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Potato Yield Response and Nitrate Leaching as Influenced by Nitrogen Management

Mohamed Errebhi, Carl J. Rosen,* Satish C. Gupta, and David E. Birong

ABSTRACT

Nitrogen management for irrigated potato (*Solanum tuberosum* L.) is important from both a production and environmental standpoint. Nitrogen deficiency can limit yield, while excessive N can leach to groundwater. The objective of this study was to investigate the effects of early-season N management on irrigated 'Russet Burbank' potato yield, N recovery, and NO_3–N leaching. A 2-yr experiment was conducted on a Hubbard loamy sand (Udorthentic Haploborolls), using four N treatments and a 0 N control. Total N applied was 270 kg N ha^{-1}; the portion applied at planting was 0, 45, 90, and 135 kg N ha^{-1}, with the remainder applied in equal quantities at emergence and hilling. In 1991, increasing the amount of N applied at planting did not affect total yield, but significantly increased the yield of nonmarketable tubers. In 1992, total yield again was not affected, but the yield of smaller tubers significantly increased and the yield of larger tubers decreased as the proportion of N applied at planting increased. During 1991, when heavy leaching occurred, an average of only 33% of applied N was recovered by the crop. In contrast, during 1992, when fewer leaching events occurred, recovery of N averaged 56%. In both growing seasons, the amount of NO_3–N leached increased linearly as the proportion of N applied at planting increased. The strategy of reducing N application at planting for irrigated Russet Burbank potato can reduce the potential for NO_3–N leaching, increase N uptake, and improve marketable yield.

NITROGEN usually is the most limiting essential nutrient for potato (*Solanum tuberosum* L.) growth, especially on sandy soils. For irrigated potato grown in humid regions, N fertilizer recommendations are based primarily on yield goal and previous crop. In some areas, the usual practice is to supply most of the N at, or just before, the time of planting (Harris, 1992). However, Ivins (1963) suggested that withholding N, or part of it, until tubers have been initiated might increase the duration of tuber bulking, and so improve final tuber yield. This hypothesis was tested by Gunasena and Harris (1968, 1969, 1971), who concluded that large benefits in delaying the application of all or part of the N fertilizer were associated with seasons when rainfall after N application was sufficiently high to bring about leaching. Westermann and Kleinkopf (1985) found that high preplant N fertilization rates delayed tuber growth. During nonleaching years, however, delaying N application until after tuber initiation did not increase yield (Ngugi, 1972).

At present, there is no consensus as to the best way to manage N applications to potato grown on irrigated, coarse-textured soils (Dow et al., 1974; Middleton et al., 1975; Roberts et al., 1982; Westermann and Kleinkopf, 1985; Haverkort and van de Waart, 1994). Iritani (1978) suggested the application of approximately one-third to one-half of the N fertilizer at planting, with the rest applied later in periodic supplements. However, from planting to emergence, potato plants are relying on the reserves of the seed tuber (Ewing, 1978). Early in the season, the potato crop does not require and will not utilize all of the N provided, especially at high rates of application. This is because, at emergence, the root system is not sufficiently developed to absorb and effectively use all the available N. It is only at later growth stages that N amounts should be increased progressively. The excess N applied early in the growing season has a high potential of being lost by leaching (Vitosh and Jacobs, 1990).

In view of recent concerns over the leaching of NO_3–N to groundwater, there is justification for withholding part of the N supply until the time of tuber initiation. Westermann et al. (1988) indicated that split N applications made according to potato growth needs would significantly improve N fertilizer use efficiency. High N rates applied on sandy soils early in the season can be leached easily below the rooting zone during heavy rainfall events or excess irrigation. This practice could result in groundwater contamination by NO_3–N, and substantial reduction in yields due to N deficiency. A recent survey in Minnesota found pesticides and NO_3 in shallow observation wells (Klaseus et al., 1988), particularly where irrigated potato was grown.

While the effects of N rate and timing on potato yield have been reported (Gunasena and Harris, 1969; Roberts et al., 1982; Westermann and Kleinkopf, 1985; Roberts et al., 1989), few studies attempted to quantify the various fractions of N inputs and outputs. Hill (1986) used a mass balance approach to estimate NO_3 leaching from the potato rooting zone. However, that study focused on temporal differences (within and between years) in NO_3 and Cl concentrations at various soil profile depths, and N management practices were not considered. Saffigna et al. (1977) carried out a more comprehensive experiment to establish an N budget for irrigated Russet Burbank potato grown on sandy soils, but only two N management schemes were examined: *conventional* and *improved*. There is a need to account for the fate of soil applied N as it relates to various options of N management strategies. Our objective, therefore, was to quantify the effect of various N management practices on potato tuber yield and quality,

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Abbreviations: DAP, days after planting; ET, evapotranspiration; PVC, polyvinyl chloride.

total N accumulation by the crop, and NO_3–N leaching below the root zone.

MATERIALS AND METHODS

Field investigations were conducted during the 1991 and 1992 growing seasons on a Hubbard loamy sand (sandy, mixed Udorthentic Haploboroll) at the University of Minnesota Sand Plain Research Farm at Becker, MN. For both years, separate experimental sites were used to avoid N carryover and confounding of treatment effects. The previous crop for each season was winter rye (*Secale cereale* L.). The potato cultivar used was Russet Burbank, a full-season indeterminate variety requiring about 120 d to reach maturity. Soil properties in the 0- to 15-cm depth, prior to planting, averaged over 2 yr, were as follows: pH, 6.7; organic matter, 25 mg g^{-1}; Bray-1 extractable P, 34 mg kg^{-1}; and exchangeable K, 100 mg kg^{-1}. Residual NO_3–N in the top 90 cm averaged 26 kg ha^{-1}. Prior to planting, 250 kg ha^{-1} K–$MgSO_4$ and 200 kg ha^{-1} KCl were broadcast and incorporated. Russet Burbank B-size whole tubers were hand planted in open furrows on 3 May 1991 and 27 Apr. 1992 at a spacing of 90 cm between rows and 25 cm within the row. Phosphorus, as triple superphosphate, and K, as KCl, were applied in bands at planting at the rate of 90 kg P ha^{-1} and 225 kg K ha^{-1}, respectively. The fertilizers were banded 7.5 cm to each side and 5 cm below the tubers. Individual plots consisted of six 9-m-long rows, with the middle two rows designated as harvest rows. Plots were arranged in a randomized complete block design replicated four times.

Each season, four N management treatments and a control were tested to evaluate the effects of early-season N management strategies on potato yield and quality, N accumulation by the plant, and NO_3 leaching below 140 cm. The total amount of N applied as NH_4NO_3 for all treatments during each growing season was 270 kg ha^{-1}, as recommended for irrigated potato production in North Dakota and Minnesota with a yield goal of 50 to 55 Mg ha^{-1} (Rosen, 1991, 1993). Nitrogen applied at planting was banded with the P and K fertilizers. At emergence (31 May 1991 and 28 May 1992), N was banded 2.5 cm deep and 20 cm from each side of the plant. At hilling, on 13 June 1991 and 11 June 1992, N fertilizer was sidedressed on the surface of each side of the plant rows and then incorporated during the hilling process. Rainfall was supplemented with overhead irrigation to supply water requirements according to the checkbook method (Wright and Bergsrud, 1991). Concentration of NO_3–N in the irrigation water averaged 10 mg L^{-1}. Irrigation water applied totaled 256 and 218 mm in 1991 and 1992, respectively, providing approximately 26 and 22 kg ha^{-1} of additional N.

Suction tubes consisting of a porous ceramic cup (Model Hi Flow, Soil Moisture Equipment, Santa Barbara, CA) inserted into the end of 38-mm-diameter PVC tubes were installed vertically in the row at the 140-cm depth, 1 wk after planting. Suction tubes were installed in three of the four replications, one tube per plot, and subjected to a continuous vacuum of 0.04 MPa. Continuous suction presents the advantage of less frequent sample collections, but has the disadvantage of sample alteration (Grossmann and Udluft, 1991). Bentonite was placed around the tube 6 cm below the soil surface, to prevent preferential flow of water down the side of the tube. For NO_3–N concentration determination, water samples were collected from the suction tubes once a week, starting 2 wk after planting and continuing until soil freeze-up in November. Saffigna et al. (1977) found that NO_3 and Cl leaching are nearly complete by the time of tuber harvest, which corresponds to mid-September in this study; therefore, water sampling beyond November was not considered necessary. Nitrate-N concentration was determined conductimetrically following reduction to NH_4 (Carlson et al., 1990).

Daily water percolation was calculated using the water balance equation:

$$\text{Percolation} = P + I - \Delta\text{Storage} - \text{ET} \quad [1]$$

where P is precipitation (mm), I is irrigation water applied (mm), ΔStorage is the change in soil water storage (mm), and ET is evapotranspiration (mm). We know or have an estimate of all the parameters in Eq. [1] except percolation. Percolation occurs whenever $(P + I)$ is greater than (ΔStorage + ET). Inputs from irrigation and rainfall were measured at the experimental site. Crop water use (ET) was determined from the estimates given by Wright and Bergsrud (1991). These estimates have been calculated using Penman's equation and depend on the daily weather conditions of the experimental site as well as the growth stage of the crop. The initial water storage was equal to the soil water holding capacity to the 140-cm depth (early spring, when soil profiles were fully charged), and subsequent ΔStorage was determined on a daily basis. A daily bookkeeping procedure was used to calculate percolation using the water balance equation (Eq. [1]). Percolation was then converted to a volume basis, and nitrate leaching was calculated by multiplying water percolation by NO_3–N concentration of soil water sampled from the suction tubes. Since soil water samples were not taken daily, water NO_3–N concentrations between two consecutive sampling dates were linearly extrapolated on a daily basis to cover the entire monitoring period (April to November). Linear extrapolation may not account for daily fluctuation of NO_3–N concentrations; however, because of the short time between sampling dates, and the use of continuous suction, the error incurred was not considered to be significant.

For N budget calculations, a mass balance approach was used in all treatments. Nitrogen outputs (N_{OUT}) should equal N inputs (N_{IN}), as follows:

$$N_{\mathrm{OUT}} = N_{\mathrm{IN}} \quad [2]$$

and

$$N_{\mathrm{OUT}} = N_{\mathrm{plant}} + N_{\mathrm{leach}} + N_{\mathrm{final}}$$
$$N_{\mathrm{IN}} = N_{\mathrm{initial}} + N_{\mathrm{fert}} + N_{\mathrm{irrig}} + N_{\mathrm{min}}$$

where N_{plant} is N uptake by vines and tubers, N_{leach} is N calculated from water leaching and soil water NO_3–N concentrations, and N_{final} is inorganic N present in the top 90 cm of soil after harvest; N_{initial} is measured inorganic N initially present in the top 90 cm of soil, N_{fert} is N input from fertilizer, N_{irrig} is N input from irrigation water, and N_{min} is N input from net mineralization of soil organic matter, estimated from control plots after equating N_{OUT} and N_{IN}. Solving for N_{min}, the input from net mineralization, we get

$$N_{\mathrm{min}} = N_{\mathrm{plant}} + N_{\mathrm{leach}} + N_{\mathrm{final}} - N_{\mathrm{initial}} - N_{\mathrm{irrig}} \quad [3]$$

In the mass balance approach, it was assumed that (i) N added from rainfall and N losses from volatilization and denitrification were negligible, (ii) N remaining in the roots was the same in the control and N treatments, (iii) there was no enhancement of mineralization caused by adding N fertilizer, and (iv) there was no significant immobilization of applied fertilizer N.

Tubers were mechanically harvested on 12 Sept. 1991 and 15 Sept. 1992, and were sorted and weighed according to size and quality. Vine and tuber subsamples were collected for dry matter and N accumulation determination, and were oven dried at 70°C until constant weight. Plant tissue was ground in a Wiley Mill to pass through a 1-mm mesh screen. Nitrogen

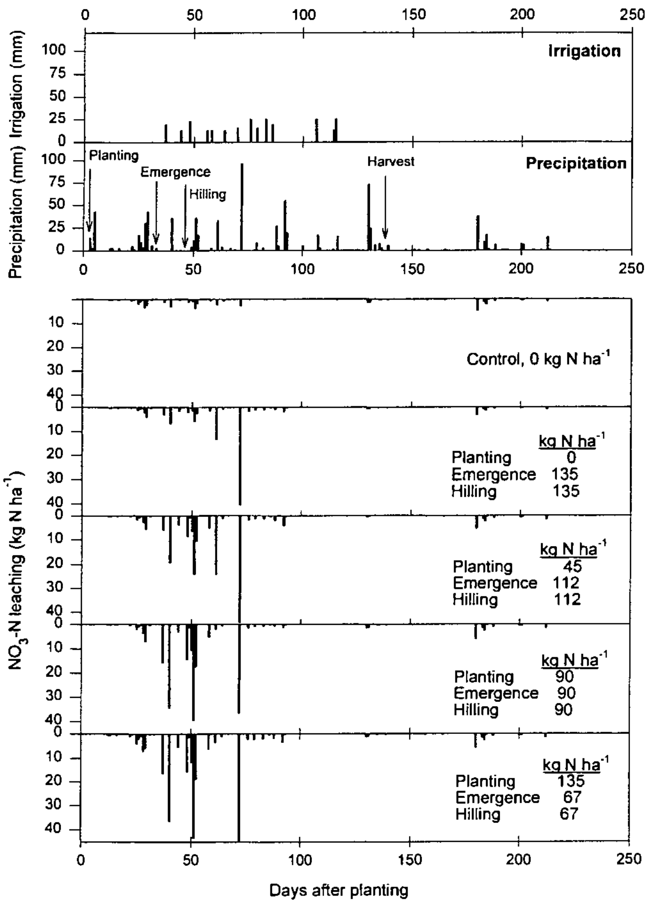

Fig. 1. Nitrogen management effect on daily nitrate leaching during the potato growing season in 1991.

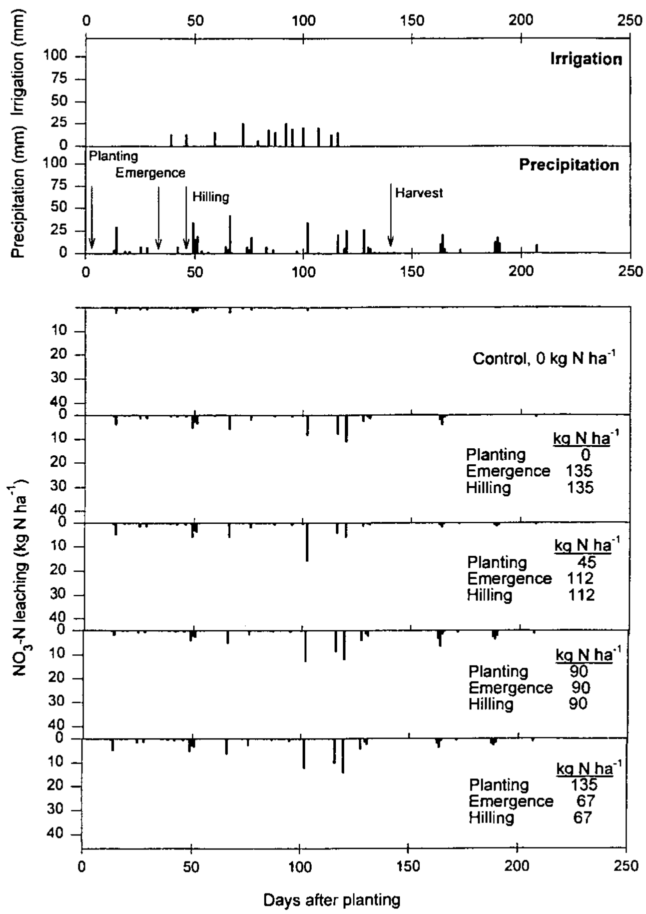

Fig. 2. Nitrogen management effect on daily nitrate leaching during the potato growing season in 1992.

concentration of vines and tubers was determined conductimetrically (Carlson et al., 1990) following the salicylic Kjeldahl N digestion procedure (AOAC, 1970). After harvest, soil samples were collected from each plot and NO_3–N was determined following extraction with 2 *M* KCl (Carlson et al., 1990).

Percent N recovery in the fertilized plots was estimated as the difference between N content (N concentration × dry weight) of the fertilized plants and N content of the control, divided by the amount of N applied to the soil. The assumption was made that uptake of mineralized and irrigation water N was similar for both fertilized and control plants.

Orthogonal contrasts and trend analysis were used to compare various treatment effects on selected parameters (Steel and Torrie, 1980).

RESULTS AND DISCUSSION

Rainfall during the 1991 growing season totaled 776 mm and was supplemented with 256 mm of irrigation. Rainfall was excessive from planting to emergence (29 d), with nearly 180 mm falling during this period (Fig. 1). The months of June and July also had above-average amounts of rainfall (118 mm in June and 184 mm in July). During the 1992 growing season, total rainfall (Fig. 2) and supplemental irrigation water were 465 and 218 mm, respectively. Based on the calculated water balance, leaching occurred only twice in 1992, at 66 and 102 days after planting (DAP). This is in contrast to five leaching events in 1991, two of which occurred before hilling.

Tuber Yield and Quality

In 1991, increasing the proportion of N applied at planting and reducing the amount of N at emergence and hilling had no effect on total yield but significantly increased the yield of undersized and misshapen tubers (Table 1). While not significant, the yield of tubers >200 g tended to decrease as the proportion of N applied at planting increased. Yield response in 1992 followed the trend of 1991 (Table 1). Total yield was not affected by varying the proportion of N applied at planting, but the yield of smaller tubers increased and the yield of larger tubers decreased as the proportion of N applied at planting increased. High N levels at planting delayed tuber bulking, thus increasing the production of small tubers and decreasing the production of large tubers. These findings agree with data of Westermann and Kleinkopf (1985), who reported that high early-season N fertilization delayed tuber growth of Russet Burbank grown at Kimberly, ID.

Based on these experiments, we conclude that increasing the proportion of N applied at planting for the Russet Burbank cultivar grown on sandy soils increases the yield of undesirable tubers and tends to reduce yield

Table 1. Effects of N application timing on tuber grade and total yield of potato for the 1991 and 1992 growing seasons.

		Tuber grade and yield											
		1991						1992					
Total‡	N treatment	Culls	<85 g	85–200 g	200–400 g	>400 g	Total	Culls	<85 g	85–200 g	200–400 g	>400 g	Total
kg ha^{-1}		Mg ha^{-1}											
0	0	1.88	4.56	21.89	9.36	0.31	38.00	0.43	6.65	23.98	2.92	0.00	33.98
270	0 + 135 + 135§	2.44	4.32	23.52	21.15	1.33	52.76	3.41	3.80	25.91	30.25	4.40	67.77
270	45 + 112 + 112	3.27	4.72	24.76	20.64	1.78	55.17	1.89	5.21	27.94	24.79	3.79	63.62
270	90 + 90 + 90	3.08	5.30	25.03	20.09	0.92	54.42	3.44	5.95	31.56	24.97	1.36	67.28
270	135 + 67 + 67	4.41	6.03	24.20	18.95	1.70	55.29	3.25	5.50	30.02	22.29	1.53	62.59
Contrasts													
Control vs. fertilizer		*	NS	NS	**	†	**	**	*	**	**	*	**
Linear N response		**	**	NS	NS	NS	NS	NS	**	**	**	*	NS
Quadratic N response		NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS

†,*,** Significant at the 0.1, 0.05, and 0.01 probability levels, respectively.
‡ Value shown is total N applied ± 1 unit, due to rounding errors.
§ The three values show amounts applied at planting, emergence, and hilling, respectively.

of marketable tubers. At Becker, MN (45° N lat), Russet Burbank is a full-season variety requiring about 120 d from planting to harvest. Therefore, different results may be obtained with other varieties, or with production in different environments, especially with varieties from the short-season group. Haverkort and van de Waart (1994) found that, for starch potato grown on sandy humic soils in the northeastern area of the Netherlands, increasing preplant N rates did not always lead to increased tuber yield. Van Loon et al. (1987) reported that, after low starter N applications, supplemental N application increased petiole NO_3 concentrations to above critical levels, but no yield increase was observed with the cultivar Bintje in their trials.

Nitrogen Recovery by the Crop

During 1991, a year of high rainfall and leaching events, an average of only 33% of the applied N was recovered by the crop (Table 2). Percent N recovery decreased from 40% (when no N was applied at planting) to 25% (with the highest input of N at planting). In contrast, the 1992 growing season was characterized by less total rainfall and fewer leaching events. Recovery of N in plant tissue averaged 56% in 1992, with no significant difference in recovery among the various N management treatments (Table 2).

Nitrogen recovery in 1991 is within the range reported in the literature. Prins et al. (1988) found that, in the Netherlands, N uptake by potato tubers varied between 90 and 150 kg N ha^{-1}. Hill (1986) found that, for the sandy soils of southern Ontario, 75 to 127 kg N ha^{-1} were recovered in tubers of 'Superior' potato. Saffigna et al. (1977) found that, under Wisconsin conditions, 135 to 180 kg N ha^{-1} were recovered in tubers of Russet Burbank potato grown on sandy soils. In 1992, N recovery in our experiment was slightly higher than values reported earlier. This difference could be due to the exceptionally low rainfall during the growing season, which is consistent with low NO_3 leaching below the root zone.

Low and high recovery of N in 1991 and 1992 agree with nitrate concentrations measured in the soil water at the 140-cm depth and the calculated nitrate leaching below the root zone (see Table 3). High N recovery, associated with better tuber quality and/or greater yield, is viewed as advantageous, since N taken up in the plant system is converted into organic forms and becomes less available for leaching loss.

Residual Soil Nitrate

Residual soil NO_3–N determined after harvest in the top 90 cm was basically at background levels in both years (Table 3). Treatments had no effect on residual NO_3–N in 1991 and had a slight effect in 1992. Residual

Table 2. Nitrogen accumulation in potato vines and tubers as influenced by N application timing for the 1991 and 1992 growing seasons.

		1991				1992			
		N content				N content			
Total N‡	N treatment	Vines	Tubers	Total	N recovery	Vines	Tubers	Total	N recovery
kg ha^{-1}					%	kg ha^{-1}			%
0	0	15.3	62.7	78.0	—	10.1	72.6	82.7	—
270	0 + 135 + 135§	65.6	119.3	184.9	39.6	25.3	206.0	231.3	55.0
270	45 + 112 + 112	51.2	126.0	177.2	36.7	22.1	202.7	224.8	52.6
270	90 + 90 + 90	35.7	126.7	162.4	31.3	27.9	219.3	247.2	60.9
270	135 + 67 + 67	32.4	112.9	145.3	24.9	26.1	207.5	233.6	55.9
Contrasts									
Control vs. fertilizer		**	**	**	—	**	**	**	—
Linear N response		**	NS	**	†	NS	NS	NS	NS
Quadratic N response		NS	NS	NS	**	NS	NS	NS	NS

†,*,** Significant at the 0.1, 0.05, and 0.01 probability levels, respectively.
‡ Value shown is total N applied ± 1 unit, due to rounding errors.
§ The three values show amounts applied at planting, emergence, and hilling, respectively.

Table 3. Residual soil NO_3–N (0–90 cm) and calculated soil water NO_3–N leached past the 140-cm depth in 1991 and 1992, as affected by timing of N fertilizer application.

Total†	N treatment	Residual soil NO_3–N (0–90 cm) 1991	Residual soil NO_3–N (0–90 cm) 1992	NO_3–N leaching (>140 cm) 1991	NO_3–N leaching (>140 cm) 1992
		kg ha^{-1}			
0	0	22	13	23	18
270	0 + 135 + 135‡	23	22	100	71
270	45 + 112 + 112	21	25	184	72
270	90 + 90 + 90	24	25	211	89
270	135 + 67 + 67	26	20	257	96
Contrasts					
Control vs. fertilizer		NS	**	**	*
Linear N response		NS	*	**	**
Quadratic N response		NS	**	NS	NS

*,** Significant at the 0.05 and 0.01 probability levels, respectively.
† Value shown is total N applied ± 1 unit, due to rounding errors.
‡ The three values show amounts applied at planting, emergence, and hilling, respectively.

NO_3–N in plots receiving N were higher than the control in 1992, and increased quadratically as the proportion of N applied at planting increased.

Nitrate Leaching

Under the various N management strategies of this study, NO_3 leaching for N fertilized plots ranged from 100 to 257 kg N ha^{-1} in 1991 and from 71 to 96 kg N ha^{-1} in 1992 (Table 3). For potato grown on sandy soils, Meisinger (1976) reported NO_3 leaching values between 100 and 200 kg N ha^{-1}. Saffigna et al. (1977) found NO_3 flux to range from 135 to 215 kg N ha^{-1}, and Hill (1986) reported values between 78 and 220 kg N ha^{-1}.

In 1991, a year characterized by heavy rain at early plant growth stages, NO_3–N leaching below 140 cm increased by 84, 111, and 157% over the zero starter N treatment as N applied at planting increased by 45, 90, and 135 kg ha^{-1}, respectively. However, in 1992, with fewer leaching events early in the season, NO_3–N leaching increased by only 1, 25, and 35% over the zero starter N treatment for the same respective N management treatments. Major NO_3 leaching in 1991 was primarily associated with heavy rain events, particularly between planting and emergence and at 72 DAP (Fig. 1). Irrigation at 45 and 48 DAP, followed by immediate rainfall, had the combined effect of leaching significant amounts of NO_3. Beyond 72 DAP, rainfall and/or irrigation did not cause major losses mainly because much of the N had already been taken up by the crop (Westermann et al., 1988) or had leached down. In contrast, during 1992, precipitation and irrigation were not a major factor in NO_3 leaching (Fig. 2). However, irrigation at 97 and 110 DAP coupled with subsequent rainfall contributed to relatively high NO_3 leaching losses. These results suggest that application of high amounts of N at planting will lead to significant NO_3–N leaching if heavy rain and/or excessive irrigation occur early in the season. Minimizing N application at planting and delaying the majority of N to the emergence and hilling stages during the year of high rainfall events significantly reduced the downward NO_3–N movement without reducing yield, even though the plots received the same total amount of N during the season.

Table 4. Nitrogen budget calculated by the mass balance method ($N_{OUT} = N_{IN}$) for the various N treatments during the 1991 and 1992 growing seasons.†

Total‡	N treatment	1991 N_{IN}	1991 N_{OUT}	1992 N_{IN}	1992 N_{OUT}
		kg ha^{-1}			
0	0	122	122	114	114
270	0 + 135 + 135§	392	307	384	321
270	45 + 112 + 112	392	382	384	323
270	90 + 90 + 90	392	398	384	361
270	135 + 67 + 67	392	428	384	350
Contrasts					
Control vs. fertilizer		—	*	—	**
Linear N response		—	**	—	**
Quadratic N response		—	NS	—	NS

*,** Significant at the 0.05 and 0.01 probability levels, respectively.
† $N_{IN} = N_{initial} + N_{fert} + N_{irrig} + N_{min}$ (or the sum of inorganic N initially present in the top 90 cm of soil, N input from fertilizer, N input from irrigation, and N input from net mineralization of soil organic matter). $N_{OUT} = N_{plant} + N_{leach} + N_{final}$ (or the sum of N uptake by vines and tubers, N loss by leaching, and inorganic N present after harvest in the top 90 cm of soil).
‡ Value shown is total N applied ± 1 unit, due to rounding errors.
§ The three values show amounts applied at planting, emergence, and hilling, respectively.

Nitrogen Budget

For each N treatment, total N input (N_{IN}) was compared with total N output (N_{OUT}) (Table 4). Because of the manner in which N_{min} was calculated (Eq. [3]), N_{IN} was always equal to N_{OUT} for the control. Estimated N_{IN} and N_{OUT} for the control was 122 and 114 kg N ha^{-1} in 1991 and 1992, respectively. For the N fertilizer treatments, N_{IN} was 392 kg N ha^{-1} in 1991 and 384 kg N ha^{-1} in 1992. N_{OUT} varied with N treatments, the differences being due primarily to differences in the amount of N leached and N recovered in vines and tubers. In 1991, N_{OUT} increased with an increase in the proportion of N applied at planting; estimated N_{OUT} was 6 and 36 kg N ha^{-1} higher than N_{IN} when 90 and 135 kg N ha^{-1} were applied at planting, respectively. This discrepancy might be due to an overestimation of leaching, particularly when a high proportion of N was applied at planting. A possible reason for overestimation of leaching at high starter N rates could be the band width. At planting, N was applied in a small band on either side of the tuber, whereas sidedress applications were in a wider band. Thus, a slight bias may have occurred with high starter N rates.

In 1992 and in the 0 and 45 kg N ha^{-1} rates in 1991, N_{IN} was numerically higher than N_{OUT}. Reasons for this difference could be associated with our earlier assumptions. Immobilization, denitrification, and volatilization (which we assumed to be negligible) may have occurred, enough to affect the balance. Saffigna et al. (1977) reported that, under Wisconsin growing conditions, the mass balance approach using large lysimeters (12 m^2) did not account for 95 kg N ha^{-1} in one treatment and overestimated N_{OUT} by 10 to 20 kg N ha^{-1} in two other treatments. They attributed the underestimation of N_{OUT} to denitrification when the automatic drainage system was not operational, but did not provide an explanation for excess N_{OUT}.

The heavy rainfall associated with high leaching in 1991 made this growing season unique and distinct from 1992. Thus, discussions on the possible errors causing discrepancies between N_{IN} and N_{OUT} are also different and specific for each growing season. In 1991, with excessive leaching occurring early in the season, overestimation of N_{OUT} may have been due to errors in overestimating actual N leaching when high proportions of N (90 and 135 kg N ha^{-1}) were band-applied at planting. This overestimation was not observed in 1992, since there was less leaching early in the season, leaving more time for N uptake by the plant.

CONCLUSIONS

Nitrogen management with reduced amounts of N applied at planting resulted in lower NO_3–N leaching, higher N recovery by the crop, and improved marketable tuber yield. During 1991, when heavy leaching occurred, NO_3–N fluxes below 140 cm for plots receiving N at planting were 83 to 158% higher than those when no N was applied at planting. In 1992, when fewer leaching events were observed early in the season, only 1 to 35% increase in NO_3–N leaching was found. The effects of minimizing N application at planting on NO_3–N leaching were more dramatic when leaching rainfall occurred early in the season. Potato growers may be able to improve the economic and environmental sustainability of their operations by reducing N application rates at planting and focusing on sidedressed applications.

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