TILLAGE AND CROPPING SYSTEMS

Residual Effects of Potassium Placement and Tillage Systems for Corn on Subsequent No-Till Soybean

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ABSTRACT

Little is known about K fertility management for no-till (NT) soybean [*Glycine max* (L.) Merr.]. This study was conducted to evaluate the residual effects of K application rate, timing, and placement for corn (*Zea mays* L.) in various tillage systems on subsequent NT soybean. Field experiments involving a corn–soybean rotation were conducted from 1998 to 2000 on long-term NT fields with medium or high exchangeable soil K levels near Kirkton and Belmont, ON, Canada. In the corn year, treatments included the combinations of three fall K rates (0, 42, and 84 kg ha^{-1}), spring K rates (two rates differing by 42 kg ha^{-1}), and three tillage systems [NT, zone till (ZT), and moldboard plow (CT)]. Both CT and ZT (also known as intermittent tillage systems) reduced soil K stratification relative to continuous NT. Trifoliate leaf K concentrations increased with residual fall and spring K applications in most site-years. Average soybean yield significantly increased by 8.3% with the application of 84 kg K ha^{-1} in fall plus 42 to 50 kg K ha^{-1} in spring to previous corn only on medium-testing (K $<$ 100 mg L^{-1}) soils. Residual tillage had no effects on leaf K or yield of NT soybean. Application of fall and spring K fertilizers to corn was equally beneficial for subsequent soybean in either continuous or intermittent NT systems. Furthermore, soil K stratification and the residual effects of tillage and K placement method were not major production issues for narrow-row NT soybean in these growing seasons.

Long-term no-till (NT) management has resulted in pronounced vertical stratification of soil exchangeable K (Blevins et al., 1983; Holanda et al., 1998; Karathanasis and Wells, 1989; Lal, 1976; Sprague and Triplett, 1986). Significantly higher soil K concentrations in the surface layer and lower K levels at subsurface depths have been observed in NT compared with soil K concentrations at similar depth intervals under moldboard plow (CT). This vertical soil K stratification is mainly attributed to limited soil mixing, surface application of K fertilizer, deposition of crop residue at the soil surface, and the relative immobility of K in soil.

Vertical stratification of soil K in NT management causes plant K uptake to be more dependent on soil K and root system characteristics in the surface layer. This may reduce plant K uptake, and thus increase the likelihood of K deficiency in crop tissues as well as yield loss in growing seasons when drought occurs because soil K availability and root growth and activity are more vulnerable to drought in the surface layer than in subsurface layers. In addition, heavy deposit of crop residue at the soil surface in NT usually results in higher soil moisture and lower soil temperature in the surface layer, which may reduce soil K availability and restrict root growth early in the season (Barber, 1971; Fortin, 1993). The risks of reduction in plant K uptake by drought or low temperature become severe when soil K concentrations in subsurface layers are too low to optimize plant K uptake in NT fields. Subsurface placement of K fertilizer, therefore, may improve applied K availability and reduce soil K stratification in NT management.

In general, K placement effects are expected to be dependent on initial soil K level, K fertilizer application rate, K diffusion rate in soil, K fixation capacity of soil, and local weather conditions. Plant factors including the volume of root system and root morphology also affect crop response to K placement. Investigations on NT corn have showed that plant K uptake and grain yield after subsurface placement of K fertilizer were greater than K uptake and grain yield from nonincorporated, surface-applied K fertilizer (Bordoli and Mallarino 1998; Randall and Hoeft, 1988).

Information about K fertilizer management for NT soybean is limited. Recent investigations in Iowa (Borges and Mallarino, 2000; Buah et al., 2000) demonstrated that NT soybean yield response to K fertilization was rarely significant when initial soil K levels were optimum or higher. Research in Illinois (Vasilas et al., 1988) also showed that NT did not affect K fertilizer recommendations for soybean compared with CT.

Subsurface placement of K fertilizer appears to be superior to surface broadcasting for NT soybean on low-testing soils. Hairston et al. (1990) reported that deep banding (15-cm depth) of K fertilizer resulted in higher yield of NT soybean than surface broadcasting of K on some Mississippi soils with low K levels. Borges and Mallarino (2000) reported that both deep-banded and planter-banded K fertilizer in NT produced slightly higher soybean yield than surface application on optimum- to very high-testing soils and that positive yield response to banding was not related to soil K levels or degree of soil K stratification. However, research in Ohio (Hudak et al., 1989) showed that K fertilizer placement did not affect NT soybean yield in a silt loam soil

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Abbreviations: CT, moldboard plow; NT, no-till; ZT, zone till.

with medium K levels. Furthermore, another investigation in Iowa (Buah et al., 2000) showed that NT soybean responded to surface application at least as well as to planter-banded application, despite significant soil K stratification when soil K levels were in the optimum, high, or very high ranges.

Little attention has been devoted to evaluating the residual effects of K fertilization and tillage system for corn on subsequent NT soybean in corn–soybean rotations. Relevant research showed that NT soybean yield response to residual starter K (102 kg ha^{-1}) was negligible on high-testing soils with at least 10-yr NT management (Buah et al., 2000). However, on fields after 6 yr in ridge till with evident vertical soil K stratification, soybean response to residual deep-banded (10-cm depth) K was evident on a high-testing soil at a high rate (148 kg ha^{-1}) of fall K fertilizer (Rehm, 1995). However, residual effects of fall- or spring-applied K to corn on subsequent NT soybean have not been documented on medium-K soils or when intermittent CT or zone till (ZT) was imposed to the preceding corn on long-term NT fields.

Because soybean K uptake in NT systems is more dependent on soil exchangeable K concentrations, root density, soil moisture, and soil temperature in the surface layer than K uptake in the CT system, traditional K management systems designed for soybean under CT may need to be modified to ensure that the greater dependence of soybean K uptake on the surface layer in NT will not restrict K nutrition and yield of soybean. The objectives of this study were to (i) evaluate the residual effects of K application rate, timing, and placement method in various tillage systems imposed to previous corn on soil K fertility, K nutrition, and yield of subsequent NT soybean on long-term NT fields with medium to high K levels and (ii) determine the relationships among soil exchangeable K concentrations and stratification, trifoliate leaf K, soybean yield, and seed K concentrations on intermittent and continuous long-term NT fields.

MATERIALS AND METHODS

Field experiments were conducted on two private farms from 1996 through 1999 near Kirkton, Perth County, and Belmont, Elgin County, in southern Ontario, to evaluate the residual effects of K application rate, timing, and method as well as tillage systems for corn on subsequent NT soybean. For the corn season, the fields chosen for experiment had been in continuous NT production for at least 6 yr before treatment initiation. At each location, the experiment was conducted on adjacent fields each year. All fields were tile-drained. The growing season received 2632, 3116, and 3036 Ontario Crop Heat Units (OCHU) at Kirkton in 1997, 1998, and 1999, respectively, and 3465 and 3597 OCHU in 1998 and 1999, respectively, at Belmont (Brown and Bootsma, 1993).

The soils were classified as a Listowel silt loam (medium, mixed weakly to moderately calcareous Typic Hapludalf) at Kirkton and a Toledo silty clay loam (medium, mixed weakly to moderately calcareous Typic Humaquept) at Belmont. Selected physical and chemical properties of these soils before the corn season were presented by Vyn and Janovicek (2001).

For the corn season, a randomized complete block split-split plot design with four replications was used in all five site-years. Tillage systems were randomly assigned to the whole plots, fall K application rates were assigned to the split plots, and spring K rates were assigned to the split-split plots. Tillage systems in this study included the tillage operations and the corresponding placement method of fall K fertilizer. The three tillage systems used in this study are described as follows:

1. NT: Potash fertilizer was surface broadcast-applied in fall, and corn was planted NT.
2. ZT: Soil loosening in strips approximately 20 cm wide and 17 cm deep at 76-cm centers was accomplished in fall using a Trans-Till (Row-Tech, Snover, MI). The Trans-Till was modified to apply K fertilizer during tillage operations in deep bands at the centers of the tilled strips.
3. CT: Moldboard plowing was performed in fall to a depth of approximately 15 cm, followed by two secondary passes to a depth of 10 cm in spring with a field cultivator and packer before corn planting. Potash fertilizer was uniformly broadcast-applied over the soil surface and incorporated by plowing.

Fall K fertilizer was applied at rates of 0, 42, and 84 kg K ha^{-1} as muriate of potash (KCl). The placement method of fall-applied K was specific to each of the tillage practices as stated above. Spring K was applied at a low rate of 8 (1996) and 0 (1997 and 1998) kg K ha^{-1} and a high rate of 50 (1996) and 42 (1997 and 1998) kg K ha^{-1} in the form of muriate of potash as part of a starter blend. All plots were fertilized with 30 kg N ha^{-1} as urea (46–0–0) and 13 kg P ha^{-1} as monoammoniun phosphate (11–52–0) as part of a starter approximately 5 cm from the row and 5 cm below the seed at planting. Each split-split plot, 21 m long and 3 m wide, was planted to four rows of corn. Detailed information about previous corn management was presented by Vyn and Janovicek (2001).

The identical experimental design and plot arrangement as the previous corn year were used for subsequent soybean in all site-years. No K fertilizer was applied after corn or during the soybean season. Soybean was NT-planted in the same direction as the rows of corn in the previous year. Soybean row widths were 38 cm at Kirkton and 50 cm at Belmont. Soybean cultivars grown at Kirkton were ‘AC Bravor’ in 1997 and ‘First Line 2801R’ in 1998 and 1999. At Belmont, ‘Pioneer 9163’ was planted in both 1998 and 1999.

Composite soil samples were taken in the spring before soybean planting at depth increments of 0 to 5, 5 to 10, 10 to 20, and 20 to 30 cm in all split-split plots in 1998 and 1999 at both locations. Soil sampling was not conducted at Kirkton in 1997 due to resource limitations. Out of 10 cores (2.5 cm in diam.) collected for each sample, five were taken from areas at the center of previous corn rows (avoiding the starter band) and five from the center of the interrow zone. This particular sampling protocol best reflected the combined effects of tillage system and fall K placement on the extent of soil K stratification approximately 17 mo after fall K application although it might have overestimated the soil K levels actually present in the bulk soil, which would have been required to arrive at recommended K fertilizer rates. The latter objective was beyond the scope of this study because only residual fertilizer effects on nonfertilized soybean were of interest. Soil samples were air-dried, ground to pass a 2-mm sieve, and mixed before analysis. Soil exchangeable K was extracted using 1 *M* (pH = 7.0) ammonium acetate solution and determined using an atomic absorption spectroscopy (Bates and Richards, 1993). Soil K at the 0- to 10-cm depth was estimated by computing an average over K levels in the 0- to 5- and 5- to 10-cm layers. Soil K in the 0- to 20-cm layer was referred to as a mean of

K levels at the 0- to 10- and 10- to 20-cm depth intervals. Soil K at the 0- to 30-cm depth interval was defined as an average of K levels in the 0- to 10-, 10- to 20-, and 20- to 30-cm layers. Soil K stratification coefficient was defined as the quotient of soil K concentrations in the 0- to 5-cm layer divided by K levels at the 10- to 20-cm depth. In this study, Ontario soil test interpretations for samples at the 0- to 15-cm depth were used. Boundaries for soil K categories of low, medium, high, very high, and excessive for soybean were 0 to 60, 61 to 120, 121 to 150, 151 to 250, and >250 mg K L^{-1} soil, respectively (Ontario Ministry of Agriculture, Food, and Rural Affairs, 1997).

Leaf samples consisting of 20 most recently developed, fully expanded trifoliate leaves (petiole included) from 20 soybean plants were collected at initial flowering stage (R1) in mid- to late July (18 July 1997, 27 July 1998, and 16 July 1999 at Kirkton and 27 July 1998 and 23 July 1999 at Belmont) from each split-split plot in all site-years. Leaf tissues were dried in a forced-air oven at 65°C for at least 3 d and ground in a Wiley mill (Arthur K. Thomas Co., Philadelphia) to pass a 1-mm screen. Trifoliate leaf samples were analyzed for tissue K concentrations using a dry ash method.

After soybean reached physiological maturity, seed yield was determined by harvesting a 1.0-m-wide area (three rows at Kirkton and two at Belmont) for the entire plot length at the center of each split-split plot using a plot combine. Seed samples were collected from the soybean yield samples for the determination of moisture and K content. Soybean yield was adjusted to a moisture content of 130 g kg^{-1}. Potassium concentrations in seed were measured using the same procedures as those for trifoliate leaf samples. Daily rainfall and air temperature were recorded or obtained from the nearest weather station for each site-year.

Data were analyzed using an analysis of variance appropriate for a randomized complete block split-split plot design. Separate analysis of variance was performed for each dependent variable. Mean separation of treatment effects was accomplished using Fisher's protected LSD. Probability levels lower than 0.05 were categorized as significant. Contrasts were used to compare soybean yield associated with the application of the highest fall K rate plus high spring K to soybean yield with the application of the lowest fall K rate plus low spring K. Pearson product-moment correlation coefficients were calculated to examine the relationships among soil exchangeable K concentrations and stratification, trifoliate leaf K, soybean yield, and seed K concentrations on a split-split-plot basis at both locations in both 1998 and 1999.

RESULTS AND DISCUSSION

Because the placement method for fall K fertilizer was different for each tillage system, subsequent soil K fertility and soybean responses (such as soil K levels before soybean planting, leaf K concentrations, soybean yield, and seed K concentrations) to tillage system were attributed not only to the degree of soil mixing associated with the tillage operation, but also to the placement method of fall K. Therefore, soil K fertility and soybean responses to tillage system in this study represent the combined effects of soil mixing and fall K placement method for the previous corn crop. Weather conditions were reasonably normal although they differed among the growing seasons at each location (data not presented).

Soil Potassium Fertility before Soybean Planting

Tillage System Effects

Tillage system imposed on the previous corn crop exerted significant effects on soil exchangeable K distribution in the soil profile (0–20 cm depth) before soybean planting at Kirkton (Table 1). When soil K data were combined for 1998 and 1999, soil K levels in the 0- to 5-cm layer under CT were 31 mg L^{-1} lower than those in NT averaged over fall K and spring K. There were no differences in soil K concentrations at the 5- to 10-cm depth between the two tillage systems. In the 10- to 20-cm layer, soil K levels in CT were 9 mg L^{-1} higher than soil K in NT. Compared with NT, ZT had similar soil K concentrations in the surface 0- to 5- and 5- to 10-cm layers but significantly higher soil K levels at the 10- to 20-cm depth interval. Soil K concentrations at the 0- to 5-cm depth were 2.12, 1.69, and 1.37 times greater than those in the 10-to 20-cm layer in NT, ZT, and CT systems, respectively, averaged over fall K and spring K, suggesting that both CT and ZT significantly reduced vertical stratification of soil K compared with NT. Although soil K distributions within the 0- to 20-cm depth were quite different in the three tillage systems, average soil K concentrations from 0 to 20 cm for each tillage system were almost equal (75–79 mg L^{-1}).

At Belmont, average (1998 and 1999) soil K concentrations were statistically similar between CT and NT in the surface 0- to 5- and 5- to 10-cm layers, but CT had 20 mg L^{-1} higher soil K levels at the 10- to 20-cm depth than NT (Table 1). Soil K after ZT did not differ from that of NT at any of the depth intervals. The ratio of soil K concentration in the 0- to 5-cm layer to that at the 10- to 20-cm depth was 1.97 for NT, 1.70 for ZT, and 1.42 for CT averaged over fall K and spring K. Average soil K concentrations in the 0- to 20-cm layer were 120 mg L^{-1} for NT, 124 for ZT, and 127 for CT.

Because soil K concentrations were still significantly stratified just 1 yr after imposing CT or ZT, our results suggest that a single year of CT or ZT could significantly reduce, but not overcome, vertical soil K stratification in long-term NT fields. Of the two tillage alternatives, CT was more aggressive than ZT in reducing soil K stratification. Overall soil K concentrations in the surface 0- to 20-cm layer were similar for all three tillage systems even though soil K distribution at the 0- to 20-cm depth was significantly affected by tillage system at both locations. In a previous investigation in Michigan, Pierce et al. (1994) also observed reduced soil K stratification by a single year of moldboard plowing in fields after 6 yr of continuous NT management. The reduction in soil K stratification with CT, relative to continuous NT, was significant at least in the year of tillage and the following year. However, in both our current study and the Michigan study (Pierce et al., 1994), intermittent CT could not eliminate soil K stratification on fields with at least 6 yr of continuous NT management. No previous report was available about the intermittent ZT effects on soil K stratification in long-term NT fields.

Table 1. Residual effects of tillage system and fall K application rate to previous corn on soil exchangeable K concentrations before soybean planting at Kirkton and Belmont averaged over 1998 and 1999.

		Soil depth, cm			
Location	Treatment	0–5	5–10	10–20	20–30
		Soil K, mg L^{-1}			
Kirkton	Tillage†				
	NT	123a‡	71a	58b	60a
	ZT	110a	74a	65a	58a
	CT	92b	73a	67a	59a
	Fall K rate, kg ha^{-1}				
	0	100b	68b	58b	58b
	42	112a	72b	62b	59a
	84	114a	78a	70a	60a
Belmont	Tillage				
	NT	181a	114a	92b	79a
	ZT	172a	120a	101ab	80a
	CT	159a	126a	112a	81a
	Fall K rate, kg ha^{-1}				
	0	169a	116a	95b	78a
	42	169a	119a	102a	80a
	84	175a	125a	107a	81a

† NT, no-till; ZT, zone till; CT, moldboard plow.

‡ Means in column within tillage or fall K rate treatment at each location followed by the same letter are not different according to Fisher's protected LSD at $P = 0.05$.

Fall Potassium Effects

At Kirkton, when the results of 1998 and 1999 were combined, application of 84 kg ha^{-1} fall K increased soil K concentrations by 14 mg L^{-1} in 0- to 5-cm layer, 10 at the 5- to 10-cm depth, and 12 in the 10- to 20-cm layer averaged over tillage systems and spring K (Table 1). However, significant increases in soil K levels with 42 kg ha^{-1} fall K occurred only in the surface 0- to 5-cm layer. At Belmont, when the data were averaged over tillage systems, spring K, and crop years, application of 84 kg ha^{-1} fall K increased soil K by 12 mg L^{-1} only at the 10- to 20-cm depth interval. Increases in soil K levels also occurred only in the 10- to 20-cm layer with the application of 42 kg ha^{-1} fall K. Averaged over tillage systems, spring K, and crop years, soil K levels at the 0- to 20-cm depth increased by 12 mg L^{-1} at Kirkton and 10 mg L^{-1} at Belmont with the application of 84 kg ha^{-1} fall K. In general, soil K concentrations increased as fall K fertilizer rate increased.

Soil exchangeable K results at both Kirkton and Belmont demonstrated that the impacts of fall K rate on soil K distribution in the soil profile (0–20 cm depth) were not affected by the placement method of fall K (data not presented). This may be possible because most of the available fall-applied K was already taken up by the preceding corn crop no matter where K fertilizer was placed. This observation did not agree with a previous report in ridge till where, after annual banding of 148 kg K ha^{-1} in fall at 10-cm depth for 3 yr, major increases in soil K were only observed in localized areas where K fertilizer was placed (Rehm, 1995). The influences of both tillage system and fall K on soil K levels in the 20- to 30-cm layer were negligible at both locations in this study (Table 1).

Table 2. Residual effects of fall and spring K application rates to previous corn on soybean trifoliate leaf K concentrations at Kirkton and Belmont from 1997 through 1999.

Location	Treatment	1997	1998	1999	Average
		Leaf K, g kg^{-1}			
Kirkton	Fall K rate, kg ha^{-1}				
	0	11.3b†	19.8b	17.7b	16.3c
	42	12.3ab	20.5b	20.6a	17.8b
	84	13.3a	21.5a	21.7a	18.8a
	Spring K rate, kg ha^{-1}‡				
	0 (8)	11.3b	20.3a	19.1b	16.9b
	42 (50)	13.3a	20.9a	20.9a	18.4a
Belmont	Fall K rate, kg ha^{-1}				
	0		20.3b	19.8a	20.1b
	42		19.9b	21.0a	20.5b
	84		21.1a	21.3a	21.2a
	Spring K rate, kg ha^{-1}				
	0		20.5a	20.3b	20.4a
	42		20.5a	21.2a	20.9b

† Means in column within fall or spring K rate treatment at each location followed by the same letter are not different according to Fisher's protected LSD at $P = 0.05$.

‡ Spring K was applied at a low rate of 8 (1996) and 0 (1997 and 1998) kg K ha^{-1} and a high rate of 50 (1996) and 42 kg K ha^{-1} (1997 and 1998) in the corn season.

Trifoliate Leaf Potassium Concentrations at Initial Flowering Stage

Fall Potassium Effects

Fall K application rate to the previous corn crop resulted in significant residual effects on trifoliate leaf K concentrations of subsequent NT soybean at initial flowering stage in all three seasons at Kirkton (Table 2). Increasing the fall K rate from 0 to 84 kg K ha^{-1} increased leaf K by 2.0 g kg^{-1} in 1997, 1.7 in 1998, and 4.0 in 1999. The application of 42 kg K ha^{-1} in fall increased leaf K concentrations only in 1999. At Belmont, fall K application rate to the previous corn crop had significant effects on leaf K concentrations in 1998 but not in 1999 (Table 2). Application of 84 kg ha^{-1} fall K increased leaf K by 0.8 g kg^{-1} compared with zero K in 1998. The residual effects of 42 kg ha^{-1} fall-applied K on leaf K were negligible in both seasons.

Spring Potassium Effects

At Kirkton, soybean leaf K concentrations responded significantly to residual spring K rate in both 1997 and 1999 but not in 1998 (Table 2). Leaf K increases with high spring K over low spring K averaged 2.0 g kg^{-1} in 1997 and 1.8 g kg^{-1} in 1999. At Belmont, the residual effects of high spring K on leaf K concentrations were significant in 1999 but not in 1998 (Table 2). Leaf K increases with high spring K averaged 0.9 g kg^{-1} in 1999.

Application of fall K fertilizer at 42 kg ha^{-1} alone to previous corn had the same impact in increasing soybean leaf K, relative to zero K, as the high vs. low rate of spring K fertilizer alone at both Kirkton and Belmont (data not presented). Residual effects of tillage system to previous corn on leaf K concentrations of subsequent NT soybean were never significant at either location even though the magnitude of vertical soil K stratification was different in the three tillage systems. This demonstrated that vertical soil K stratification was not detrimental to soybean K uptake on these medium- and high-K soils.

Increases in leaf K concentrations with both fall and spring K applications were much greater at Kirkton than at Belmont, perhaps because the overall soil K levels were lower at Kirkton. A previous investigation (Hudak et al., 1989) also demonstrated increased leaf K concentrations in soybean from the early- to midbloom stage with deep-banded or surface-applied K in various tillage systems. However, significant increases in soybean leaf K concentrations resulting from K fertilization are uncommon on fields with high to very high soil K levels (Buah et al., 2000; Rehm, 1995). It was unexpected that leaf K concentrations at Kirkton were much lower in 1997 than those in 1998 and 1999. This may have been the result of environment or (and) genotype. The soybean cultivar grown in 1997 was different from those used in 1998 and 1999 at this location.

Small and Ohlrogge (1973) recommended that the range of adequate trifoliate leaf K concentrations for soybean was 17.1 to 25.0 g kg^{-1} during the initial flowering stage. Using this criterion, leaf K concentrations at Kirkton in both 1998 and 1999 and at Belmont in 1998 from the zero-K plots were consistently within the sufficiency range; the implication is that soybean was able to obtain adequate K nutrition for optimum yield without additional K fertilization in these site-years. However, leaf K levels in all zero-K plots at Kirkton in 1997 were far below the recommended range. In addition, there were a couple of the zero-K plots in which leaf K concentrations were slightly below 17.0 g kg^{-1} at Belmont in 1999. Therefore, yield response to K fertilization at Kirkton in 1997 was expected based on the obviously insufficient leaf K concentrations from the zero-K plots and significant increases in leaf K concentrations with K application if the recommended adequate leaf K range was indicative of final soybean yield.

Soybean Yield

Residual effects of tillage system on soybean yield were not significant in any of the five site-years (data not presented), which suggests that NT soybean yield was not affected by tillage practice or associated K fertilizer placement method used in the previous corn crop. At Kirkton, averaged over tillage systems and crop years, the application of 84 kg K ha^{-1} in fall plus 42 to 50 kg K ha^{-1} in spring increased soybean yield by 8.3% (0.25 Mg ha^{-1}) compared with the control treatment (zero fall K plus low spring K) ($P < 0.05$, Fig. 1). This trend was also observed in all three seasons at this location. However, no such yield increases were observed in either individual season or the combined data at Belmont (Fig. 1).

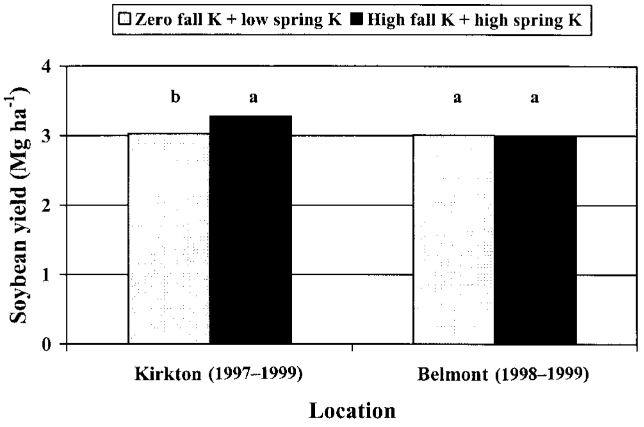

Fig. 1. Soybean yield response to fall plus spring K application at both Kirkton and Belmont. At each location, bars labeled by the same letter are not different according to the contrast at $P = 0.05$.

Table 3. Residual effects of fall and spring K application rates to previous corn on soybean yield at Kirkton and Belmont from 1997 through 1999.

Location	Treatment	1997	1998	1999	Average
		Yield, Mg ha^{-1}			
Kirkton	Fall K rate, kg ha^{-1}				
	0	2.21a†	3.49a	3.53a	3.08b
	42	2.29a	3.54a	3.45a	3.09b
	84	2.32a	3.60a	3.71a	3.21a
	Spring K rate, kg ha^{-1}‡				
	0 (8)	2.21b	3.52a	3.51a	3.08b
	42 (50)	2.33a	3.57a	3.62a	3.17a
Belmont	Fall K rate, kg ha^{-1}				
	0		3.16a	2.82a	2.99a
	42		3.13a	2.95a	3.04a
	84		3.12a	2.96a	3.04a
	Spring K rate, kg ha^{-1}				
	0		3.13a	2.88a	3.01a
	42		3.15a	2.94a	3.05a

† Means in column within fall or spring K rate treatment at each location followed by the same letter are not different according to Fisher's protected LSD at $P = 0.05$.

‡ Spring K was applied at a low rate of 8 (1996) and 0 (1997 and 1998) kg K ha^{-1} and a high rate of 50 (1996) and 42 kg K ha^{-1} (1997 and 1998) in the corn season.

Fall Potassium Effects

At Kirkton, the residual effects of applying 84 kg ha^{-1} K fertilizer in fall to the preceding corn (averaged for the 3-yr results over tillage and spring K treatments) significantly increased subsequent NT soybean yield by 4.2% (0.13 Mg ha^{-1}) compared with the control (Table 3). Fall application of the intermediate-rate K fertilizer did not increase soybean yield. These results are generally in agreement with previous research in ridge till on high-testing soils showing that soybean response to residual K fertilizer treatments could be positive, but a high rate of K fertilizer was needed to produce effects equal to those of lower annual applications (Rehm, 1995). No positive soybean yield response to the main effects of residual fall K rate was observed in either season or for the combined data at Belmont (Table 3).

Spring Potassium Effects

At Kirkton, soybean yield increased 5.4% (0.12 Mg ha^{-1}) with the application of 50 kg K ha^{-1} relative to 8 kg K ha^{-1} in spring (averaged over tillage systems and fall K) in 1997, which was probably related to the significant increases in leaf K with the high-rate spring K at the initial flowering stage (Table 3). When combined for the 3-yr period, high spring K significantly increased yield by 2.9% (0.09 Mg ha^{-1}). No significant yield response to the main effects of residual spring K rate was

Table 4. Residual effects of tillage system × fall K × spring K interactions on soybean yield at Belmont averaged over 1998 and 1999.

Fall K rate, kg ha^{-1}	Tillage and spring K rate, kg ha^{-1}†					
	NT		ZT		CT	
	0	42	0	42	0	42
	Yield, Mg ha^{-1}					
0	3.05a‡	2.99a	2.89a	3.01a	3.09a	2.92a
42	2.94a	3.13a	2.82b	3.23a	3.06a	3.06a
84	3.11a	2.80a	3.10a	2.98a	2.98a	3.14a

† NT, no-till; ZT, zone till; CT, moldboard plow.
‡ Means in row within each tillage followed by the same letter are not different according to Fisher's protected LSD at $P = 0.05$.

observed, averaged over tillage systems and fall K rates, at Belmont (Table 3).

Interactions of tillage system × fall K × spring K were significant on soybean yield averaged over the 2-yr data at Belmont (Table 4). Soybean yield was increased by 14.5% (0.41 Mg ha^{-1}) in ZT by high spring K at the intermediate fall K rate; no significant yield response to spring K was observed at other rates of fall K. No interactions of tillage system × fall K × spring K on yield were observed in any of the three seasons or for the combined data at Kirkton (data not presented).

Despite the yield increases with high spring K in ZT and the evidence of soil K stratification observed above, the overall results suggest that soil K levels at Belmont were adequate for achieving optimum soybean yield. The lack of significant and positive yield response to fall K rate in all three tillage systems and to spring K in NT and CT may be attributed, in part, to the higher initial soil K fertility before the corn season (150 mg K L^{-1} in 1998 and 100 mg K L^{-1} in 1999) at this location. Average leaf K concentrations at the initial flowering stage for the treatment receiving neither fall K nor spring K at Belmont exceeded 19.0 g kg^{-1} in each season, which indicated that initial soil K fertility was less likely to limit soybean yield potential at Belmont. Although the relationship between soil K levels and soybean yield is understood to be both positive and consistent (deMooy et al., 1973), soybean yield response to K fertilization on soils with high (130 mg kg^{-1} < K < 170 mg kg^{-1}) and very high K levels (K > 170 mg kg^{-1}) have not generally been observed (Borges and Mallarino, 2000; Buah et al., 2000). The degree of soil K stratification at Kirkton was similar to that at Belmont, yet K fertilization increased soybean yield only on the medium-testing Kirkton soils. Our results generally support current K fertilizer recommendations derived originally for CT soybean in their relevance to soybean on continuous or intermittent long-term NT fields.

Because yield response to the residual K fertilizer rate was relatively small (although statistically significant) for soybean growing on medium-testing soils at Kirkton, and negligible for soybean growing on medium- to high-testing soils at Belmont, the high fall K plus high spring K fertilizer applications for corn in a corn–soybean rotation on soils with medium or high K levels seemed to be adequate for both crops. Application of high-rate K fertilizer to previous corn and relying on the residual K fertilizer for the subsequent NT soybean could be a recommended K management practice in a corn–soybean rotation on intermittent or continuous NT fields with medium or high K levels. Rehm (1995) reported a significant soybean yield response of 6% (0.2 Mg ha^{-1}) to residual fall K at the highest rate of 148 kg ha^{-1} in ridge till on a high-testing soil. However, Buah et al. (2000) observed that soybean yield response to residual K fertilization was negligible on high-testing soils. Both authors concluded that, on high-K soils, application of K in fall of the corn production year should be adequate for 2 yr of crop production in a corn–soybean rotation even though a higher K rate was needed to produce effects equal to those of lower annual applications.

Seed Potassium Concentrations

The residual effects of fall-applied K at 84 kg ha^{-1} increased soybean seed K concentrations by 0.5 g kg^{-1} at Kirkton in 1998 and by 0.3 g kg^{-1} at Belmont in 1999 averaged over tillage systems and spring K (Table 5). However, fall K did not increase seed K concentrations in the alternate site-years. Increases in seed K concentrations following previous spring K applications were only significant in 1999 at both locations (Table 5). Increases in seed K concentrations may affect soybean seed composition [such as concentrations and (or) composition of protein, oil, and phytochemicals] because K is involved in a variety of metabolic activities in plants.

Residual effects of tillage system on seed K concentrations were not observed in any of the five site-years (data not presented). No significant interactions of tillage system × fall K × spring K were observed on seed K concentrations (data not presented). The increases in seed K concentrations with fall K or (and) spring K applications were much smaller than those observed in leaf K concentrations at the initial flowering stage. The phenomenon of seed K concentrations being increased by K direct fertilization on soybean has been reported previously (Coale and Grove, 1991; Terman, 1977). However, this may be the first report on the residual

Table 5. Residual effects of fall and spring K application rates to previous corn on soybean seed K concentrations at Kirkton and Belmont from 1998 through 1999.

Location	Treatment	1998	1999	Average
		Seed K, g kg^{-1}		
Kirkton	Fall K rate, kg ha^{-1}			
	0	17.0c†	16.4a	16.7c
	42	17.3b	16.5a	16.9b
	84	17.5a	16.7a	17.1a
	Spring K rate, kg ha^{-1}			
	0	17.2a	16.3b	16.8b
	42	17.3a	16.8a	17.1a
Belmont	Fall K rate, kg ha^{-1}			
	0	18.9a	16.7b	17.8a
	42	18.9a	16.9a	17.9a
	84	18.7a	17.0a	17.9a
	Spring K rate, kg ha^{-1}			
	0	18.8a	16.8b	17.8b
	42	18.9a	16.9a	17.9a

† Means in a row within fall or spring K rate treatment at each location followed by the same letter are not different according to Fisher's protected LSD at $P = 0.05$.

Table 6. Correlation coefficients among soil exchangeable K concentrations and stratification, leaf K, soybean yield, and seed K concentrations at Kirkton and Belmont from 1998 through 1999.†

Location	Season	Measurement	Soil K, 0–10 cm	Soil K, 0–20 cm	Soil K, 0–30 cm	SKSC‡	Leaf K
			mg L^{-1}				g kg^{-1}
Kirkton	**1998**	**Leaf K, g kg^{-1}**	**0.38****	**0.39*****	**0.31****	**0.15ns§**	
		Yield, Mg ha^{-1}	**0.10ns**	**0.13ns**	**0.10ns**	**−0.04ns**	**0.19ns**
	1999	**Leaf K, g kg^{-1}**	**0.43*****	**0.39*****	**0.31****	**0.22ns**	
		Yield, Mg ha^{-1}	**0.34****	**0.32****	**0.34****	**−0.08ns**	**0.01ns**
Belmont	**1998**	**Leaf K, g kg^{-1}**	**0.67*****	**0.64*****	**0.62*****	**0.28***	
		Yield, Mg ha^{-1}	**0.27***	**0.32****	**0.28***	**−0.06ns**	**0.26***
	1999	**Leaf K, g kg^{-1}**	**0.33****	**0.35****	**0.31****	**0.00ns**	
		Yield, Mg ha^{-1}	**−0.08ns**	**−0.07ns**	**−0.10ns**	**0.00ns**	**0.18ns**

*** Significant at the 0.05 level.**
**** Significant at the 0.01 level.**
***** Significant at the 0.001 level.**
† Correlation coefficients were calculated on a basis of 72 split-split plots ($n = 72$).
‡ SKSC, soil K stratification coefficient that was defined as the quotient of soil K concentrations in the 0- to 5-cm layer divided by K levels at the 10- to 20-cm depth.
§ ns, nonsignificant effect.

effects of K fertilizer applied to corn on the seed K concentrations of subsequent NT soybean on intermittent or continuous long-term NT fields.

Correlation among Soil Exchangeable Potassium Concentrations and Stratification, Trifoliate Leaf Potassium, Soybean Yield, and Seed Potassium Concentrations

Leaf K concentrations were positively correlated with soil K levels at the 0- to 10-, 0- to 20-, and 0- to 30-cm depth intervals at Kirkton and Belmont in both 1998 and 1999 (Table 6). Correlation of leaf K with soil K was stronger at the 0- to 10- and 0- to 20-cm depths. A positive correlation between leaf K concentrations and soil K stratification coefficients was observed at Belmont in 1998, which suggests that vertical soil K stratification could be beneficial to soybean leaf K levels on very high-testing soils. The latter might occur as a result of soybean root distribution with depth in conservation tillage systems. Relative to CT, a much higher proportion of roots may be present in the surface layer compared with deeper layers in NT management. When soil moisture and temperature don't limit root proliferation and activity or K diffusion in the surface layer, high soil K concentrations in surface layer may actually be helpful (Coale and Grove, 1990). However, no significant correlation between leaf K and soil K stratification was observed in the site-years where soil K levels were all in the medium range. Thus, soil K stratification was neither beneficial nor detrimental to plant K nutrition at initial flowering on these medium-testing soils.

Soybean yield had a significant correlation with soil K at all depth intervals at Kirkton in 1999 and at Belmont in 1998 but was not related to soil K concentrations in the other two site-years (Table 6). Soil K stratification was not correlated with soybean yield in any of the four site-years. Correlation of soybean yield with leaf K concentrations was only significant at Belmont in 1998. Seed K concentrations were consistently and positively related to leaf K concentrations at the initial flowering stage at both locations in 1998 and 1999 (data not presented).

Two previous investigations by Buah et al. (2000) and Borges and Mallarino (2000) also showed that soil K stratification was not detrimental to K nutrition—and thus, soybean yield—in medium- to high-testing soils. Deibert and Utter (1989) even demonstrated that soil K stratification with conservation tillage actually increased soybean early growth when root development was not extensive.

CONCLUSIONS

Both CT and ZT significantly reduced, but did not eliminate, vertical soil K stratification in the spring before soybean planting relative to NT. Soil K concentrations at the 0- to 20-cm depth were approximately equal among CT, ZT, and NT systems on these medium- to high-K soils although tillage system for the previous corn crop significantly affected soil K distribution. Soil K levels increased as residual fall K rate increased.

Subsequent NT soybean responded more to residual K fertilizer rate than to application timing, tillage, and K fertilizer placement method in preceding corn. Tillage systems for corn had no significant effects on soybean leaf K concentrations, yield, or seed K levels despite obviously reduced soil K stratification with CT and ZT compared with NT. Soybean leaf K concentrations were frequently increased by K fertilization at a high rate in both fall and spring on these medium- K to high-K soils. Soybean yield increases averaged 8.3% with the application of 84 kg K ha^{-1} in fall plus 42 to 50 kg K ha^{-1} in spring on soils with exchangeable K concentrations below 100 mg L^{-1}. Similar yield increases were not observed at Belmont where initial soil K levels were above 100 mg L^{-1}.

Because yield response of NT soybean to residual K were relatively small and soybean leaf K concentrations from K-fertilized plots were generally in the sufficiency range on both medium- and high-K soils, our results suggest that on intermittent or continuous NT fields with medium- or high-K levels, application of 84 kg ha^{-1} fall K plus 42 to 50 kg ha^{-1} spring K as part of a starter to corn in a 2-yr cropping sequence was adequate for both corn and subsequent NT soybean. Furthermore, soil K stratification and the residual effects of tillage and K placement method were not major production issues for narrow-row NT soybean production in normal growing seasons. The lack of soybean response to residual tillage and K placement method suggests that farmers have considerable flexibility (in an agronomic sense) in selecting appropriate tillage and K placement methods for corn preceding NT soybean.

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