Furrow vs Hill Planting of Sprinkler-Irrigated Russet Burbank Potatoes on Coarse-Textured Soils

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ABSTRACT

Surface water runoff from the hill, where potatoes are planted, to the furrow may exacerbate potato drought sensitivity. Planting into furrows and constructing midrow ridges may improve water use efficiency and relieve water stress on potato by directing water toward, not away from, the plants. A 3-year field study was conducted to compare yields and tuber size distributions of furrow- and hill-planted potato (*Solanum tuberosum* L., 'Russet Burbank') on coarse-textured, well-drained soils under sprinkler irrigation. A split-plot experimental design with main plots of row orientation (N-S vs E-W) and subplots of planting method (hill and furrow) combined with two planting depths was used at two central North Dakota sites. Except for planting method and limiting the post-emergence cultivation in the furrow treatments, all cultural practices (fertilizer, irrigation, etc.) were identical and corresponded with conventional practices for hill planted potato. Row orientation did not affect yield for any tuber size category. Averaged over 3 years, furrow-planted potato produced 24% larger tubers (188 vs 151 g), 31% smaller yield for tubers <113 g (4.99 vs 7.21 Mg ha^{-1}), 28% smaller yield for tubers 113 to 170 g (8.14 vs 11.3 Mg ha^{-1}), 8% larger yields for tubers 170 to 283 g (18.0 vs 16.6 Mg ha^{-1}), 103% larger yields for tubers 283 to 454 g (10.9 vs 5.36 Mg ha^{-1}), 341% larger yields for tubers >454 g (2.65 vs 0.60 Mg ha^{-1}), and 10% larger total yields (46.2 vs 41.9 Mg ha^{-1}) compared with hill-planted potato. There were no differences in tuber specific gravity. Preliminary soil water measurements indicated an inter-row water-harvesting effect for furrow planting compared with hill planting. The furrow-planting method may offer significant potential for ameliorating the drought sensitivity of potato.

RESUMEN

El agua que corre del camellón donde se siembra papa hacia el fondo del surco puede exacerbar la sensibilidad de la planta a la sequía. Sembrando en el fondo de los surcos y construyendo camellones centrales se puede mejorar la eficiencia en el uso del agua y aliviar el estrés si se dirige el agua hacia la planta y no al revés. Durante tres años se realizó un estudio de campo para comparar el rendimiento y distribución del tamaño de los tubérculos en pruebas donde se sembró papa (*Solanum tuberosum* L. 'Russet Burbank') en el surco y en el lomo del surco en suelo de textura gruesa, con

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ABBREVIATIONS: EC, electrical conductivity; E-W, east-west; FD, furrow planting with deep seed placement; FS, furrow planting with shallow seed placement; GLM, general linear model; HD, hill planting with deep seed placement; HS, hill planting with shallow seed placement; LSD, least significant difference; n, number of paired data points for soil water content sensor calibration or number of sets of readings for soil water content comparisons; N-S, north-south; r^2, coefficient of determination; RMSE, root mean square error between measured and model estimates of θ_v; *t* test p, p-value from a two-tailed, paired-sample *t* test between $\theta_{v\text{-grav}}$ and $\theta_{v\text{-HS}}$; t_{HS}, HydroSense period; UAN, urea-ammonium-nitrate; W_a, weight in air; W_w, weight in water; θ_v, volumetric soil water content, cm^3 cm^{-3}; $\theta_{v\text{-grav}}$, volumetric water content determined by soil coring and oven drying; $\theta_{v\text{-HS}}$, volumetric water content readout from the HydroSense soil water content sensor; γ, specific gravity of potato tubers.

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buen drenaje y riego por aspersión. Se utilizó el diseño experimental de parcela dividida con la principal orientación de las hileras (N-S vs. E-O) y los métodos de siembra (lomo y surco) de las sub-parcelas combinado con dos profundidades en dos lugares cerca de North Dakota central. Con excepción del método de siembra y limitando las labores de cultivo de post-emergencia en los tratamientos en el surco, todas las labores culturales (fertilización, irrigación) fueron idénticas y correspondieron a las prácticas convencionales para siembra de papa en el lomo del surco. La orientación de las hileras no afectó el rendimiento ni la categoría de tamaño del tubérculo. El promedio de rendimiento de los tres años de papas sembradas en el fondo del surco fue del 24% de tubérculos más grandes (188 vs 151 g), 31% de menor rendimiento para tubérculos de <113 g (4.99 vs 7.21 Mg ha^{-1}), 28% de menor rendimiento para tubérculos de 113 a 170 g (8.14 vs 11.3 Mg ha^{-1}), 8% de mayor rendimiento para tubérculos de 170 a 283 g (18.0 vs 16.6 Mg ha^{-1}), 103% de mayor rendimiento para tubérculos de 283 a 454 g (10.9 vs 5.36 Mg ha^{-1}), 341% de mayor rendimiento para tubérculos >454 g (2.65 vs 0.60 Mg ha^{-1}) y 10% de mayor rendimiento total (46.2 vs 41.9 Mg ha^{-1}) en comparación con papa sembrada en el lomo del surco. No hubo diferencias en la gravedad específica del tubérculo. Las mediciones preliminares del agua del suelo indicaron un efecto del agua entre hileras al momento de la cosecha en comparación con la siembra en el lomo. El método de siembra en el surco puede ofrecer un significativo potencial para mejorar la sensibilidad de la papa a la sequía.

INTRODUCTION

Potatoes are widely recognized as a drought-sensitive crop (Singh 1969; Costa et al. 1997), and there has been much research on irrigation water management and its effects on yield, plant growth, tuber size distribution, and tuber quality (Wright and Stark 1990; Lynch et al. 1995; Prunty and Greenland 1997; Shae et al. 1999; Waddell et al. 2000).

Potato seedpieces are typically planted in a hill with a subsequent hilling or earthing up operation (Lewis and Rowberry 1973; Chow and Rees 1994). We refer to conventional “ridge” planting in the literature as “hill” planting here to distinguish it from our later references to a midrow ridge associated with furrow planting. The primary reasons for planting potatoes in a hill include ease of harvesting (Dean 1994), to avoid seedpiece decay in fine-textured and slowly draining soils, and to provide ease of driving in the furrows for cultivation and harvest. During irrigation applications and intense rainfall events on potato fields, the hills shed water toward the furrow when the water application rate exceeds the soil water infiltration rate (Saffigna et al. 1976; Stieber and Shock 1995), especially early in the season when canopy cover is incomplete. Thus current hill-planting practices may exacerbate the drought sensitivity of potato.

Several alternatives to planting potato in hills have been studied, including wide beds (Mundy et al. 1999), “quad” planting (Bouman 1998), and conventional hill planting with dammer-dike, a smaller hill with a shallower furrow, and flat planting (Alva et al. 2002). Hill vs flat planting and every-furrow vs every-other-furrow irrigation was studied by Sharma and Dixit (1992) and by Sharma et al. (1993). Agassi and Levy (1993) studied furrow diking vs conventional cultural practices and Lewis and Rowberry (1973) compared hill and flat planting.

Inter-row water harvesting through the use of furrow planting and midrow ridges is a method of directing incident rainfall and irrigation toward the plant rather than away from it. Li et al. (2000, 2001) studied the use of plastic-covered midrow ridges and gravel-mulched furrows for nonirrigated corn production on a sandy loam soil in a semi-arid region of China. The midrow ridges served as a water-harvesting area, i.e., an area that generated runoff and directed it toward the furrow. The furrow served as the planting area and could be covered with a mulch to further improve water use efficiency by reducing evaporation. They found that this approach conserved soil water and improved grain yield and water use efficiency compared with flat planting.

Limited research has been done on furrow vs hill planting of potatoes. In a 2-year study on a sandy loam soil in India, Gupta and Singh (1994) compared hill- and furrow-planting methods and five fertility levels for irrigated potatoes. In their study, the hill-planting method produced significantly higher yields and tuber numbers, and they attributed the results to better soil aeration in the hill system. They did not mention water harvesting as part of their study. In Pakistan, Arshad et al. (1999) compared flat, furrow, and hill planting and found that flat planting with seed coverage from one side produced the highest yields and that furrow planting with no ridges produced the greatest number of damaged and green tubers.

Furrow planting to achieve inter-row water harvesting for potato production apparently has not been studied in the western hemisphere.

The objective of this study was to compare yields and tuber size distributions for furrow planting with a midrow ridge to the conventional practice of planting in a hill configuration. In this study, the comparisons were limited to sprinkler-irrigated potato production on coarse-textured, well-drained soils. Limited soil water content measurements are also presented to compare hill and furrow moisture conditions. It should be noted that this is a preliminary study intended to help direct future research efforts.

METHODS

Small plot field studies were conducted from 2001 to 2003 at two locations in east-central North Dakota, USA. In 2001, research was conducted near Dawson, ND (46º55' N latitude, 99º46' W longitude, 530 m elevation), with plots located on a Towner loamy fine sand (sandy over loamy, mixed, superactive, frigid Calcic Hapludoll). In 2002 and 2003, the experiment was moved to a site near Tappen, ND (46º53' N latitude, 99º35' W longitude, 543 m elevation), and experiments were on an Arvilla sandy loam soil (sandy, mixed, frigid Calcic Hapludoll). Total normal precipitation for May through September was approximately 307 mm in the Dawson and Tappen area (USDC 1982). Irrigation was applied via center pivot (Dawson) or lateral-move (Tappen) sprinkler irrigation systems.

Plots were 3.6 m wide (4 rows) by 12.2 m long with a row spacing of 0.91 m. A 7.6-m length of the center two rows in each plot was used for all yield determinations. The Russet Burbank cultivar was used and agronomic data are summarized in Table 1. Irrigation and precipitation were measured at each site with 15 cm-diameter tipping-bucket rain gauges and recorded with event-based data loggers.

A split-plot experimental design with four replications was used. Main plots were row orientation and contained two treatments: (1) north-south (N-S) row orientation and (2) east-west (E-W) row orientation. Subplots were planting configurations and contained four treatments: (1) furrow planting with shallow seed placement (FS), (2) furrow planting with deep seed placement (FD), (3) hill planting with shallow seed placement (HS), and (4) hill planting with deep seed placement (HD). The seed placement depth refers to the relative amount of soil coverage after completion of the planting operation (Table 1).

For each year, all furrow- and hill-planted plots were treated identically with respect to planting dates, plant populations, schedules and amounts of irrigation, fertilizer, herbicides, and fungicides, using production practices typical of those for potatoes grown in the hill configuration. Fertilizer applications of N, P, and K at each site followed NDSU recommendations for potatoes (Scherer et al. 1999) with a yield goal of 56.0 Mg ha^{-1}. The last 84 kg N ha^{-1} was added biweekly after the time of hilling in increments of 17 or 11 kg N ha^{-1} as foliar applications of 28% UAN diluted sufficiently to avoid leaf burn.

Potato seedpieces were planted with a two-row planter in both the hill- and furrow-planting configurations. The use of an interchangeable planter for both configurations was intended to eliminate variation from factors such as seed spacing, row spacing, and insecticide rates that may have occurred if separate planters had been used for hill and furrow configurations. No fertilizer was added with the planter. A midseason example of a furrow-planted row is shown in Figure 1.

To accomplish the furrow planting, disk openers were added to the front of the planter and the hill-forming disk closers at the rear of the machine were raised or removed.

TABLE 1—*Agronomic summary of the furrow- vs hill-planting experiment.*

Activity or Item	Dawson 2001	Tappen 2002	Tappen 2003
Planting date	16 May	21 May	8 May
Seed spacing, cm	30	30	30
Average depth of seed coverage after planting, cm	FS[1]: 8 FD: 18 HS: 15 HD: 20	FS: 4 to 9 FD: 13 to 15 HS: 13 to 15 HD: 20	FS: 5 FD: 9 HS: 13 HD: 18
Harvest date	26 Sep, 1 Oct[2]	30 Sep, 2 Oct[2]	24 to 25 Sep
Irrigation[3], mm	N/A[4]	237	555
Rainfall, mm	N/A[4]	383	100
Total Water, mm	581	620	655

[1]FS = furrow shallow; FD = furrow deep; HS = hill shallow; HD = hill deep; N/A = data not available.
[2]For 2001, HS harvested 26 Sept, other treatments harvested 1 Oct. Differences in harvest dates in a given year for any site were assumed to not affect yields because all harvest areas were mechanically defoliated prior to the first harvest date.
[3]Rainfall and irrigation amounts are values from planting through harvest (planting through 26 Sept for 2001 at Dawson).
[4]Rainfall and irrigation data not recorded separately.

FIGURE 1.
Example of furrow-planted potatoes near Dawson, ND, on 6 August 2001. The elevation difference between the furrow and mid-row ridge is approximately 9 cm (3.5 in.).

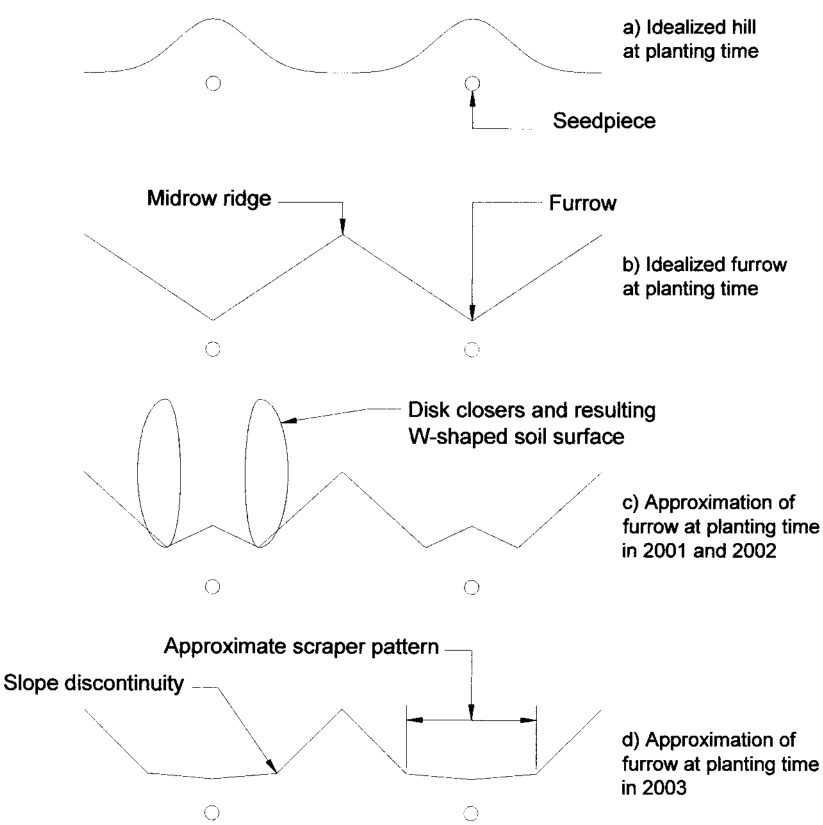

FIGURE 2.
Cross-sections of planting configurations. The scale is approximate.

When used for furrow planting, the disk closers were raised and positioned to cover the seedpieces by turning or scraping soil over them. The typical hill configuration is sketched in Figure 2a, while an idealized soil surface for the furrow configuration is shown in Figure 2b. It can be seen that the hill configuration has potential for considerable surface runoff from high to low areas, while the furrow configuration's sharp midrow ridge and the sharp trough in the row, here designated as a V shape, would be expected to provide the maximum inter-row water-harvesting effect. In 2001 and 2002, the planter with disk openers produced a V-shaped profile, but disk closers were used to cover the seedpieces. The disk closers cut into the sides of the V shape, producing approximately a W shape as shown in Figure 2c. Although the W shape was produced in 2001, soil erosion and sloughing from the midrow ridge transformed the W shape in Figure 2c to the smoother shape in Figure 1. In 2002, we tried dragging a heavy chain in the furrow behind the disk closers to develop more nearly the V or a U shape, but did not achieve the intended result. In 2003, we again obtained the V shape with the disk openers, but used a blade or soil scraping approach to cover the seedpieces in an attempt to achieve a soil profile at planting time like that shown in Figure 1. The result was in a smaller, narrower midrow ridge and more of a flat or slight U shape in the furrow at planting (Figure 2d).

Yield results were summarized for each experimental unit (plot) by individually weighing the tubers and computing yields for various tuber weight categories. In 2001 and 2003, tubers were graded as culls if they had any cuts, nicks, growth cracks, green spots, excessive knobbiness, or spoiled or rotten tubers. In 2002, tubers with these defects were graded as culls only if the defect was sufficient to prevent the tuber from producing good french fries. Specific gravity was determined on a subsample of tubers using the equation $\gamma = W_a / (W_a - W_w)$ (Dean 1994). Data were analyzed using the general linear model (GLM) routine of SAS software (SAS Institute 1991) and means were separated with the Fisher's F-protected LSD at a 0.05 level of significance.

Measurements of θ_v were taken in 2003 with a capacitance-type soil water sensor (model CS620 "HydroSesnse" handheld water-content sensor and CD620 display; Campbell Scientific, Inc., Logan, UT, USA) with 20-cm waveguides. The water-content sensor provided readings of both $\theta_{v\text{-}HS}$ and t_{HS}, the latter of which was used to develop a calibration equation of the form $\theta_{v\text{-}grav} = mt_{HS} + b$, where $\theta_{v\text{-}grav}$ is volumetric water content obtained from gravimetric sampling and oven drying (Gardner 1986) and m and b are slope and intercept, respectively, obtained from least squares linear regression. The gravimetric samples were paired with sensor readings and were selected to represent approximately equal intervals of $\theta_{v\text{-}HS}$ over the range of $\theta_{v\text{-}HS}$ values encountered during sampling. Gravimetric samples were taken with a soil probe that produced a sample size of 1.9 cm diameter and 20 cm length. A larger soil core would have been preferred, but disturbance to the plants needed to be minimized to preserve the plants for yield determinations. Gravimetric samples were taken after sensor readings to avoid bias from the hole left by coring. Soil cores were taken within the 3-cm radius of influence of the waveguides (Campbell Scientific 1999) wherever possible. Soil samples were placed in sealed aluminum cans and transported the same day to the lab for weighing and oven drying at 105 to 107 C for a minimum of 24 h. A unit density of water was assumed when converting soil water content from a mass basis to a volume basis. Soil electrical conductivity (EC) was determined in a 1:1 soil:water ratio by the NDSU Soil Testing Laboratory using the procedure described by Whitney (1998). The EC testing was done to determine whether soil salinity adversely affected water-content sensor readings.

On each sampling date, one set of soil water-content sensor readings was taken in the hill position of a hill-planted plot (in the crop row), a second set of readings was taken in the adjacent furrow position of the same hill-planted plot (in the midrow area), and a third set of readings was taken in the furrow position of a nearby furrow-planted plot (in the crop row). Sensor readings were taken at 30-cm spacings, i.e., approximately midway between plants and in the row for the first and third measurement sets or in the corresponding furrow position for the second set of measurements. Sampling dates were randomly selected and were not intended to represent specific pre- or post-irrigation conditions. Measurements were taken in two plots with an E-W orientation and within the same block (replication) of plots on 17 June and in two plots with an N-S orientation (in the same block) on 24 July. For each date, calibrated θ_v means for each measurement position were separated with Fisher's F-protected LSD test at the $P = 0.05$ level of significance. It should be noted that the soil θ_v measurements were not taken in all plots, so we cannot apply the same statistical model as described for yields and tuber sizes.

RESULTS

Tuber yield and grade data were analyzed separately for each year since the seedpiece-covering technique varied for the furrow-planting configuration each year. Row orientation (N-S vs E-W) was not significant for any tuber yield parameter so those data are not reported. There were no interactions between row orientation and planting configuration for any yield or tuber size parameter for any year of the study. For each year of the study, row orientation and planting configuration did not affect specific gravity, nor were row orientation by planting configuration interactions present, and thus, specific gravity data are not presented.

Planting configuration significantly affected mass and yields of tubers in various size categories for each year (Table 2). Both FS and FD treatments produced significantly larger mean tuber mass because tuber size distributions shifted toward the larger size categories compared with the HS and HD treatments in each year of the study. In 2001 and 2002, the shift in size distribution resulted in significantly greater total yield for the furrow treatments. In 2002 and 2003, the hill treatments produced more small tubers (<113 g and 113- to 170-g size categories) than the furrow treatments. The shifts in tuber size distributions are summarized in Table 3, which compares mean furrow yields with mean hill yields for various tuber size categories averaged over all years of the experiment. Table 3 was obtained directly from Table 2 and does not represent the application of another statistical model to the yield data.

A simple economic comparison of gross returns based on yields and tuber size distributions indicates the furrow configurations have the potential for a considerable advantage compared with the hill configurations. For example, suppose a grower contract contained a base price of \$110.23 Mg^{-1} and tuber size premiums resulted in an additional \$6.39 Mg^{-1} for furrow-planted plots and \$1.10 Mg^{-1} for hill-planted plots based on percentages of tubers ≥170 g (Table 3). Calculated gross

TABLE 2—*Yield and tuber size summaries for each planting configuration.*

		Mean Tuber Yield (Mg ha^{-1})								
		Tuber Size Class								
Planting Configuration	Mean Tuber Mass (g)	<113 g	113 to <170 g	170 to <283 g	283 to <454 g	≥454 g	Cull	Total	≥113 g	≥170 g
2001										
Furrow shallow	159.5a[1]	8.35a	9.58a	17.9a	9.06a	1.35ab	3.25a	49.5a	38.0a	28.4a
Furrow deep	169.2a	7.44a	8.97a	18.2a	9.42a	1.93a	3.17a	49.1a	38.4a	29.5a
Hill shallow	143.2b	7.98a	8.63a	14.9ab	5.44b	0.96bc	0.88b	38.8b	29.9b	21.3b
Hill deep	144.8b	8.22a	9.62a	14.5b	6.14b	0.57c	1.05b	40.0b	30.8b	21.2b
LSD	14.24	2.26	2.01	3.26	1.80	0.75	1.07	4.79	3.58	4.05
p-value	0.003	0.84	0.68	0.0475	0.0002	0.0088	<0.0001	0.0001	<0.0001	0.0003
2002										
Furrow shallow	193.8a	3.63b	7.09b	17.2a	10.31a	2.21a	0.05a	40.4a	36.8a	29.7a
Furrow deep	202.1a	3.25b	6.95b	18.2a	11.58a	2.46a	0.09a	42.5a	39.2a	32.2a
Hill shallow	158.5b	5.20a	9.70a	16.2a	5.41b	0.53c	0.12a	37.1b	31.8b	22.1b
Hill deep	169.6b	4.82a	8.45ab	16.4a	7.28b	0.77bc	0.22a	37.9b	32.9b	24.4b
LSD	11.95	0.94	1.59	2.24	2.72	1.46	0.22	3.87	3.78	3.78
p-value	<0.0001	<0.0001	0.0008	0.1728	0.0004	0.0111	0.4462	0.0747	0.0076	0.0003
2003										
Furrow shallow	195b	3.83c	8.44b	18.1a	11.9a	3.41a	1.13a	46.8a	41.9ab	33.4a
Furrow deep	207a	3.42c	7.80b	18.3a	12.9a	4.55a	1.53a	48.5a	43.6a	35.8a
Hill shallow	143c	9.10a	15.7a	18.2a	3.99b	0.55b	0.89a	48.5a	38.5b	22.8b
Hill deep	147c	7.91b	15.7a	19.3a	3.90b	0.23b	1.94a	49.0a	39.2b	23.5b
LSD	10.1	0.96	1.50	2.31	2.11	1.48	0.82	3.10	3.41	3.21
p-value	<0.0001	<0.0001	<0.0001	0.6694	<0.0001	<0.0001	0.0723	0.4904	0.0189	<0.0001

[1]Values in each column and section followed by the same letter are not statistically different at $P = 0.05$.

TABLE 3—*Comparison of mean furrow and hill treatment results for tuber size, tuber yields, and selected yield percentages, averaged across 3 years.*

Yield Parameter	Mean of Furrow Treatments	Mean of Hill Treatments	Advantage for Furrow Treatment[1]
Mean tuber size, g	188	151	+24%
Yield of tubers <113 g, Mg ha^{-1}	4.99	7.21	-31%
Yield of 113-170 g tubers, Mg ha^{-1}	8.14	11.3	-28%
Yield of 170-283 g tubers, Mg ha^{-1}	18.0	16.6	+8%
Yield of 283-454 g tubers, Mg ha^{-1}	10.9	5.36	+103%
Yield of tubers ≥454 g, Mg ha^{-1}	2.65	0.60	+341%
Yield of cull tubers, Mg ha^{-1}	1.54	0.85	+81%
Total yield, Mg ha^{-1}	46.2	41.9	+10%
Yield of tubers ≥113 g, Mg ha^{-1}	39.7	33.9	+17%
Yield of tubers ≥170 g, Mg ha^{-1}	31.5	22.6	+40%
(Yield of tubers ≥113 g) / (total yield)	86.3%	81.0%	5.3%
(Yield of tubers ≥170 g) / (total yield)	68.7%	54.5%	14.2%

[1]Computed as [(Mean of Furrow Treatments) / (Mean of Hill Treatments) – 1] x 100% for tuber size and tuber yield values. Computed as [(Mean of Furrow Treatments) – (Mean of Hill Treatments)] for percentage values.

incomes from the 3-year means for furrows and hills would be approximately \$5380 and \$4670 ha^{-1} respectively. Thus, the furrow configuration provided approximately \$720 ha^{-1} or 15% more in gross income compared with the hill configuration. This analysis does not incorporate lower base prices or lot rejections for undersized tubers (<113 g), but based on Table 3, the percentages of yield for tubers <113 g averaged 10.7% for furrows and 17.2% for hills. The analysis also does not consider factors such as bruise-free percentages, high sugars, specific gravity, sugar ends, or hollow heart. The reader will need to substitute local information as appropriate to make a more detailed analysis.

The soil water content calibrations are summarized in Table 4. Soil EC values were 0.18 and 0.20 dS m^{-1} on 23 June and 24 July, respectively, which is nearly an order of magnitude smaller than the 2 dS m^{-1} specified by the manufacturer (Campbell Scientific 1999) for which the HydroSense θ_v accuracy is stated as ± 0.03 $cm^3\ cm^{-3}$. Hence it can be concluded that soil electrical conductivity effects did not adversely affect the soil water content readings. The RMSE values of 0.0071 and 0.0078 $cm^3\ cm^{-3}$ on the respective dates are within the specified 0.03 $cm^3\ cm^{-3}$ sensor accuracy.

The comparisons of soil water contents in the three sampling positions are summarized in Table 5. On both of the sampling dates, both of the furrow positions were significantly wetter than the hill position of the hill-planted plot.

DISCUSSION

The furrow-planting method consistently produced a shift toward larger tuber sizes and toward greater yields in the larger tuber size categories compared with the hill-planting method. We attribute these shifts to higher soil water contents in the furrow compared with the hill. The soil water content measurements indicate that on both of the sampling dates, the furrow positions in the furrow-planted plots and in the hill-planted plots were wetter than the hill position of the hill-planted plots. These preliminary data suggest that an inter-row water-harvesting phenomenon may have occurred. If the drier conditions in the hill of the hill-planted plot were due solely to root water uptake in the row, we would expect soil water contents in the row (furrow) of the furrow-planted plots to be similar to the corresponding values in the hill of the hill-planted plots or at least drier than the furrows of the hill-planted plots. The data indicate, however, that the furrow of the furrow-planted plots maintained water contents similar to the values in the furrows of the hill-planted plots. Systematic studies of soil water content and surface water redistribution were beyond the objectives of this study, but should be conducted to more rigorously test whether and to what extent an inter-row water-harvesting phenomenon occurs with furrow planting compared with hill planting.

An inter-row water-harvesting effect may have produced a secondary effect of better nutrient utilization in the furrow-planting configuration compared with the hill configuration. In this study, all fertilizer was broadcast and none was banded in the row. Nutrients may have moved from the ridge areas to the furrow areas via transport in soil water, in surface water runoff, or by erosion of soil particles. Regardless of the transport mechanism, the furrow-planting configuration would appear to have been at an advantage compared with the hill configuration because the destination of the transported nutrients would be closer to the plants in the furrow configuration. Moreover, the greater soil water contents in the furrows may have increased the nutrient availability and uptake in the furrow, a situation again favoring the furrow configurations. An inter-row water-harvesting effect may be especially significant for nutrients applied through sprinkler irrigation systems.

Differences in the closing systems and the shapes of the soil profile produced by the planter may have reduced the inter-row water-harvesting effect in 2003 compared with 2001 and 2002. Note the discontinuity in the slope of the soil surface in 2003 (Figure 2d), which may have produced a focusing of water infiltration at the discontinuity rather than at the trough of a V-shaped furrow. Thus, for furrow planting, we recommend that the furrow and midrow ridge be formed as nearly as possible into a V shape (Figure 2b) to maximize the inter-row water-harvest-

TABLE 4—*Summaries of HydroSense water content sensor calibrations at Tappen, ND, in 2003.*

	Linear Regression Calibration[1]					Range of	Soil Bulk
				RMSE[2]		$\theta_{v\text{-}grav}$	Density
Date	Slope	Intercept	r^2	$cm^3\ cm^{-3}$	n	$cm^3\ cm^{-3}$	$g\ cm^{-3}$
17 June	1.0382	-0.8126	0.9286	0.0071	9	0.082 to 0.17	1.24
24 July	0.5891	-0.4138	0.9387	0.0078	10	0.098 to 0.18	1.24

[1]The equation is $\theta_{v\text{-}grav} = mt_{HS} + b$, where t_{HS} is sensor period (ms) and m and b are slope and intercept, respectively, from least squares linear regression.
[2]$\theta_{v\text{-}grav}$ = volumetric water content determined by soil coring and oven drying; r^2 = coefficient of determination; RMSE = root mean square error between measured and model estimates of θ_v; n = number of paired data points.

TABLE 5—*Mean soil volumetric moisture contents for furrow and hill positions based on calibrated soil moisture sensor readings at Tappen, ND, in 2003.*

		Volumetric Water Content, $cm^3\ cm^{-3}$				
		Measurement Location				
		Furrow Plot,	Hill Plot,	Hill Plot,		
Date	n[1]	Furrow Position	Hill Position	Furrow Position	LSD	p-value
17 Jun	39	0.142a[2]	0.109c	0.133b	0.008	<0.0001
24 Jul	28	0.167a	0.116b	0.169a	0.009	<0.0001

[1]n = number of observations in each position; LSD = least significant difference.
[2]Values in each row followed by the same lowercase letter are not significantly different at the P = 0.05 level according to Fisher's F-protected LSD test.

ing effect. Due consideration must be given, however, to providing sufficient soil coverage and thus a W shape may be the most practical solution. For more information on seedbed design, the reader is referred to Yang et al. (1996), who modeled ridge and furrow water contents and temperatures as a means of designing ridge spacing and height for optimal production. Their study was based on observations of a dry soil zone beneath ridges in water-repellent sandy soils in Western Australia and that furrow sowing increased crop yields.

The average advantage in total yield for furrow planting compared with hill planting was 25%, 11%, and -2% in 2001, 2002, and 2003, respectively. Two factors in 2003 may have contributed to lower total yields for the furrow-planting configurations. First, we note that the inter-row water-harvesting effect may have been hindered by failing to achieve a V-shaped soil profile for the furrow planting mode in 2003, as discussed previously. Second, we observed some herbicide injury shortly after emergence in all but two adjacent plots that were unaffected because a data logger blocked the travel path of a spray vehicle through an alley, preventing herbicide application. Despite the slightly lower total yield in 2003, the furrow treatments maintained an average of 49% more yield of tubers ≥170 g compared with the hill treatments.

Studies on the management of wheel traffic in field-scale settings, especially with respect to post-emergence chemical applications and harvesting operations, may indicate a hybrid planting approach is best. For example, an eight-row planter could have the center two rows planted in the hill configuration to facilitate vehicle travel and the three outside rows on each side planted in the furrow configuration to increase tuber size and yield. Alternatives include driving on midrow ridges, nonuniform row spacing, or the exclusive use of aerial means or center-pivot irrigation systems to deliver all post-planting chemical applications. Driving on the ridges may be possible through the use of global positioning systems coupled with vehicle steering or guidance systems capable of centimeter-scale accuracy. A hybrid or combination of planting approaches, such as an M-shaped hill, may provide the best tradeoff between the inter-row water-harvesting advantages of a true furrow and the ease of harvesting offered by a hill.

Further research on furrow planting of potato has the potential to address many questions, perhaps the most important of which is to determine the potential for furrow planting to ameliorate the drought sensitivity of potato and thereby increase its productivity in water-short regions or on soils with low water-holding capacity. Additional topics for research include studies on production practices, physiological responses, responses of the physical environment, and others. Production practices will need refinement from those presented in this preliminary study and topics for study include seed spacing, planting depth, and fertility management. For example, if the shift toward a larger tuber size distribution produced by furrow planting is undesirable, planting density may need to be increased. Physiological responses that should be studied for furrow- vs hill-planting configurations include tuber quality parameters, speed of crop emergence that may be attainable with shallower planting in the furrow, root distributions of furrow vs hill planted potatoes, and canopy development rates. Physical responses that should be studied include heat, water, and solute regimes and transport in the soil of various planting configurations. Possible interactions between the above factors should also be studied. For example, soil erosion in the conventional hill tends to expose tubers to sunlight, while erosion from a midrow ridge toward a furrow-planted potato would tend to provide additional soil coverage. As a result, the furrow-planting technique may enable shallower planting depths and, in turn, faster crop emergence, faster canopy development, and cooler soil temperatures early in the season, the last of which may affect tuber quality. Finally, the furrow planting approach should be tested on a variety of soils, in a variety of climatic settings, and with other potato cultivars.

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