

Importance of Early-Season Nitrogen Rate and Placement to Russet Burbank Potatoes

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Abstract Early-season nitrogen (N) is necessary for optimal potato vegetative growth and creating an optimal growing condition for high yields; however, on sandy soils it also increases the risk of losing fertilizer N through leaching. This 3-year field experiment evaluated whether a smaller amount of N placed near the plant roots could provide the benefits associated with higher rates of early N applications that were less well placed. Two rates of N applied at emergence (40 or 80 kg N ha⁻¹) were spot-placed (5 to 7 cm around each plant), banded along the row, or broadcast applied, and compared to no N or where all of the in-season N was applied at tuberization. All plots except the zero N controls received a total of 170 kg ha⁻¹ of in-season N. Where emergence N was spot-applied in some years, tuber numbers were reduced compared to where the N was broadcast, and in these situations, resulted in increased tuber size and higher yields of prime-sized tubers (U.S. No. 1, 170 to 370 g). Where differences existed, results from banded treatments were intermediate between those from the spot and broadcast treatments. However, in spite of apparent N placement effects likely associated with having a higher concentration of N near the plant roots early in the season, no differences were evident between the two rates of emergence N within a given placement. In this experiment, total yields were not affected by rate or placement of emergence N. Overall, this experiment provides support for the

concept of placing early-season N near the plant roots, and band applications along the row may be a grower-manageable alternative for achieving this goal.

Resumen El nitrógeno (N) al inicio del ciclo es necesario para el crecimiento vegetativo óptimo de la papa y para generar una condición óptima de crecimiento para altos rendimientos; no obstante, en suelos arenosos también se aumenta el riesgo de pérdida de fertilizante nitrogenado por lixiviación. En este experimento de campo de tres años se evaluó si una cantidad menor de N ubicada cerca de las raíces de la planta pudiera suministrar los beneficios asociados con niveles más altos de aplicaciones tempranas de N que no estuvieran tan bien ubicadas. Se aplicaron dos niveles de N a la emergencia en manchones (40 u 80 kg N ha⁻¹, 5 a 7 cm alrededor de cada planta), en banda a lo largo del surco, o disperso, y se compararon con ausencia de N, o cuando todo el N del ciclo se aplicó a la tuberización. Todos los lotes, con excepción de los testigos de cero N, recibieron un total de 170 kg ha⁻¹ de N en el ciclo. Cuando se aplicó el N en manchones a la emergencia, en algunos años, se redujo el número de tubérculos en comparación a cuando se aplicó disperso, y en estas situaciones, resultó en el aumento en el tamaño del tubérculo y en rendimientos más altos de tubérculos de tamaño de primera (U.S. No. 1, 170 a 370 g). En donde hubo diferencias, los resultados de los tratamientos en banda fueron intermedios entre los de manchones y los dispersos. No obstante, a pesar de los efectos aparentes de la ubicación del N, probablemente asociados con el contenido mayor en la concentración de N cerca de las raíces de las plantas temprano en el ciclo, no se evidenciaron diferencias entre los dos niveles del N de emergencia dentro de una misma ubicación. En este experimento, no se afectaron los rendimientos totales por el nivel o ubicación del N a la

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emergencia. En general, este experimento proporciona respaldo al concepto de la ubicación del N temprano en el ciclo cerca de las raíces, y las aplicaciones en banda a lo largo del surco pudieran ser una alternativa manejable por el agricultor para lograr esta meta.

Keywords Nitrogen leaching · Nitrogen timing · Tuber number · *Solanum tuberosum* L.

Introduction

The amount and timing of fertilizer nitrogen (N) applications to potato (*Solanum tuberosum* L.) is one of the most important decisions growers have to make, especially when the crop is grown on sandy soils. Insufficient available N results in reduced growth and light interception, lower yields, and early crop senescence (Kleinkopf et al. 1981; Millard and Marshall 1986; Love et al. 2005). Excessive available N can delay tuber set, decrease tuber dry matter, delay tuber maturity and result in excessive N leaching losses (Kleinkopf et al. 1981; Lauer 1986; Errebhi et al. 1998; Waddell et al. 2000).

In early-season N-deficient situations, Ivins and Bremner (1965) showed that plant shoot growth is reduced, and carbohydrates that would typically be used for producing leaves are shifted toward tuber initiation. Conversely, many researchers have observed that an adequate supply of early-season N results in increased vegetative lateral branching, leaf number, leaf size, and leaf area index (Benepal 1967; Westermann and Kleinkopf 1985; Millard and Mackerron 1986; Millard and Robinson 1990; Vos 1995; Vos and van der Putten 1998). However, N supply has little impact on rate of photosynthesis (Firman and Allen 1988; Vos and van der Putten 1998), and the effect on other yield components such as number of stems per square meter or number of tubers per plant has been mixed. Sommerfeldt and Knutson (1965, 1968), Benepal (1967), Dyson and Watson (1971), Clutterbuck and Simpson (1978), and De la Morena et al. (1994) concluded that high levels of early-season N either decreased or had no effect on numbers of tubers, whereas others observed that tuber numbers were increased when adequate amounts of N was available early (Hanley et al. 1965; Dubetz and Bole 1975; Roberts et al. 1982). Early-season N fertilization has consistently resulted in a delay in tuber initiation by 7 to 10 days (Clutterbuck and Simpson 1978; Sattelmacher and Marschner 1979; Kleinkopf et al. 1981) and significant increases in tuber size (Benepal 1967; De la Morena et al. 1994; Belanger et al. 2002). Knowles and Knowles (2006) documented that tuber set was correlated with stem number for two Russet varieties from different seed sources.

It is generally accepted that tuberization is controlled by phytohormones, including gibberillic and abscisic acids, and that these are influenced by exogenous factors such as N

nutrition (Moorby and Milthorpe 1975; Sattelmacher and Marschner 1979). Considering the potential negative effect of N on delaying tuberization, some researchers proposed withholding N applications until after tuber set; however, this practice can reduce the amount of time the crop has with full vegetative cover and has at times resulted in lower yields (Grewal et al. 1979; Roberts et al. 1982; Millard and Robinson 1990). In a review of several Wisconsin studies, Fixen and Kelling (1981) concluded that 70 to 110 kg N ha⁻¹ needed to be applied prior to tuberization or there would be a loss of crop yield or tuber quality. Since only about 30 kg N ha⁻¹ is taken up by potatoes in the first 30 days after emergence (Saffigna and Keeney 1977; Roberts et al. 1991; Horneck and Rosen 2008), the need for early N is somewhat puzzling. This need for early N has also been seen on sandy soils in other states (Hensel and Locasio 1987; Joern and Vitosh 1995).

There is some evidence that a threshold N concentration must be present in the soil solution for the plant to effectively utilize the N (Doll et al. 1971; Edwards and Barber 1976). However, Edwards and Barber (1976) and Frota and Tucker (1978) noted that N uptake continued at near constant rates until the N was nearly depleted. Kirkham et al. (1974) concluded that a minimum soil solution concentration of 50 mg NO₃-N L⁻¹ is needed to support potato growth, whereas Burns (1980) suggests this level is 20 to 25 mg NO₃-N kg⁻¹ soil and Westermann and Kleinkopf (1985) determined that sufficient N was available for optimum uptake if soil NO₃⁻-N concentrations were greater than 7.5 mg kg⁻¹.

One approach to supplying adequate early N, while at the same time minimizing the risk of losing the N by leaching, is to concentrate the early-applied N around the plant, but keeping the total amount applied at this time relatively low. This experiment therefore evaluated the influence of N placement and rate of N applied at emergence on early-season plant growth, soil and crop N status, and tuber yield and quality with the objective of achieving optimal growth with a relatively small amount of strategically placed N.

Methods and Materials

From 1996 through 1998, field experiments were conducted at the University of Wisconsin Hancock Agricultural Research Station (44°7'N, 89°32'W) on Plainfield loamy sand soils (sandy, mixed, mesic, Udipsamments) with two rates of fertilizer N (40 or 80 kg N ha⁻¹) at crop emergence in three different placements. The placements used were: (1) in a circle around each individual plant 5 to 7 cm away (spot); (2) banded along the shoulder of each row; or (3) broadcast over the entire plot. A zero-N treatment and a treatment where the full supplemental N fertilizer rate (170 kg N ha⁻¹) was applied at early tuberization were also included. The various placements were

only used for the N applied at emergence. A second N application at early tuberization banded along the shoulders of the row brought all treatments except for the zero-N control to the full rate of 170 kg N ha⁻¹. This somewhat lower than optimal rate (Kelling and Speth 2004) was used with the expectation of exacerbating rate or placement treatment differences. The emergence application was made as ammonium sulfate and the early-tuberization application as ammonium nitrate and both applications were followed by a light hilling. All plots, including the zero supplemental N control, received 34 kg N ha⁻¹ as a part of the starter fertilizer split about 5 cm to each side of the seed piece furrow at planting.

Individual seed pieces of Russet Burbank cv. were hand planted in mid- to late-April each year on exactly 30-cm in-row spacing so that the spot treatments could be precisely placed. Each plot was four rows wide (92 cm between rows) by 6.1 m long and a different field was used each year. Treatments were arranged in randomized complete blocks with five replications. Other fertilization, pest management, and irrigation practices were performed by research station personnel and were according to UW recommendations, and common to grower practices used in the region.

Each year plant growth evaluations were conducted 10 to 14 days after tuberization (approx. 50 % of plants with recognizable tubers ≥ 0.3 cm) and again about 10 to 14 days later by

digging two adjacent plants from each of the outside two rows of each plot, counting stems and tubers, and measuring dry weights of vegetation and tubers. Specific dates of these samplings and other experimental details are provided in Table 1. Just before applying the tuberization N treatments, soil samples were systematically taken in the root zone of the plants by taking one core to a depth of 30 cm in each quadrant about 8 cm away from each of four plants. The 16 cores were mixed, subsampled, and put on ice until dried in a 60 °C forced-air drier and ground to pass a 2.11-mm screen. A similar set of samples were collected 10 to 14 days later. The samples were analyzed colorimetrically for NO₃⁻-N using a Lachat autoanalyzer (Lachat Instruments 1996a) following extraction with 2M KCl. Starting at about 40 days after emergence (dae), 40 of the most recently matured petioles (fourth or fifth from the top of the plant) were sampled from each plot and samplings continued every 8 to 12 days for five samplings. Petioles were dried at 65 °C and ground to pass a 0.63-mm screen. Samples were extracted with distilled water with analyses performed using a Lachat autoanalyzer (Lachat Instruments 1996b).

Potato tubers from the two center rows of each plot were mechanically harvested in mid-September each year. The tubers were graded into U.S. No. 1, undersize (not retained on a 5.1-cm screen), and cull (off-shape, green,

Table 1 Experimental details for the nitrogen placement study at Hancock, Wisconsin, 1996 to 1998

	1996	1997	1998
Planting	24 April	24 April	23 April
Previous crop	Rye	Cucumber/sweet corn	Field corn
Variety	Russet Burbank	Russet Burbank	Russet Burbank
Starter fertilizer			
Amount	672 kg ha ⁻¹	560 kg ha ⁻¹	672 kg ha ⁻¹
Grade	5-10-30 w/imidocloprid	6-24-24 w/imidocloprid	5-10-30 w/imidocloprid
Emergence	22 May	24 May	16 May
Emergence N tmt	22 May	23 May	19 May
Tuberization N tmt	6 June (15 dae) ^a	6 June (13 dae)	4 June (19 dae)
Soil samples			
Tuberization (T)	6 June (15)	6 June (13)	4 June (19)
T+10 days	19 June (27)	16 June (23)	16 June (31)
Plant evaluations			
T+10 days	19 June (27)	16 June (23)	16 June (31)
T+20 days	1 July (39)	26 June (33)	30 June (45)
Petiole sampling	1 July (39)	7 July (44)	26 June (41)
	13 July (51)	15 July (52)	6 July (51)
	27 July (65)	24 July (61)	15 July (60)
	5 August (74)	1 August (69)	27 July (72)
	14 August (83)	11 August (79)	4 August (80)
Harvest	12 September	17 September	28 September

^a Number in parentheses is days after emergence (dae)

diseased or blemished). The U.S. No. 1 tubers were electronically size graded into <113, 114 to 170, 171 to 284, 285 to 370, 371 to 454, and >454 g categories. Tuber specific gravity was determined by weighing about 3.6 kg of washed U.S. No. 1 tubers in air and again suspended in water (Kleinschmidt et al. 1984). Fifteen of the largest tubers were evaluated for internal defects. Tuber total N content of samples combined across replications was measured after drying (60 °C), grinding (<1 mm), and Kjeldahl digestion (Nelson and Sommers 1973) using a Lachat autoanalyzer (Lachat Instruments 1992).

Crop and soil data (growth evaluations, tuber yield, grade, quality parameters, petiole NO₃⁻-N, and soil NO₃⁻-N were statistically analyzed using PROC ANOVA for a single factor (SAS Institute 1990). Data were not combined across years as the growing seasons were quite different. Tuber total N content data were not statistically analyzed since subsamples from each replication for a given treatment were combined into one sample per treatment per year.

Results and Discussion

The early-season plant growth evaluations conducted 10 to 13 days after the tuberization N treatment and again 10 to 13 days later showed that where no N was applied (except for the 34 kg ha⁻¹ in the starter fertilizer) vegetation biomass was substantially reduced especially at the second evaluation (Table 2). Furthermore, in 2 of the 3 years, the first evaluation showed higher tuber numbers and size where no N was applied, and there is a clear tendency for the lowest number of tubers and tuber biomass to be associated with the treatments that concentrated the applied N near the plant (spot and band treatments). This was also apparent at the second evaluation, but only in 1997. The greater amount of plant vegetative growth with early N application is consistent with results from several others (Ivins and Bremner 1965; Benepal 1967; Grewal et al. 1979; Kleinkopf et al. 1981; Vos 1995), who showed earlier tuberization and larger early-season allocation of carbohydrates to the tubers when N supply is low. The treatment effect on tuber number is less consistent in the

Table 2 Effect of placement and rate of emergence fertilizer N treatment on potato growth evaluated about 10 and 20 days after initial tuberization, Hancock, Wisconsin, 1996 through 1998^a

N rate		Emergence N placement	Vegetation dry weight			Tuber number			Tuber dry weight		
Emergence kg ha ⁻¹	Tuberization		1996 g plant ⁻¹	1997	1998	1996 no. plant ⁻¹	1997	1998	1996 g plant ⁻¹	1997	1998
First evaluation (tuberization+10 to 13 days)											
0	0	–	82	116	43	17.3	16.7	22.3	13.5	15.4	18.7
0	170	–	129	135	47	14.5	11.2	21.3	8.2	6.0	12.8
40	130	Spot	161	145	55	10.0	8.4	22.7	5.5	4.0	17.0
40	130	Band	145	143	58	11.7	9.2	23.1	9.0	2.8	14.5
40	130	Broadcast	165	140	59	13.5	10.4	23.2	5.5	5.4	14.0
80	90	Spot	162	129	48	8.7	6.0	18.9	6.5	1.4	12.5
80	90	Band	159	129	52	10.7	6.8	21.7	3.7	2.8	13.2
80	90	Broadcast	154	136	46	12.7	7.2	18.5	8.0	3.2	9.5
Pr > F			<0.01	0.20	0.03	0.02	0.01	0.71	0.01	<0.01	0.09
LSD _{0.05}			29	NS ^b	11	4.7	5.4	NS	4.9	3.6	NS
Second evaluation (tuberization+20 to 26 days)											
0	0	–	106	156	84	16.2	24.4	20.2	152	121	89
0	170	–	181	275	182	20.0	21.2	21.2	140	98	75
40	130	Spot	226	237	180	19.0	16.8	22.7	160	49	84
40	130	Band	195	264	165	22.7	21.6	22.6	138	67	80
40	130	Broadcast	209	258	190	22.5	22.4	19.4	147	81	83
80	90	Spot	213	276	160	21.0	16.4	19.5	172	52	72
80	90	Band	202	253	190	20.7	18.4	20.4	143	66	78
80	90	Broadcast	209	258	172	22.7	22.4	19.5	178	66	77
Pr > F			<0.01	<0.01	<0.01	0.19	0.02	0.70	0.41	<0.01	0.78
LSD _{0.05}			36	42	21	NS	5.0	NS	NS	23	NS

^a All plots received 34 kg N ha⁻¹ as a part of the starter fertilizer at planting

^b NS, not significant at Pr≤0.05

Table 3 Effect of emergence fertilizer N placement and rate on soil NO_3^- -N values, Hancock, Wisconsin, 1996 through 1998 ^a

N rate		Emergence N placement	Sampled at tuberization (T)			Sampled at T+10–12 d		
Emergence kg ha^{-1}	Tuberization		1996	1997	1998	1996	1997	1998
0	0	–	4.1	1.2	8.9	0.7	2.7	3.0
0	170	–	3.5	8.7	8.1	2.7	44.5	23.2
40	130	Spot	16.0	17.9	15.7	3.8	48.4	22.4
40	130	Band	6.8	23.9	15.6	2.7	32.1	22.7
40	130	Broadcast	5.8	8.9	13.1	2.5	25.0	18.4
80	90	Spot	17.9	38.2	28.5	4.0	40.5	26.3
80	90	Band	10.8	29.4	27.0	2.9	42.5	16.9
80	90	Broadcast	11.3	21.1	20.0	2.7	28.7	21.2
Pr>F			<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
LSD _{0.05}			4.7	8.9	6.2	1.4	11.6	6.1

^a All plots received 34 kg N ha^{-1} as a part of the starter fertilizer at planting

literature as some researchers have also noted fewer tubers where N was applied (Sommerfeldt and Knutson 1968; Clutterbuck and Simpson 1978), whereas others observed tuber number increases (Hanley et al. 1965; Dubetz and Bole 1975; Roberts et al. 1982; Belanger et al. 2002) or no change (Benepal 1967; Dyson and Watson 1971; De la Morena et al. 1994) in tuber number with increasing N application rate.

In this experiment, applying all of the supplemental N at tuberization resulted in vegetative biomass at the second evaluation equal to the treatments where some N was applied at emergence. In 1997, the overall best growing season and only year where treatments affected the second evaluation tuber number and biomass, adding all of the N at tuberization resulted in tuber biomass intermediate to where no N was applied and where N was applied at emergence. In 1996, there were three precipitation events greater than 2.5 cm that occurred between the emergence

N treatment and the second plant evaluation, in 1997 none, and in 1998 two large storms. On this soil, 2.5 cm of water will leach N to about 30 cm (Endelman et al. 1974; Starr et al. 2005), and this is the zone that contains most of the potato roots (Fulton 1970; Lesczynski and Tanner 1976; Tanner et al. 1982). In addition, the early 1998 growing season was significantly warmer as noted by the 6 to 8 day earlier crop emergence. This could partly explain the general lack of treatment response seen in that year. Although few differences were apparent in this study between treatments that received N at emergence and where N was delayed until tuberization, others have seen reduced yield and quality by delaying all non-starter N until this time or later (Fixen and Kelling 1981; Roberts et al. 1982; Millard and Robinson 1990).

Other measured parameters including stem number per plant and root biomass were not affected by treatment (data not shown) in any of the years. Results of soil samples taken

Table 4 Effect of emergence fertilizer N placement and rate on petiole NO_3^- -N levels for the first and third samplings, Hancock, Wisconsin, 1996 through 1998 ^a

N rate		Emergence N placement	First sampling (39–44 dae) ^b			Third sampling (60–65 dae)		
Emergence kg ha^{-1}	Tuberization		1996	1997	1998	1996	1997	1998
0	0	–	0.6	0.6	0.3	0.3	0.4	0.4
0	170	–	24.8	13.4	22.3	1.6	4.4	15.2
40	130	Spot	22.5	13.3	18.6	0.7	4.6	10.3
40	130	Band	20.0	13.3	19.9	1.0	3.0	10.1
40	130	Broadcast	18.9	12.3	21.0	1.0	3.4	11.7
80	90	Spot	18.1	15.1	23.2	1.2	3.6	10.5
80	90	Band	18.4	14.8	23.1	1.4	4.5	12.9
80	90	Broadcast	16.5	11.6	21.5	0.7	2.8	8.3
Pr>F			<0.01	<0.01	<0.01	0.07	<0.01	<0.01
LSD _{0.05}			3.1	1.4	3.2	NS ^c	1.4	3.2

^a All plots received 34 kg N ha^{-1} as a part of the starter fertilizer at planting

^b dae, days after emergence

^c NS, not significant at $\text{Pr} \leq 0.05$

systematically from around each of four plants to a depth of 30 cm just prior to application of the tuberization N treatment and again 10 to 12 days later are shown in Table 3. These data clearly show that at the first sampling where the fertilizer was concentrated around the plant because of the spot placement, soil NO_3^- -N levels are highest, are intermediate for the banded treatment, and lowest where the fertilizer was broadcast. The second sampling in 1996 and 1997 also shows the emergence treatment placement effects, but less dramatically. In addition, the second sampling was significantly influenced by the tuberization N treatments at various rates all of which were band-applied.

Soil nitrate-N concentration differences between years are likely due to the number of precipitation events large enough to cause leaching that occurred between application and the first or second sampling (one in 1996 and zero in 1997 and 1998 between emergence and the first sampling, and two, zero, and one, respectively, between the first and second sampling).

Table 4 presents the petiole NO_3^- -N results for the first and third samplings. Although the first sampling was 3 to 4 weeks after the tuberization N treatments and 39 to 44 days after crop emergence, there is a clear trend that in 1996 and 1997, where the emergence N was concentrated around the plant, petiole NO_3^- -N levels were higher than where the N was broadcast.

Table 5 Effect of emergence fertilizer N placement and rate on tuber yield and grade, Hancock, Wisconsin, 1996 through 1998^a

N rate		Emergence N placement	Total yield Mg ha ⁻¹	U.S. No. 1		Yield U.S. No. 1 170–370 g Mg ha ⁻¹
Emergence kg ha ⁻¹	Tuberization			All sizes %	>170 g %	
1996						
0	0	–	30.5	63	16	3.1
0	170	–	46.7	74	30	10.2
40	130	Spot	43.4	73	24	7.7
40	130	Band	40.2	72	18	5.3
40	130	Broadcast	43.3	71	15	4.6
80	90	Spot	42.9	69	19	6.3
80	90	Band	44.9	74	23	7.8
80	90	Broadcast	45.0	70	21	6.4
Pr > F			<0.01 ^b	0.01	0.01	<0.01
LSD _{0.05}			6.0	6	8	3.0
1997						
0	0	–	47.1	65	18	5.4
0	170	–	59.1	82	36	17.8
40	130	Spot	58.7	82	48	22.8
40	130	Band	62.1	82	40	19.6
40	130	Broadcast	57.2	78	30	13.7
80	90	Spot	56.0	81	51	21.7
80	90	Band	58.6	81	39	18.0
80	90	Broadcast	56.4	77	36	15.4
Pr > F			0.02	<0.01	<0.01	<0.01
LSD _{0.05}			7.3	5	8	5.4
1998						
0	0	–	33.0	60	4	0.8
0	170	–	46.3	68	23	6.9
40	130	Spot	49.2	74	22	7.7
40	130	Band	44.4	75	21	7.2
40	130	Broadcast	46.9	75	23	8.2
80	90	Spot	49.8	80	23	9.1
80	90	Band	48.0	75	25	8.8
80	90	Broadcast	47.1	74	20	6.8
Pr > F			<0.01	<0.01	<0.01	<0.01
LSD _{0.05}			5.0	5	7	2.8

^a All plots received 34 kg N ha⁻¹ as a part of the starter fertilizer at planting

To a limited extent, this trend continued at the third sampling (60 to 65 dae) across all 3 years. As expected, where all of the non-starter N was applied at tuberization, the petiole NO_3^- -N values were highest at all samplings; however, by the third sample in 1996 and 1997, all of the levels would be considered deficient (Kelling 2000) and in 1998, only the all tuberization treatment showed sufficient petiole NO_3^- -N levels present. Petiole NO_3^- -N levels measured at the fourth and fifth samplings in 1998 (72 and 80 dae, respectively) continued to show significantly more NO_3^- -N where the emergence treatments were spot applied (average of 4.1 g NO_3^- -N kg^{-1}) than where the fertilizer was broadcast (2.2 g kg^{-1}) (full data set not shown). In the other 2 years, all values were very low ($<1.5 \text{ g NO}_3^-$ -N kg^{-1}) and showed no differences between treatments (data not shown). Since the first petiole sampling did not occur until at least 22 days after the tuberization N treatment, there were no differences in petiole NO_3^- -N levels apparent between where the two rates of emergence N were used. Although Kleinkopf et al. (1981) emphasized the importance of early N for determinant potato varieties, these data showing variable responses from emergence N placement suggest that early N treatments can also impact N status well into the season for an indeterminate variety like Russet Burbank.

By the end of the season, these early-season differences had no effect on total crop yield (Table 5). Where 170 kg N ha^{-1} was applied irrespective of timing or placements, total yields were similar across treatments within each of the 3 years, and unlike the data of Roberts et al. (1982) or Millard and Robinson (1990), delaying all of the non-starter N did not negatively affect total yields. It is also clear from these data that 1997 was the best of the growing seasons as total yields averaged 30 % higher than the other 2 years. It is, therefore, noteworthy that it was in 1997 where the proportion of U.S. No. 1 tubers greater than 170 g was significantly higher where the emergence N was concentrated near the plant at both the low and high rates of emergence N. This trend also exists at the lower rate of emergence N in 1996, but not where the higher rate was used. It is also these treatment situations where lower tuber numbers were associated with N placement effects (Table 2), and where the yield of prime-sized tubers was significantly higher with spot-placed than broadcast N (Table 5). Where these differences exist, the results from the band treatment were generally intermediate to the spot and broadcast placements. Tuber specific gravity and internal defects were not affected by treatment in any of the years (data not shown).

It is not clear as to why these apparent treatment responses were seen in some years and not others, although they are likely related to the existing environmental conditions for each year. As noted previously, both 1996 and 1998 experienced several more precipitation events large enough to leach N beyond the crop root zone than were seen in 1997. In addition, the total amount of fertilizer in this experiment is about

45 kg N ha^{-1} below the recommended rate for Russet Burbank on this soil (Kelling and Speth 2004). It is possible that in the less optimal 1996 and 1998 seasons that this lower rate was still adequate to obliterate any treatments effects.

Since a subsample of tuber tissue for each treatment was taken for total N analysis from each replication and combined across all replications, it was not possible to do statistical analysis on tuber N content. Where emergence and tuberization N was applied, tuber N averaged 12.1, 15.6, and 18.2 g N kg^{-1} for 1996, 1997, and 1998, respectively. Within years, no obvious differences appeared to exist between emergence N placement or rate treatments. However, because of the yield trends in 1997, the calculation of tuber N uptake also tends to show advantages to the non-broadcast N treatments in that year averaged across the two rates of emergence N (169 , 148 , and 138 kg N ha^{-1} for spot, band, and broadcast placements, respectively).

Overall, results from this experiment confirms the work of others that showed the need for an adequate amount of N sufficiently early in the season to set up the crop vegetatively to produce high yields (Ivins and Bremner 1965; Kleinkopf et al. 1981; Roberts et al. 1982; Westermann and Kleinkopf 1985). While applying some N at this time clearly delays tuberization, and in some cases appears to reduce tuber number and has the potential to increase N leaching, this infusion of early N seems to be required for the crop to attain its yield potential. Westermann and Kleinkopf (1985) also suggested that 67 to 134 kg N ha^{-1} was needed early for Russet Burbank to optimize yield, whereas Fixen and Kelling (1981) determined that 67 to 112 kg N ha^{-1} should be applied at emergence for top yield and quality. In addition, this research emphasizes that concentrating the N near the plants results in maximizing the benefits from the application. Similar results were also shown by Grewal et al. (1979). Although it may not be practical to place N around individual plants, banding the N along the row followed by a light hilling appears to be a workable alternative compared to where the N is less concentrated following broadcast applications.

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