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Tillage and Nitrogen Placement Effects on Nutrient Uptake by Potato

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ABSTRACT

Deep tillage of compacted soils can improve potato (*Solanum tuberosum* L.) tuber yield and quality if no other production factors are limiting. We hypothesized that within-row subsoiling and N placement would affect tuber yields and availability of plant nutrients. Potato (cv. Russet Burbank) was grown after winter wheat (*Triticum aestivum* L.) in 1989 and after dry bean (*Phaseolus vulgaris* L.) in 1990 on a furrow irrigated Portneuf silt loam (coarse-silty, mixed, mesic Durixerollic Calciorthid). Fall tillage treatments (disking, chiseling, and moldboard plowing) were split with zone subsoiling after planting. Nitrogen was broadcast before planting or banded beside the seed piece at planting across all tillage combinations. We estimated plant nutrient status and uptake each year with whole-plant and petiole samplings during tuber growth. Final tuber yield and quality were determined in early October. Fall tillage did not influence nutrient concentration and uptake, tuber yield, or quality. Zone subsoiling increased average plant dry weights 9%, total tuber yields 10% (4 Mg ha^{-1}), and quality, and increased P uptake an average of 11.6% (1.8 kg P ha^{-1}) without appreciably changing whole-plant or petiole P concentrations. Banding N increased average plant dry weight 6.4%, total tuber yield 9%, and N uptake 28% compared with broadcast N. Petiole NO_3-N, P, K, and Zn concentrations were higher where N was banded. There were no consistent zone subsoiling × N placement interactions. Higher nutrient applications may be required with zone subsoiling or to compensate for soil compaction problems.

Many soils used for irrigated crop production contain indigenous or tillage-induced compacted layers. Potato is particularly sensitive to soil compaction (Bishop and Grimes, 1978; Dickson et al., 1992; Ross, 1986; von Loon and Bouma, 1978). McDole (1975) observed that a plow pan restricted potato root growth to the plow layer in silt loam and coarser textured soils. Compaction can also affect external tuber quality by physically constraining developing tubers.

It is difficult to predict compaction's effect on plants because many soil properties and processes affect root growth, nutrient movement, and uptake. Even a slight uptake reduction may seriously affect plant growth and yield when nutrient availability is marginal. Reduced root growth from compaction may limit the plant's water and nutrient extraction zone to a smaller soil volume or to a soil volume with lower available nutrient concentrations. If water uptake is not seriously influenced, reduced root growth and exploration may reduce uptake of ions that move to the root by diffusion (e.g., P) more than those that move to the root by mass flow, e.g., NO_3-N (Parish, 1971). Potassium might be intermediate since it moves to the root by both diffusion and mass flow (Barber, 1995). Some compaction may actually increase nutrient uptake if it increases the movement of ions to the roots via diffusion. Roots may also partially compensate for reduced root growth with increased uptake per unit length (Hoffmann and Jungk, 1995; Shierlaw and Alston, 1984).

Subsoil compaction of a fine-loamy soil reduced P and K uptake by corn (*Zea mays* L.) 25% when rainfall was low but enhanced it when rainfall was average or above average (Dolan et al., 1992). Surface compaction affected P uptake less than subsoil compaction. In irrigated cotton (*Gossypium hirsutum* L.) grown on a low-K, claypan soil, K uptake was not increased by deep K placement compared with surface-broadcast K when both placement treatments were in-row subsoiled, even though tillage increased subsoil root densities (Mullins et al., 1994). Deeper tillage is not always necessary or desirable for best crop growth or yields if available soil nutrients and plant root distributions are similar, as in the surface soil layer under conservation tillage systems (Hargove, 1985).

Zone subsoiling of furrow-irrigated potato hills before plant emergence increased infiltration and reduced soil erosion, while improving tuber yields and grade (Sojka et al., 1993a). Tuber yield and quality effects from zone subsoiling were also favorable under sprinkler irrigation (Halderson et al., 1993; Sojka et al., 1993b). Many arid soils in the western USA have subsoils or tillage-induced pans that restrict root growth (Linford and McDole, 1977). These subsoils often have high lime concentrations and typically are low to very low in plant available P, K and Zn. Nitrogen fertilizer is normally required for high crop yields on these soils. The advantage of zone subsoiling in potato production is dependent on identifying its effect on nutrient availability and uptake. This information will facilitate the development and use of improved tillage and nutrient management strategies. Our objectives were to identify zone subsoiling and N placement effects on potato yield and selected plant nutrient uptake.

METHODS AND MATERIALS

Potato was grown after winter wheat in 1989 and after dry bean in 1990 on a Portneuf silt loam. Most experimental details were given by Sojka et al. (1993a). In summary, half of each fall tillage (FT) treatment (disking, chiseling, and moldboard plowing) was in-row zone subsoiled (ZS) after spring planting. Zone subsoiling was done with paratill shanks after hilling as the last tillage operation before fall harvesting. The shanks were placed such that the soil disturbance was below the potato hill. The disturbed area was about 0.6 m wide at the soil surface and tappered down to the paratill shank point, 0.45 m below the soil surface.

Each subplot was split and N fertilizer (urea ammonium nitrate, UAN-32, at 220 kg N ha^{-1}) was either broadcast and immediately tilled in (disking followed by roller harrowing) before planting or banded 0.12 m to the side of the seed piece at planting across all tillage combinations. Furrow irrigations were

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Abbreviations: FT, fall tillage; ZS, zone subsoiling; NPlac, nitrogen placement.

scheduled to maintain available soil water above 60% at the seed piece depth. The 1989 statistical design was a randomized split plot, split block with four replications, while the 1990 design was a randomized split-split plot with three replications.

The experimental areas were soil sampled (0–0.3 and 0.3–0.6 m) each spring and fertilizer applied according to University of Idaho soil test recommendations for potato (McDole et al., 1987). Preplant residual soil NO_3-N and NH_4-N concentrations were 9.7 and 2.8 mg kg^{-1} in 1989, and 10.5 and 3.1 in 1990, respectively. Besides the broadcast N treatment, 60 and 100 kg P ha^{-1} [as $Ca(H_2PO_4)_2$, 0-45-0] were broadcast across all plots in early April 1989 and 1990, respectively, and incorporated by disking ($\approx$0.1–0.15 m) and roller harrowing ($\approx$0.02–0.04 m) before planting. All other nutrients were sufficient according to soil tests. Potato seed pieces (cv. Russet Burbank) were planted 27 Apr. 1989 and 2 May 1990 in 0.91-m rows, with 0.3-m within-row seed piece spacing. All individual plots were eight rows wide and either 33.5 m long in 1989 or 53.5 m long in 1990.

Whole plants from 1.5 m of row were divided into tops, easily recoverable roots, and tubers in 1989 on 19 July (S1) and 24 August (S2), and in 1990 on 18 July (S1) and 27 August (S2). Both the tubers and roots were washed to remove adhering soil particles. The tubers were weighed and subsampled for dry matter determination. Samples of the fourth petiole down from the meristem tip were obtained from each plot during tuber growth (late June, D1; middle July, D2; and early August, D3) both years. All plant samples were dried at 60°C, weighed, and ground through a 635-μm stainless steel screen. Plant N and P concentrations were determined after Kjeldahl digestion by flow injection analysis (Lachat Instrument, Milwaukee, WI, Methods no. 13-107-06-2-A and 12-115-01-1-A)[1]. For sample K, Zn, Cu, Mn, Ca, and Mg concentrations, 0.5 g dried sample was dry ashed for 6 h at 500°C; the residue was then dissolved in 0.05 L of 0.2 *M* HNO_3 and analyzed by atomic absorption spectrophotometry. The petiole NO_3-N concentrations were determined by specific-ion electrode (Milham et al., 1970). Petiole P was determined colorimetrically after dry ashing (Kitson and Mellon, 1944).

Final tuber yield and quality (individual tuber conformation and weight) were determined in early October on machine-harvested samples from 15.2 m of two center rows in each plot. Potato market grade was determined using USDA grading standards (U.S. Department of Agriculture, 1983) and specific gravity on a representative sample by the weight-in-air minus weight-in-water method (Kleinschmidt et al., 1984). Tubers grading into *ones* are those meeting the U.S. grading standards for Grade 1; *tens* are those tubers ≥0.28 kg in U.S. Grades 1 and 2; *total yield* includes all harvestable tubers.

Data were statistically analyzed with PROC ANOVA outlined by the SAS Institute (1985). Stepwise and linear regression relationships were estimated between petiole nutrient concentrations and tuber yield parameters to identify limiting nutrients (Neter et al., 1989). The stepwise regression procedure used an *F* ratio of 4.0 to select or reject a variable in deriving the final model.

RESULTS

Tuber Yields and Plant Weights

The ZS and FT effects on tuber yields were reported by Sojka et al. (1993a). Generally, ZS increased the percentage of the larger, marketable-grade tubers (tens) with smaller effects on total tuber yields. There was also a corresponding yield increase of ones. Fall tillage practices (disking, chiseling, or plowing) only influenced total yields in 1990 (α = 0.01). In addition, the ZS × FT interactions for tuber yields were generally nonsignificant. Major emphasis will be placed on the main effects of ZS and NPlac, and the ZS × NPlac interaction, since FT effects and associated interactions were generally not significant for the nutritional characteristics measured.

Table 1. Zone subsoiling (ZS) and N placement (NPlac, ba = banded, bc = broadcast) effects on tuber yields.‡

		1989			1990		
ZS	NPlac	Ones	>Tens	Total	Ones	>Tens	Total
		Mg ha^{-1}					
– ZS	ba	24.8	18.9	39.5	24.3	8.6	44.8
	bc	17.3	9.0	33.0	26.8	8.9	45.5
+ ZS	ba	28.3	21.6	41.2	34.0	10.2	52.5
	bc	21.4	9.9	37.5	30.5	8.9	47.8
F tests	ZS	**	NS	*	**	**	**
	NPlac	**	**	**	NS	NS	NS
	ZS × NPlac	NS	NS	NS	*	*	†

†,*,** Significant at α = 0.10, 0.05, and 0.01, respectively; NS = α > 0.10.

‡ Ones = U.S. No. 1 tubers; Tens = tubers ≥ 0.28 kg; Total = total tuber yields.

Zone subsoiling increased average total tuber yields 10% or 4 Mg ha^{-1}, as previously reported (Sojka et al., 1993a,b). Nitrogen placement significantly affected tuber yields in 1989 but not in 1990 (Table 1). There were no significant FT × NPlac tuber yield interactions either year (data not shown). Other two- and three-way interactions (ZS × FT, ZS × FT × NPlac) were not consistently significant. The ZS × NPlac interaction was significant in 1990 (Table 1). The larger NPlac effect on tuber yields in 1989 (14.4%) compared with 1990 (4%) may be partially related to the previous crop, as fertilizer N requirements should be higher following wheat than after dry bean because of the potential N mineralization differences from the crop residues.

Zone subsoiling significantly increased whole-plant dry weights in three out of four samplings in the two experiments (Table 2). As reported previously (Sojka et al., 1993a), higher soil temperatures (0.5°C) and lower soil bulk densities in the ZS plots probably contributed to earlier seed piece sprouting and plant emergence. Nitrogen placement significantly affected plant dry weights in 1989 but had no effect in 1990. We do not have an explanation for the ZS × NPlac interaction at the first sampling in 1990 where broadcast N without zone-subsoiling treatment had larger plants. Generally, the whole plants tended to be larger when N was banded under ZS in both 1989 and 1990.

Nitrogen

Zone subsoiling increased total N uptake in only the second sampling of 1989 (Table 3). The lack of significance in the other samplings occurred because increased plant size (Table 2) was offset by decreased N concentra-

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[1] Trade names are used to provide specific information to the reader. Mention of a trade name does not constitute an endorsement over other similar products by the USDA.

Table 2. Zone subsoiling (ZS) and N placement (NPlac, ba = banded, bc = broadcast) effects on whole-plant dry weight at two sampling dates (S1 and S2) in 1989 and 1990.

ZS	NPlac	1989 S1	1989 S2	1990 S1	1990 S2
		$\mathrm{Mg\ ha^{-1}}$			
– ZS	ba	6.2	11.5	4.4	10.9
	bc	5.5	8.9	5.2	10.9
+ ZS	ba	6.7	12.2	6.0	12.6
	bc	5.7	11.5	5.8	11.9
F tests	ZS	NS	*	*	*
	NPlac	**	*	NS	NS
	ZS × NPlac	NS	NS	†	NS

†,*,** Significant at $\alpha = 0.10$, 0.05, and 0.01, respectively; NS = $\alpha > 0.10$.

tion when zone subsoiled (Table 4). Banding the N increased plant N concentration and uptake in three out of four samplings (Tables 3 & 4). There was no significant ZS × NPlac interaction for N uptake, while the interaction was significant ($\alpha = 0.05$) for N concentration in the first 1989 sampling (Table 4).

Petiole NO_3-N concentrations were smaller where zone subsoiled in the first 1989 sampling and in all 1990 samples (Table 5). Nitrate-N concentration was higher where the N was banded compared with broadcast placement, particularly in 1989. In 1989, the concentrations reflect a low to very low plant N status for the broadcast treatments at all samplings (Westermann and Kleinkopf, 1985). In 1990, the concentrations in the broadcast and banded treatments were more comparable. The ZS × NPlac interaction was significant at the first sampling both years, i.e., D1 (Table 5), because petiole NO_3-N concentrations were lowest where zone subsoiled and the N broadcast. There were similar trends in later 1990 samplings.

Other Nutrients

Nitrogen placement affected the whole-plant concentration and uptake of Mn, Cu, Ca, and Mg in 1989 and 1990 primarily via growth differences (data not shown). Similar effects were also observed for petiole nutrient concentrations. Zone-subsoiling effects on these nutrients also reflected growth and tuber yield differences. Fall tillage effects and interactions were generally not significant either year. Nitrogen placement and ZS tillage effects on P, K, and Zn whole-plant data and petiole P and Zn concentrations will be discussed further.

Zone subsoiling increased P uptake in the second and first samplings of 1989 and 1990, respectively (Table 3), with a trend for increased uptake evident in the other two samplings. Potassium uptake was not affected by zone subsoiling, while Zn was affected ($\alpha = 0.05$) in only the second 1989 sampling. Nitrogen placement did not influence P uptake in any sampling or K uptake in three out of four samplings. Zinc uptake was significantly lower in all samplings with broadcast N (Table 3). There were no significant ($\alpha = 0.05$) ZS × NPlac interactions for P, K, and Zn uptake.

Zone subsoiling decreased whole-plant P, K, and Zn concentrations in both 1990 samplings, while only affecting Zn in 1989 (Table 4). Plant K and Zn concentrations tended to be lower when the N was broadcast both years. Phosphorus concentrations were similar for both N placements in 1990, but higher in 1989 when N was broadcast. Again there were no significant ZS × NPlac interactions for P, K, or Zn concentrations in the whole plant.

In the first petiole sampling of both years, ZS and broadcast N decreased Zn concentrations (Table 5). Similar NPlac trends occurred in the second sampling; however, ZS effects were not as apparent. By the third sampling, the NPlac effect was significant only in 1989, possibly because the plants were approaching senescence where N was broadcast (note very low petiole NO_3-N concentrations in 1989). Similar results were obtained for petiole Cu, Mn, and K concentrations (data not shown). Petiole P concentrations were not affected by ZS nor was the ZS × NPlac interaction important. The higher P concentration with broadcast N in 1989 probably reflects a reduced growth rate caused by lower whole-plant N concentration (Table 4). None of the petiole nutrient concentrations (P, K, Zn, Mn, Cu, Ca, or Mg) was low enough to limit plant growth or yields (Westermann, 1993). Fall tillage treatments and two-way and

Table 3. Zone subsoiling (ZS) and N placement (NPlac, ba = banded, c = broadcast) effects on whole-plant N, P, K, and Zn uptake at two sampling dates (S1 and S2) in 1989 and 1990.

Year	ZS	NPlac	S1 N	S1 P	S1 K	S1 Zn	S2 N	S2 P	S2 K	S2 Zn
			$\mathrm{kg\ ha^{-1}}$							
1989	– ZS	ba	164	13.1	232	0.126	219	21.9	294	0.232
		bc	85	12.2	184	0.111	139	21.0	238	0.197
	+ ZS	ba	159	14.1	254	0.126	224	24.5	321	0.234
		bc	83	13.4	195	0.106	160	24.8	269	0.217
F tests		ZS	NS	NS	NS	NS	†	*	NS	*
		NPlac	**	NS	*	**	**	NS	NS	*
		ZS × NPlac	NS	NS	NS	NS	NS	NS	NS	NS
1990	– ZS	ba	122	8.5	168	0.088	200	19.0	260	0.163
		bc	134	9.5	174	0.084	188	18.7	248	0.138
	+ ZS	ba	140	10.6	198	0.104	204	21.2	282	0.148
		bc	133	10.3	177	0.084	178	19.7	250	0.123
F tests		ZS	NS	*	NS	NS	NS	†	NS	NS
		NPlac	NS	NS	NS	*	**	NS	NS	*
		ZS × NPlac	NS	†	NS	NS	NS	NS	NS	NS

†,*,** Significant at $\alpha = 0.10$, 0.05, and 0.01, respectively; NS = $\alpha > 0.10$.

Table 4. Zone subsoiling (ZS) and N placement (NPlac, ba = banded, bc = broadcast) effects on whole-plant N, P, K, and Zn concentration at two sampling dates (S1 and S2) in 1989 and 1990.

			S1				S2			
Year	ZS	NPlac	N	P	K	Zn	N	P	K	Zn
			g kg^{-1}			mg kg^{-1}	g kg^{-1}			mg kg^{-1}
1989	− ZS	ba	26.6	2.11	37.5	20.5	19.2	1.91	25.6	20.2
		bc	15.4	2.23	33.2	20.2	13.7	2.08	23.4	19.7
	+ ZS	ba	23.6	2.10	37.7	18	18.4	2.00	26.2	19.1
		bc	14.5	2.32	33.6	18.7	13.7	2.14	23.1	18.7
F tests		ZS	**	NS	NS	†	NS	NS	NS	*
		NPlac	**	*	**	NS	**	**	*	NS
		ZS × NPlac	*	NS	NS	NS	NS	NS	NS	NS
1990	− ZS	ba	27.3	2.15	37.6	19.8	18.3	1.74	23.8	14.9
		bc	25.9	2.06	33.9	16.4	17.2	1.70	22.6	12.8
	+ ZS	ba	23.6	1.98	34.3	17.5	16.3	1.68	22.5	11.8
		bc	23.1	1.98	30.6	14.8	15.0	1.64	21.0	10.3
F tests		ZS	**	*	**	†	*	†	*	*
		NPlac	NS	NS	**	**	†	NS	NS	*
		ZS × NPlac	NS	NS	NS	NS	NS	NS	NS	NS

†,*,** Significant at α = 0.10, 0.05, and 0.01, respectively; NS = $\alpha > 0.10$.

three-way interactions for petiole nutrients were generally not significant either year.

DISCUSSION AND CONCLUSIONS

Broadcast N applications under furrow irrigation are generally not as effective as banded N. This occurs because evaporation-induced upward water movement concentrates broadcast NO_3-N and other soluble salts in the upper portions of the potato hill where it is less available for plant uptake. Any soil NO_3-N below the irrigation furrow would be moved to lower soil depths by the wetting front, possibly out of the rooting zone. Alternatively, banded N would tend to move back and forth in the root zone with the wetting front of repeated irrigations.

Banded N may influence plant N concentrations more than broadcast N during early growth when rooting volume is limited. Most of the water infiltration differences between ZS treatments also occurred in the early irrigations when plants were small (Sojka et al., 1993a). This may have reduced early NO_3-N availability in the rooting zone and, subsequently, petiole NO_3-N concentrations in the first sampling. Petiole NO_3-N concentrations also tended to decrease faster with time where zone subsoiled (Table 5). This may be from increased plant growth and tuber yields rather than higher leaching losses where zone subsoiled, since total N uptake was not appreciably affected by zone subsoiling (Table 3). Both petiole NO_3-N and plant N concentration trends were similar (Table 4 vs. Table 5). In addition, fall tillage effects were usually nonsignificant (data not shown).

Most potato roots are found in the plow layer of mineral soils, although some roots penetrate to 1.5 m (Linford and McDole, 1977; Lesczynski and Tanner, 1976). A Portneuf silt loam contains a calcic layer starting at about 0.45 m that restricts root growth but not downward water movement. This restrictive layer is probably less than 0.45 m in many furrow-irrigated fields because of past erosion and land leveling activities. The ZS depth in this study was 0.45 m, about 0.15 m deeper than normal moldboard plowing. Zone subsoiling should have fractured any antecedent tillage pan and the upper portions of the calcic layer under the potato hills. We evaluated the ZS effects on rooting depth in late July 1990 using a surface-spray washing technique (Linford and McDole, 1977). No root density differences or tillage-

Table 5. Zone subsoiling (ZS) and N placement (NPlac, ba = banded, bc = broadcast) effects on petiole NO_3-N, Zn, and P concentrations at three sampling dates (D1 = late June, D2 = mid-July, and D3 = early August) in 1989 and 1990.

			NO_3-N			Zn			P		
Year	ZS	NPlac	D1	D2	D3	D1	D2	D3	D1	D2	D3
			mg kg^{-1}						g kg^{-1}		
1989	− ZS	ba	18 610	13 150	9 860	39	33	30	3.26	2.92	2.64
		bc	4 590	1 220	860	35	24	44	3.58	2.64	1.89
	+ ZS	ba	16 310	12 650	8 620	34	32	29	3.18	2.88	2.65
		bc	4 170	1 730	1 000	32	24	42	3.72	2.78	1.93
F tests		ZS	**	NS	NS	*	NS	NS	NS	NS	NS
		NPlac	**	**	**	**	**	**	**	†	**
		ZS × NPlac	*	†	NS	†	NS	NS	†	NS	NS
1990	− ZS	ba	21 950	17 570	9 000	38	35	23	3.43	2.99	2.11
		bc	20 710	15 990	9 370	32	33	22	3.21	2.90	2.08
	+ ZS	ba	21 270	14 740	7 630	35	32	21	3.29	2.91	2.08
		bc	18 430	12 920	7 240	30	31	24	3.07	2.68	2.14
F tests		ZS	†	*	*	**	*	NS	NS	NS	NS
		NPlac	**	*	NS	**	†	NS	**	**	NS
		ZS × NPlac	**	NS	NS	NS	NS	NS	NS	NS	NS

†,*,** Significant at α = 0.10, 0.05, and 0.01, respectively; NS = $\alpha > 0.10$.

induced layers were observed between ZS treatments. Soil bulk density in the center of the ZS potato hill (at 0.3-m depth) was 0.1 g cm^{-3} lower than the control (Sojka et al., 1993a).

In 1989 the prefertilization soil test P, K, and Zn concentrations (mg kg^{-1}) in the 0- to 0.3-m depth were 14.7, 160, and 1.9 and were 7.4, 112, and 0.6 in the 0.3- to 0.6-m depth. In 1990 soil test P, K, and Zn concentrations (mg kg^{-1}) in the upper layer were 8.5, 148, and 1.1 and were 6.1, 108, and 0.5 in the lower layer. Increased rooting in the lower soil layer (0.3–0.6 m) would be in soil having nutrient availabilities lower than in the upper layer.

The coefficients of multiple determination (R^2) from the stepwise linear regression analysis between petiole nutrient concentrations and tuber yield variables ranged from 0.15 to >0.7, with coefficients slightly higher in 1989 than in 1990 (data not shown). Nutrients commonly selected were a combination of NO_3–N, P, K, and Zn, even though N placement was the only nutrition-related treatment. Petiole NO_3–N concentrations were significantly correlated to Zn concentrations in five out of six samplings, to K in the second 1989 and third 1990 sampling, and to P in the third 1989 sampling. These data suggest that other plant nutrients besides N were affecting yields. Petiole nutrient relationships tend to be complex and correlated (James et al., 1994).

Part of the nutrient uptake differences occurred because of different plant and tuber yields. We attempted to separate growth differences from tillage-treatment effects on nutrient uptake by comparing N/P, P/Zn, and N/K ratios (Table 6). The ratios should not be affected by treatments if only dilution (via growth) caused the differences; however, if factors other than dilution are contributing then the ratios will be affected by treatment. Zone subsoiling reduced the N/P ratio in all samplings. If tillage or antecedent compaction did not affect plant water use, then N uptake would not be affected by compaction, as NO_3–N moves to the root primarily by mass flow. There was no apparent effect of ZS on crop water use (Sojka et al., 1993a) nor did ZS generally affect N uptake in the whole-plant samplings (Table 3). Phosphorus uptake, however, was increased by zone subsoiling. This was more than just an increase from additional growth, since neither the whole plant (Table 4) nor the petiole P concentration (Table 5) was appreciably changed by ZS (none in 1989, slightly lower whole-plant P [i.e., <0.1 g kg^{-1}] in 1990, Table 4).

The P/Zn ratio was increased by ZS in three out of four samplings, while ZS decreased the N/K ratio in only the first 1989 sampling (Table 6). Both K and Zn move to the root by both diffusion and mass-flow processes (Barber, 1995). In addition, the relative mobility of P, K, and N is larger than Zn in higher plants. This may tend to limit Zn uptake as it would not be as readily translocated from the vegetative portions of the plant to the developing tubers as N, P, and K. Only in the second 1989 sampling did ZS increase Zn uptake. Zinc concentration was decreased by ZS in all samplings. The N/K was generally not affected by ZS, since whole-plant K uptake and concentration changes were similar to N. Unless soil aeration is significantly reduced, K uptake may not be affected by compaction (Wolkowski, 1990). The K/P ratio was not affected by ZS (data not shown). The higher soil temperatures of the ZS treatments may have also stimulated root growth, root hairs, and mycorrhizae infection. This would have affected P uptake more than K or Zn.

Nitrogen placement affected the nutrient ratios primarily through increased N uptake when banded. There were no significant ZS × NPlac interactions (Table 6) nor were there any significant fall tillage effects on the ratios (data not shown).

None of the petiole nutrient concentrations, except NO_3–N, were low enough to limit plant growth or yields in this study. There was a general tendency for the petiole concentration of P, K, Zn, and Mn to be lower after zone subsoiling. Yield increases from zone subsoiling could cause incipient deficiencies if the availability of any essential nutrient was initially marginal and no additional fertilizer material was applied. A 4 Mg ha^{-1} tuber yield increase would contain about 13, 2, and 16 kg ha^{-1} of N, P, and K, respectively. These are not large amounts but both fertilizer uptake and plant translocation efficiencies must also be considered. The higher yields after zone subsoiling may require that fertilizer rates be in-

Table 6. Zone subsoiling (ZS) and N placement effects (NPlac, ba = banded, bc = broadcast) on uptake ratios of N/P, K/P, and N/K for two sampling dates (S1 and S2) in 1989 and 1990.

			S1			S2		
Year	ZS	NPlac	N/P	P/Zn	N/K	N/P	P/Zn	N/K
1989	– ZS	ba	12.5	103.9	0.71	10.1	94.4	0.75
		bc	7.0	109.9	0.46	6.6	106.6	0.58
	+ ZS	ba	11.3	111.9	0.63	9.2	104.7	0.70
		bc	6.2	126.4	0.43	6.4	114.3	0.58
F tests		ZS	**	*	*	*	*	NS
		NPlac	**	NS	**	**	NS	**
		ZS × NPlac	NS	NS	NS	NS	NS	†
1990	– ZS	ba	12.6	106.7	0.73	10.2	116.6	0.76
		bc	12.5	126.2	0.77	10.6	135.5	0.76
	+ ZS	ba	11.6	114.4	0.71	9.2	143.2	0.72
		bc	11.9	136.9	0.75	9.8	160.2	0.71
F tests		ZS	*	NS	NS	†	*	NS
		NPlac	NS	**	†	NS	*	NS
		ZS × NPlac	NS	NS	NS	NS	NS	NS

†,*,** Significant at α = 0.10, 0.05, and 0.01, respectively; NS = α > 0.10.

creased to supply the larger nutrient requirements. In addition, higher nutrient availabilities may also be necessary when soil compaction reduces root growth. Growers will need to carefully evaluate both initial (preplant soil testing) and growing season (via monitoring plant tissue concentrations) nutrient availabilities to receive full benefits of zone subsoiling in potato management systems.

Fall tillage treatments did not affect tuber yield, petiole nutrient concentration, or nutrient uptake. Neither were there consistent significant interactions between fall tillage, N placement, or ZS. Zone subsoiling increased tuber yield and quality on this silt loam soil under furrow irrigation. Plant N uptake averaged 28% greater where the N was banded than a broadcast N application in this management system. Petiole P, K, and Zn concentrations were generally higher where N was banded, even though whole-plant growth increased. Nitrogen, K, and Zn uptake were generally not affected by zone subsoiling; however, P uptake was increased. A larger plant yield did not account for all of the increased P uptake. Greater root exploration and growth in the zone-subsoiled tilled zone may be responsible for the increased uptake of this diffusion-controlled nutrient. The ZS × NPlac interaction was not important in most nutrient uptake relationships. Higher nutrient applications may be required to achieve the higher yield potential possible with zone subsoiling or to partially compensate for soil compaction problems.

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