THE EFFECT OF VARIOUS TILLAGE OPERATIONS ON NUTRIENT AVAILABILITY [1/]

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Tillage selection is just one of the issues that farmers must address when making crop production decisions. Among the factors that will influence the choice of tillage for a given field is the condition of the residue and soil in the field; the residue management practices needed to meet conservation plan specifications; the tools, time, and money that are available; the need to incorporate amendments such as lime, fertilizer, and manure; and personal experience as to what works for their rotation, soil type, and production system. The soil will have a varied condition depending on the tillage management and this may influence the response of the crop to applied nutrients.

Conservation tillage continues to be an important component of crop production systems in Wisconsin and its surrounding states. The Conservation Technology Information Center (CTIC) (www.ctic.purdue.edu) has published the following facts that demonstrate the level of adoption of high residue management systems in the region.

- The eight Midwestern states (MN, WI, MI, IA, MO, IL, IN, and OH) have 106 million acres of cropland, or about 37% of all cropland in the U.S.

- 46% of all no-till acres in the USA can be found in the Midwest.

- 17 million acres of no-till soybeans and 7 million acres of no-till corn were planted in the Midwest in 2002.

- Forty-five million acres, or 42.5%, of all cropland used conservation tillage in the Midwest in 2002.

The adoption of conservation tillage in Wisconsin has been stagnant for corn, while it has increased for soybean and forages in the past decade according to the CTIC crop residue management survey. Data for 1992 and 2002 are compiled in Table 1. These data show some interesting trends. For corn, there has been nearly a doubling of no-till acres, but there has been a decrease in mulch-till and reduced-till which are often accomplished by chisel plowing. There has also been a substantial increase in conventional tillage that could include moldboard plowing or aggressive chiseling and deep tillage of fragile residue crops such as soybean and alfalfa. Progress in residue management for soybean has increased substantially due to the adoption of herbicide resistant varieties. Modest changes in adoption of higher residue systems for forage establishment are encouraging, perhaps reflecting farmer awareness of the erosion potential in this system.

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Table 1. CTIC residue management survey data comparison for Wisconsin, 1992 and 2002.

	No-till		Mulch-till		Reduced-till		Conventional	
Crop	1992	2002	1992	2002	1992	2002	1992	2002
	% of acreage							
Corn	6	11	26	20	21	15	46	54
Soybean	10	32	17	25	21	14	51	29
Forage	2	6	8	14	9	17	81	63

No-till includes in-row systems: mulch-till is full width tillage leaving > 30% residue; reduced-till leaves 15-30% residue; and conventional tillage leaves < 15% residue.

Tillage Effects on Soil Properties

Tillage practice affects crop growth and yield because of the effect on surface residue coverage, which in turn affects soil temperature and moisture regimes, mineralization of the soil organic matter, nutrient and organic matter incorporation, and weed, pest, and disease pressure. A substantial covering of crop residues that shade the soil and leaves a cooler, wetter soil obviously creates a condition that is much different than what occurs when tillage aggressively fluffs the soil and incorporates residue. An example of the tillage effect on residue levels in a continuous corn and corn/soybean rotation is shown in Table 1. These data show that chisel tillage can be and excellent conservation practice for managing corn stubble, but it leaves inadequate residue coverage when applied to soybean residue. These data also show that strip-tillage can be method to reduce residue coverage in the row while leaving adequate overall coverage for soil protection. A study that examined early season

Table 2. Surface crop residue coverage as affected by crop rotation and tillage, Arlington, Wis., 2001 and 2003 (Wolkowski, unpublished data).

	2001			2003		
Tillage	CC	SbC	CSb	CC	SbC	CSb
	%			%		
Chisel	36	17	34	50	15	40
Strip-till	66	57	65	72	59	69
No-till	86	76	82	72	73	68
Pr>F						
Rotation (R)		<0.01			<0.01	
Tillage (T)		<0.01			<0.01	
R*T		0.08			0.27	

CC=Continuous corn; SbC=Corn after soybean; CSb=Soybean after corn. Rotations established in 1997. Each value is the mean of 12 measurements.

soil temperature and water content found significantly warmer and drier conditions in the seed zone in a chisel and residue clearing systems compared to no-till (Wolkowski, 2000). These differences appeared to be related to the reduced early season growth that was observed in no-till compared to the other tillage systems.

At the extreme continuous no-till will create a relatively compact surface soil condition, especially where traffic from various field operations is not restricted to defined lanes. No-till soils typically have lower total porosity and a re-arrangement of its pore size distribution skewed toward more small pores, with larger pores destroyed by compaction. Katsvairo et al. (2002) found higher penetration resistance and bulk density in a till-plant system compared to moldboard, which was similar to that observed by Moncrief (1981). The increased bulk density is consistent with a reduction in aeration in fine-textured soils that will inhibit root growth, and can induce denitrification and reduce K uptake.

Controlled traffic farming is currently being evaluated countries such as Australia where GPS guidance is used as a tool to maintain traffic to consistent lanes within fields, but its use in the USA is relatively limited. The value of controlled traffic is noted by Voorhees and Lindstrom (1984), who found that where traffic is controlled conservation tillage took 3-4 years to have porosity greater than moldboard plowing. Continuous conservation tillage produced larger, more porous aggregates. Similarly, Larney and Kladivko (1989) found reduced penetrometer resistance below the former plowed zone following the establishment of no-till on a poorly structured, low organic matter soil suggesting a possible improvement of the soil condition over time in no-till. Where traffic is controlled Logsdon et al, 1990 found that long-term no-till increased macro-porosity and saturated hydraulic conductivity. It is often believed that long-term no-till will improve the soil condition over a period of years.

Some of the improvement in porosity, penetration resistance, and ped strength has been associated with improvements in soil biological properties. Karlen et al. (1994) found that soil aggregates collected from a site that had been in 12 years of no-till had greater stability, organic carbon, and microbial activity compared to plowed treatments. The no-till treatment also had a greater earthworm population and had a lower soil loss from simulated rainfall. No-till and reduced tillage management may become more important in future governmental programs because of their ability to sequester C. Halvorson et al. (2002) found that no-till sequestered substantially more C compared to minimum and conventional tillage.

Tillage and N Availability

There are several factors associated with reduced tillage that may affect, and likely lower the availability of N to crops. These include the cooler soil temperatures that reduce N mineralization from soil organic matter, increased immobilization in the surface of the soil because of the enrichment of organic C from residue, and denitrification where the soil porosity has been altered by traffic. These factors either independently, or in combination, have been shown to reduce the N uptake by crops no-till compared to conventionally tilled treatments (Matowo et al., 1997; Bundy et al., 1992). Currently UWEX recommendations call for an additional 30 lb N/a in a corn following corn system when using no-till or another conservation tillage system that leaves more than 50% residue.

The reduced and shallower residue incorporation associated with the decreased tillage intensity of conservation tillage will result in the stratification of organic carbon in the soil. Karlen et al. (1994) found about 1.5 and 2.5 as much C in the top two inches of soil following 12 years of no-till, compared to a chisel and moldboard system, respectively. The C enrichment from no-till in this layer led to significantly greater microbial activity and total N. Nitrate was also higher in this layer in no-till compared to the other two tillage systems, but tended to be lower at depth in the soil. They attributed this to greater microbial activity in the surface that attenuated the N at that position and therefore limited mineralization and leaching into the profile.

As has been previously discussed soil bulk density tends to be higher in no-till and as a result more, fine pores that do not drain may be expected. This additional water may be available to plants and may sustain yields in periods of drought. This property may also increase the risk of N loss through denitrification. Hilton et al. (1994) measured N loss from denitrification both in the wheel track and non-wheel tracked area in a no-till, chisel, and moldboard system. Cumulative N losses for the growing season were 23, 14, and 10 lb N/a for the no-till, chisel, and moldboard systems, respectively. Average loss in the wheel track area was 1.6 times greater than the non-wheel tracked area.

Surface applications of urea-containing N sources should be avoided in no-till or other reduced tillage systems that perform little incorporation (e.g., strip-till) because of the potential loss of N by ammonia volatilization. The potential for loss will be affected by the temperature and precipitation. The warmer the weather the greater the risk and loss will be higher when precipitation does not occur for several days after application. In Wisconsin, the measurement of ammonia volatilization of preplant N urea and UAN applied to a chisel/disk system produced average losses of 22 and 14%, respectively (Bundy and Oberle, 1988). Greater loss might be expected in high residue systems because the fertilizer will be placed on the residue where the liberated ammonia will not be absorbed into the soil water. Randall et al. (1997) found that a preplant application of injected anhydrous ammonia or UAN was superior to a 30:70, preplant: V7 or V16 split application where the latter was surface banded or broadcast in a ridge-till system. Finally, surface applications of urea-containing fertilizers should be avoided to soils that have recently been limed because the localized pH increase will enhance the ammonia volatilization process (Howard and Essington, 1998).

Tillage and Nitrogen Crediting

Conservation planning is required as part of nutrient management planning and often results in tillage practices (if any) that leave considerable residue on the surface to meet allowable soil loss. Livestock producers will likely have to allocate manure to some of these fields with considerable residue cover because it will not be permissible to make large application to high P testing fields that are commonly found near the farmstead. Manure will have to either be left on the surface or incorporated with methods that leave a substantial amount of residue on the soil surface. It may be presumed that manure left on the surface will have a lower first-year N availability because of delayed mineralization since it is not incorporated.

Regardless of whether manure application rates are based on a N or P basis some assessment of N availability should be made to determine the appropriate N credit for the year of application. This should also be done for P and K, but it can be argued that soil testing can be used to confirm the impact of manure application on the availability of those nutrients. A study that evaluated both fresh and composted manure found similar corn grain yields when comparing conventional versus no-till systems in 3 of 4 years (Eghball and Power, 1999). The first-year N availability of the composted material was about half that of the fresh manure.

Table 3 shows the 2003 data from a current study by this author that evaluated the response of corn to spring-applied manure over corn stalks and subsequent tillage method. Straw-bedded manure was applied at 0, 15, and 30 t/a to different fields for the 2002 and 2003 studies. Manure was applied in mid-April, providing two months for mineralization before the corn entered its period of maximum N uptake. Tillage systems included moldboard, chisel, light disking, strip-till, and no-till. Four fertilizer N rates between 0 and 150 lb N/a were placed in all manure and tillage combinations. In general the high residue systems had lower yields than moldboard and chisel at the zero N fertilizer rate regardless of manure rate. Where no manure was applied the optimum N rate appeared to be near 100 lb N/a suggesting that there was substantial residual N in the soil in each year. Manure application was found to increase yield independent of N fertilization. Assuming a manure N credit of 3 lb/ton the two manure/fertilizer combinations that provided a total of 140-150 lb N/a (15 ton manure + 100 lb N/a <u>or</u> 30 ton manure + 50 lb N/a) resulted in remarkably similar yields across the tillage systems. This suggests that the benefits of the manure that included not only nutrients, but also improvements in the soil condition were equally beneficial in all tillage systems.

Similarly when legumes are rotated to corn or other N demanding crops there may be a concern regarding the availability of N. This issue often involves what is termed the synchrony or the timing of when the N is mineralized from a residue and when it is needed by the succeeding crop. A controlled-environment study by Mohr et al. (1998) found that in the short-term, herbicide treatment of alfalfa followed by tillage resulted in the release of significantly more legume N than no-till because of accelerated mineralization. This may not be an issue where alfalfa is killed several months (either fall or spring) prior to planting corn as time will be available for the legume N to mineralize. Wolkowski (1992) conducted a study at Lancaster and Arlington that compared moldboard, chisel, and no-till following spring herbicide treatment of alfalfa. No consistent tillage differences in yield were found and the response to applied N supported current N replacement credits.

Kelling et al. (2002) examined the response of wheat following herbicide treated alfalfa to moldboard plowing or no-till. In general where tillage was performed it appeared that more N was mineralized as there was no response to applied N fertilizer and the wheat had greater lodging at the higher N rates with plowing. Yields declined with added N more rapidly in the moldboard compared to no-till because of loss due to lodging.

Tillage and P and K Availability

Numerous studies have documented the effect of tillage on soil test stratification, which may be important for P and K fertilizer, and lime management. Nutrient contributions to the soil come from not only fertilizers and amendments, but also decaying crop residues that cycle nutrients from deeper in the soil. Surface application of ammonium containing N fertilizers and amendments will tend to acidify the surface. Stratification has been shown to develop in as little as two years following the cessation of moldboard plowing (Karlen et al., 2002). While the degree of stratification may be more pronounced in no-till, it is also found in chisel and disc systems that do no completely invert and mix the soil (Crozier et al., 1999). Stratification in no-till fields can also be found horizontally, as well as vertically. Varsa and Ebelhar, 2000 found higher soil test K levels near the corn plant compared to the mid-row that they attributed to re-deposition of K leached from plant tissue. Thus, consistency in sampling depth is especially important when sampling fields with a history of reduced tillage. Sub-surface banding P and K fertilizer complicate the sampling scenario as these bands may persist at recognizably higher concentrations for 5-7 years (Stecker and Brown, 2001). They concluded that an impractically large number of cores would have to be collected to reduce the variability associated with determining soil test P. This variability could only be overcome by collecting a "slice" sample perpendicular to row position.

Nutrient stratification has been assessed by this author in a study conducted at the Arlington Agricultural Research Station where a tillage x rotation study was initiated in 1997. Soil samples were collected in two in. increments to eight in. from the field in 2002. The results are reported for chisel and no-till from the unfertilized (P and K) portion of the study in Table 4 to directly reflect the rotational and tillage effects without the interference of added nutrients. When corn was the crop 160 lb N/a as ammonium nitrate was applied to all plots. The field had a recent history of chisel tillage prior to the establishment of the study and soil test in 1997 no stratification in pH, but noticeable stratification of P and K. The acidification of the surface layer is similar in both the chisel and no-till in continuous corn, with much less change in the corn/soybean rotation. Below this layer there is no difference between rotations, however there was a weak trend for higher pH in no-till at depth. It is surprising that there has been little change in soil test P following five years of cropping and demonstrates the buffer capacity of this soil with respect to P. There has been change with respect to K, which tended to be lower in the corn/soybean rotation. This observation was attributed to the greater removal of K by the corn/soybean rotation compared to continuous corn and its lower contribution of residue that may have absorbed K from layer below the sample depth (Wolkowski, 2003).

A question that continues to be asked is whether nutrient stratification will adversely affect yield. Nutrient stratification would be just one effect of reduced tillage and might be not be as critical as compaction, cooler and wetter conditions, changes in microbial activity. In the case of the Arlington study the answer could indirectly be yes if surface acidification reduced the efficacy of a herbicide treatment. It is therefore important that a 0-2 in. soil sample be collected, as is currently recommended, from long-term no-till situations to address this issue.

Various researchers have taken different approaches to assess the impact of P and K stratification. Kaspar et al. (1991) demonstrated that corn plants will produce more roots and likely have greater fertilizer use efficiently when fertilizer is placed in non-tracked portions of a field. They found root length volume to be nearly twice as great in untracked interrows, compared to tracked interrows. Therefore, it is possible that compacted no-till fields may not have access to all of the broadcast nutrients, some of which will fall in wheel tracked areas. This has lead to the support of banded P and K application below the soil surface, either with the planter on a 2 x 2 placement or with a separate tool or attachment that places the fertilizer much deeper. Vyn and Janovicek (2001) optimized yield in no-till and zone-till corn when K was shallow-banded with the planter at relatively high rates of potash. Similarly Ebelhar and Varsa (2000) found that the 2 x 2 placement increased corn whole plant K concentration above that of broadcast when sampled a month after emergence suggesting better utilization of the banded material. This difference was not found in samples collected at the early reproductive stage.

Yin and Vyn (2002) examined the residual response of K fertilizer applied to corn in different tillage systems on the subsequent soybean crop. They concluded that K stratification was not a major production issue for narrow-row soybean production following corn. Ebelhar and Varsa (2000) also noted that soybean was much less responsive to K fertility management.

Unpublished research conducted by this author reported in Table 5 shows the effect of rotation, tillage, and fertilizer placement on the average corn yield at the Arlington Agricultural Research Station. These data support the 2 x 2 placement, which produced equal or better grain yields in the continuous corn rotation. This placement did not perform as well in the soybean/corn portion of the rotation where the broadcast treatment was slightly superior. Deep placement of fertilizer, which was limited to the strip-till system, did not produce yields that were better than conventional placements. There was an apparent tillage response for strip-till compared to no-till and strip-till often compared favorably with chisel. As has been seen in previous studies at Arlington (Wolkowski, 2000) the greatest relative response to fertilizer was found in the no-till treatment. The results for the 2001-2003 study show similar effectiveness in no-till when comparing broadcast and row-applied treatments.

Summary

Tillage, or the lack thereof, has a profound effect on soil physical, biological, and chemical properties. No-till soils tend to be more compact and have a pore size distribution skewed toward smaller pores, especially when traffic is not well controlled. This may increase denitrification and limit root distribution in the soil volume, thereby reducing nutrient uptake. Properties, such as organic carbon, microbial activity, and soil test will be stratified with higher concentrations in the surface layer. No-till and other reduced tillage systems perform satisfactorily when traffic is controlled, nutrients are applied so that losses do not occur, and other management practices are optimized. High residue production systems are the farmer's best conservation alternative and will reduce erosion significantly. As has been known for a long time they require a higher level of management to perform effectively.

Table 4. Effect of five seasons of rotation and tillage on the incremental soil test under unfertilized conditions, Arlington, Wis. 2002.

		CC		CSb		Pr>F		
Depth	1997	CH	NT	CH	NT	Rotn.	Till.	R*T
			pH					
0-2	6.8	5.5	5.7	6.3	6.3	0.05	0.45	0.51
2-4	6.8	6.3	6.4	6.4	6.7	0.35	0.23	0.80
4-6	6.9	6.6	6.9	6.6	6.9	0.96	0.12	0.49
6-8	6.8	6.8	6.7	6.4	6.7	0.34	0.19	0.06
			P (ppm)					
0-2	47	49	53	50	43	0.52	0.77	0.38
2-4	46	46	60	45	40	0.06	0.55	0.21
4-6	40	34	49	42	39	0.77	0.35	0.20
6-8	32	26	30	26	29	0.92	0.37	0.85
			K (ppm)					
0-2	151	133	136	114	104	0.11	0.76	0.57
2-4	103	93	101	80	70	0.11	0.83	0.32
4-6	88	75	82	65	64	0.17	0.60	0.48
6-8	78	67	75	59	60	0.21	0.44	0.52

Table 5. Effect of rotation, tillage, and fertilizer placement on corn yield, Arlington, Wis., 2001-2003 (3-year average).

Fertilizer	CC			SbC		
Placement	Chisel	Strip-till	No-till	Chisel	Strip-till	No-till
	----	----	---- bu/a	----	----	----
None	169	173	147	192	184	177
Broadcast	176	168	163	194	209	200
2 x 2	186	172	164	195	201	197
Deep	--	172	--	--	208	--

Pr>F	2001	2002	2003
Rotation (R)	0.04	0.08	0.10
Tillage (T)	0.13	0.40	0.62
R*T	<0.01	0.43	0.93
Fertilizer (F)	0.04	<0.01	0.02
R*F	0.79	0.07	0.14
T*F	1.00	0.02	1.00
R*T*F	0.88	0.60	0.07

CC=Continuous corn; SbC=Corn after soybean.
Fertilizer rate=18+46+60 lb N+P_2O_5+K_2O/a.

Table 3. Yield of corn as affected by manure rate (ton/a), tillage, and N fertilization, Arlington, 2002-2003 (2-year average).

	Moldboard			Chisel			Disk			Strip-till			No-till		
N rate	0	15	30	0	15	30	0	15	30	0	15	30	0	15	30
lb/a	bu/a														
0	142	172	182	128	172	171	119	153	163	115	151	160	111	151	164
50	168	185	181	155	174	184	153	170	177	151	166	179	142	170	174
100	172	183	186	167	173	183	160	182	184	166	178	187	154	173	183
150	172	194	196	172	188	187	160	183	180	170	186	190	156	182	182

Main effects

Manure (t/a)	bu/a	Tillage	bu/a	N Rate (lb/a)	bu/a
0	151	Moldboard	178	0	150
15	174	Chisel	171	50	169
30	179	Disk	165	100	175
LSD $_{(0.05)}$	18	Strip-till	167	150	180
		No-till	162	LSD $_{(0.05)}$	4
		LSD $_{(0.05)}$	7		

Significance (Pr>F)

Manure	0.02	N*M	<0.01
Tillage	<0.01	N*T	0.14
M*T	0.94	N*M*T	1.00
N	<0.01		

References

Bundy, L.G., and S.L. Oberle. 1988. Evaluation of methods for control of ammonia volatilization fro surface-applied urea-containing fertilizers. J. Fert. Issues. 5:24-30.

Bundy, L.G., T.A. Andraski, and T.C. Daniel. 1992. Placement and timing of nitrogen fertilizers for conventional and conservation tillage corn production. J. Prod. Agric. 5:214-221.

Ebelhar, S.A., and E.C. Varsa. 2000. Tillage and potassium placement effects on potassium utilization by corn and soybean. Commun. Soil Sci. Plant Anal. 31:2367-2377.

Eghball, B., and J.F. Power. 1999. Composted and noncomposted manure application to conventional and no-tillage systems: Corn yield and nitrogen uptake. Agron. J. 91:819-825.

Crozier, C.R., G.C. Naderman, M.R. Tucker, and R.E. Sugg. 1999. Nutrient and pH stratification with conventional and no-till management. Commun. Soil Sci. Plant Anal. 30:65-74.

Halvorson, A.D., B.J. Weinhold, and A.L. Black. 2002. Tillage, nitrogen, and cropping system effects on soil carbon sequestration. Soil Sci. Soc. Am. J. 66:906-912.

Hilton, B.R., P.E. Fixen, and H.J. Woodard. 1994. Effects of tillage, nitrogen placement, and wheel compaction on denitrification rates in the corn cycle of a corn-oats rotation. J. Plant Nutr. 17:1341-1357.

Howard, D.D., and M.E. Essington. 1998. Effects of surface-applied limestone on the efficiency of urea-containing nitrogen sources for no-till corn. Agron. J. 90:523-528.

Katsvairo, T., W.J. Cox, and H. Van Es. 2002. Tillage and rotation effects on soil physical characteristics. Agron. J. 94:299-304.

Karlen, D.L., N.C. Wollenhaupt, D.C. Erbach, E.C. Berry, J.B. Swan, N.S. Eash, and J.L Jordahl. 1994. Long-term tillage effects on soil properties. Soil Tillage Res. 32:313-327.

Karlen, D.L., K.A. Kohler, D.A. Laird, R.L. Thompson, and D.D. Buhler. 2002. Soil-test dynamics throughout a five-year 'Thompson Farmer' rotation in Iowa. Am. J. Altern. Agric. 17:9-17.

Kaspar, T.C., H.J. Brown, and E. M. Kassmeyer. 1991. Corn root distribution as affected by tillage, wheel traffic, and fertilizer placement. Soil Sci. Soc. Am. J. 55:1390-1394.

Kelling, K.A., P.E. Speth, K. Killian, T. Wood, and M. Mlynarek. 2002. Direct comparison of alfalfa nitrogen credits to corn and wheat. Proc. Wis. Fert., Aglime, Pest Mgmt. Conf. 41:304-310.

Larney, F.J., and E.J. Kladivko. 1989. Soil strength properties under four tillage systems at three long-term study sites in Indiana. Soil Sci. Soc. Am. J. 53:1539-1545.

Logsdon, S.D., R.R. Allmaras, L. Wu, J.B. Swan, and G.W. Randall. 1990. Macroporosity and its relation to saturated hydraulic conductivity under different tillage practices. Soil Sci. Soc. Am. J. 54:1096-1101.

Matowo, P.R., G.M. Pierzynski, D. A. Whitney, and R.E. Lamond. 1997. Long-term effects of tillage and nitrogen source, rate, and placement on grain sorghum production. J. Prod. Agric. 10:141-146.

Mohr, R.M., H.H. Janzen, E. Bremer, and M.H. Entz. 1998. Fate of symbiotically fixed $^{15}N_2$ as influenced by method of alfalfa termination. Soil Biol. Biochem. 30:1359-1367.

Moncrief, J.F. 1981. The effect of tillage on soil physical properties and the availability of nitrogen, phosphorus, and potassium to corn (*Zea mays* L.). Ph.D. diss. Dept. of Soil Science. Univ. of Wisconsin-Madison.

Randall, G.W, T.K. Iragavarapu, and B.R.Bock. 1997. Nitrogen application methods and timing for corn after soybean in a ridge-till system. J. Prod. Agric. 10:300-307.

Stecker, J., and J.R. Brown. 2001 Soil phosphorus distribution and concentration from repeated starter phosphorus band application. Commun. Soil Sci. Plant Anal. 32:803-819.

Varsa E.C., and S.A. Ebelhar. 2000. Effect of potassium rate and placement on soil test variability across yield. Commun. Soil Sci. Plant Anal. 31:2155-2161.

Voorhees, W.B., and M.J. Lindstrom. 1984. Long-term effects of tillage method on soil tilth independent of wheel traffic compaction. Soil Sci. Soc. Am. J. 48:152-156.

Vyn, T.J., and K.J. Janovicek. 2001. Potassium placement and tillage system effects on corn response following long-term no-till. Agron. J. 93:487-495.

Wolkowski, R.P. 1992. Effect of tillage system on alfalfa N credits. Proc. Wis. Fert., Aglime, Pest Mgmt. Conf. 31:202-212.

Wolkowski, R. P. 2000. Row-placed fertilizer for maize grown with an in-row crop residue management system in southern Wisconsin. Soil Tillage Res. 54:55-62.

Wolkowski, R.P. 2003. Wisconsin corn and soybean responses to fertilizer placement in conservation tillage systems. Proc. Wis. Fert., Aglime, Pest Mgmt. Conf. 42:99-106.

Yin, X., and T.J Vyn. 2002. Residual effects of potassium placement and tillage systems for corn and subsequent no-till soybean. Agron. J. 94:1111-1119.