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Use of Hill Shape with Various Nitrogen Timing Splits to Improve Fertilizer Use Efficiency

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Abstract The efficient use of fertilizer nitrogen (N) is critical for potato production in regions with sandy soils as concerns for groundwater contamination have become more apparent. The interactive effects of different hill shapes and distribution of in-season N fertilizer applications at various timings were evaluated in a 3-year potato (*Solanum tuberosum* L. cv. Russet Burbank) field experiment on a sandy soil in central Wisconsin. A split-plot design was used with hill shape (standard, shaped-plateau, or pointed) as the main plots and 202 kg N ha^{-1} divided into two, three, or four applications as the split plots. Broader, flatter hills provided tuber yield increases of 7 to 10 %, tuber size and grade improvements of 8 to 25 %, and increased tuber N uptake an average of 22 % in some years; however, post-emergence hilling operations negatively affected yield and tuber size and grade out in 1 of 2 years. Splitting the N into three in-season applications (emergence, early tuberization, and tuberization+20 days) increased tuber yield by about 4 % or tuber size by 19 % in years where rain increased leaching potential on this sandy soil, but further splitting increased the proportion of small tubers that passed a 5.1-cm screen. This study confirmed that more blocky-shaped hills with only one hilling operation at emergence can significantly benefit potato yield and quality, and fertilizer N use efficiency on these sandy soils.

Resumen El uso eficiente de fertilizante nitrogenado (N) es crítico para la producción de papa en regiones con suelos arenosos, a medida que se ha vuelto más aparente la preocupación sobre la contaminación del agua del suelo. Se evaluaron los efectos interactivos de diferentes formas del surco y la distribución de las aplicaciones del fertilizante nitrogenado en el ciclo del cultivo en varios tiempos en un experimento de campo de tres años en papa (*Solanum tuberosum* L. var. Russet Burbank) en un suelo arenoso en el centro de Wisconsin. Se usó un diseño de parcelas divididas con la forma del surco (normal, surco aplanado o en punta) como parcelas principales y 202 Kg N ha^{-1} divididos en dos, tres, o cuatro aplicaciones como las parcelas divididas. Los surcos mas anchos, aplanados, arrojaron incrementos en el rendimiento de tubérculos de 7 a 10 %, mejoras en el tamaño del tubérculo y en su calidad de 8 a 25 %, y aumento en la absorción del N por el tubérculo en un promedio de 22 % en algunos años; no obstante, las operaciones de aporque de post-emergencia afectaron negativamente el rendimiento y el tamaño y calidad de tubérculo en uno de dos años. La división en tres aplicaciones del N en el ciclo (emergencia, inicio de la tuberización y 20 días después) aumentó el rendimiento de tubérculo en cerca del 4 % o en su tamaño en 19 % en años donde la lluvia aumentó el potencial de lixiviación en este suelo arenoso, pero la división en más aplicaciones aumentó la proporción de tubérculos pequeños que pasaron por la malla de 5.1 cm. Este estudio confirmó que más surcos en forma de bloques con una sola operación de aporque a la emergencia pueden beneficiar significativamente el rendimiento y calidad de la papa y la eficiencia en el uso del fertilizante nitrogenado en estos suelos arenosos.

Keywords Nitrogen uptake · Tuber greening · Specific gravity · Petiole nitrate

Introduction

The efficient use of applied fertilizer N by potatoes is especially important on sandy soils as unused N can easily leach to groundwater (Saffigna and Keeney 1977; Stites and Kraft

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2001). Two proposed management practices for optimizing the utilization of applied N fertilizer is to time the N applications to match the periods of greatest crop N need (Westermann et al. 1988; Errebhi et al. 1998; Waddell et al. 2000) and to use advanced hill shapes that improve water use and minimize in-season N leaching (Prestt and Carr 1984; Kelling et al. 1998; Jordan et al. 2013).

Division and timing of the N applications is important because too much N during the early stages of plant growth delays tuber initiation and bulking, and is prone to excessive leaching loss especially on sandy soils (Saffigna et al. 1977; Kleinkopf et al. 1981; Westermann and Kleinkopf 1985; Errebhi et al. 1998; Waddell et al. 2000). However, insufficient early N results in limited leaf growth and poor tuber set (Ivins and Bremner 1965; Roberts et al. 1982). Excessive N applications during mid-season tuber bulking can cause late-season vegetative growth, promote secondary tuber growth, reduce specific gravity, and delay tuber maturity (Lauer 1986; Ojala et al. 1990; Roberts et al. 1991).

Data from N uptake studies show that 80 to 90 % of the total potato N is taken up by about 60 days after emergence (DAE) (Kleinkopf et al. 1981; Roberts et al. 1991; Munoz et al. 2005; Horneck and Rosen 2008). In addition, N applied later than 60 to70 DAE is unlikely to contribute to tuber production (Kelling and Speth 1998; Vos 1999). Although results from several studies have demonstrated benefits of split N applications for improving fertilizer N use efficiency (Saffigna et al. 1977; Roberts et al. 1982; Joern and Vitosh 1995; Errehbi et al. 1998; Kelling and Speth 1998), others observed no improvement in crop yield, quality or apparent recovery of fertilizer N when fertilizer was split versus applied in a single application (MacLean 1984; Evanylo 1989; Waddell et al. 1999; Zebarth et al. 2004). These differences in responses are mainly attributable to soil and climatic conditions. For example, in a 6-year, sandy soil, Wisconsin study by Kelling and Speth (1998), no benefit was seen with split applications of N in the 2 years where rainfall did not produce excessive drainage and leaching (1991 and 1995), but splitting was clearly superior with respect to yield, tuber size and grade out, and fertilizer N recovery in all 4 years of the study when leaching was apparent (1992, 1993, 1994, and 1996). When split N applications are used, the initial rate must be adequate to optimize foliar growth and tuber set, and subsequent applications should be made during the first half of the growing season to ensure that adequate N is available within the plant for N transfer to the tubers (Vos 1999; Munoz et al. 2005).

Tuber yield and grade are generally favored when potato plants are grown in low, broad hills compared to those that are steeper and higher (Moore 1937; Kouwenhoven 1970; Bohl and Love 2005). In addition, Jordan et al. (2013) demonstrated that recovery of fertilizer N was increased and irrigation water infiltrated better with broader hills. The study reported here was conducted in conjunction with the work reported by Jordan et al. (2013) with the objective of demonstrating that through the use of hill shape and appropriate division of N at various times, it might be possible to achieve improved fertilizer N use efficiency.

Methods and Materials

Experiments were conducted from 2002 through 2004 at the University of Wisconsin Hancock Agricultural Research Station (44°7’N, 89°31’W) on Plainfield loamy sand soils (sandy, mixed, mesic, Typic Udipsamments). The experiment was conducted using a split-plot design with hill shape (shaped-plateau, standard early, standard late, and pointed) as the main plot treatments and timing of in-season fertilizer N (applications split into two, three, or four treatments) as the subplots.

The standard hill for the Hancock Agricultural Research Station is relatively broad and 16 to 20 cm high, whereas the pointed hill was 26 to 30 cm high and steeply sided, and the shaped-plateau hill was formed just prior to emergence into a 25-cm steep-sided plateau with small ridges on the hill shoulders. Treatments were arranged in randomized complete blocks with four replications. The standard-early shape, which was only hilled following the emergence N application, was only included in 2003 and 2004. The standard-late and pointed shapes were hilled following both the emergence and tuberization N applications. A more complete description of the hill-shapes and their formation is given in Jordan et al. (2013). The in-season N treatments were applied at 202 kg N ha^{-1}, split into two, three, or four applications (2-4×). The 2× application received 67 kg N ha^{-1} at emergence and 135 kg N ha^{-1} at early tuberization (T), whereas the 3× treatment received 67 kg N ha^{-1} at emergence, 101 kg N ha^{-1} at T, and 34 kg N ha^{-1} at T+20 days and the 4× treatment received 67 kg N ha^{-1} at emergence, 67 kg N ha^{-1} at T, and 34 kg N ha^{-1} at T+20 days and 34 kg N ha^{-1} at T+40 days. All N treatments were applied by hand in a band along the row for the emergence and early tuberization treatments and broadcast for the two later applications. The rate of N used was somewhat less than the recommended rate (202 versus 235 kg N ha^{-1}) for Russet Burbank (Kelling and Speth 2004) with the expectation that the lower rate would exacerbate treatment differences. Actual application dates are given in Table 1. The emergence fertilizer treatment was made as ammonium sulfate, and all subsequent treatments were applied as ammonium nitrate. All plots received 616 kg ha^{-1} of either 5-10-30 or 6-24-24 fertilizer, depending on the field soil test P level in each year, split 5 cm on each side of the seed piece furrow at planting.

Russet Burbank potato (*Solanum tuberosum* L.) seed pieces were planted with 30 cm in-row spacing in mid- to late-April each year. Individual plots were four rows wide (92 cm between rows) by 6.1 m long. A new field that was

Table 1 Nitrogen fertilizer application and petiole NO_3^--N sampling dates at Hancock, Wisconsin, 2002 through 2004

Activity	2002	2003	2004
N applications			
Emergence (E)	21 May (29 DAP)[a]	16 May (18 DAP)	17 May (28 DAP)
Early tubrization (T)	6 June	9 June	7 June
T+20 days	1 July	1 July	23 June
T+40 days	22 July	21 July	12 July
Petiole sampling			
40 days after emergence	1 July (41) [b]	30 June (39)	28 June (42)
50 days after emergence	10 July (50)	10 July (50)	8 July (52)
60 days after emergence	22 July (62)	21 July (61)	19 July (63)
70 days after emergence	2 August (73)	31 July (71)	28 July (72)

[a] DAP, days after planting

[b] Number in parentheses is the actual number of days after emergence when the plants were sampled for each respective growing season

not in potatoes the previous year was used each year. Irrigation scheduling was based on the Wisconsin irrigation scheduling program (Curwen and Massie 1990) and was performed by research station staff, as were pest management practices.

Starting at about 40 DAE, 40 of the most recently matured petioles (fourth or fifth from the plant top) were sampled from each plot. Samplings continued every 10 days for four samplings. Sampling dates are given in Table 1. Petioles were dried at 65 °C and ground to pass through a 0.63-mm screen. Subsamples (0.1 g) of the ground material were extracted with distilled water and NO_3^--N analysis performed using a Lachat autoanalyzer model QuikChem IV (Lachat Instruments 1996).

Potato tubers from the two center rows of each plot were mechanically harvested in late September or early October each year. The tubers were graded into U.S. No. 1, those not retained on a 5.1-cm screen, or cull. In 2003 and 2004, the cull tubers were further separated into off-shape, green, diseased, and blemished groupings. All of the U.S. No. 1 tubers were scanned electronically and separated by computer-driven grading equipment into <113, 114 to 170, 171 to 284, 285 to 370, 371 to 454, and >454 g size 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 from each plot were examined for internal defects. A 20-tuber, washed subsample from each plot was put through a stainless steel french fry cutter, mixed, and 800 to 1000-g sample dried (60 °C) in a forced air drier. Tuber total N content was measured after grinding the dried tuber pieces (<1 mm), and Kjeldahl digestion of a 250-mg tissue subsample in Pyrex Folin tubes following procedures adapted from Nelson and Sommers (1973). The digests were analyzed for NH_4^+-N using a Lachat autoanalyzer model QuikChem IV (Lachat Instruments 1992). Additional experiment details are presented in Jordan et al. (2013).

Tuber yield, grade, quality parameters, petiole NO_3^--N, and tuber N uptake data were analyzed using PROC ANOVA for a two factor split-plot design with hill shape as the main plot and N timing as the split plot in randomized complete blocks (SAS Statistical Analysis System 1999). Data were not combined across years as the growing seasons were quite different each year and not all hill shape treatments were included in 2002.

Rainfall and irrigation were measured with an Onset RG3 tipping bucket rain gauge (Onset Computer Corporation, Bourne, MA 02532) connected to a CR10 Campbell Scientific datalogger (Campbell Scientific, Logan, UT, 84321). Drainage was estimated using a water balance equation as reported by Arriaga et al. (2009). With this approach the sandy soil profile is assumed to reach water content field capacity after a day of drainage following saturation, thus drainage is equal to precipitation plus irrigation minus evapotranspiration. In this process, the storage of soil water is assumed to not change, and runoff is assumed to be zero. Cumulative drainage was estimated for the three growing seasons using this approach. Air temperature data and evapotranspiration estimates were obtained from data of the automatic weather network located at the Hancock Agricultural Research Station (http://agwx.soils.wisc.edu/uwex_agwx/awon).

Results and Discussion

Potato emergence to vine kill precipitation plus irrigation totals for 2002 to 2004 were 921, 717, and 886 mm, respectively. Both 2002 and 2004 were considered significant leaching years. In 2002, between 15 May and 15 September, there were five storms greater than 25 mm (the amount about equal to the water holding capacity of 30 cm of this soil) (Starr et al. 2005), whereas during the same period in 2004 there were six storms of this magnitude (Fig. 1). The most severe storm produced about 222 mm of rainfall from 20 to 22 June 2002 (59 to 60 days after planting, DAP) (Fig. 1). Other notable precipitation events in these 2 years ranged from 25 to 83 mm. Estimated cumulative drainage during the growing seasons was 757, 467, and 682 mm for 2002, 2003, and 2004,

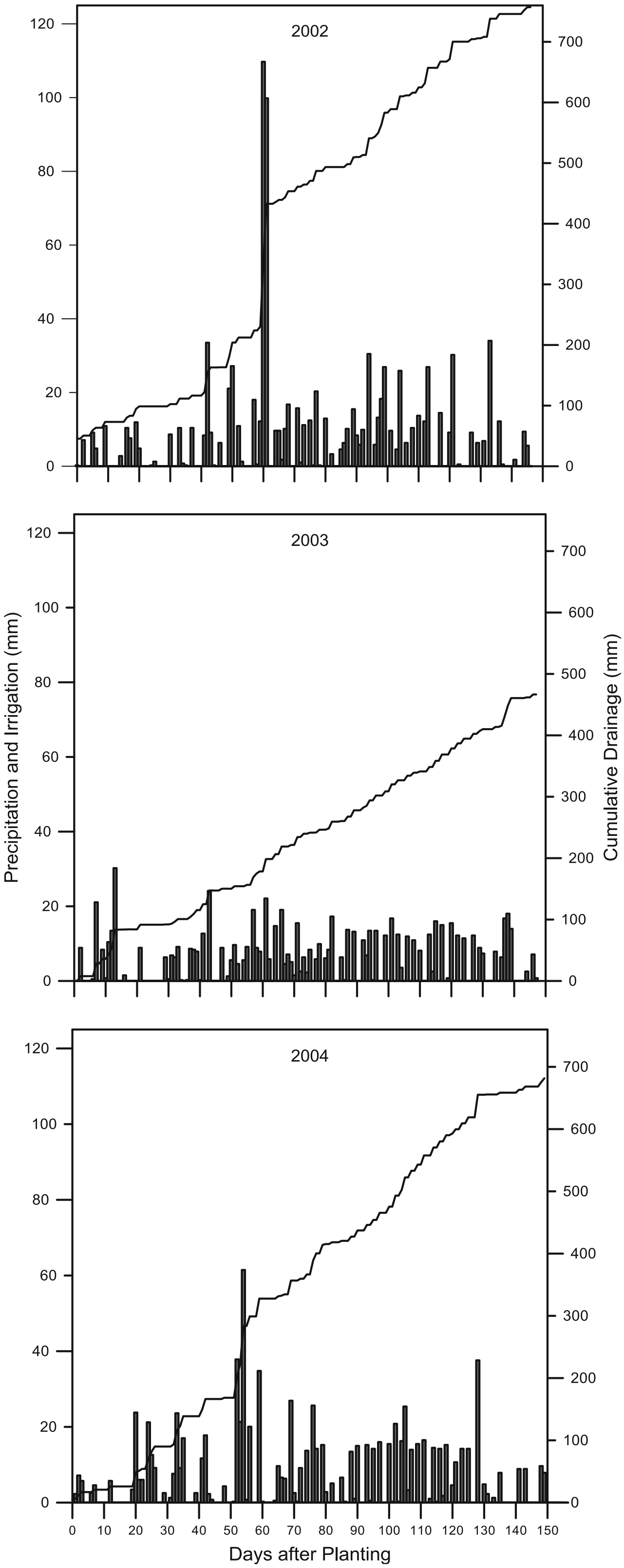

Fig. 1 Rainfall plus irrigation (vertical bars) and calculated cumulative drainage (line) for the 2002, 2003, and 2004 growing seasons, Hancock, Wisconsin

respectively. As was noted by Jordan et al. (2013), 2004 was very cool and wet in the early part of the season, and overall, a much poorer growing season (Fig. 2). The minimum temperature on several days in the early part of 2002 and 2004 growing seasons was below freezing. In 2002, there were

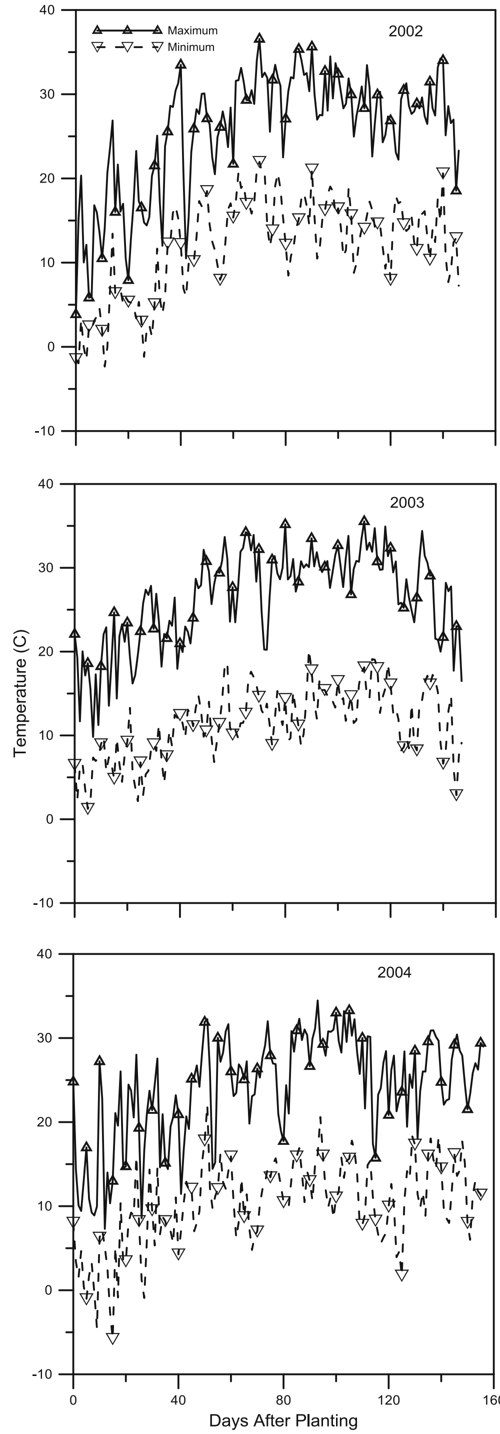

Fig. 2 Maximum and minimum air temperatures during the 2002, 2003, and 2004 potato growing seasons, Hancock, Wisconsin

Table 2 Effect of hill shape and various splits of in-season fertilizer N applications on total tuber yield and grade, Hancock, Wisconsin, 2002 through 2004

Hill shape	N splits[a]	Total yield			U.S. No. 1 tubers			Tubers > 170 g		
		2002 Mg ha^{-1}	2003	2004	2002 %	2003	2004	2002 %	2003	2004
Standard early	2×	—	57.0	32.7	—	76	65	—	18	28
	3×	—	59.4	28.2	—	82	57	—	26	23
	4×	—	64.1	28.5	—	80	53	—	25	17
Standard late	2×	52.5	53.1	26.2	54	76	59	28	24	25
	3×	51.7	47.7	32.2	55	76	63	33	26	33
	4×	52.7	55.2	27.3	53	74	54	29	23	26
Shaped-plateau	2×	52.7	59.2	28.9	55	81	62	43	21	22
	3×	56.7	61.7	28.5	55	78	63	46	23	25
	4×	48.9	64.1	29.4	49	81	54	35	23	18
Pointed	2×	46.3	52.6	28.8	51	79	61	32	19	15
	3×	49.3	54.9	30.9	55	78	64	35	18	24
	4×	51.7	58.1	27.1	51	81	55	31	21	19
Statistical significance (Pr > F)										
Hill shape (S)		0.04	0.01	0.92	0.74	0.24	0.88	<0.01	0.64	0.16
N timing (N)		0.37	0.07	0.34	0.22	0.81	0.01	0.04	0.26	0.02
S x N		0.04	0.73	0.17	0.73	0.45	0.17	0.37	0.36	0.16
Main effects										
Hill shape effect										
Standard early		—	59.2	29.8	—	79	58	—	22	21
Standard late		52.3	52.0	28.6	54	75	59	30	24	27
Shaped-plateau		52.8	61.7	29.0	53	80	60	41	23	20
Pointed		49.1	55.2	28.9	52	79	60	33	19	19
$LSD_{0.05}$		[b]	5.3	NS [c]	NS	NS	NS	3	NS	NS
N timing effect										
2×			50.5	55.5	29.1	54	62	34	18	22
3×			52.6	55.9	30.0	55	62	38	19	25
4×			51.1	59.5	28.1	51	54	32	20	19
$LSD_{0.05}$		[b]	NS	NS	NS	NS	3	5	NS	4

[a] All N applied at 202 kg N ha^{-1} . Nitrogen splits: 2×=33 % emergence (E), 67 % tuberization (T); 3×=33 % E, 50 % T, 17 % T+20 days; 4×=33 % E, 33 % T, 17 % T+20 days, 17 % T+40 days

[b] Interaction significant at *Pr*≤0.05

[c] *NS*, not significant at *Pr*≤0.05

6 days after planting with minimum temperatures below zero, and in 2004 days 5, 8, and 9 after planting had minimum temperatures below zero (Fig. 2). These cold temperatures resulted in delayed plant emergence in 2002 and 2004 compared to 2003 by about 10 days (Table 1) (Epstein 1966; MacKerron and Waister 1985; MacKerron 1985; Marinus 1993; van Dam et al. 1996). Epstein (1966) showed that potato did not germinate even after 60 days when the soil temperature is 8 °C, whereas at 22 and 29 °C potato emerged within 13 to 18 days. This is similar to our findings in 2003. Epstein (1966) also noted that potato growth and tuber formation increased with temperatures up to 29 °C, but at higher temperatures tuber yield decreased. It is likely the somewhat lower yields in 2002 and 2004 were due to the generally poorer growing seasons seen in those years (Dwelle 2003).

In both 2002 and 2003, hill shape significantly affected total tuber yield with the shaped-plateau and standard hills performing consistently better than pointed hills (Table 2). In 2003, when the standard-late hill treatment was reformed at early tuberization (9 June), this later hilling operation

Table 3 Effect of hill shape and various splits of in-season fertilizer N applications on petiole nitrate-N concentrations and tuber N concentrations and uptake, Hancock, Wisconsin, 2002 through 2004

Hill shape	N splits	Petiole NO_3-N 50-52 DAE [b]			Petiole NO_3-N 71-73 DAE			Tuber N concentration			Tuber N uptake		
		2002 g kg^{-1}	2003	2004	2002	2003	2004	2002	2003	2004	2002 kg ha^{-1}	2003	2004
Standard early	2×[a]	–	13.2	9.2	–	3.6	6.9	–	20.0	18.3	–	218	111
	3×	–	17.9	11.6	–	5.9	8.0	–	20.2	19.6	–	207	99
	4×	–	18.6	11.4	–	11.9	8.0	–	19.9	17.7	–	211	87
Standard late	2×	6.6	14.2	10.9	0.8	5.6	6.7	13.0	20.1	18.1	127	223	88
	3×	11.8	20.7	13.2	0.9	7.1	8.2	14.5	20.2	17.6	136	226	108
	4×	9.4	18.1	11.0	6.1	10.6	8.3	13.8	20.1	18.4	134	235	92
Shaped- plateau	2×	8.0	14.5	9.2	1.1	6.0	7.2	13.2	21.1	17.2	124	212	87
	3×	12.5	20.3	8.4	3.3	6.4	6.7	11.6	21.4	17.3	122	200	88
	4×	11.1	19.0	10.9	6.8	11.8	8.9	13.3	21.1	18.1	112	194	91
Pointed	2×	7.0	8.5	8.0	0.9	4.0	5.8	11.3	19.6	17.3	92	168	90
	3×	9.8	14.6	13.0	1.9	6.4	8.0	9.9	20.3	17.2	88	183	100
	4×	7.9	16.3	10.5	5.1	9.6	8.7	10.2	19.5	17.4	97	196	87
Statistical significance (Pr > F)													
Hill shape (S)		0.01	0.02	0.12	0.05	0.32	0.97	<0.01	0.02	0.37	<0.01	0.04	0.39
N timing (N)		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.69	0.66	0.79	0.99	0.82	0.09
S x N		0.50	0.28	0.01	0.32	0.73	<0.01	0.23	0.99	0.15	0.66	0.51	0.09
Main effects													
Hill shape effect													
Standard early		–	16.5	10.7	–	7.1	7.6	–	20.0	18.5	–	212	99
Standard late		9.3	17.7	11.7	2.6	7.8	7.7	13.7	20.2	18.0	132	228	95
Shaped-plateau		10.5	17.9	9.5	3.7	8.0	7.6	12.7	21.2	17.5	118	202	88
Pointed		8.2	13.1	10.5	2.6	6.6	7.5	10.5	19.8	17.3	93	183	92
$LSD_{0.05}$		1.3	2.9	[c]	1.0	NS [d]	[c]	1.3	0.8	NS	14	30	NS
N timing effect													
2X		7.2	12.6	9.3	1.0	4.8	6.7	12.5	20.2	17.7	114	205	94
3X		11.4	18.4	11.5	2.0	6.4	7.7	12.0	20.5	17.9	115	204	99
4X		9.5	18.0	11.0	6.0	11.0	8.5	12.4	20.0	17.9	114	208	90
$LSD_{0.05}$		1.3	1.4	[c]	1.0	1.7	[c]	NS	NS	NS	NS	NS	NS

Statistical significance (*Pr*>F)

[a] All N applied at 202 kg N ha^{-1} . Nitrogen splits: 2×=33 % emergence (E), 67 % tuberization (T); 3×=33 % E, 50 % T, 17 % T+20 days 4×=33 % E, 33 % T, 17 % T+20 days, 17 % T+40 days

[b] *DAE*, day after emergence

[c] Interaction significant at $Pr \leq 0.05$

[d] *NS*, not significant at $Pr \leq 0.05$

apparently set the crop back probably because of root and/or stolon pruning. Moreau (1999) and Bohl and Love (2005) also reported yield reductions with post-emergence hilling operations. This later hilling also reduced tuber size in 2002, but not in subsequent years. In this experiment, the negative impact of the taller pointed hill on yield was less apparent than it was in the previously reported work (Jordan et al. 2013) as yields for this hill shape were only less than the yields of the other hill shapes in 2002, and in that year were interactively affected by the amount of N applied at various times.

The influence of increasing the number of times the N applications were split was most noticeable on tuber size in the stronger leaching years (2002 and 2004). In both of those years, applying the N in three applications rather than four resulted in a greater proportion of tubers larger than 170 g, and although not statistically significant, in 10 of the 11 individual treatment comparisons, the 3× split resulted in numerically more large tubers than the 2× split. The effect of N splitting on tuber size was also seen in the detailed size grading where in 2002 and 2004 there were significantly fewer tubers in the<

113 g and 114 to 170 g size categories, and more in the 171 to 284 g category when the N was split into three applications (data not shown). Where the N was split into four applications at this somewhat less than optimal rate of applied N, it is likely that insufficient N was available early enough in the season to support complete bulking. Furthermore, the significantly smaller proportion of U.S. No. 1 tubers associated with the 4× N timing in 2004 showed a proportional increase in undersize tubers. Love et al. (2005) also saw more U.S. No. 1 tubers with Russet Burbank when N applications were concentrated in the middle of the season and Kelling et al. (1998) reported higher small tuber numbers with eight in-season N applications compared to three. However, Waddell et al. (1999) observed no potato yield or quality improvements with five versus three splits of a higher rate of N to Russet Burbank, and Errebhi et al. (1998) observed more small tubers when a majority of the N was applied at planting. Other tuber quality parameters including specific gravity, percent greening or presence of internal defects were not affected by hill shape or distribution of the N applications (data not shown).

The N status of the growing crop as indicated by petiole NO_3^--N levels sampled at about 50 and 70 DAE is shown in Table 3. In all years, the 50 DAE sampling was about 10 days after the third N application, but before the fourth application, whereas the 70 DAE sampling occurred 10 to 14 days after the fourth N application. As expected, the levels of petiole NO_3^--N reflect when the N was applied. At 50 DAE, where N was only applied twice, the petiole NO_3^--N concentrations were consistently lower than where N was applied three or four times. However, almost all of the petiole levels at 50 DAE in 2002 and 2004 would be considered deficient based on a sufficiency level of ≥12.0 g NO_3^--N kg^{-1} for Russet Burbank at this growth stage (Kelling 2000). By 70 DAE, the highest NO_3^--N levels are associated with the 4× treatments where the last N was only applied about 10 days previously. At 70 DAE, the 2002 2× and 3× treatments were clearly deficient (≥5 g NO_3^--N kg^{-1}) and in the other years the 2× treatments are borderline deficient (Kelling 2000).

Petiole NO_3^--N levels were significantly affected by hill shape at 50 DAE in 2002 and 2003 and at 70 DAE in 2002 (Table 3). In both 2002 and 2003 at 50 DAE, the pointed hills resulted in lower petiole NO_3^--N concentrations than the shaped-plateau or standard hill shapes. In 2004, the significant hill shape x N timing interaction results from a trend for petiole NO_3^--N levels to be highest for the 3× treatments for all hill shapes except the shaped-plateau where this treatment showed the lowest NO_3^--N concentration. We have no explanation for this trend, but it is consistent through the 70 DAE sampling in that year. By 70 DAE, a slightly higher petiole NO_3^--N level was observed for the shaped-plateau hills in 2002. These results provide some evidence that N is being used somewhat more efficiently by plants grown in the shaped-plateau hills than in the other hills evaluated.

The case for broader, flat hills resulting in better fertilizer N use is strengthened by noting that in 2002 tuber N concentrations and tuber N uptake were significantly less for the pointed hills compared to the shaped-plateau or standard hills, and in 2003 the shaped-plateau resulted in a higher tuber N concentration than all of the other hill shapes (Table 3). Also in 2003 the pointed hill had the lowest amount of tuber N uptake, but was only significantly smaller than the uptake seen with the standard-late hills. Somewhat surprisingly, no significant differences in tuber N concentration or tuber N uptake attributable to N distribution were observed.

Summary

Similar to the findings reported in Jordan et al. (2013), this experiment showed some potato yield and tuber size and grade advantages where broader, flatter hills are used. In addition, post- emergence hilling operations reduced yield in 1 of the 2 years where this effect could be measured. Tuber size was significantly increased with the shaped-plateau treatments in 1 year of the 3-year study; however, these results are confounded by the timing of the hilling operations. Splitting the in-season N into three applications (33 % emergence, 50 % early tuberization, 17 % early tuberization+20 days) improved yield and quality especially in years with significant leaching of N. However, further dividing the N fertilizer into four applications may not have supplied enough early N as this treatment resulted in more small tubers in one of the years where leaching of N was greatest. Fertilizer N utilization by the potato crop as measured by tuber N concentration and N uptake was significantly greater when broad, low hills (standard or shaped-plateau) were used. In this study, N timing had no effect on tuber N concentration or uptake.

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