Effects of nitrogen fertilization on potato yields and soil nitrate leaching

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Abstract
A 2-year field trial with a randomized complete block design with four replications was conducted in New Brunswick, Canada to evaluate N fertilization effects on potato (*Solanum tuberosum* L.) tuber yields and quality as well as soil nitrate leaching. Eight N fertilizer treatments were examined, including three N sources (i.e. conventional, controlled-release and organic fertilizers) at two application rates (100 and 200 kg N ha^{-1}), a split application of conventional fertilizer at the high rate and a zero N fertilizer input as control. Application of N-fertilizer significantly increased tuber yield (by 76% maximum) and quality over the unfertilized treatments whereas differences between the two N fertilizer application rates were non-significant. Fertilizer use efficiency varied from 16% to 56% over treatments and years. Low application rates resulted in lower seasonal soil and soil solution NO_3^- concentrations than high application rates. The controlled-release and organic form of fertilizer both reduced seasonal mean soil and soil solution N concentrations than conventional fertilizer, with low leaching potential.

Key words
Atlantic Canada; potato production system; fertilizer; productivity, leaching.

Introduction

N fertility management in potato production is a key component in potato production because of the fast response of potato (*Solanum tuberosum* L.). The low fertilizer use efficiency (Zebarth et al., 2004) and the low cost of fertilizer relative to the value of any additional yield produced by high rates of fertility lead growers to add lot of fertilizer which may not be fully used by the crop. Excess N fertilizer can negatively impact quality (e.g. specific gravity) of tuber while also resulting in N leaching, leading to economic waste and potential for negative environmental impacts.

Nitrogen management strategies have been proposed to reduce the risk of NO_3^- leaching in potato production, including split fertilizer N application and use of controlled-release fertilizer products or organic fertilizers (Hopkins et al., 2008). However, because of the complexity of the leaching process, there is no single and simple solution to the NO_3- leaching problem. For medium-textured soils in Atlantic Canada under rain-fed production, split application of N fertilizer resulted in loss of tuber yield and reduction of N use efficiency only under dry soil conditions (Zebarth et al., 2004) but the effect of split N application on NO_3^- leaching has not yet been examined. There are no studies on the effect of controlled-release fertilizer products on NO_3^- leaching in the region. Previous research has illustrated use of poultry manure in potato production but focussed primarily on its effects on tuber yield and quality, and improvement of soil properties (Rees et al., 2011) with NO_3^- leaching remaining unknown.

This study were to examine the effects of different fertilizer sources, application rates and methods on 1) tuber yield and quality, and 2) NO_3^- leaching losses under rain-fed potato production in Atlantic Canada.

Materials and methods

Study site, experimental design, and field operations

The study was conducted at the Agriculture and Agri-Food Canada Potato Research Centre located in Fredericton, New Brunswick from 2004 to 2006. Extremely wet soil conditions in the spring of 2006 resulted in crop failure and consequently only results from 2004 and 2005 are presented. Soils at the experimental site belong to the Fredericton soil association (coarse loamy fluvial material over coarse loamy morainal lodgement till) with 65-100 cm of relatively friable permeable material over dense, compact, and slowly permeable subsoil on a 2-3% slope. A potato - barley (*Hordeum vulgare* L.) rotation was used. The barley was not fertilized.

The experiment used a randomized complete block design with eight fertility treatments and four replicates on plots of 5.5 m by 5.5 m in size, 6 potato rows per plot. The outer rows of each plot served as guards. The fertility treatments were three N sources [conventional mineral fertilizer (Con; NH_4NO_3 (34-0-0)), organic fertilizer (Env), controlled-release fertilizer (CRF)] applied at two application rates (100 and 200 kg N ha^{-1}) plus one split treatment of conventional N with 50% applied at planting and 50% at final hilling (44 days since planting), and one and an unfertilized treatment served as a control. The CRF used was Environmentally Smart Nitrogen (ESN), a polymer-coated urea product (44-0-0), produced by Agrium Advanced Technologies, Calgary, AB. The organic fertilizer was produced by Envirem (Envirem Organics Inc., Fredericton, NB, Canada), and is made from steam-treated and granulated poultry manure with a fertilizer analysis of 4-1-2 at an application rate of 4000 kg ha^{-1} based on Dean et al. (2000).

The experiment fields were planted around June 3 in each year with band application of the conventional and CRF fertilizer treatments on each side (5 cm depth and 5 cm from row centre) of the potato row. The organic fertilizer was manually banded at planting. All treatments received 150 kg ha^{-1} of P_2O_5 and K_2O, banded at planting using the planter. Hand-cut Russet Burbank seed pieces weighing approximately 49 g were hand-planted at 0.91 m between row spacing and 0.41 m in-row spacing. Weed control and pest management followed standard methods for commercial rainfed potato production. On September 30, 2004 and October 3, 2005, four adjacent plants from the two rows in the middle of each plot were harvested, and the plant tissues were partitioned into tubers, vines, and stolons plus readily recoverable roots. Dry matter and N accumulation in each plant component were determined as described by Zebarth and Milburn (2003). After vine desiccation with diquat, the four central rows of each plot were harvested in early to mid October to determine tuber yield following the standards described in previous studies (Xing et al., 2012). Tuber specific gravity was determined using the Weight in air / Weight in water method (Zebarth et al., 2004).

Soil temperatures at 10-20 cm soil depth and the soil moisture over 30 cm depth were monitored with an hourly average for each variable computed and recorded. Air temperature and precipitation data were obtained from the Environment Canada climate station located approximately 700 m away from the experimental field.

Soil solution samples at 30 and 60 cm soil depths were collected weekly from each plot using a set of six (three at each depth, combined) custom-built suction lysimeters and analyzed for NO_3-N concentration with a Technicon Auto-Analyzer II (Pulse Instrumentation Ltd., Saskatoon, SK, Canada) using a hydrazine sulfate reduction technique based on EPA method 353.2 (USEPA 1983). Soil sampling was done in each plot at three times each year (pre-hilling, post-hilling, and before vine desiccation) and the concentrations of NO_3-N and NH_4-N in the soil samples were determined following Zebarth and Milburn (2003).

Statistical analysis
The one-way ANOVA and GLM function of SPSS 13 (SPSS Inc. Chicago, IL, USA) was used for determining effects of fertility treatments on variables such as tuber yields and quality indicators, soil NO_3-N and NH_4-N contents, and soil solution NO_3-N concentrations at 30 and 60 cm depths.

Results and discussions
Climatic conditions and soil physical properties during experiment periods
The mean air temperatures during the growing seasons (May to September) were very close to the long-term (1971-2000) normal of 15.6^{o}C. However, the total rainfall during the growing season was lower than the long-term average, indicating that both years were drier than the climate normal in this region. No differences in soil temperature and moisture were found among treatments.

Effects of fertilizer sources and application rates
Table 1 shows that fertilizer sources had no significant effect on tuber yield or quality parameters. The NO_3-N and NH_4-N concentrations in the soil with organic fertilizer (Env) were significantly lower than with conventional mineral fertilizer (Con) and the differences between CRF and Env were non-significant. There were no significant differences among fertilizer sources in soil solution NO_3-N concentrations at 60 cm

depth but soil solution NO_3-N concentration at 30 cm depth with Con was significantly greater than that with Env whereas that with CRF was intermediate. While the tuber yields (both total and marketable tuber yields) were significantly increased for both N fertilizer application rates over the unfertilized control, the differences between the two fertilizer application rates were not significant. There was a trend of increased tuber sizes with greater N fertilizer application rates. The proportion of small tubers decreased significantly with the increased N application. For other tuber quality measures (percentages of hollow heart tubers, culls and scab tubers), no significant effects of N fertilizer rate were observed. In contrast, for all measurements of N in soil and soil solution, significant differences were found among all three levels of application rates with only one exception (surface layer soil NH_4-N with the application rate of 100 kg N ha^{-1}). These results suggest that increasing the N fertilizer application rate from 100 to 200 kg N ha^{-1} had limited positive effects on potato yield and quality but could significantly increase the N concentrations of the soil and soil solution and therefore, potentially pose threats to the environment.

Table 1. The overall effects of N fertilizer formulation and N application rate on R. Burbank potato tuber yields and qualities

	Fertilizer sources			Application rate (kg N ha^{-1})		
	Con	CRF	Env	0	100	200
Total yield (t ha^{-1})	31.6a	30.3a	31.0a	23.8a	30.1b	31.9b
Marketable yield (t ha^{-1})	28.7a	27.6a	28.4a	21.9a	27.6b	28.9b
Small tubers (%)^x	11.7a	12.8a	10.7a	18.5c	12.8b	10.6a
Canada #1 tubers (%)^x	71.3a	72.4a	74.5a	73.2a	74.2a	71.3a
Large tubers (%)^x	17.1a	14.8a	14.8a	8.3a	13.0ab	18.1b
Hollow heart tubers (%)^x	4.2a	4.3a	5.0a	6.2a	4.2a	4.8a
Culls (%)†	9.0a	8.7a	8.1a	8.1a	8.0a	9.2a
Scabbed tubers (%)†	1.2a	0.7a	0.3a	0.6a	0.9a	0.6a
Tuber specific gravity (dimontionless ratio)	1.088a	1.090a	1.087a	1.093b	1.090ab	1.087a
Soil NO_3-N at 30 cm depth (mg kg^{-1})	44.7b	31.6a	22.0a	10.4a	25.4b	40.2c
Soil NH_4-N at 30 cm depth (mg kg^{-1})	12.0ab	14.1b	5.8a	3.0a	8.9ab	11.1b
Soil solution NO_3-N at 30 cm depth (mg L^{-1})	57.4b	49.5ab	43.7a	21.3a	42.9b	57.2c
Soil solution NO_3-N at 60 cm depth (mg L^{-1})	20.0a	18.1a	19.0a	11.4a	17.0b	21.0c

Plant N uptake and unused fertilizer

Nitrogen uptaken by plant in the unfertilized Ctrl treatment, being considered as a measure of soil N supply, was greater in 2004 (117 kg N ha^{-1}) than in 2005 (80 kg N ha^{-1}) (Table 2). Plant N uptake was significantly greater for all the high rate N-fertilized treatments than for the Ctrl treatment, but did not differ significantly among the N- fertilized treatments in 2004 in comparison with less responsive to the N-fertilized treatments in 2005. Fertilizer N utilization (% recovery of fertilizer) was higher in 2004 than in 2005 except for Env200. The highest fertilizer N utilization was 56%, which was found in the CRF100 treatment in 2004, and the lowest was 16%, found with Env100 in 2005.

Table 2. Plant (vine plus tuber) N uptake and unused nitrogen (kg N ha-1) for potato treated with different formulation and rate N fertilizer in 2004 and 2005

Treatment^z	2004 Plant uptake (PU)^y	Unused fertilizer^x	% recovery of fertilizer^w	2005 Plant uptake^y	Unused fertilizer^x	% recovery of fertilizer^w
Ctrl	117.3 a	0	na	80.5 a	0	na
Con100	171.3 ab	46	54	99.1 abc	81.5	18.6
Env100	169.4 ab	47.9	52.1	96.0 ab	84.5	15.5
CRF100	173.0 ab	44.3	55.7	115.1 abc	65.4	34.6
Con200	216.3 b	101	49.5	150.0 bc	130.5	34.8
Env200	190.0 b	127.3	36.4	161.0 c	119.5	40.3
CRF200	188.0 b	129.3	35.4	144.9 bc	135.6	32.2
Split	210.6 b	106.7	46.7	135.4 abc	145.1	27.5
Treatment ef	****			***		

^{z} treatments are defined in details in Table 1; ^{y} means in the same column followed by the same letter are not significantly different ($P > 0.05$); ^{x} Unused fertilizer = PUctrl+FR-PUtrt, Where PUtrt is the plant uptake for treatment, PUctrl is the plant uptake for control treatment and FR is fertilizer ratex Unused fertilizer = PUctrl+FR-PUtrt, Where PUtrt is the plant uptake for treatment, PUctrl is the plant uptake for control treatment and FR is fertilizer rate; ^{w} % recovery of fertilizer =(PUtrt-PUctrl)/FR*100; ^{u} ns, not significant; *, significant at P = 0.1; **, significant at P = 0.05; ***, significant at P = 0.01;, ****, significant at P = 0.001

Soil N concentrations in the surface layer

An overall statistical analysis based on two year data indicates that soil NO_3-N concentration in the surface layer (0-30cm) varied significantly with the N fertilizer treatment ($P \leq 0.001$), sampling time ($P = 0.004$, not included in this paper) and their interactions ($P < 0.001$, not included in this paper). Soil NO_3-N concentrations in the surface layer were significantly greater prior to hilling than at post-hilling or at vine desiccation for all N-fertilized treatments in both years (Table 3). The difference in surface layer soil NO_3-N concentrations between N fertility treatments were more pronounced early in the season than late. Similar patterns but less pronounced responses were found in 2005 than in 2004.

NO_3-N concentration in the soil solution

Soil solution NO_3-N concentrations at 30 cm depth were significantly affected by N fertility treatments in both years (Table 4). In 2004, soil solution NO_3-N concentrations were significantly lower for the Ctrl treatment than for all other treatments except for Env100 and Env200 treatments. The average soil solution NO_3-N concentration for the Con 200 treatment was significantly greater than for all other treatments except for Split. The Split treatment did not show any significant difference in soil solution NO_3-N from other high N fertilizer application rate treatments (Con200, Env200 and CRF200). In 2005, soil solution NO_3-N concentrations at 30 cm depth were generally lower than in

Table 3. Mean soil NO_3-N concentrations measured at different points in the 2004 and 2005 growing seasons in potato fields treated with different rates and formulations of N fertilizer

Treatment	2004			2005		
	Pre-hilling	Post-hilling	Vine desiccation	Pre-hilling	Post-hilling	Vine desiccation
Ctrl	27.1 a	3.4 a	4.9 a	20.0 a	3.8 a	3.1 a
Con100	71.2 ab	12.5 ab	11.8 ab	64.8 b	17.1a	7.9 ab
Env100	54.6 a	6.1 a	9.6 ab	27.2 ab	4.3 a	4.2 a
CRF100	58.8 a	9.8 a	15.7 abc	54.9 ab	15.8 a	10.6 ab
Con200	116.2 b	40.0 b	25.7 cd	111.6 c	34.6 bc	23.4 c
Env200	64.2 ab	17.6 ab	16.6 bc	32.5 ab	18.7 ab	8.7 ab
CRF200	50.2 a	20.5 ab	34 d	46.0 ab	43.7 c	18.7 bc
Split	65.1 ab	28.9 ab	23.1 cd	60.3 ab	45.8 c	18.6 bc
Treatment effect	***	***	****	****	****	****

2004, and were also significantly affected by the N-fertilizer application rate and fertilizer source. Soil solution NO_3-N concentrations were the greatest for the Con200 and the lowest for control among treatments. Again, all fertility treatments had a systematically higher soil solution NO_3-N concentration than Ctrl by at least 73% in 2004 and 65% in 2005.

Crop response to N fertilizer application rates, methods and sources

Increasing the N fertilizer application rate from 0 to 200 kg N ha^{-1} generally resulted in numerically increased total and marketable tuber yields, increased percentage of large tubers, decreased percentage of small tubers, and reduced tuber specific gravity in both years. In most cases, crop responses were not significantly different between the 100 and 200 kg N ha^{-1} N fertilizer application rates. This suggests that the crop response to fertilizer decreased progressively with the higher N fertilizer application rates. Soil N supply (i.e., the plant N accumulation for the zero fertilizer N rate) was 117 and 80 kg N ha^{-1} in 2004 and 2005, respectively, which were higher than commonly measured values following a preceding cereal crop for soils in this region (Zebarth et al., 2004). Use of slow release source of N (CRF) had no beneficial or detrimental effect compared with the conventional fertilizer with respect to tuber yield or quality parameter. The lack of benefit from using CRF in current study may again reflect the limited risk of NO_3^- leaching during the short growing season in this region (Milburn et al., 1990), especially in relatively dry years while the higher soil N residual could be an additional reason. The steam-treated and granulated poultry manure (Dean et al., 2000) in this study resulted in plant N accumulation levels that were not significantly different from those for the Con treatements. This suggests that 50% was a reasonable estimate of the N availability from the organic N source.

Table 4. Soil solution NO3-N concentrations (mg L^{-1}), means over the growing season measured at two soil depths in a potato field treated with different N fertilizer rates and formulations in 2004 and 2005.

Treatment	30 cm depth		60 cm depth	
	2004	2005	2004	2005
Ctrl	29.1 a	10.1 a	15.0 a	6.7
Con100	53.8 bc	30.0 bcd	20.3 ab	11.2
Env100	50.3 ab	16.7 ab	28.3 bcd	10.5
CRF100	61.6 bc	24.6 abc	22.1 abc	10.7
Con200	89.7 d	40.4 d	34.3 d	11.7
Env200	74.2 abc	16.7 ab	25.2 abcd	10.5
CRF200	75.7 bc	17.9 ab	26.9 abcd	9.1
Split	75.5 cd	39.2 cd	32.6 cd	9.8
Treatment effect	****	****	****	ns

Fertilizer effects on NO_3-N concentration in the surface layer soil and the soil solution

Fertilizer application rates have varying effects on the soil solution NO_3-N leaching potential, dependent upon the fertilizer source and year. The high N application rate treatments resulted in greater soil solution NO_3-N concentration by at least 23% than their corresponding low rate treatments at 30 cm soil depths in 2004. However, in 2005, this type of trend was only observed in Con source treatment while both CRF and Env types showed either reduced or equal soil solution NO_3-N concentrations for high fertilizer application rate than for low fertilizer application rate. This complexity may be related to the interactions among fertilizer source, soil characteristic and weather conditions. In particular, the release of N from CRF and Env is highly related to soil temperature and the soil water condition (Hopkins et al., 2008). Apparently, when the treatment effect is relatively marginal, the variation resulted from different weather conditions among the two test years may have canceled out the effects of the CRF and Env type treatments. The application of fertilizer added beyond 100 kg N ha^{-1} may only increase the risk of the NO_3^- leaching potential of the Con type treatment. Considering a NO_3^- leaching rate of 5-33 kg N ha^{-1} reported by Milburn et al. (1990) in the same potato field treated with fertilizer rates of 120-150 kg N ha^{-1}, this study suggest that the optimal N fertilizer application rate is probably between 100 and 150 kg N ha^{-1} assuming the soil has good N supply capability.

Conclusions

In high value crop like potatoes, the end result of excessive application of N is no yield gain, but a potential reduction in processing quality, increased costs and potential damage to the environment in the form of leaching potential. This study suggests increasing from 100 kg N $ha^{-1}$to a full rate of conventional fertilization application (200 kg N ha^{-1}) did not significantly increase tuber yield or improve tuber quality but had significant effects on N concentrations in soil and soil solutions sometimes, increasing their potential for N leaching. Controlled-release and organic fertilizer formulation both resulted in lower soil and soil solution N concentrations than conventional fertilizer, therefore are potentially better for environments. An N application rate between 100 – 150 kg ha^{-1} was proposed for the site which already had high amount of soil N supply.

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