
	0	2014	475	5.9	0.23	0.46 **b**	8.4 **b**	0.70	6.2
	50	1998	463	6.3	0.22	0.49 **b**	8.0 **b**	0.75	6.0
	100	1991	458	6.0	0.23	0.61 **a**	10.5 **a**	0.74	6.0

[†] Different letters indicates significant differences at P<0.05.

[‡] Different letters indicates significant differences at P<0.10.

Table 12. Soil nutrient availability at 0-90 cm in Spring 2011. Average across tillage systems

	Residue removal rate	**Soil nutrient availability at 0-90 cm- Spring 2011**							
		Ca	**Mg** [†]	**S**[‡]	**B**	**Zn**	**Mn**[†]	**Cu**[‡]	**pH**
	%	**……………………….....mg kg^{-1} (ppm)…………..……..………….**							
Northfield									
	0	4162	563	10.3 **a**	0.43	1.78	12.4	1.62	6.7
	50	3937	522	7.4 **b**	0.44	1.80	12.4	1.51	6.7
	100	3877	532	9.5 **a**	0.47	1.78	10.7	1.52	6.6
Lamberton									
	0	4642	478	5.2	0.59	0.28	8.8	1.12 **a**	7.1
	50	4101	524	5.7	0.57	0.27	8.9	1.16 **a**	7.0
	100	5766	412	6.9	0.72	0.26	7.9	1.02 **b**	7.2
Rosemount									
	0	1899	432 **a**	3.7	0.16	0.43	7.8 **b**	0.71	6.2
	50	1882	423 **a**	4.5	0.16	0.42	8.9 **a**	0.73	6.1
	100	1851	409 **b**	4.2	0.19	0.45	7.8 **b**	0.75	6.1

† Different letters indicates significant differences at P<0.05.

‡ Different letters indicates significant differences at P<0.10.

Table 13. Soil nutrient availability at 0-15 cm in Spring 2010-2011. Average across tillage systems

		Ca	**Mg**	**S**	**B**	**Zn**	**Mn**	**Cu**	**pH**	**TOC**
	Year				**……………..mg kg^{-1} (ppm)……………..**					
Northfield										
	2010	3361	318	21 **a**	0.93 **a**	6.85 **a**	38 **a**	2.13 **a**	6.08	3.6
	2011	3290	307	7.3 **b**	0.69 **b**	5.47 **b**	28 **b**	1.88 **b**	6.11	3.4
Lamberton										
	2010	3755 **a**	457 **a**	11 **a**	0.83 **a**	0.79 **a**	33 **a**	1.23 **a**	6.04 **a**	2.1
	2011	3094 **b**	402 **b**	6.9 **b**	0.69 **b**	0.51 **b**	27 **b**	1.12 **b**	5.81 **b**	2.1
Rosemount										
	2010	2280 **a**	523 **a**	9.3 **a**	0.32 **a**	1.37 **a**	25	0.68	6.39	2.2
	2011	2022 **b**	433 **b**	4.4 **b**	0.27 **b**	1.13 **b**	24	0.66	6.41	2.2
Critical levels		**300**	**100**	**-**	**-**	**0.75**	**1**	**-**		

* S only in low OM soils (<2%).

** B and Cu no response (0.25 for sweet corn).