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Hill Shape Influences on Potato Yield, Quality, and Nitrogen Use Efficiency

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Abstract As hill shape significantly influences water infiltration into potato hills, modification of hill shape may be an opportunity for improving fertilizer nitrogen use efficiency on sandy soils. The interactive effect of different hill shapes and rate of nitrogen (N) fertilizer application on N use efficiency was assessed in a 3-year potato (*Solanum tuberosum* L. cv, Russet Burbank) field experiment on Plainfield loamy sand soil at Hancock, Wisconsin, USA. A split-plot design was used with hill shape (shaped-plateau, pointed, or standard) as the main plots and in-season N rates (0, 135, 202, 269 kgN ha^{-1}) as the split plots with four replications in randomized complete blocks. In 1 of 3 years, potato yield and quality were increased and less N was needed to optimize yield and quality where the hills were shaped. In the other 2 years, the more blocky hills (shaped-plateau and standard) showed consistent tendencies (p=0.02 to 0.19) toward better crop performance; however, time of hill formation was influencing these results with root pruning likely the influencing factor. Results of this study show more blocky hills with only one hilling operation at emergence can significantly improve potato yield and quality and N use efficiency on these sandy soils.

Resumen La forma del surco tiene influencia significativa en la filtración del agua al interior del surco. La modificación de su forma pudiera ser una oportunidad para mejorar la eficiencia en el uso de fertilización nitrogenada en suelos arenosos. Se hicieron evaluaciones sobre el efecto interactivo de diferentes formas de surco y de aplicación de niveles de fertilización nitrogenada sobre la eficiencia del uso de N en tres años en papa (*Solanum tuberosum* L. var. Russet Burbank) en experimentos de campo en suelo limo-arenoso en la localidad de Plainfield, Hancock, Wisconsin, EUA. Se utilizó un diseño de parcelas divididas con forma del surco (forma aplanada, en punta, o estandar) como las parcelas grandes y niveles de N en el campo (0, 135, 202, 269 kgN ha^{-1}) como las parcelas chicas, con cuatro repeticiones en bloques completos al azar. En uno de los tres años el rendimiento y calidad de la papa aumentaron y se necesitó menos N para optimizar rendimiento y calidad donde se conformaron los surcos. En los otros dos años, entre más cuadrada la forma del surco (aplanados y estándar) mostraron tendencias consistentes (p=0.02 a 0.19) hacia un mejor comportamiento del cultivo; no obstante, el tiempo en la formación del surco estuvo influenciando estos resultados siendo probablemente la poda de raíz el factor de influencia. Los resultados de este estudio muestran que los surcos más cuadrados con una sola operación de aporque a la emergencia pueden mejorar significativamente el rendimiento y la calidad de la papa, y la eficiencia de uso de N en estos suelos arenosos.

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Introduction

Environmental concerns related to the expansion of irrigated potato production on sandy soils with relatively shallow groundwater tables in the north-central USA have existed since the 1960s (Saffigna et al. 1977; Waddell et al. 2000; Stites and Kraft 2001). As both water and N stress can significantly reduce yield of marketable tubers (Singh 1969; Stark et al. 1993; Lynch et al. 1995; Dalla Costa et al. 1997; Errebhi et al. 1998), there is a tendency for growers to over-irrigate and over-fertilize. Both policy makers and producers are looking for better water- and nutrient-management practices that will reduce ground-water contamination on these sandy soils without significantly reducing crop yield or quality.

Manipulation of potato hill shape is one alternative that has been suggested that has the potential for affecting both the amount of water usable by the crop and the effective recovery of applied N. Traditionally, potatoes have been planted in hilled or ridged rows for several reasons, including: (1) protection of the seed piece or tubers from frost; (2) control of weeds; (3) reduction of greening or sun scalding; (4) reduction of rotting diseases, especially on finer-textured soils; (5) ease of driving for cultivation and harvest; and (6) reduction in the amount of soil to be handled at harvest (Kouwenhoven 1970; Lewis and Rowberry 1973; Steele et al. 2006). Furthermore, hilling following an in-season fertilizer application has the additional benefit of moving the fertilizer into the hill where it may be more effectively utilized (Saffigna et al. 1977; Kelling et al. 1998).

There have been several alternatives to planting potatoes in hills studied, including wide beds (Wayman 1969; Prestt and Carr 1984; Mundy et al. 1999; King et al. 2011), flat planting (Lewis and Rowberry 1973; Sharma and Dixit 1992; Arshad et al. 1999), conventional hill planting with dammer-dike (Alva et al. 2002), and furrow planting (Arshad et al. 1999; Steele et al. 2006). Although the general conclusion has been that there are more benefits associated with hilling (Wayman 1969; Arshad et al. 1999; Mundy et al. 1999) than with using these alternatives, Prestt and Carr (1984) and King et al. (2011) showed substantial yield and water use efficiency benefits with wide beds. The ideal size and shape of hills is less clear, although Kouwenhoven (1970) presented arguments for wide (600 to 700 cm^2 ridge cross-sectional area) rounded ridges. Lewis and Rowberry (1973) increased total and Ontario No. 1 yields (primarily due to less sun-scalding) of Kennebec in 1 of 2 years with a 13-cm high hill compared to no hilling. Conversely, Mundy et al. (1999) saw more greening in one of three trials with conventional ridges compared to wide beds. Moore (1937) observed a reduction in total and U.S. No. 1 yield and number of tubers per plant as hill height increased from level to 18 cm. Bohl and Love (2005) obtained lower total and U.S. No. 1 yield of Russet Burbank and to a lesser extent Gem Russet with all post-emergence hilling treatments. They did see less greening with Russet Burbank with 23-cm high hills.

Previous researchers have clearly shown that hill shape significantly affects the amount of irrigation and precipitation that infiltrates the hill (Prestt and Carr 1984; Donohue 1990; Chow and Rees 1994; Robinson 1999) with more water running off into the furrows with higher, more steeply sided hills. Although higher furrow infiltration amounts were first qualitatively reported by Saffigna et al. (1976), Donohue (1990) quantified furrow versus hill infiltration to be three to four times greater, and Chow and Rees (1994) measured about double the runoff from hilled versus unhilled plots. Less infiltration into the hill can result in the creation of very dry conditions in the hill during parts of the growing season (Robinson 1999; Cooley et al. 2007), and although this may increase the risk of crop moisture stress, it may also reduce the loss of soluble nutrients placed within the hill (Saffigna et al. 1976; Kelling et al. 1998). The importance of the hill zone for water and nutrient uptake is magnified with the recognition that most of potato roots (about 85 %) are in the top 30 cm of soil within the hill (Lesczynski and Tanner 1976; Gregory and Simmonds 1992).

The objective of this study was to evaluate the interactive effect of several hill shapes and fertilizer N rates on the efficiency of crop N use. We also monitored the hill and furrow soil moisture status throughout the growing season.

Methods and Materials

From 2002 through 2004, split-plot, field experiments were conducted at the University of Wisconsin-Madison Agricultural Research Station at Hancock, Wisconsin (44°7’N, 89°32’W) on Plainfield loamy sand soils (sandy, mixed, mesic, Typic Udipsamments) with hill shape as the main plot and in-season fertilizer N rate as the splits in randomized complete blocks with four replications. The three hill shapes used were (1) a moderate height (16 to 20 cm), relatively broad hill that is standard for the Hancock Station; (2) a high (25 to 30 cm), pointed, steeply sided hill, and (3) a 25-cm shaped-plateau with small ridges on the hill shoulders and steep sides (Fig. 1). In 2002, the shaped-plateau hill was formed just prior to emergence, whereas the standard and pointed hills were formed at emergence and reformed with a light hilling 21 to 25 days later (early tuberization). In 2003 and 2004, an additional hill shape treatment was added where one treatment of the standard hill was only formed at emergence (standard early) and the other treatment of the standard (standard late) and the pointed were reformed at early tuberization. The in-season N treatments (0, 134, 202, and 269 $kg ha^{-1}$) were split with one-third applied just prior to the emergence hilling as ammonium sulfate and two-thirds applied just prior to the early tuberization hilling as ammonium nitrate. The treatments were pre-weighed and hand-applied in approximate 10-cm bands on top of appropriate rows. Individual plots were four rows wide (92 cm between rows) by 6.1 m long. A new field that did not have potato the previous year was used each year to reduce disease risks.

All plots, including the zero in-season N control, received 616 $kg ha^{-1}$ of either 5-10-30 or 6-24-24 starter fertilizer impregnated with imidocloprid, split 5 cm on each side of

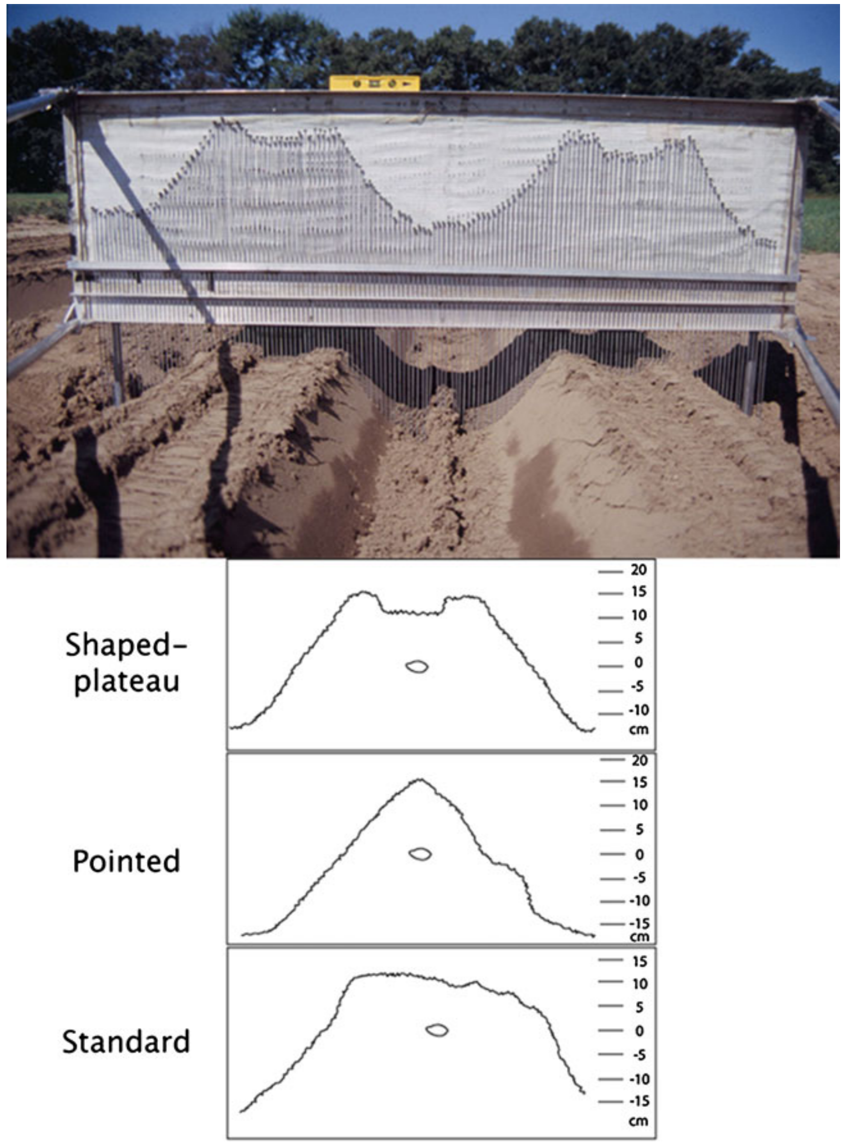

Fig. 1 Rillmeter used to detail hill shapes created and results of measurements from 16 May 2003, Hancock, Wisconsin. Measurements centered on seed piece position

the planting furrow. All plots also received 224 to 375 kg ha^{-1} 0-0-60 broadcast preplant and 560 $kg ha^{-1}$ gypsum broadcast between emergence and early tuberization. Preplant soil test results for these fields obtained from the University of Wisconsin-Madison Soil and Plant Analysis Laboratory (Combs et al. 2001) were pH 6.3 to 6.5, organic matter by ignition 7 to 10 $g kg^{-1}$, Bray P_1 P 95 to 123 mg kg^{-1}, Bray P_1 K 88 to 113 $mg kg^{-1}$, ammonium acetate Ca 330 to 555 $mg kg^{-1}$, and ammonium acetate Mg 70 to 115 $mg kg^{-1}$.

Russet Burbank potato (*Solanum tuberosum* L.) seed pieces were planted with 30 cm in-row spacing in mid- to late April each year. Irrigation scheduling was based on the Wisconsin irrigation scheduling program (WISP) (Curwen and Massie 1990) and was performed by research station personnel as were the needed pest management practices common to those used in the region.

Each year, early-season plant evaluations were conducted 4 to 5 weeks after emergence by digging two non-adjacent plants from each border row of the low, middle, and high N rates for all hill shape plots by inserting a potato fork on each side of the hill and carefully lifting a plant while retaining as much of the root system as possible. Stems and tubers were counted, and vegetation, roots and tubers washed, air-dried and weighed. In 2003 and 2004, the inorganic soil N content (NH_4^+-N + NO_3^--N) of the top 30 cm of the hills was measured by systematically combining four cores taken in a square around three separate plants per plot (i.e., one core 8 cm north, south, east and west of each plant). The 12 cores for each plot were mixed and a 500- to 800-g subsample was put on ice until dried in a 60 °C forced-air drier and ground to pass a 2.11-mm screen. The samples were analyzed colorimetrically for NH_4^+-N and NO_3^--N using a Lachat autoanalyzer (Lachat Instruments 1996a) following extraction with

2 M 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 10 days for four samplings. Petioles were dried at 65 °C and ground to pass a 0.63-mm screen. Samples (0.1 g) were extracted with distilled water and NO_3^--N analysis performed using a Lachat autoanalyzer (Lachat Instruments 1996b).

Hill configuration and size were measured using a drop-pin rillmeter (Fig. 1) (Morrison et al. 1996; Grande et al. 2005). The instrument consisted of 140 pins spaced 13 mm apart. The rillmeter was placed over two hills near the center of the plots for each treatment. The pins were allowed to drop freely to touch the hill and the shape recorded photographically. Measurements were taken about 10 days after the first hilling and in late August each year.

Soil volumetric moisture content (θ_v) was measured using frequency domain reflectometry (FDR). Frequency domain reflectometer probes (model CS-615, Campbell Scientific, Logan, Utah) were installed after plant emergence at depths of 15 and 45 cm below the top of the hill and 45 cm below the furrow. Probes consisting of two parallel stainless steel rods 3.0 cm on center and 30 cm in length were inserted by digging a hole perpendicular to the row and furrow at the end of the respective plots. Probes were placed in two replicates of the high N rate for each of the hill shapes, excluding the standard early hill shape in 2003 and 2004. Measurements were collected on 15-min intervals with a datalogger. The FDR system and equipment used are described in more detail in Cooley et al. (2007). Frequency domain reflectometer probes were removed before vine kill.

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, undersize (not retained on a 5.1-cm screen) and cull. In 2003 and 2004, the cull tubers were further separated into the proportions that were off-shape, green, diseased or blemished. All of 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 examined for internal defects. Tuber total N content was measured after drying (60 °C), grinding (< 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 (Lachat Instruments 1992).

Crop and soil data (early growth evaluations, tuber yield, grade, quality parameters, petiole NO_3^--N, soil inorganic N, and tuber N uptake) were analyzed using PROC ANOVA for a two factor split plot design with hill shape as the main plot and N rate as the split in randomized complete blocks (SAS Institute Inc. 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. Optimum N rates were determined by regression for each hill shape and year based on total yield using a quadratic plateau model (SAS Institute Inc. 1999). Soil moisture data error bars for each time period are the standard deviation divided by the square root of the number of observations.

Results and Discussion

Emergence (mid-May) to vine kill (mid-September) precipitation plus irrigation totals were 92.1, 71.7, and 88.6 cm for 2002, 2003, and 2004, respectively. In 2002, there were five storms greater than 2.5 cm (4.7 cm on 3 June, 5.8 cm on 11 June, 24.0 cm on 22 June, 2.6 cm on 22 July, and 3.3 cm on 22 August). However, 2003 was a much drier growing season with only one large event (2.6 cm on 12 May; 4 days before emergence N application). In 2004, six storms equaled or exceeded 2.5 cm in magnitude (2.7 cm on 21 May, 3.2 cm on 9 June, 8.3 cm on 10 June, 3.1 cm on 4 July, 2.5 cm on 1 Aug., and 2.5 cm on 25 August). As the Plainfield loamy sand soil has a water holding capacity of approximately 2.5 cm per 30 cm of soil (Starr et al. 2005), these data show that conditions for significant nutrient leaching existed in both 2002 and 2004, but not in 2003.

Soil Water Content Fig. 2 shows the volumetric water content 15 and 45 cm beneath the hill and at 45 cm beneath the furrow for selected mid-summer periods of each year (31 July 2002 to 19 August 2002, 17 to 26 August 2003, and 27 July to 7 August 2004). It was the intent to choose time periods for each year for which data were available when the crop was in full canopy and with at least one precipitation event of 2.5 cm or more; however, in 2003 there were no precipitation events of this magnitude when the crop was in full canopy. Although the data are somewhat inconsistent at 15 cm below the top of the hill, the shaped-plateau hill generally contained less water at this depth than the other hill shapes (θ_v=about 0.14 m^3m^{-3} versus approximately 0.18 m^3m^{-3}), and in both 2003 and 2004, the pointed hill contained the most water. This was somewhat unexpected as a variety of researchers have previously established that high, steeply sloping hills shed precipitation and irrigation at a greater rate than broader, flatter hills (Donohue 1990; Prestt and Carr 1984; Chow and Rees 1994). However, the results reported herein may be partly due to the somewhat more vigorous plant growth and therefore greater evapotranspirtion (ET) rates seen with the shaped-plateau and

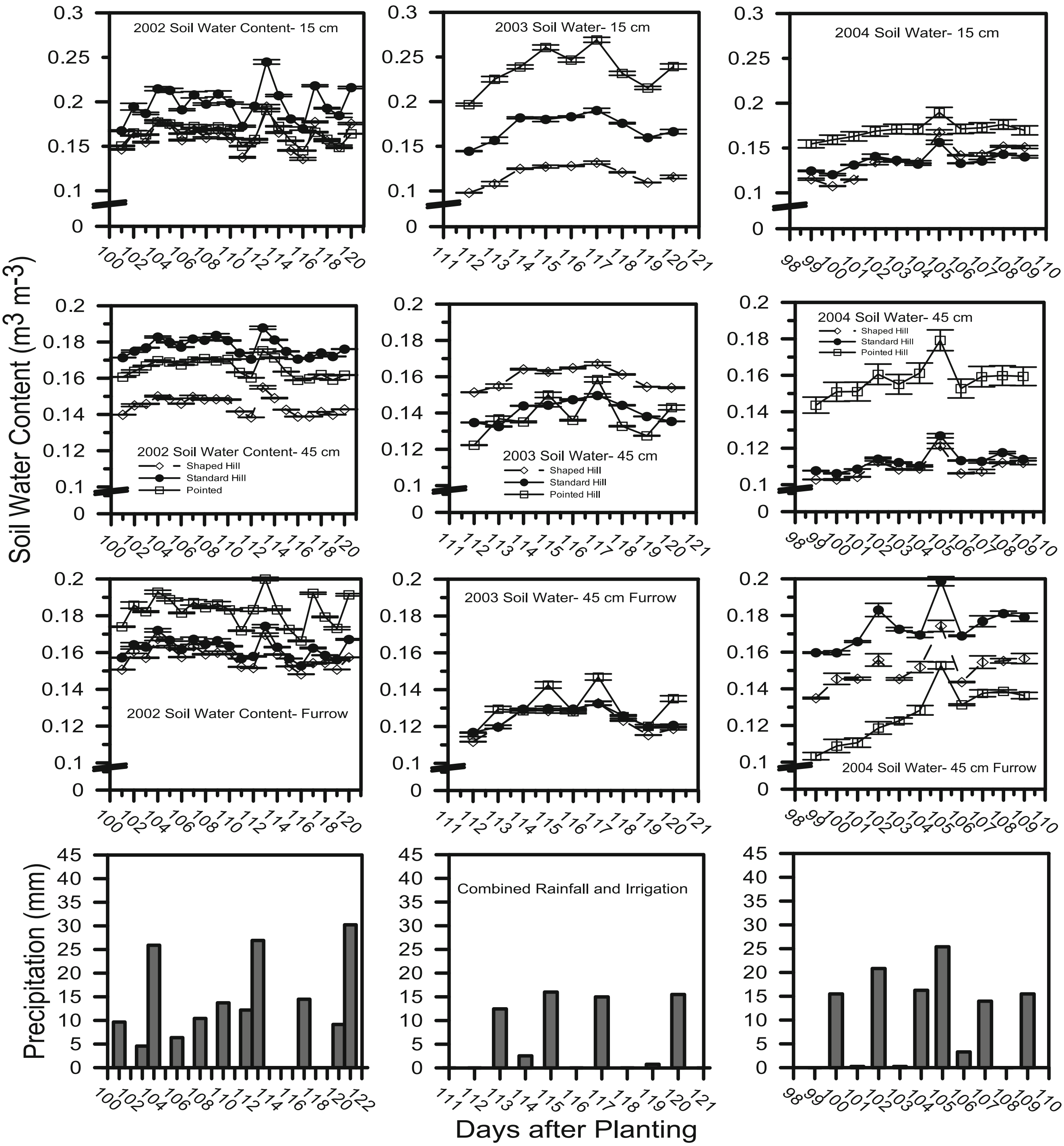

Fig. 2 Volumetric soil water content (θ_v) for 11- to 21-day periods during the late July to early August 2002 through 2004 growing seasons measured 15 cm and 45 cm below the hill and 45 cm below the furrow, Hancock, Wisconsin

standard hills. Furthermore, by the time in the season when these measurements were made, the crop was at full canopy, thereby providing an umbrella effect (Saffigna et al. 1976; Jury et al. 1976; Cooley et al. 2007), effectively shedding water into the furrow and potentially leading to development of dry zones within the potato hill (Robinson 1999; Cooley 2005; Cooley et al. 2007).

Results of the soil water measurement at the other depths and locations showed no clear pattern with respect to hill shape. For example, in 2003, at 45 cm below the hill the shaped-plateau hill contained more water than the other two hill shapes, whereas in 2004, it was the pointed hill shape that had clearly separated itself from the others (θ_v=0.18 versus 0.13 m^3m^{-3}). Furrow measurements also showed no pattern across the years with the pointed hill showing the highest volumetric water content in 2002, but the lowest in 2004. In 2003 at 45 cm below the furrow, the pointed hills also consistently showed higher θ_v peaks following any precipitation or irrigation event. For the reasons given previously, this was expected for all years.

Plant Growth The effects of hill shape and in-season fertilizer N rate on early-season crop growth are shown in Table 1. As expected, increasing N rate significantly increased early-season vegetation growth in all 3 years, and it decreased tuber number and early-season fresh tuber weight in 2002. Other studies have also shown that high N rates applied early in the season can delay tuber set (Dyson 1965; Kleinkopf et al. 1981; Millard and Robinson 1990) and decrease tuber number (Benepal 1967; Sarkar and Naik 1998; Kelling et al. 1999). These responses are likely primarily due to the level of supplemental N applied at emergence since all plots received the same amount of N in any given year as starter fertilizer (31 to 37 kgN ha^{-1}) and the early-season evaluations were done only to 10 to 14 days after the tuberization N application. In 2004, hill shape significantly affected early-season growth with the higher pointed and shaped hills showing less vegetation and tuber growth. Pavek and Thornton (2009) also documented changes in Russet Burbank early-season growth associated with plant depth. The results reported herein for 2004 are likely due to the generally cloudy, wet and cool early-season growing conditions in that year where May and June averaged1.0 and 0.7 °C below normal, respectively, and May and June total precipitations were 18.2 and 19.5 cm, respectively (NOAA 2004). Although a severe storm resulted in 24 cm of rainfall on 22 June 2002 (4 days after the early-season evaluations), both 2002 and 2003 had much more normal weather conditions for growing potato than 2004.

The overall influence of the growing seasons is especially noticeable in total tuber yields for the 3 years, where 2004 yields were only about 40 % of those for 2002 and 2003 (Table 2). Furthermore, yields showed a more pronounced increase to higher N rates in 2004 than in the other years in spite of the lower yield level.

A significant yield response to hill shape was observed in 2002 (Table 2), with the shaped-plateau treatment showing the highest yields and the pointed hill the lowest. In 2002, however, the shaped-plateau hill was formed only at emergence, whereas both the standard and pointed hills were reformed after the tuberization N treatment (6 June). It is possible that this second hilling, which may have some weed control and N placement benefits (moving fertilizer back into the hill) resulted in some root pruning or plant physical damage that reduced yields. While the effect of hill shape was not statistically significant in 2003 ($p=0.19$) or in 2004 ($p=0.12$), it is noteworthy that the two treatments that received a second hilling (standard late and pointed) averaged over 3.1 Mgha^{-1} less yield than the two treatments that were only hilled at emergence (standard early and shaped-plateau). Several studies that compared hilled treatments with planting potatoes in beds or flat planting showed no disadvantage to the hilling (Mundy et al. 1999; Sharma and Dixit 1992), whereas others observed distinct hilling advantages (Kouwenhoven 1970; Lewis and Rowberry 1973; Prestt and Carr 1984; King et al.2011). Conversely, Bohl and Love (2005) observed yield reductions with Russet Burbank and to a lesser extent with Gem Russett for all treatments that included a post-emergence hilling operation. Moreau (1999) saw lower yields of Shepody when they were hilled 39 to 57 days after planting. However, hilling effects may be variety specific as Bohl and Love (2005) saw a less pronounced hilling effect with Gem Russet (9 versus 23 % decrease) and Moreau (1999) reported no hilling effect with Russet Burbank.

In no year was the yield hill shape x N rate interaction term significant; however, regression analysis of N rate effect on yield within each hill shape showed that optimum N rates for the shaped-plateau hills were lower than those for the standard hills in all years (data not shown). Shaped-plateau optimum N rate was also lower than that for the pointed hill in 2004, and although optimum N rates were similar between the two shapes in 2002, the shaped-plateau out-yielded the pointed hill in that year. These observations provide some indirect evidence that the shaped-plateau hill may be more effectively sequestering N within the hill and allowing for more efficient use of fertilizer N applied. This is likely because the emergence N treatment is moved into the formed hill and the tuberization N stays within the small ridges on each side of the plateau and thereby moves downward into the hill (Fig. 1).

In 2002, the pointed hill resulted in a smaller proportion of U.S. No. 1 tubers than either the shaped-plateau or standard late hills (Table 2). In 2004, both the hill shape factor and the hill shape x N rate interaction term of the ANOVA were significant with respect to percent of U.S. No. 1 tubers. These data show that N rate had less effect on the proportion of U.S. No. 1 tubers in combination with the shaped-plateau hills (57 % U.S. No. 1 with 0 in-season N versus 60 % with 269 kgN ha^{-1}); however, for the other three hill shapes there was an average of 41 % U.S. No. 1 at zero N versus 67 % at 269 kgN ha^{-1}. Averaged over N rates, the standard late and pointed hills resulted in 55 % U.S. No. 1 tubers versus 60 % for the standard early and shaped-plateau hills. These differences were primarily the result of more undersize tubers with the standard late and pointed hill shapes where there were 37 % less than 5.1 cm versus 30 % small tubers for standard early and shaped-plateau hills. It is likely the hill shapes that resulted in more undersize tubers were using the applied fertilizer N less efficiently. Sharma

Table 1 Effect of N rate and hill shape on early season potato growth, Hancock, Wisconsin, 2002 through 2004[a]

Hill shape	In-season N rate	Veg. fresh weight			Tuber number			Tuber fresh weight		
	$kg\,ha^{-1}$	2002	2003 (g $plant^{-1}$)	2004	2002	2003 (no. $plant^{-1}$)	2004	2002	2003 (g $plant^{-1}$)	2004
Standard early	0	—	513	261	—	15.7	13.5	—	440	360
	134	—	769	409	—	18.0	13.9	—	560	341
	269	—	875	451	—	16.4	11.3	—	447	289
Standard late	0	219	447	230	15.1	17.7	15.3	86	471	375
	134	456	737	366	12.7	13.8	14.2	69	374	366
	269	491	841	457	12.0	15.8	13.3	63	434	395
Shaped-plateau	0	267	515	184	18.4	16.7	9.8	104	414	190
	134	457	737	363	11.0	14.3	12.4	50	408	280
	269	484	860	372	11.0	17.7	12.3	59	483	244
Pointed	0	255	436	244	16.5	18.2	12.2	96	445	245
	134	367	654	332	10.2	15.6	13.3	46	401	228
	269	440	827	300	8.1	15.3	12.3	42	395	265
Statistical significance (Pr > F)										
Hill shape (S)		0.25	0.31	0.02	0.34	0.66	0.08	0.36	0.06	<0.01
N rate (N)		<0.01	<0.01	<0.01	<0.01	0.09	0.45	<0.01	0.96	0.95
S × N		0.52	0.99	0.24	0.44	0.06	0.51	0.34	0.02	0.80
Main effect										
Hill shape										
Standard early		—	716	373	—	16.7	12.9	—	483	330
Standard late		389	675	351	13.3	15.8	14.3	73	426	379
Shaped-plateau		403	704	306	13.4	16.2	11.5	71	435	238
Pointed		354	639	292	11.6	16.7	12.6	61	414	246
$LSD_{0.05}$		NS [b]	NS	50	NS	NS	NS	NS	* [c]	84
N rate										
0		247	478	230	16.7	17.1	12.7	95	442	292
134		426	722	367	11.3	15.4	13.4	55	436	304
269		472	851	395	10.3	16.5	12.3	55	439	298
$LSD_{0.05}$		61	76	43	2.7	NS	NS	17	*	NS

[a] Evaluations conducted on 18 June 2002, 30 June 2003, and 17 June 2004

[b] NS, not significant at $p \leq 0.05$

[c] Interaction of hill shape x N rate significant at $p \leq 0.05$

Table 2 Effect of N rate and hill shape on Russet Burbank tuber yield and grade, Hancock, Wisconsin, 2002 through 2004

Hill shape	In-season N rate	Total yield			U.S. No. 1 tubers			Tuber > 170 g		
		2002	2003	2004	2002	2003	2004	2002	2003	2004
	$kg ha^{-1}$	$Mg ha^{-1}$			%			%		
Standard early	0	—	49.0	16.3	—	72	44	—	12	14
	134	—	58.5	29.8	—	74	62	—	16	20
	202	—	57.0	32.7	—	76	65	—	17	27
	269	—	62.7	33.1	—	83	69	—	21	33
Standard late	0	39.8	50.3	12.6	36	72	32	20	13	17
	134	47.9	48.8	26.4	49	67	59	26	21	27
	202	52.5	53.2	26.3	54	76	59	28	25	25
	269	52.6	53.3	31.0	55	77	61	33	25	33
Shaped-plateau	0	43.6	49.1	19.8	42	68	57	21	10	35
	134	53.5	57.3	30.7	55	78	61	36	19	28
	202	52.7	59.2	28.9	55	81	62	43	22	22
	269	52.7	56.8	29.4	54	79	60	40	25	37
Pointed	0	39.9	49.9	17.0	32	73	46	18	7	12
	134	49.6	58.1	22.7	52	74	53	32	18	16
	202	46.3	52.6	28.8	51	79	61	32	19	15
	269	47.9	54.6	33.0	51	82	70	34	20	25
Statistical significance (Pr > F)										
Hill shape (S)		0.04	0.19	0.12	0.02	0.22	0.02	0.04	0.18	0.01
N rate (N)		<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
S × N		0.72	0.54	0.36	0.43	0.72	<0.01	0.46	0.85	0.08
Main effect										
Hill shape										
Standard early		—	56.8	28.0	—	76	60	—	16	23
Standard late		48.2	51.4	24.1	49	73	52	27	21	25
Shaped-plateau		50.7	56.1	27.7	51	76	60	34	19	30
Pointed		45.9	53.8	25.4	46	77	58	30	16	17
$LSD_{0.05}$		3.6	NS [a]	NS	3	NS	* [b]	4	NS	8
N rate										
0		41.2	49.6	16.4	37	71	45	19	11	19
134		50.4	55.7	27.4	52	73	59	31	19	23
202		50.5	55.5	29.1	54	78	62	34	21	23
269		51.0	56.8	31.7	53	80	65	37	23	32
$LSD_{0.05}$		4.1	4.5	3.4	4	5	*	5	3	6

[a] NS, not significant at $p \leq 0.05$

[b] Interaction of hill shape x N rate significant at $p \leq 0.05$

Table 3 Effect of N rate and hill shape on hill 0 to 30 cm soil inorganic N, petiole nitrate-N concentrations and tuber N uptake, Hancock, Wisconsin, 2002 through 2004

Hill shape	In-season N rate	Soil inorganic N [a]		Petiole NO_3–N [b] (39 to 42 DAE)			Petiole NO_3–N [c] (61 to 63 DAE)			Tuber N uptake		
	$kg\,ha^{-1}$	2003	2004	2002	2003	2004	2002	2003	2004	2002	2003	2004
		$mg\,kg^{-1}$		$g\,kg^{-1}$			$g\,kg^{-1}$			$kg\,ha^{-1}$		
Standard early	0	5	8	—	2.8	4.9	—	1.0	3.7	—	179	49
	134	7	16	—	13.3	16.8	—	0.9	5.5	—	220	93
	202	8	26	—	19.0	21.1	—	2.6	6.1	—	223	111
	269	10	35	—	23.7	24.6	—	3.6	7.0	—	248	109
Standard late	0	4	8	0.7	2.3	8.6	1.4	0.5	6.1	87	176	38
	134	5	15	6.9	14.2	19.1	4.6	1.9	5.1	100	179	76
	202	8	26	9.3	17.6	23.5	4.9	4.0	6.9	127	208	88
	269	10	35	11.2	22.5	26.1	5.6	7.9	7.1	129	211	99
Shaped-plateau	0	5	7	1.4	2.5	6.7	1.5	0.6	3.8	71	175	58
	134	5	23	5.8	15.7	16.1	4.5	1.0	5.6	131	214	95
	202	8	31	10.8	16.6	17.4	7.0	3.6	5.5	124	239	87
	269	8	35	12.4	23.2	22.8	8.0	6.8	6.5	148	233	99
Pointed	0	5	9	0.7	1.9	6.7	0.8	0.4	3.7	82	175	52
	134	5	14	4.6	13.1	15.8	2.3	1.1	5.6	83	225	65
	202	6	16	9.5	14.7	16.4	4.7	2.0	5.0	92	200	90
	269	9	32	10.5	21.7	24.4	6.3	3.7	6.3	102	215	109
Statistical significance (Pr > F)												
Hill shape (S)		0.54	0.09	0.04	0.08	0.10	<0.01	0.03	0.04	<0.01	0.09	0.04
N rate (N)		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
S × N		0.58	0.22	0.37	0.90	0.57	0.22	0.23	0.28	0.01	0.35	0.31
Main effects												
Hill shape												
Standard early		7	22	—	14.7	16.8	—	2.0	5.6	—	217	91
Standard late		7	21	7.0	14.1	19.3	4.1	3.6	6.3	111	194	75
Shaped-plateau		6	24	7.6	14.5	15.7	5.2	3.0	5.3	119	215	85
Pointed		6	17	6.3	12.8	15.8	3.5	1.8	5.1	91	204	78
$LSD_{0.05}$		NS [d]	NS	1.0	NS	NS	0.9	1.2	0.8	* [e]	NS	10
N rate												
0		5	8	0.9	2.4	6.7	1.2	0.6	4.3	80	176	49
134		5	17	5.7	14.1	16.9	3.8	1.2	5.4	105	209	83
202		7	25	9.8	17.0	19.6	5.6	3.1	5.9	114	218	94
269		9	34	11.4	22.7	24.5	6.7	5.5	6.7	126	226	104
$LSD_{0.05}$		2	6	1.1	2.1	2.2	1.1	1.2	0.8	*	18	12

[a] Soils sampled 24 June 2003 and 22 June 2004 (NH_4-N + NO_3–N)

[b] Petioles samples 1 July 2002, 30 June 2003, and 28 June 2004

[c] Petioles sampled 22 July 2002, 21 July 2003, and 19 July 2004

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

[e] Interaction of hill shape x N rate significant at $p \leq 0.05$

and Dixit (1992) also found more small tubers with higher ridges.

In 2002 and 2004, the shaped-plateau hill tended to have somewhat more cull tubers than the other hill shapes (p= 0.09 and 0.14, respectively), averaging 18 % culls versus 15 % for the other hill shapes in 2002 and 13 % versus 8 % in 2004 (data not shown). The detailed examination of types of cull tubers in 2003 and 2004 showed no effect of N rate or hill shape in 2003, but in 2004, the pointed hills had significantly fewer off-shape tubers (27 % of the cull tubers) compared to 41 % for the other three hill shapes (p=0.03). In contrast to some other studies (Kouwenhoven 1970; Mundy et al. 1999; Bohl and Love 2005), the amount of green or sun-scalded tubers was not affected by the hill shapes used in this study in either of the years when the detailed examination was conducted.

Hill shape consistently affected size of the harvested U.S. No. 1 tubers with the shaped- plateau resulting in proportionally more tubers > 170 g and the pointed hill generally having the fewest large tubers (Table 2). The standard hills did not have statistically fewer large tubers than the shaped-plateau in 2003 or 2004. As noted earlier, these larger sized tubers may be related to the influence of hill shape on fertilizer N use efficiency, especially in high leaching years like 2002 and 2004.

Tuber specific gravity was not affected by hill shape in any of the study years (data not shown). Steele et al. (2006) also saw no gravity effect with hill- versus furrow-planted potatoes. As has been shown in many other studies (Laboski and Kelling 2007), this study showed a consistent decrease in tuber specific gravity as N rate increased.

Nitrogen Monitoring The ability of the various hill shapes to sequester applied N was evaluated using soil inorganic N tests, petiole NO_3-N sampling, and harvested tuber N uptake (Table 3). Measurement of soil inorganic N ($NH_4^+ + NO_3^-$) tended to confirm that in 2004 the pointed hill had less fertilizer N available in the top 30 cm of soil than the other hill shapes (17 mg kg^{-1} versus 21 to 24 mg kg^{-1}) (p=0.09). In 2002 and 2003, the early season (39 to 42 DAE) petiole NO_3^--N levels were lowest for the pointed hills compared to the other hill shapes (p=0.04 and 0.08, respectively). However, in 2004 the standard late hill appeared to show somewhat higher levels of petiole NO_3^--N present than the other shapes (p=0.10) in spite of 2004 being a much stronger leaching year than 2003. Furthermore, based on the soil data, less N was in the top 30 cm of soil in 2003 than 2004, while the petiole NO_3^--N levels were generally similar. Soil inorganic N was not measured in 2002. Apparently the severe mid-June 2002 storm (24 cm) had a greater impact on N loss than the multiple, moderate storms seen in May and June 2004 as 2002 early petiole NO_3-N levels were about half of those seen in 2003 or 2004. Petiole samplings later in the season also showed more NO_3^--N in the petioles from shaped-plateau hills in 2002 with less present in pointed hills in 2002 and 2003 (Table 3).

Nitrogen uptake by the harvested tubers was affected by hill shape in 2002 (p=< 0.01) and 2004 (p=0.04) and tended to be affected in 2003 (p=0.09). In 2002, the significant hill shape x N rate interaction showed that in addition to the shaped-plateau hill having the most uptake (119 kg N ha^{-1} averaged across N rates), it also had the greatest increase as N rate increased (77 kg N ha^{-1} from 0 to 239 kg fertilizer N ha^{-1}). Conversely, the pointed hill had the lowest average uptake (91 kg N ha^{-1}) and increased only from 82 to 102 kg N ha^{-1} as fertilizer N increased from 0 to 239 kg ha^{-1}. In both 2003 and 2004, following the trend for yield, the hill shapes that were only hilled at emergence tended to have the highest N uptake amounts. This is as expected since hill shape did not affect tuber N concentration in any year (12.3, 19.5, and 17.4 g N kg^{-1} in 2002 to 2004, respectively). The tuber N uptake data, especially for 2002 and 2004 where the shaped-plateau resulted in more N being removed in the tubers, or a greater amount removed at lower N rates, is additional evidence that the shaped-plateau resulted in more efficient fertilizer N use.

Conclusions

Forming hills into a shaped-plateau resulted in significantly greater total tuber yields, a greater proportion of U.S. No. 1 tubers, and a greater proportion of tubers > 170 g in 1 year out of 3, and optimum N rates based on yield were generally less with the shaped-plateau hills in all years. These results may be confounded by the timing of the hilling operations as the yield and tuber quality values were generally similar for the shaped-plateau and standard early hill in the last 2 years of the study when both were only formed at emergence. Based on crop performance, in-season N tests and tuber recovery of applied N showed that the shaped-plateau hill and standard hill were the most efficient of those tested in fertilizer N utilization. Based on all parameters, it is very clear, however, that a high, pointed hill is the least desirable. These data also suggest that if post-emergence hilling is not needed for weed control, this practice should be avoided as this study showed a light hilling at tuberization to reform a relatively low, broad hill was generally detrimental to crop yield and quality.

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