

Surfactant Impact on Nitrogen Utilization and Leaching in Potatoes

Francisco J. Arriaga · Birl Lowery · Keith A. Kelling

Published online: 16 June 2009
© Potato Association of America 2009

Abstract Some producers face a unique problem with potato (*Solanum tuberosum*) production on sandy soils where a dry zone can develop in the potato hill. Surfactants may reduce this dry zone by decreasing water surface tension, thus enhancing water and nutrient uptake. A study was established to determine if band applying nonionic surfactant at 9.35 L ha⁻¹ in the seed furrow at planting would reduce nitrate-nitrogen (NO₃-N) leaching and increase potato yield and quality. Nitrogen (N) fertilizer was applied at 34, 168, 236, and 303 kg N ha⁻¹. Porous cup samplers were installed beneath the row at 1-m depth in three treatments, with soil solution samples collected weekly. Nitrate-N concentration and irrigation+rainfall data were used to estimate nitrate leaching. Surfactant application resulted in changes of total NO₃-N load between +6.0 and -46.7% for this 3-year study; however, because of high within-treatment variation for the soil water NO₃-N samples, these differences were not statistically significant at the < 0.10 p-value, although a two sample t-test of +/- surfactant treatments across N rates and years resulted in a < 0.01 p-value. Nitrate-N leaching increased with increasing N fertilization rate. Soil NO₃-N concentration 20 days

after the last N fertilization was significantly less (30.1%) with surfactant application across all years and N rates. Soil NH₄-N at this time also tended to be decreased with surfactant application (19.7% reduction, *p*=0.12). Total potato yield was not affected by surfactant use, but increased with increasing N rate. Tuber N content increased with surfactant use, resulting in increased crop N uptake.

Resumen Algunos productores se enfrentan a un problema único con la producción de papa (*Solanum tuberosum*) en suelos arenosos, donde se puede desarrollar una zona seca en la zona radicular de siembra de papa. Tensioactivos pueden reducir esta zona seca mediante la disminución de la tensión superficial del agua, mejorando así la absorción de agua y nutrientes. Se estableció un estudio para determinar si la aplicación en banda a la siembra de surfactante no iónico 9.35 L ha⁻¹ en el surco de siembra reduciría la lixiviación del nitrato-nitrógeno (NO₃-N) y aumentaría el rendimiento y la calidad de la papa. Se aplicó fertilizante nitrógeno (N) a 34, 168, 236, y 303 kg N ha⁻¹. Se instalaron muestreadores de taza porosa debajo de la hilera a 1-m de profundidad en tres tratamientos, con muestras de solución del suelo recogidas cada semana. Datos de concentración de nitrato-N y de riego+precipitación fueron usados para estimar la lixiviación de nitrato. La aplicación del surfactante dio lugar a cambios en la carga total de NO₃-N entre +6,0 y -46,7% para este estudio de tres años; sin embargo, debido a la alta variación dentro de tratamientos para las muestras de agua del suelo NO₃-N, estas diferencias no fueron estadísticamente significativas en el valor *p*<0.10, a pesar de que una prueba t para dos muestras de los tratamientos surfactante +/- a través de dosis de N y años dio lugar a un *p*<0.01. La lixiviación de nitrato-N aumentó con la dosis de fertilización N. La concentración de NO₃-N del suelo 20 días después de la última fertilización N fue significativamente menor (30.1%)

Mention of a company or trade name does not imply endorsement by the USDA-Agricultural Research Service or the University of Wisconsin-Madison to the exclusion of others.

F. J. Arriaga (✉)
USDA-Agricultural Research Service,
National Soil Dynamics Laboratory,
411 S. Donahue Drive,
Auburn, AL 36832, USA
e-mail: francisco.arriaga@ars.usda.gov

B. Lowery · K. A. Kelling
Department of Soil Science, University of Wisconsin-Madison,
1525 Observatory Drive,
Madison, WI 53705-1299, USA

con la aplicación del surfactante en todos los años y dosis de N. El $\text{NH}_4\text{-N}$ del suelo en ese momento también tendió a ser disminuido con la aplicación del surfactante (19.7% de reducción, $p=0.12$). El rendimiento total de papa no fue afectado por el uso del surfactante, pero aumentó con la dosis de N. El contenido de N en el tubérculo aumentó con el uso del surfactante, lo que resultó en el aumento de absorción de N del cultivo.

Keywords Drainage · Groundwater · N uptake · N rate · Wetting agent

Abbreviations

USDA- United States Department of Agriculture-
NASS National Agricultural Statistical Service
WDATCP/ Wisconsin Department of Agriculture,
WDNR Trade and Consumer Protection/ Wisconsin
Department of Natural Resources

Introduction

Potato (*Solanum tuberosum*) production makes an important contribution to the agricultural segment of the United States economy. In 2002, the total value of the potato production in the United States was approximately \$3 billion (USDA-NASS 2008). The total amount of land planted to potatoes in Wisconsin was about 33,000 ha year⁻¹ between 2000 and 2002 (USDA-NASS 2008). The primary potato production area in Wisconsin is located in the Central Sand Plain region. The soils in this area were formed in an ancient glacial lake bed and consist of deep lacustrine sandy deposits from glacial melt waters and have a shallow depth to groundwater (< 7 m). These soils are frequently used for intensive irrigated vegetable production and are susceptible to chemical leaching into the groundwater (WDATCP/WDNR 1989; Wietersen et al. 1993; Hart et al. 1994). Thus, producers in this region are under substantial pressure to use management practices that reduce chemical leaching past the root zone.

A specific potato production issue in sandy soils is that an irregular wetting pattern can develop in potato hills (Saffigna et al. 1976; Robinson 1999; Cooley et al. 2007). Canopy interception and hill shape favors water infiltration in the furrows (Robinson 1999; Saffigna et al. 1976). In part, differences in water content in potato hills have been attributed to the type and timing of irrigation (Robinson 1999; Starr et al. 2005; Cooley et al. 2007). Water content values in the center portion of the potato hill, where the greatest densities of roots occur, were greater under trickle irrigation than sprinkler irrigation by an average of 0.032 m³m⁻³ for values averaged over two

growing seasons (Cooley et al. 2007). Robinson (1999) published water content and matric potential data along with a photograph and diagram showing that when potatoes are grown in hills on sandy soil, hill-center hydrophobic conditions are possible. He suggested that most of the water applied by sprinkler irrigation to potatoes planted in ridges was shed off and infiltrating in furrows. This was attributed to the water repellent nature of the sandy soil. Similar to Robinson (1999) observations, Cooley et al. (2007) noted that the most significant water content variations between drip and sprinkler irrigation were exhibited in the hill center as compared to the furrow. Differences in water content values averaged for the growing season between furrow and hill center were much more substantial in the sprinkler irrigation plots than the drip irrigation plots with values often being significantly lower in the hill center compared to the furrow in the sprinkler irrigation plots. Additionally, the difference in water content becomes more substantial later in the growing season as a dry zone or localized dry spot can develop where the bulk of the roots are located in the center of the potato hill (Dekker et al. 1999; Cooley and Lowery 2000). In-season applied nitrogen fertilizer is often banded to the side of the potato hill and is more likely to bypass the dry zone in the center of the potato hill where it is most needed, increasing the potential for N leaching (Cooley and Lowery 2000). Since infiltration and leaching can be affected by soil surface geometry and fertilizer placement, this has important implications on N fertilizer use by the potato crop (Kemper et al. 1975; Saffigna et al. 1977; Kelling et al. 1998b).

Surfactant application at planting is a management technique that may reduce nitrate ($\text{NO}_3\text{-N}$) leaching losses from potato fields. Surfactant can decrease the surface tension of soil water, thus decreasing the contact angle between soil water and soil particles resulting in increased infiltration (Pelishek et al. 1962; Watson et al. 1971; Lowery 1981; Karagunduz et al. 2001). The effect of surfactants on crop production has been studied on several row crops. McCauley (1993) evaluated the effect of a nonionic surfactant on soybean (*Glycine max*) in a fine-sandy loam in Texas. Soybean yields increased with surfactant application; however, at high application rates, surfactant decreased yields when compared to lower surfactant rates. Soybean yield for the high rates was still greater than the no surfactant control. Additionally, surfactant use increased irrigation efficiency. However, others have reported no increase in crop yield with surfactant application to corn (*Zea mays* L.), soybean, wheat (*Triticum aestivum*), and potato (Fenster et al. 1978; Laughlin et al. 1982; Wolkowski et al. 1985). Nevertheless, relatively little information is available on surfactant use in row crops and N leaching.

Since there is some literature that suggests that the use of surfactant for potato production has the potential to decrease N losses (Kelling et al. 2003; Cooley 2005), we hypothesize that a surfactant applied in the seed furrow at planting, will decrease nitrate leaching. Therefore, the objectives of this study were to evaluate the effects of a nonionic surfactant application on NO₃-N leaching and potato yield at several N fertilization rates.

Materials and Methods

This study was conducted during the 2000 through 2002 growing seasons at the University of Wisconsin Hancock Agricultural Research Station (44° 7'N, 89° 32'W) near Hancock, Wisconsin. Soil at the site was Plainfield loamy sand (sandy, mixed, mesic, Typic Udipsamments). A nonionic surfactant composed of 89.5% alkylphenol ethoxylate, sodium salts of soya fatty acids, isopropyl alcohol and 10.5% constituents ineffective as spray adjuvant (Preference®, Agrilience LLC, St. Paul, Minnesota) was evaluated at two rates of application, 0 and 9.35 L ha⁻¹, for an irrigated potato (*Solanum tuberosum* 'Russet Burbank') production system. The surfactant was applied in the seed piece furrow at planting, with a CO₂ sprayer mounted to the planter, in a band approximately 20 cm wide before the potato hill was closed. Irrigation was applied as needed.

All treatments received 34 kg N ha⁻¹ as part of the starter fertilizer. Supplemental N was applied at 0, 134, 202, and 269 kg ha⁻¹ across both surfactant rates. Therefore, total N rates in the study were 34, 168, 236, and 303 kg N ha⁻¹. The typical University of Wisconsin recommendation for this soil is 258 kg N ha⁻¹ (Kelling et al. 1998a). Supplemental nitrogen application was split, with 33% applied at emergence as ammonium sulfate and 67% at mid-tuberization as ammonium nitrate. In all years, the fertilizer was hand-applied slightly to the side of the top of the potato row and was followed by a light hilling.

Porous cup soil water samplers (Timco Mfg. Co., Prairie du Sac, Wisconsin) were installed approximately 2 weeks after planting to a depth of 1 m in the center row of those plots that received 34, 168, and 303 kg N ha⁻¹, including the with and without surfactant treatments. These samplers were equipped with a porous ceramic cup where soil solution samples were collected under a decaying vacuum by applying a 60 kPa vacuum to the samplers and the soil water sample was collected a week later. Thus, water samples were collected every 5 to 14 days during the growing season. The samples were collected in glass bottles and stored in a cooler with ice packs for transportation to the laboratory where they were stored in a cooler at 5°C. The soil solution samples were prepared for analysis by filtering samples with a 2.0-μm syringe filter and analyzed

for NO₃-N with a Dionex DX-500 ion chromatograph (Dionex Corporation, Sunnyvale, California). Nitrate-N concentrations in the soil solution data were used with weekly drainage estimates to calculate loading.

Water drainage was estimated for the study area using rainfall and irrigation data. The following equation was used to estimate drainage,

$$D_w = (P + I) - (ET_p + R) \pm \Delta S$$

where D_w is the drainage rate (mm d⁻¹), P is rainfall (mm d⁻¹), I is irrigation (mm d⁻¹), ET_p is the potential evapotranspiration (mm d⁻¹) calculated using data from a local automated weather station, R is runoff (mm d⁻¹), and ΔS is the change in water storage (mm d⁻¹). Runoff for this sandy soil is assumed to be zero and ΔS for a long period of time was assumed to be in equilibrium for the Plainfield soil (Hart et al. 1994; Lowery et al. 1998). Nitrate-N flux was then estimated by,

$$J_w = D_w C$$

where, J_w is the solute flux (kg ha⁻¹d⁻¹) and C is the NO₃-N concentration in the soil solution (mg L⁻¹) (Lowery et al. 1998). Total NO₃-N load was estimated for each year as the flux sum for the entire growing season and values for C were obtained from soil water samples taken with suction cup samples located at 1-m depth below soil surface.

Soil samples were taken to a depth of 30 cm for NO₃-N analysis approximately 20 days after the final N application. Four soil cores were systematically taken from 8 cm around each of three potato plants per plot. These 12 cores per plot were composited into one sample per plot and dried at 55°C in a forced air oven. The dried samples were ground to pass a 12-mesh sieve and extracted with a 2 M KCl solution. The extracted solution was analyzed for NO₃-N and NH₄-N colorimetrically using a Lachat auto-analyzer (Lachat Instruments 1992a).

In-season crop N status was provided by NO₃-N analysis of petioles sampled four times [38 to 44, 50 to 55, 62, and 70 to 77 days after emergence (DAE)]. Each sample consisted of 40 petioles per plot, taken from the fourth petiole from the top of the plants. Petioles were dried at 65°C and ground to pass through a 40-mesh screen. Samples (0.1 g) were extracted with distilled water and NO₃-N analysis performed colorimetrically using a Lachat autoanalyzer following QuikChem method 12-101-04-1-B (Lachat Instruments 1992b).

The two center rows of each plot were harvested using a mechanical digger for yield and grade determination. Total wet tuber weights were recorded for each plot. The harvested tubers were graded into U.S. No. 1, undersize (not retained on a 5.1-cm screen) and cull (off-shape, blemished, green, and diseased). All of the U.S. No. 1

tubers were electronically size graded into less than 170-, 170- to 369-, and greater than 369-g categories. Total tuber N content was measured on a 15-tuber subsample randomly taken from the 170 to 369 g U.S. No. 1 tubers following drying (60°C), grinding (<1 mm), and digestion following a semi-micro Kjeldahl digestion procedure adapted from Liegel et al. (1980). The digestions were performed on 250 mg of plant tissue in Pyrex Folin-Wu tubes graduated at 50 mL. The digests were diluted, filtered, and analyzed for NH_4^+ -N using a Lachat autoanalyzer (QuikChem method 13-107-06-2-D; Lachat Instruments 1992b).

Plots were arranged in a randomized complete block design with four replications. Soil NO_3 -N data were analyzed using the ANOVA procedure in SAS 8.0 (SAS Institute Inc. 1999). Crop data (yields, grade and petiole NO_3 -N) were analyzed using PROC ANOVA for a three factor randomized complete block design with year, N rate and surfactant as the factors. Although the year factor was typically significant, the interaction including year and surfactant was only occasionally significant. Furthermore, some of these data are presented by individual years for the first 2 years of the study in Kelling et al. (2003); therefore, in this paper, these data are presented averaged across years. Total NO_3 -N loads were analyzed for each year individually since there were considerable differences among rainfall storms among years. Statistical significance level was established at 0.10 *a priori*.

Results and Discussion

Drainage

Total water drainage for the 3 years was similar, averaging 92.9, 81.1, and 84.8 cm for 2000, 2001, and 2002, respectively. The total rainfall plus irrigation was 153.3, 142.7, and 150.0 cm for 2000, 2001, and 2002, respectively. There were some differences in rainfall storm distributions among years, with the greatest storm event taking place in 2002 during the month of June (Fig. 1). This single storm on 21 June 2002, accounts for 28.1% of the total growing season drainage for 2002. During the 2000 and 2001 growing seasons there were some significant storms on 17 May and 7 Sept, accounting for 4.7 and 6.7% of the total drainage in 2000 and 2001, respectively, but these did not dominate the season drainage like the storm on 21 June 2002.

Nitrogen Balance Under Different Fertilizer rates

Nitrogen rate significantly affected the measured crop and soil N components (Tables 1 and 2). Both soil NH_4 -N and NO_3 -N increased dramatically as N rate increased, as did

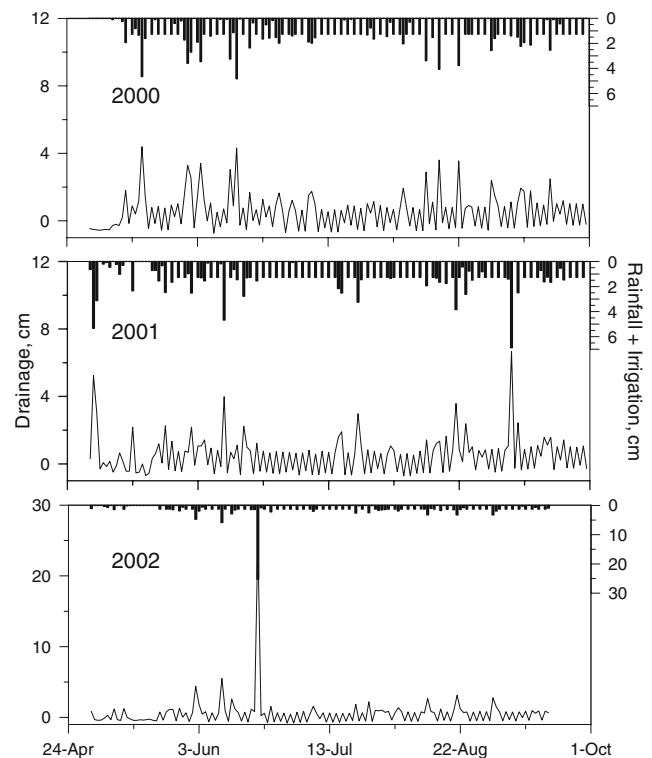


Fig. 1 Estimated drainage (line) and rainfall+irrigation (bars) at the Hancock Agricultural Research Station research site during the 2000, 2001, and 2002 growing seasons

petiole NO_3 -N at all four of the petiole sampling dates. When viewed across the crop parameters presented in Table 2 (total tuber yield, yield of U.S. No. 1 > 170 g, and tuber N uptake), the crop was affected by N rate (Table 2). Regression analysis of yield by N rate revealed an optimum rate of 288 kg N ha⁻¹ using a quadratic-plateau model ($y = 29.67 + 0.168x - 0.00029x^2$; $p < 0.01$). This is similar to the recommended rate of N for Russet Burbank on these soils (Kelling et al. 1998a).

Although N rate significantly affected total NO_3 -N load in 2000 and 2002 ($p = 0.02$ and 0.04 , respectively), there was no significant effect in 2001 ($p = 0.11$) (Table 3). Further, p -values were 0.01 or less for NO_3 -N flux in all three years (Table 4). Nitrate leaching increased with increasing N fertilization rate for all 3 years (Tables 3 and 4; Fig. 2). An interesting observation is the relatively large drainage flux values for both 34 kg N ha⁻¹ treatments, especially in 2002 where maximum estimated values were about 23 to 33 kg ha⁻¹d⁻¹ compared to 5 to 10 kg ha⁻¹d⁻¹ in the previous 2 years (Fig. 2). Even though this treatment, as well as all other treatments did receive 34 kg N ha⁻¹ as a starter fertilizer which likely partly contributed to these flux values, a more significant input may be attributed to the irrigation water, which has been estimated to contribute between 3.9 to 5.2 kg N ha⁻¹ for every 25 mm of irrigation applied (Bundy and Andraski 2005; Speth PE, personal

Table 1 Three-year average soil NH₄-N, soil NO₃-N and petiole NO₃-N concentrations as affected by fertilizer nitrogen rate and surfactant use at the Hancock Agricultural Research Station, Hancock, Wisconsin, 2000 to 2002

N rate kg ha ⁻¹	Surfactant L ha ⁻¹	Soil nitrogen ^a		Petiole NO ₃ -N			
		NH ₄ -N mg kg ⁻¹	NO ₃ -N mg kg ⁻¹	Days after emergence			
				38–44	50–55	62	70–77
34	0	0.4	2.0	3.2	0.9	0.7	0.8
168	0	9.1	5.7	10.5	5.5	2.1	1.4
236	0	11.3	9.7	15.2	10.1	5.1	2.9
303	0	19.8	13.1	17.2	13.2	6.7	4.5
34	9.35	3.4	1.0	2.6	1.2	3.2	0.9
168	9.35	5.6	4.2	11.4	6.3	2.5	1.4
236	9.35	12.7	9.0	14.4	9.6	5.2	3.1
303	9.35	14.6	9.3	17.2	13.0	8.4	5.8
Statistical significance (Pr > F)							
Year (Y)		< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Surfactant (S)		0.12	< 0.01	0.78	0.82	0.11	0.03
N rate (N)		< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Y×S		0.09	0.05	0.92	0.02	0.28	0.27
Y×N		< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
S×N		< 0.01	0.13	0.42	0.64	0.04	0.03
Y×S×N		0.51	0.03	0.70	0.57	0.94	0.32

^a Soil samples collected 20 days after final N fertilizer application to a depth of 30 cm.

communication, Univ. of Wisconsin-Madison, 10 and 11 Dec 2008). However, the much greater flux values for 2002 are not solely explained on this basis since similar amounts of starter N and irrigation water were used in all years. It is also possible that more residual N was present in this field following the plow-down of the fall green manure cover

crop. However, Bundy and Andraski (2005) also showed this input to be relatively minor on this soil in most years.

Days after emergence also had a significant effect on NO₃-N flux for the 2000 through 2002 study period (Table 4). This was expected since sampling of the soil solution started shortly after planting and additional N

Table 2 Three-year average Russet Burbank tuber yield, yield of U.S. No. 1 >170 g tubers, and tuber N uptake as affected by fertilizer nitrogen rate and surfactant use at the Hancock Agricultural Research Station, Hancock, Wisconsin, 2000 to 2002

N rate kg ha ⁻¹	Surfactant L ha ⁻¹	Total yield Mg ha ⁻¹	Yield U.S. No. 1 >170g	Tuber N uptake kg ha ⁻¹
34	0	35.8	2.7	76.3
168	0	49.0	6.6	120.1
236	0	52.3	8.2	138.5
303	0	54.0	8.9	135.7
34	9.35	34.3	2.3	74.1
168	9.35	50.6	7.8	131.4
236	9.35	53.8	9.0	140.2
303	9.35	54.0	9.0	148.2
Statistical significance (Pr > F)				
Year (Y)		< 0.01	< 0.01	< 0.01
Surfactant (S)		0.60	0.29	0.09
N rate (N)		< 0.01	< 0.01	< 0.01
Y×S		0.13	0.23	0.03
Y×N		< 0.01	< 0.01	0.03
S×N		0.29	0.44	0.34
Y×S×N		0.20	0.07	0.35

Table 3 Total NO₃-N loading to groundwater for three nitrogen fertilization rates and surfactant use in potato during three growing seasons at the Hancock Agricultural Research Station, Hancock, Wisconsin, 2000 to 2002

N rate kg ha ⁻¹	Surfactant rate L ha ⁻¹	Total NO ₃ -N load					
		Year			Year		
		2000	2001	2002	2000	2001	2002
			kg ha ⁻¹				
34	0	26.7	(-9.2) ^a	39.7	(6.0)	75.8	(-10.3)
	9.35	24.3		42.0		68.0	
168	0	43.0	(-6.6)	50.6	(-6.0)	90.4	(-4.6)
	9.35	40.2		47.6		86.2	
303	0	71.4	(-3.8)	120.2	(-46.7)	105.3	(-20.3)
	9.35	68.7		64.1		83.9	
Statistical significance (Pr > F)							
N rate (N)		0.02		0.11		0.04	
Surfactant (S)		0.99		0.24		0.85	
N×S		0.91		0.61		0.60	

^a Values in parenthesis represent the percent change in total NO₃-N load when using a surfactant compared to no surfactant at the same N fertilization rate.

fertilizer was applied after sampling was initiated. Additionally, there was a DAE×N rate interaction in 2000. The majority of these differences were between the three N rates in DAE 39 and other sampling times. In DAE 46 and 54, most of the differences were between the 168 and 303 kg N ha⁻¹ N treatments, while in DAE 61 it was between 303 kg N ha⁻¹ and other sampling dates/N rate combinations (Fig. 2).

Surfactant Effect on Nitrogen Balance

The effect of surfactant use on soil and plant N status is shown in Table 1, with surfactant significantly ($p < 0.01$) reducing the amount of soil NO₃-N measured about 20 days after the last supplemental fertilizer N application and tending to similarly decrease soil NH₄-N values ($p = 0.12$). The consistently lower soil NO₃-N concentrations and the trend toward lower soil NH₄-N concentrations in the 0- to 30-cm layer associated with surfactant application may be

Table 4 Multifactor analysis of variance probability values for estimated drainage NO₃-N flux estimated weekly throughout three growing seasons at the Hancock Agricultural Research Station, Hancock, Wisconsin, 2000 to 2002 (data shown in Fig. 2)

Factor	2000	2001	2002
		<i>p</i> values	
DAE ^a	<0.01	<0.01	<0.01
N rate (N)	<0.01	<0.01	0.01
Surfactant (S)	0.54	0.04	0.27
DAE×N	<0.01	0.70	0.56
DAE×S	0.99	0.43	0.76
N×S	0.98	0.01	0.88
DAE×N×S	0.99	0.82	0.34

^a DAE, days after emergence.

the result of more uniform redistribution of the applied N throughout the entire hill area and/or an increase in plant use of the applied N. The latter explanation is partially supported by a trend of greater petiole NO₃-N concentration ($p = 0.11$) and a significant increase ($p = 0.03$) with surfactant use during the last two sampling dates (Table 1).

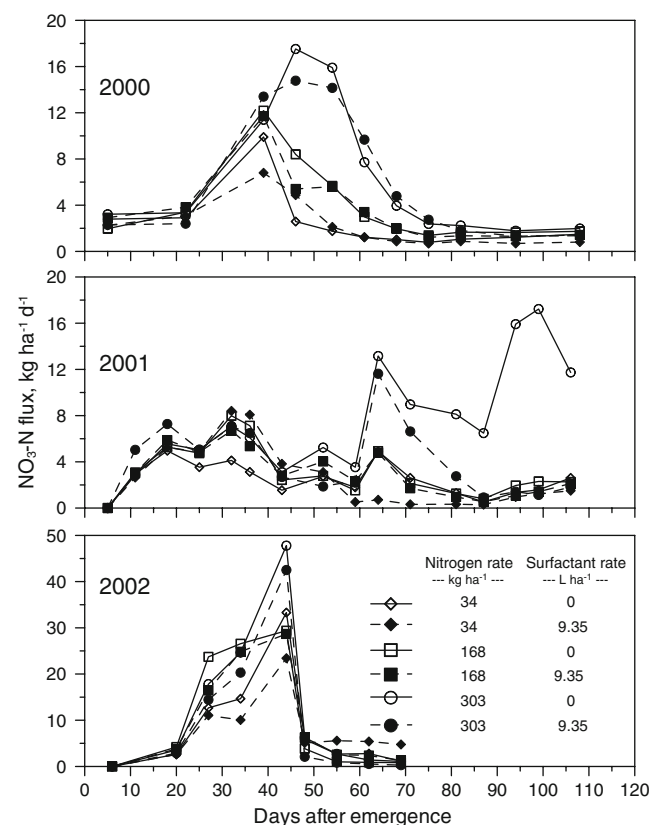


Fig. 2 Nitrate-N flux for the no surfactant and surfactant applied treatments at three N fertilization rates during 2000, 2001 and 2002

This is an indication that plants in the surfactant-treated areas were taking up more N.

Surfactant treatment did not increase total tuber yield ($p=0.60$) or yield of > 170 g U.S. No. 1 tubers ($p=0.29$) over the 3-year term of the experiment; however, over these three years, surfactant significantly increased tuber N uptake ($p=0.09$). This increase was primarily the result of higher tuber N concentration where surfactant was applied since there was no effect of surfactant on yield.

This increase in tuber N uptake is particularly important because this represents a net gain in N removal in the harvested portion of the crop from this highly sensitive environment (Stites and Kraft 2001). Although the magnitude of the increase is relatively small (8.5 kg N ha⁻¹ averaged across all rates where N was applied), it represents an improvement in apparent fertilizer N recovery. On this soil, the only effective treatments are those that result in a greater proportion of applied N being removed with the harvested crop since any remaining N will have leached to the groundwater by the following spring.

Surfactant application significantly decreased NO₃-N leaching in 2001, as reflected by a N rate×surfactant interaction (Table 4). Nitrate flux for the 303 kg N ha⁻¹ with surfactant treatment was not significantly different from the 34 or 168 kg N ha⁻¹ with and without surfactant treatments. The no-surfactant 303 kg N ha⁻¹ treatment had the greatest NO₃-N load (Table 3). In general, maximum peaks of NO₃-N flux were observed for the no-surfactant treatments when compared to surfactant treatment at the same N rate (Fig. 2). The solute flux curves in 2000 and 2002 follow the expected breakthrough bell-shape curve. However, the curves during the 2001 growing season did not follow this pattern. A possible explanation is that storm events were less extreme in 2001. Also, the total amount of drainage was 37.0 and 31.9% lower in 2001 than in 2000 and 2002, respectively. The lower amount of drainage could have potentially affected solute movement.

Total NO₃-N loading to the groundwater amounts were calculated by summing flux rates for an entire season (Table 3). Although not statistically significant for any of the 3 years, the observed values of the surfactant appeared somewhat lower for total load amounts from 2000 through 2002 for all N rates, except for the 34 kg N ha⁻¹ in 2001 where surfactant use increased the total load by 6.0%. A single degree of freedom contrast on the with- and without-surfactant means presented in Table 3 resulted in a p value of 0.06 and the average reduction in NO₃-N total loading with surfactant use was 11.3%. Where the surfactant use is effective, it is likely that the surfactant application reduced total loading by allowing water and N to infiltrate into the dry center of the potato hill, and thus, increasing the potential for plant uptake (Cooley and Lowery 2000). Nevertheless, reducing the total amount of NO₃-N leached

should have a positive impact in groundwater NO₃-N concentration.

Conclusions

Producers, in general, are under pressure to conduct environmentally friendly farming practices. The search for conservation practices that protect the environment is ongoing. Although this field study showed variable results in some respects, the use of a nonionic surfactant provided some indication that NO₃-N leaching may be reduced. Benefits seen included reductions in 1 out of 3 years of soil water NO₃-N flux with surfactant application, and over the whole 3-year study, surfactant use resulted in a significant reduction in soil NO₃-N concentrations ($p<0.01$) and a tendency for reduced soil NH₄-N levels ($p=0.12$), increased late-season petiole NO₃ concentrations ($p=0.03$), and increased tuber N uptake ($p=0.09$). We speculate that the surfactant is aiding in water and N redistribution in the potato hill and improving N use efficiency by the plant.

Data presented here show some potential for surfactants to reduce N losses in potato fields. Perhaps different modes of application, application rates, and/or surfactant types could have a greater impact in controlling chemical losses and improve water and N use efficiency. Also, different soil types need to be studied to ensure surfactants do not have a negative impact. Nevertheless, surfactants appear to have some potential for reducing N leaching into the groundwater.

References

- Bundy, L.G. and T.W. Andraski. 2005. Recovery of fertilizer nitrogen in crop residues and cover crops on an irrigated sandy soil. *Soil Science Society of America Journal* 69: 640–648.
- Cooley, E.T. 2005. Quantifying dry zones in potato hills and the use of surfactant to reduce dry zones and nitrate leaching. MS thesis, Univ of Wisconsin-Madison, Madison, Wisconsin.
- Cooley, E. and B. Lowery. 2000. Nitrogen leaching and use of surfactants to reduce the impacts of the potato dry zone. *Proceedings of Wisconsin's Annual Potato Meetings* 14: 89–93. Stevens Point, Wisconsin, 14–16 Feb 1998. Univ. of Wisconsin-Extension, Madison, Wisconsin.
- Cooley, E.T., B. Lowery, K.A. Kelling, and S. Wilner. 2007. Water dynamics in drip and overhead sprinkler irrigated potato hills and development of dry zones. *Hydrological Processes* 21: 2390–2399.
- Dekker, L.W., C.J. Ritzema, O. Wendroth, N. Jarvis, K. Oostindie, W. Pohl, M. Larsson, and J.P. Gaudet. 1999. Moisture distributions and wetting rates of soils at experimental fields in the Netherlands, France, Sweden and Germany. *Journal of Hydrology* 215: 4–22.
- Fenster, W., G. Randall, W. Nelson, S. Evans, and R. Schoper. 1978. Effect of WEX on nutrient uptake and crop yields, 1976–1977. In Compendium of research reports on the use of nontraditional materials for crop production. NCR-103 Committee on Non-

- traditional Soil Amendments and Growth Stimulants, E.3.1.1–13. Ames, Iowa: Iowa State Press.
- Hart, G.L., B. Lowery, K. McSweeney, and K.J. Fermanich. 1994. In situ characterization of hydrologic properties of Sparta sand: relation to solute movement. *Geoderma* 64: 41–55.
- Karagunduz, A., K.D. Pennell, and M.H. Young. 2001. Influence of a nonionic surfactant on the water retention properties of unsaturated soils. *Soil Science Society of America Journal* 65: 1392–1399.
- Kelling, K.A., L.G. Bundy, S.M. Combs, and J.B. Peters. 1998a. Soil test recommendations for field, vegetable and fruit crops. UWEX Publ. A2809. Univ. of Wisconsin-Extension, Madison, WI.
- Kelling, K.A., S.A. Wilner, R.F. Hensler, and L.M. Massie. 1998b. Placement and irrigation effects on nitrogen fertilizer use efficiency. *Proceedings of Wisconsin's Annual Potato Meetings* 11: 79–88. Stevens Point, Wisconsin, 3–4 Feb 1998. Univ. of Wisconsin-Extension, Madison, Wisconsin.
- Kelling, K.A., P.E. Speth, F.J. Arriaga, and B. Lowery. 2003. Use of nonionic surfactant to improve nitrogen use efficiency of potato. *Hort Acta* 619: 225–232.
- Kemper, W.D., J. Olsen, and A. Hodgdon. 1975. Fertilizer salt leaching as affected by surface shaping and placement of fertilizer and irrigation water. *Soil Science Society of America Proceedings* 39: 115–119.
- Instruments, L. 1992a. *Nitrate in 2 M KCl soil extracts*. Milwaukee, Wisconsin: Lachat Instruments.
- Instruments, L. 1992b. *Total Kjeldahl nitrogen in soil/plant*. Milwaukee, Wisconsin: Lachat Instruments.
- Laughlin, W.M., G.R. Smith, and M.A. Peters. 1982. A multipurpose wetting agent, WEX, and a cultured biological product, Agrispon, leave potato yields unchanged. *American Potato Journal* 59: 87–91.
- Liegel, E.A., C.R. Simson, and E.E. Schulte. 1980. Wisconsin procedures for soil testing, plant analysis and feed and forage analysis. Soil Fertility Series no 6 (Revised). Univ of Wisconsin-Madison, Madison, WI.
- Lowery, B. 1981. The potential for wetting agents as soil additives. *Proceedings of Fertilizer, Aglime, and Pest Management Conference* 20: 86–90. Univ of Wisconsin-Extension, Madison, Wisconsin.
- Lowery, B., R.C. Hartwig, D.E. Stoltenberg, K.J. Fermanich, and K. McSweeney. 1998. Groundwater quality and crop-yield responses to tillage management on a Sparta sand. *Soil & Tillage Research* 48: 225–237.
- McCauley, G.N. 1993. Nonionic surfactant and supplemental irrigation of soybean on crusting soils. *Agronomy Journal* 85: 17–21.
- Pelishak, R.E., J. Osborn, and J. Letey. 1962. The effect of wetting agents on infiltration. *Soil Science Society of America Proceedings* 26: 595–598.
- Robinson, D. 1999. A comparison of soil-water distribution under ridge and bed cultivated potatoes. *Agriculture Water Management* 42: 189–204.
- Saffigna, P.G., C.B. Tanner, and D.R. Keeney. 1976. Non-uniform infiltration under potato canopies caused by interception, stem-flow, and hilling. *Agronomy Journal* 68: 337–342.
- Saffigna, P.G., D.R. Keeney, and C.B. Tanner. 1977. Nitrogen, chloride and water balance with irrigated Russet Burbank potatoes in a sandy soil. *Agronomy Journal* 69: 251–257.
- SAS Institute Inc. 1999. *SAS procedures guide, version 8*. Cary, NC: SAS Institute Inc.
- Starr, G.C., E.T. Cooley, B. Lowery, and K. Kelling. 2005. Soil water fluctuations in a loamy sand under irrigated potato. *Soil Science* 170: 77–89.
- Stites, W. and G.J. Kraft. 2001. Nitrate and chloride loading to groundwater from an irrigated North-Central US sand-plain vegetable field. *Journal of Environmental Quality* 30: 1176–1184.
- USDA-National Agricultural Statistical Service. (<http://www.nass.usda.gov/>) accessed 19 Feb 2008.
- Watson, C.L., J. Letey, and M.A. Mustafa. 1971. The influence of liquid surface tension and liquid-solid contact angle on liquid entry into porous media. *Soil Science* 112: 178–183.
- WDATCP/WDNR. 1989. Compilation of private water supply well sampling in the LWRV. Wis Dept of Agric, Trade, and Consumer Protection and Wis Dept of Natural Resources. Madison, Wisconsin (Memo Report).
- Wiertsen, R.C., T.C. Daniels, K.J. Fermanich, B.D. Girard, K. McSweeney, and B. Lowery. 1993. Atrazine, alachlor, and metolachlor mobility through two sandy Wisconsin soils. *Journal of Environmental Quality* 22: 811–818.
- Wolkowski, R.P., K.A. Kelling, and E.S. Oplinger. 1985. Evaluation of three wetting agents as soil additives for improving crop yield and nutrient availability. *Agronomy Journal* 77: 695–698.