Nutr Cycl Agroecosyst (2016) 104:175–185
DOI 10.1007/s10705-016-9765-2

ORIGINAL ARTICLE

Fertilizer nitrogen uptake efficiencies for potato as influenced by application timing

Libby Rens · Lincoln Zotarelli · Ashok Alva · Diane Rowland · Guodong Liu · Kelly Morgan

Received: 12 October 2015 / Accepted: 9 February 2016 / Published online: 13 February 2016

Abstract Estimation of N uptake efficiency of fertilizer applications at different growth stages of crop plants is critical to develop management recommendations that enhance fertilizer use by minimizing N losses. In this study, the N-fertilizer uptake efficiency (FNUE) of two chipping potato (*Solanum tuberosum* L.) varieties ('Atlantic' and 'FL1867') under three typical fertilizer application timings was investigated. All treatments received a total of 225 kg ha^{-1} of N throughout the season, split into three applications of 75 kg ha^{-1} as ammonium nitrate (NH_4NO_3) applied at pre-plant, plant emergence and tuber initiation. FNUE at each application timing was evaluated by the substitution of conventional N-fertilizer by isotope labeled ammonium nitrate ($^{15}NH_4^{15}NO_3$). Total tuber yield was similar between the two varieties at 48.8 and 37.5 Mg ha^{-1} in 2013 and 2014, respectively. Likewise, the overall FNUE was also similar at 45 % across both varieties and years. FNUE was 11 % for the pre-plant application, while 62 % for the applications at emergence and tuber initiation stages. Since a small fraction of the N applied at pre-plant was recovered in the plant, N fertilizer application closer to the potato planting may increase the FNUE.

Keywords ^{15}N · Isotopes · *Solanum tuberosum* · Seepage irrigation · Florida

L. Rens · L. Zotarelli (✉) · G. Liu
Horticultural Science Department, University of Florida, 1241 Fifield Hall, Gainesville, FL 32611, USA
e-mail: lzota@ufl.edu

A. Alva
U.S. Department of Agriculture-Agricultural Research Service, Sidney, MO, USA

D. Rowland
Agronomy Department, University of Florida, Gainesville, FL, USA

K. Morgan
Soil and Water Sciences Department, University of Florida, Immokalee, FL, USA

Introduction

Deciding on a fertilizer program depends on using the right rate, source, placement and timing of application, all of which are influenced by the characteristics of the crop nutrient uptake and environment (IFA 2009). Knowing the N fertilizer recovery at each application timing would aid in the decision support for timing of N applications. This study is focused on evaluation of N uptake efficiency across different fertilizer application timings for potatoes grown under seepage irrigation.

Both environmental and crop characteristics lead to the low nitrogen uptake efficiency (NUpE) of potato (*Solanum tuberosum*). Potato has a limited effective rootzone, further restricted by seepage irrigation

(Munoz-Arboleda and Hutchinson 2006) and short growing seasons (Dunbabin et al. 2002; Lesczynski and Tanner 1976). Additionally, potato is mostly grown in well-drained coarse textured soils which further facilitate the potential for loss of N though leaching and runoff (Errebhi et al. 1998). Under seepage irrigation (a form of subirrigation), a consistent flow of water is distributed across the field through furrows spaced 18 m apart. Water seeping out of these furrows saturates the soil profile above an impermeable soil layer so that it creates an upward movement of water from an artificially maintained water table (Dukes et al. 2010). The furrows also drain the field after rainfall. As the water table is raised, N fertilizer in the effective rootzone is solubilized and available to the plants (Stanley and Toor 2010). When the water table is lowered, the soluble fertilizer can leach from the root zone and move laterally by subsurface flow, eventually to be transported off-site through the furrows and connected drainage ditches (Shukla et al. 2010).

Multiple applications of N fertilizer throughout the season is a best management practice (BMP) designed to increase the potential for plant N uptake and assimilation while reducing the risk of leaching and runoff of N associated with large rain events. Potato growers in Florida generally practice three applications of N fertilizer throughout the season (Asci et al. 2012), with a first application at 30–40 days before planting ($N_{pre\text{-}pl}$) that accounts for up to 60 % of the total N fertilizer. Available soil N resulting from the $N_{pre\text{-}pl}$ application is often low or not available in the 0–20 cm soil depth layer by the time of plant emergence (Zotarelli et al. 2014, 2015), presumably due to loss from leaching and runoff during rain events. However, this N application has resulted in an increase in tuber yield of the chipping potato variety 'FL1867' (Rens et al. 2016). The second N fertilizer application is at plant emergence, and ranges from 0 to 70 % of the total N (N_{emerg}). Potato plant growth and tuber yield and quality have been most responsive to N application rates at this timing. Excessive N at this growth stage has led to increased vegetation at the expense of tuber growth and production (Alva 2004; Lauer 1985, 1986). The final application of N occurs at tuber initiation ($N_{tuber\ init}$), with 0–50 % of total N, which is the final chance to apply fertilizer without significant plant damage to aboveground tissues due to the expanding plant canopy. Supplementing the crop with N fertilizer at the tuber initiation stage may be considered as insurance against losing prior N applications to leaching and runoff during large rain events. The majority of plant N uptake occurs after tuber initiation (Zotarelli et al. 2014; Lauer 1985), however increasing N fertilizer application from 56 to 112 kg ha^{-1} at this growth stage did not increase yield (Rens et al. 2015a, b), and applying over 50 % of N at tuber initiation decreased the yield (Rens et al. 2016). A farmer's decision to supply N at the above application timings is based on historical methods, crop need, and accessibility to the field by application machinery. Information about the FNUE at each application timing would assist in the decision process for timing and rate of N-fertilizer application.

Calculating FNUE can be done by indirectly by calculating the difference between the amounts of N recovered by the fertilized crop as compared to an unfertilized control. The drawback of this method is that it assumes soil processes and nutrient transformations are identical between treatments (IAEA 2001). Additionally, this method evaluates the total N application of the season and does not allow a comparison between the timings of split N applications. An alternative method to calculating FNUE is by the use of stable ^{15}N isotope. Fertilizer labeled with a specific ratio of ^{15}N:^{14}N is supplied to the plant and can be traced throughout the season in crop tissues, soil, and weeds. Using ^{15}N isotope enriched fertilizer is an accurate method to determine the amount of N fertilizer taken up by the plant (IAEA 1983, 2001) and has successfully been used to analyze potato N uptake (Jiao et al. 2013; Halitligil et al. 2002; Janat 2007).

The objective of this study was to determine the N-fertilizer uptake efficiency of potato for three different fertilizer application timings, as described above, typically practiced by commercial growers in Florida. The hypothesis is that higher FNUE will be associated with N fertilizer applications closest to times of plant N accumulation at emergence and tuber initiation.

Materials and methods

The experimental field was one 16-row potato bed, 18 m by 90 m at the Hastings Agricultural Extension Center located in Hastings, FL, USA (29.690531 N, −81.441505 W). The soil at the experimental field has been classified as hyperthermic Grossarenic Ochraqualf belong to the Holopaw fine sandy series (USDA 1981). The parent material consists of sandy and loamy marine deposits. The natural drainage class is poorly drained and the field slope is <2 % (USDA 1981). The soil particle size was 916 g kg^{-1} of sand, 37 g kg^{-1} of clay and 47 g kg^{-1} of silt. Soil organic matter average was 16 g kg^{-1}. During the summer and fall, between annual potato crops, a sorghum sudangrass (*Sorghum sudanense Staph*) cover crop was grown in each season, which was cut and incorporated into the soil in mid-November. Field fumigation with 1, 3-dichloropropene (63.3 %) + 149 chloropicrin (34.7 %) (Telone® C-35; Dow AgroScience; Indianapolis, IN, USA) at a rate of 103 L ha^{-1} occurred on 8 and 16 January (30 and 26 days before planting) in 2013 and 2014, respectively. Rainfall and air temperature were measured on-farm by the Florida Automated Weather Network (FAWN) at the University of Florida. Accumulated growing degree-days (*GDD*) were calculated using the formula:

$$GDD = \frac{Tmax + Tmin}{2} - Tbase$$

where *Tmax* is the daily maximum temperature, *Tmin* is the daily minimum temperature, and *Tbase* is the reference temperature with a value of 7 °C (Sands et al. 1979). The spacing between potato rows was 1.01 m. Each 8-row experimental plot was 55 m^2 and flanked by an irrigation furrow on one side. Potato seed pieces were planted on 7 February and 11 February in 2013 and 2014, respectively. Seepage irrigation began at the time of plant emergence.

Experimental design

Treatments were combined in a complete factorial design with two potato varieties ('Atlantic' and 'FL1867') and three fertilizer timings. All fertilizer timing treatments received a total of 225 kg ha^{-1} of N split into three applications of 75 kg ha^{-1} at each growth stages, i.e. pre-plant, emergence and tuber initiation. The FNUE of each application timing was evaluated by the substitution of conventional N-fertilizer by enriched ^{15}N ammonium nitrate ($^{15}NH_4^{15}NO_3$) in sub-plots (Table 1). Sub-plots receiving enriched N fertilizer consisted of three adjacent potato rows, 1.4 m long, each with seven plants. Treatments were replicated four times within a randomized complete block design. Unlabeled fertilizer was used between sub-plots, with a minimum distance of 4 m.

Yield, plant biomass accumulation and N uptake

Aboveground plant samples were collected six times throughout the season from plots with unlabeled N fertilizer. At each sample date, two representative potato plants were collected from each plot, and the aboveground plant parts and tubers were separated. Tubers were mechanically harvested using a 1-row digger following crop senescence and occurred on 3 June, 111 days after planting (DAP) and 22 May, 100 DAP in 2013 and 2014, respectively, and involved harvesting 9 m of row length within each plot, and collecting, washing, and weighing all tubers.

Tuber and tissue samples were subsequently oven dried at 65 °C to a constant weight and ground using a tissue grinder (Laboratory Mill Model 4, Arthur Thomas Company, Philadelphia, PA, USA). Tissue samples were digested using the aluminum block digestion procedure (Gallaher et al. 1975). Nitrogen was quantified by the Kjeldahl method using U.S. EPA method 351.2 (O'Dell 1993c). Total N uptake was calculated as the product of the total biomass and N concentration at each crop growth stage. Nitrogen Harvest Index (NHI) was calculated as:

$$NHI = \frac{\text{kg ha}^{-1} \textit{ of } \text{N} \textit{ in tubers}}{\text{kg ha}^{-1} \textit{ of } \text{N} \textit{ in whole plant}}$$

Soil nitrogen sampling and analysis

Soil nitrate and ammonium concentrations were measured in the 0–20 cm soil depth zone throughout each growing season from plots with unlabeled N fertilizer. At each sampling date, a minimum of eight sub-samples were taken from the center rows of each plot. These samples were combined as a composite soil sample. Samples were air-dried, sieved and tested for NO_3–N according to EPA Method 353.2 (O'Dell 1993b) and NH_4–N (O'Dell 1993a) according to EPA Method 350.1 at the University of Florida's Analytical Research Laboratory (ARL), Gainesville, FL, USA.

Soil samples were collected six times throughout the season: just before the pre-plant N-fertilization at fumigation, at planting, at plant emergence just before the N_{emerg} fertilization, during the vegetative growth

Table 1 Nitrogen fertilizer rates at pre-plant ($N_{pre\text{-}pl.}$), plant emergence ($N_{emerg.}$) and tuber initiation timings ($N_{tuber\ init}$) and total N fertilizer applied in the 2013 and 2014 potato seasons in northeastern Florida

N treatment	$N^{a}_{pre\text{-}pl}$ (kg ha^{-1})	N_{emerg} (kg ha^{-1})	$N_{tuber\ init}$ (kg ha^{-1})	Total N (kg ha^{-1})
1	75[b]	75	75	225
2	75	75[b]	75	225
3	75	75	75[b]	225

[a] Source of N was granular ammonium nitrate (34 % N)

[b] Application of ^{15}N enriched fertilizer to sub-plots

stage just before the $N_{tuber\ init}$ fertilization, at tuber bulking, and at harvest.

FNUE evaluation

The FNUE was evaluated at two times in each season, at max tuber bulking at 89 and 86 days after planting (DAP) in 2013 and 2014, respectively and at final harvest at 111 and 97 DAP in 2013 and 2014, respectively. The center row of each sub-plot was harvested for FNUE evaluation, as suggested by Olson (1980). At maximum tuber bulking, two plants were harvested, and divided into plant parts consisting of aboveground vegetative growth (leaves and stems), roots, and tubers. At harvest, a 0.4 m section of the ^{15}N labeled potato row was selected for ^{15}N recovery sampling. Two potato plants and weeds were collected from each 0.4 m section of row. Potato plants were divided into aboveground biomass, roots, and tubers. A volume of soil (0.4 m × 1.01 m × 0.30 m depth) was collected from the same section where the plants were harvested. Fresh soil was weighed and subsampled for subsequent mineral N and ^{15}N analysis. Soil samples were air dried, and potato plant tissues and weeds were oven dried at 65 °C to a constant weight and ground using a tissue grinder (Laboratory Mill Model 4, Arthur Thomas Company, Philadelphia, PA, USA).

^{15}N analysis

Tissue and soil samples were ball milled to a fine powder and submitted to the soil and Water Science Biogeochemistry Core Laboratory (University of Florida, Gainesville, FL, USA) for ^{15}N analysis. The amount of nitrogen in the plant derived from fertilizer (Ndff), measured as kg ha^{-1} of N, at each application time, presented by IAEA (1983), was calculated as:

$$Ndff = \frac{\%\,15\,\mathrm{N}\,atom\,excess\,of\,the\,plant\,sample}{\%\,15\,\mathrm{N}\,atom\,excess\,of\,the\,fertilizer\,applied} \times plant\,\mathrm{N}\,uptake\,(\mathrm{kg\,ha^{-1}})$$

where atom excess is the measured percent above natural abundance of 0.3663 % ^{15}N, and the ^{15}N atom excess of the fertilizer was 0.7537 % (Promy Chemical, Inc., El Sobrante, CA, USA).

The percent N fertilizer uptake efficiency (FNUE) of N at each application time, presented by IAEA (1983), was calculated as:

$$FNUE = \frac{Ndff}{applied\,\mathrm{N}\,rate(\mathrm{kg\,ha^{-1}})} \times 100$$

where the applied N rate at each period was 75 kg ha^{-1}. Plant N derived from soil (Ndfs) was calculated as:

$$Ndfs = Total\,plant\,\mathrm{N}\,accumulation - Ndff$$

Unaccounted for N fertilizer was calculated as:

$$Unaccounted\,\mathrm{N}\,fertilizer = \mathrm{N}\,fertilizer\,applied - Ndff - Ndfs$$

where Ndff includes plant N from the potato crop and weeds.

Statistical analysis

Analysis of variance (ANOVA) for each measured variable was conducted by the PROC GLM procedure within the Statistical Analyses System (SAS 2008). A combined ANOVA including main effects of year, variety and ^{15}N fertilizer timing were performed. When the combined ANOVA resulted in significant first and second interactions the analysis was performed ‘by year.’ When the interaction between variety and ^{15}N-timing was not significant only the main effects were presented. Multiple means comparisons were performed using Tukey–Kramer at a p value of 0.05 when the F value was significant.

Results and discussion

Soil nitrogen and rainfall

The pool of plant available mineral N (NO_3–N and NH_4–N) in the soil was quantified throughout each season (Fig. 1). At the time of field fumigation, before N fertilizer was applied, soil mineral N concentration was 14 and 2 mg kg^{-1} (mg of N per kg of soil) in 2013 and 2014, respectively. The beginning of the 2013 season was abnormally dry, accumulating 20 mm of rainfall in the 52 days between $N_{pre\text{-}pl}$ and plant emergence (Figs. 1, 2), whereas the 35-year average rainfall for this period is 161 mm (NOAA 2014). There was no difference in soil N between potato varieties. After the first application of 75 kg ha^{-1} of N at fumigation, soil N increased to 183 mg kg^{-1} at planting in 2013, and settled at 131 mg kg^{-1} of N by the time of plant emergence. In contrast, the beginning of the 2014 season had higher rainfall, yet more typical for this region, than 2013, with 156 mm of rain between $N_{pre\text{-}pl}$ application and plant emergence. Soil N was lower during this period in 2014, presumably due to a greater level of N loss through leaching and runoff as a result of the higher rainfall. At planting, soil N increased to 58 mg kg^{-1}, but then reduced to 8 mg kg^{-1} by the time of plant emergence, similar to the unfertilized soil N at field fumigation (Fig. 1). The low soil N concentration at plant emergence in 2014 was not surprising, as the time between $N_{pre\text{-}pl}$ application and plant emergence was long (50–60 days), paired with rainfall at or below the average, 161 mm, often leading to leaching and runoff during this period (Zotarelli et al. 2014). Even without examining plant N fertilizer uptake, the low soil N at emergence from $N_{pre\text{-}pl}$ suggests there may be

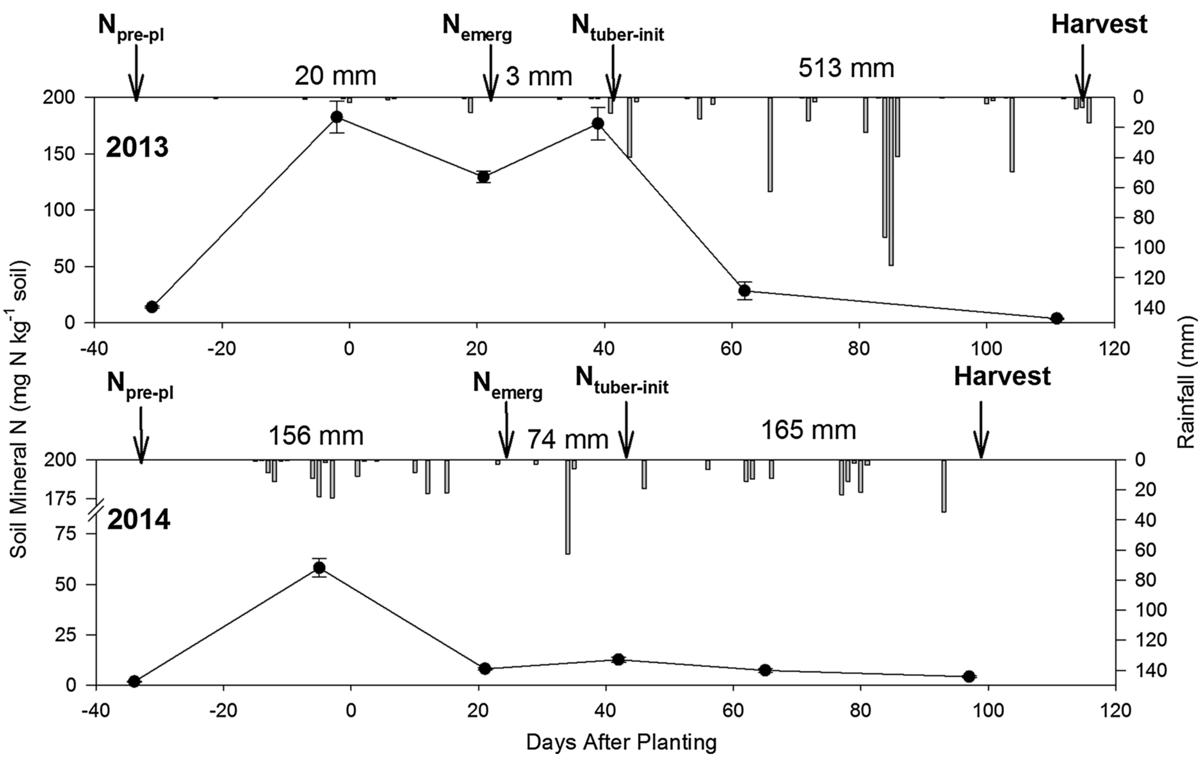

Fig. 1 Rainfall and soil mineral N concentration (mg of NO_3–N + NH_4–N kg^{-1} of soil) at 0–20 cm soil depth in Hastings, FL in 2013 and 2014 (note a break on Y-axis in 2014). N-fertilizer was applied at pre-plant ($N_{pre\text{-}pl}$), potato emergence ($N_{emerg.}$) and at tuber initiation ($N_{tuber\ init.}$), each at a rate of 75 kg ha^{-1}. Zero in the X-axis means the planting date. The *arrows on the top of graphs* indicate N fertilizer application. *Numbers on top of the graphs* indicate cumulative rainfall in mm between N fertilizer applications and harvest

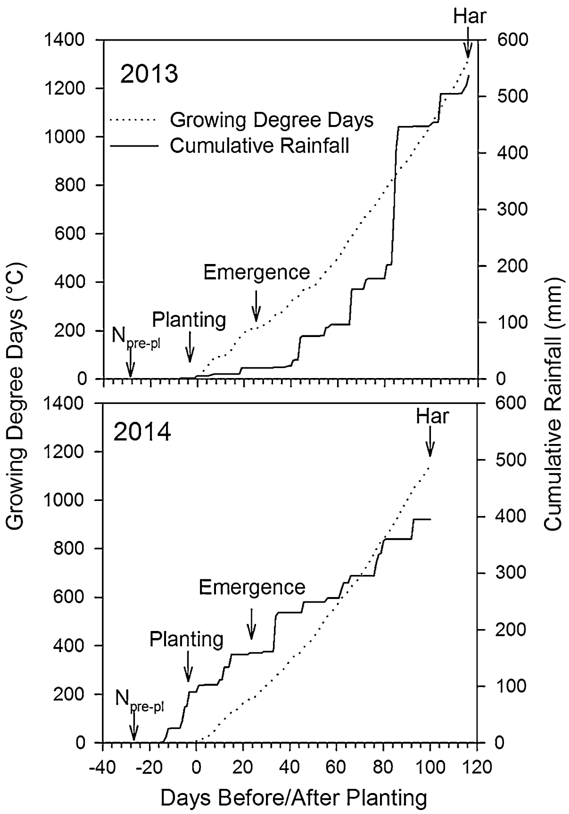

Fig. 2 Growing degree days (°C) and cumulative rainfall (mm) in the 2013 and 2014 potato seasons. *Arrows* indicate $N_{pre\text{-}pl}$ application, potato planting, emergence, and harvest

opportunities to improve N fertilizer management to increase the probability of plant uptake.

The second application of 75 kg ha^{-1} of N occurred at plant emergence, 26 and 21 DAP in 2013 and 2014, coinciding with the initiation of seepage irrigation involving the rise of the water table. In 2013, this application increased mineral soil N to 177 mg kg^{-1} at the time of tuber initiation. In 2014, however, there was 74 mm of rainfall between the application of N_{emerg} and tuber initiation, therefore soil N remained low, at 13 mg kg^{-1}. The third and final application of 75 kg ha^{-1} of N occurred at tuber initiation. Rainfall in the remainder of the 2013 season, from tuber initiation to harvest, was very high at 513 mm. During tuber bulking, a large rainfall event accumulated 244 mm within 3 days starting at 84 DAP. There was less rainfall during this period in the 2014 season, with 165 mm of rainfall distributed more evenly throughout the same period. In each year, the total quantity of N in the soil at harvest, including TKN (Total Kjeldahl Nitrogen), averaged 34.0 and 32.3 kg ha^{-1} in 2013 and 2014, respectively.

The water table was managed at around 60 cm from the top of the potato row. Commercial growers make every attempt to predict rainfall events and prepare the field by draining water to lower the water table to increase the soil's potential rainfall storage (Hendricks and Shukla 2011), however small rainfall events can lead to leaching when paired with high water table levels of seepage irrigation (Shukla et al. 2010). Even rainfall events on the order of 8–11 mm have been reported to increase the water table by 24 cm (Jaber and Shukla 2006). Soluble N will move downward with the water flow from rainfall, and once it reaches the water table the N becomes diluted. The further lowering of the water table in preparation for rain events, carries N deeper from the rootzone. The historical, 35-year average rainfall for the dates of $N_{pre\text{-}pl}$ application to harvest used in this study was 376 mm (NOAA 2014). Rainfall in 2014 was more characteristic of the average conditions for the region at 395 mm, as compared to 536 mm of rainfall in 2013. The more even distribution of seasonal rainfall in 2014 resulting in low mineral soil N provides a good example of why splitting N applications throughout the season would be a beneficial practice for the sandy soils of Florida.

Biomass, N accumulation and yield

Plants emerged in March at 26 and 21 DAP in 2013 and 2014, respectively, and gradually accumulated N in aboveground tissues until tuber initiation (Fig. 3). This establishment period was followed by a rapid increase in aboveground N accumulation, reaching a peak at the tuber bulking stage at around 60–70 DAP. Aboveground N accumulation was similar between varieties at all measured dates except in 2013 at 89 DAP when N accumulation for 'Atlantic' was reduced more than expected and was 16 kg ha^{-1} lower than for 'FL1867' ($p < 0.01$). Aboveground N accumulation was then similar between varieties by the time of harvest. While N content of aboveground tissues was reduced after about 60 DAP, the aboveground biomass accumulation (data not presented) reached a plateau and maintained 2.1 and 1.9 Mg ha^{-1} in 2013 and 2014, respectively. The reduction in aboveground N between 60 DAP and harvest was therefore due to the

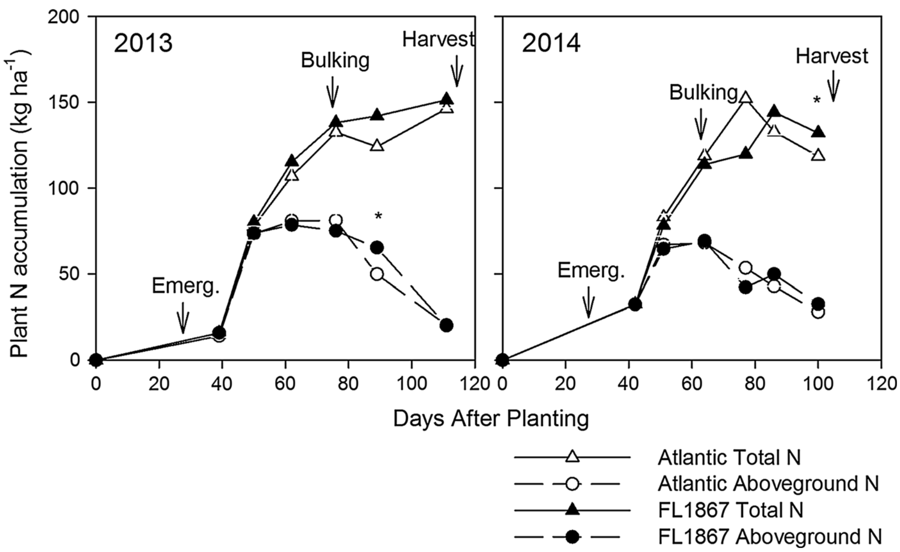

Fig. 3 Seasonal total and aboveground nitrogen accumulation for the potato crop. *Asterisk* indicates significant difference between varieties at $p < 0.05$. *Arrows* indicate crop growth stages of emergence, tuber bulking and harvest

concentration of N in the tissues, as opposed to a reduction in biomass resulting from plant senescence.

N accumulation in tubers was similar between varieties in both years and remained below 35 kg ha^{-1} until 50 DAP, at which point tuber N content increased quickly while aboveground N content decreased for the remainder of the season (Fig. 3). Tuber N accumulation continued to increase exponentially until harvest in 2013; however in 2014, tuber growth slowed at around 80 DAP, about 20 days before harvest. Differences in growth between years may be due to the difference in average daily temperature. Accumulated GDD was 1318 and 1145 °C in 2013 and 2014, respectively (Fig. 2). Nitrogen harvest index (NHI) was similar between years and varieties, averaging 0.82 (Table 2).

Likely due to that fact that the same amount of N was applied to all treatments, total yield was similar between varieties and averaged 48.7 and 37.5 Mg ha^{-1} in 2013 and 2014, respectively (Table 2). After the removal of the small tubers (<4.8 cm), and tubers with external defects, marketable yield was similar between varieties and averaged 36.6 and 30.9 Mg ha^{-1} in 2013 and 2014, respectively (Table 2). Marketable yield for this trial was slightly higher than the commercial average reported for this region of 28 Mg ha^{-1} (USDA-NASS 2014), but similar to trials performed under similar conditions in commercial fields (Rens et al. 2015a, b; Worthington et al. 2007; Worthington and Hutchinson 2006). The difference between total and marketable yield in the 2013 season was primarily due to the large rain event at 84–86 DAP leading to a loss of 7.7 Mg ha^{-1} to decay.

Specific gravity of tubers was similar between varieties in 2013, averaging 1.079. In 2014, variety 'FL1867' had higher specific gravity, which is one benefit of this more recently developed variety as compared to 'Atlantic' (Cipar 2004). Gravity of potatoes typically ranges from 1.068 to 1.085 under the conditions of NE Florida (Rens et al. 2015a, b; Worthington et al. 2007).

Plant N allocation

Ndff of the potato plant at the time of maximum tuber bulking (89 and 86 DAP in 2013 and 2014, respectively) was 92 kg ha^{-1} of the 225 kg ha^{-1} of N applied, and was similar between years. By the time of final harvest (111 and 97 DAP for 2013 and 2014, respectively), Ndff was 101 kg ha^{-1}, which represented an overall FNUE of 45 % considering all three applications (Table 3). After considering the total plant N accumulation (Table 2), the average plant N derived from soil (Ndfs) was 49 and 28 kg ha^{-1} in 2013 and 2014, respectively. The soil mineralization

Table 2 Tuber yield, specific gravity, plant N, tuber N, and nitrogen harvest index (NHI) of two potato cultivars in the 2013 and 2014 growing seasons

	Total yield (Mg ha^{-1})	Marketable yield (Mg ha^{-1})	Specific gravity	Total plant N (kg ha^{-1})		Tuber N (kg ha^{-1})		NHI
				Bulking stage	Harvest	Bulking Stage	Harvest	
2013								
Atlantic	49.2	36.5	1.078	117 b†	146	67	117	0.80
FL1867	48.3	36.8	1.080	142 a	151	77	124	0.82
p value	*ns*	*ns*	*ns*	*	*ns*	*ns*	*ns*	*ns*
2014								
Atlantic	36.9	30.0	1.078 b	133	119 b	90	99	0.83
FL1867	38.1	31.9	1.086 a	153	132 a	103	19	0.83
p value	*ns*	*ns*	**	*ns*	*	*ns*	*ns*	*ns*

All plots received 75 kg ha^{-1} of N at pre-plant, emergence and tuber initiation for a total of 225 kg ha^{-1} of N

* Significant at $p < 0.05$; ** significant at $p < 0.01$; *** significant at $p < 0.0001$ or "ns", not significant

† Values followed by the same letter indicate not significantly different according to LS-means test within the same year, by column

Table 3 Effect of N-fertilizer timing on N fertilizer use efficiency (FNUE), measured at tuber bulking and harvest

Ndff† (kg ha^{-1})								% FNUE§
^{15}N fertilizer timing	Above ground	Roots	Tubers	Total crop	Weeds	Soil	Unaccounted$^{\delta}$	
Tuber bulking								
Pre-plant	2.9 b‡	0.2 b	5.1 b	8.2 b	na	na	na	10.9 b
Emergence	17.5 a	0.9 a	25.1 a	43.4 a	na	na	na	57.9 a
Tuber initiation	15.9 a	0.6 a	24.2 a	40.7 a	na	na	na	54.3 a
Total	36.3	1.7	54.3	92.3	na	na	na	41.0
Harvest								
Pre-plant	1.6 b	0.1 b	6.7 b	7.7 b	0.1 a	0.3 b	67.0 a	10.2 b
Emergence	7.2 a	0.7 a	35.9 a	46.5 a	0.2 a	0.7 a	29.6 b	62.0 a
Tuber initiation	8.7 a	0.7 a	34.5 a	46.4 a	0.3 a	0.7 a	30.9 b	61.9 a
Total	17.5	1.5	77.1	100.6	0.6	1.7	127.5	44.7

All plots received 75 kg ha^{-1} of N at pre-plant, emergence and tuber initiation, with ^{15}N labeled ammonium nitrate fertilizer substituted at timing treatments

na not available

† Ndff is the Nitrogen derived from fertilizer for each of the three application timings

‡ Values followed by the same letter indicate not significantly different ($p < 0.05$) according to LS-means test within the same sample timing

$^{\delta}$ Unaccounted is N not recovered in potato tissues, weeds, or soil

§ FNUE is Fertilizer Nitrogen Uptake Efficiency

rate was not examined in this study, and merits further investigation.

The allocation of fertilizer N within the aboveground vegetation, roots, and tubers of the potato plant was evaluated at both maximum tuber bulking stage and at harvest (Table 3). While the magnitude of Ndff differed between timing treatments, the proportion of Ndff from each application timing allocated to the different plant parts was similar for all timing treatments, meaning N applied early in the season did not preferentially accumulate in the aboveground tissues or tubers as compared to N applied later in the season.

Whole plant Ndff was similar between the two sample dates, however the allocation of Ndff in different plant parts did differ between sample dates. At the time of tuber bulking, 39 % of the N from fertilizer was allocated in the aboveground tissues, with 59 % in tubers and the remaining 2 % in the roots. By the time of harvest, the proportion of Ndff in aboveground tissues decreased to 18 %, while the proportion of Ndff in tubers increased to 80 % of Ndff. This exchange demonstrated the N reallocation from aboveground tissues to tubers late in the season. Plant senescence and N reallocation from aboveground tissues to tubers is one sign of plant maturation (Ojala et al. 1990), and when N is applied late in the season or at high rates it can delay tuber bulking and plant maturation (Kleinkoph et al. 1981; Vos 2009).

The Ndff accumulated in weeds and remaining in the soil at the time of harvest was also quantified. Weeds accumulated <0.3 kg ha^{-1} of the N from fertilizer at each application and did not differ between treatments. Residual N from fertilizer remaining in the soil at the time of harvest amounted to 1.7 kg ha^{-1} from the total 225 kg ha^{-1} applied. Recoverable soil N from the emergence and tuber initiation N applications were significantly higher than from $N_{pre\text{-}pl}$ (Table 3).

The remainder of fertilizer N not accounted for in the potato plant, weeds, or soil residual was presumably lost primarily to leaching, runoff as an effect of the rainfall received in each year (Fig. 1). Of the total 225 kg ha^{-1} of N applied, the total unaccounted for fertilizer was on average 127 kg ha^{-1} for both seasons. Unaccounted for fertilizer-N was highest for the pre-plant N application in both years, with 89 % of the N fertilizer applied not being recovered at the time of harvest (Table 3). Unaccounted N fertilizer was similar for the N applications at plant emergence and tuber initiation, and averaged 40 % N fertilizer loss from each application.

Any fertilizer remaining in the soil postharvest is at increased risk of loss to the environment (Stanley and Toor 2010). For this reason, cover crops are commonly planted soon after potato harvest to capture remaining N from fertilizer and mineralization, and to improve soil structure (Creamer and Baldwin 2000; Mary et al. 1996). Residual N fertilizer in the rootzone at harvest was low in both years, <2 kg ha^{-1} from the total 225 kg ha^{-1} applied throughout the season (Table 3). When comparing residual N resulting from each of the N applications, that from $N_{pre\text{-}pl}$ was lower than from N_{emerg} and $N_{tuber\ init}$.

FNUE

The pre-plant N application had the lowest FNUE evaluated at harvest, accounting for an average of 11 % of the N applied and was similar between years. The N accumulated in the plant from the $N_{pre\text{-}pl}$ application was associated with very low FNUE for both varieties, and similar between years despite the difference in early season rainfall and soil N. Despite the high, early-season, soil N in 2013 resulting from the $N_{pre\text{-}pl}$ application, the FNUE from this application was low, presumably because this N application timing was 26–30 days before planting, while plant N uptake was low until tuber initiation, after 40 DAP. The typical $N_{pre\text{-}pl}$ application by commercial growers occurs very early in the season, about 30–40 days before planting, followed by an additional 20–30 days until plant emergence. This extensive period between fertilizer application and potential plant uptake is a particularly inefficient practice given the risk of leaching and runoff, even in early seasons with comparatively low rainfall, as recorded in 2013. In contrast, the FNUE from the emergence and tuber initiation applications were similar between varieties at 62 %. Alternatively, moving the $N_{pre\text{-}pl}$ application closer to planting, or allocating a higher proportion of the N during the period of active plant uptake, may increase the uptake and uptake of early applications. This may also allow a lower total N rate without decreasing yield. Studies with N applied close to planting report FNUE in the order of 30–60 %, however these studies applied 100 % the N supply at planting as opposed to the split application in the present study (Jiao et al. 2013; Westermann et al. 1988).

Cumulative FNUE for the 225 kg ha^{-1} of N fertilizer applied throughout the season was 45 %, and was similar between varieties and years (Table 3). Jiao et al. (2013) reports FNUE of 32 % for field grown in potato China when 120 kg ha^{-1} of N applied only at planting. The present study uses a higher total N rate, which is usually associated with a lower FNUE, however splitting the N fertilizer into three applications as opposed to one may be a contributing advantage resulting in higher NFUE than Jiao et al. (2013). Janat (2007), however, split 210 kg ha^{-1} of N fertilizer into five applications and achieved between 28 and 31 % FNUE for furrow irrigated potato. Their use of furrow irrigation pushed a large portion of nitrate below the rootzone, which may be a factor in their lower FNUE in comparison to the present study. When drip irrigation was used instead of furrow irrigation, the FNUE increased to 42 %. While the subirrigation system used in northeastern Florida is a high water use system, the wetting front created by the water table moves water and soluble fertilizer upward, as opposed to downward and potentially out of the rootzone in furrow irrigation systems (Sato et al. 2009). Of course, the maintenance of N in the rootzone may be negated during rainfall events when growers lower the water table, and rain from above leaches N from the rootzone. Westermann et al. (1988) recovered 60 % of N when 134 kg ha^{-1} of N was supplied at planting. Their precise management of sprinkler irrigation to field capacity paired with the low rainfall conditions of Kimberly, ID resulted in the conservation of N in the rootzone. Additionally the climate of the Pacific Northwest extends the potato season to at or over 135 days allowing for an extended period of plant growth and N uptake as compared to 100–110 days in Florida.

Conclusions

The purpose of this study was to examine the efficiency of N fertilizer at the three timings using ^{15}N labeled fertilizer to determine the FNUE by two chipping potato varieties. The cumulative FNUE was 45 % for the 225 kg ha^{-1} of N applied. All three N application timings resulted in detectable plant uptake, with the FNUE application at pre-plant being significantly lower than the FNUE when applied at emergence and tuber initiation. Despite low rainfall between $N_{pre\text{-}pl}$ and plant emergence, and high soil N resulting from the $N_{pre\text{-}pl}$ application early in the 2013 season, the resulting FNUE from the $N_{pre\text{-}pl}$ application remained low. Unaccounted for N fertilizer was over 120 kg ha^{-1} of the 225 kg ha^{-1} applied, with the majority resulting from the $N_{pre\text{-}pl}$ application. To increase the FNUE, the $N_{pre\text{-}pl}$ application may occur closer to the potato planting, or high proportion of seasonal N should be applied during emergence or tuber initiation. Distribution of N fertilizer between planting and tuber initiation instead of at $N_{pre\text{-}pl}$ may minimize loss of N and consequently may reduce the total N rate requirement to maintain similar tuber yields.

Acknowledgments We would like to acknowledge the staff of the University of Florida, Hastings Agricultural Extension Center in Hastings, FL, Scott Taylor, Doug Gergela, Bart Herrington, Thaddis Merrick, Hugh Burnham, Dana Burhams, Scott Chamber for their assistance with field operations, sampling and sample analysis.

References

Alva AK (2004) Potato nitrogen management. J Veg Crop Prod 10(1):97–130

Asci S, Borisova T, Vansickle J, Zotarelli L (2012) Risk and nitrogen application decisions in Florida potato production. Southern Agricultural Economics Association, Birmingham

Cipar M (2004) Potato Cultivar FL 1867. Patent 6,762,351

Creamer N, Baldwin K (2000) An evaluation of summer cover crops for use in vegetable production systems in North Carolina. HortScience 35(4):600–603

Dukes MD, Zotarelli L, Morgan KT (2010) Use of irrigation technologies for vegetable crops in Florida. HortTechnology 20(1):133–142

Dunbabin VM, Diggle AJ, Rengel Z, van Hugten R (2002) Modelling the interactions between water and nutrient uptake and root growth. Plant Soil 239:19–38

Errebhi M, Rosen CJ, Gupta SC, Birong DE (1998) Potato yield response and nitrate leaching as influenced by nitrogen management. Agron J 90:10–15

Gallaher RNN, Weldon CO, Fuxral JG (1975) An aluminum block digester for plant and soil analysis. Soil Sci Soc Am Proc 39:803–806

Halitligil MB, Akin A, Ylbeyi A (2002) Nitrogen balance of nitrogen-15 applied as ammonium sulphate to irrigated potatoes in sandy textured soils. Biol Fertil Soils 35:369–378

Hendricks GS, Shukla S (2011) Water and nitrogen management effects on water and nitrogen fluxes in Florida Flatwoods. J Environ Qual 40(6):1844–1856

IAEA (1983) A guide to the use of nitrogen-15 and radioisotopes in studies of plant nutrition: calculations and interpretation of data. International Atomic Energy Agency, Vienna

IAEA (2001) Use of isotope and radiation methods in soil and water management and crop nutrition. International Atomic Energy Agency, Vienna

IFA (2009) The global "4R" nutrient stewardship framework; developing fertilizer best management practices for delivering economic, social and environmental benefits. International Fertilizer Industry Association, Paris

Jaber FH, Shukla S (2006) Effects of soil moisture sensor spacing and zone of influence on recharge calculations. Soil Sci 171(4):305–312

Janat M (2007) Efficiency of nitrogen fertilizer for potato under fertigation utilizing a nitrogen tracer technique. Commun Soil Sci Plant Anal 38(17–18):2401–2422

Jiao F, Wu J, Yu L, Zhai R (2013) 15N tracer technique analysis of the absorption and utilisation of nitrogen fertiliser by potatoes. Nutr Cycl Agroecosyst 95(3):345–351

Kleinkoph GE, Westermann DT, Dwelle RB (1981) Dry matter production and nitrogen utilization by six potato cultivars. Agron J 73:799–802

Lauer D (1985) Nitrogen uptake patterns of potatoes with high-frequency sprinkler-applied N fertilizer. Agron J 77:193–197
Lauer DA (1986) Russet Burbank yield response to sprinkler-applied nitrogen fertilizer. Am Potato J 63:61–69
Lesczynski DB, Tanner CB (1976) Seasonal variation of root distribution of irrigated, field-grown Russet Burbank potato. Am Potato J 53:69–78
Mary B, Recous S, Darwis D, Robin D (1996) Interactions between decomposition of plant residues and nitrogen cycling in soil. Plant Soil 181:71–82
Munoz-Arboleda F, Hutchinson CM (2006) Soil moisture in the potato root zone under seepage irrigation. Fla State Hortic Soc 119:218–220
NOAA (2014) National Oceanic and Atmospheric Administration. www.noaa.gov
O'Dell JW (ed) (1993a) Determination of ammonia nitrogen by semi-automated colorimetry. Method 350.1. US EPA, Cincinnati
O'Dell JW (ed) (1993b) Determination of nitrate-nitrate nitrogen by automated colorimetry. Method 353.2. US EPA, Cincinnati
O'Dell JW (ed) (1993c) Determination of Total Kjeldahl nitrogen by semi-automated colorimetry. US Environmental Protection Agency, Cincinnati
Ojala J, Stark J, Kleinkopf GE (1990) Influence of irrigation and nitrogen management on potato yield and quality. Am Potato J 67:29–43
Olson RV (1980) Plot size requirements for measuring residual fertilizer nitrogen and nitrogen uptake by corn. Soil Sci Soc Am J 44:428–429
Rens LR, Zotarelli L, Cantliffe DJ, Stoffella PJ, Gergela D, Fourman D (2015a) Biomass accumulation, marketable yield, and quality of atlantic potato in response to nitrogen. Agron J 107:931–942
Rens LR, Zotarelli L, Cantliffe DJ, Stoffella PJ, Gergela D, Fourman D (2015b) Effect of rate and timing of nitrogen fertilizer application on potato 'FL1867' part II: marketable yield and tuber quality. Field Crops Res 183:267–275
Rens LR, Zotarelli L, Cantliffe DJ, Stoffella PJ, Gergela D, Burhans D (2016) Commercial evaluation of seasonal distribution of nitrogen-fertilizer for chipping potato. Potato Res. doi:10.1007/s11540-015-9304-6
Sands PJ, Hackett C, Nix HA (1979) A model of the development and bulking of potatoes (*Solanum tuberosum* L.) I. Derivation from well-managed field crops. Field Crops Res 2:309–331
SAS (2008) The SAS System for Windows. SAS Institute, Cary, NC
Sato S, Morgan KT, Ozores-Hampton M, Simonne EH (2009) Spatial and temporal distributions in sandy soils with seepage irrigation: I. Ammonium and nitrate. Soil Sci Soc Am J 73:1044–1052
Shukla S, Boman BJ, Ebel RC, Roberts PD, Hanlon E (2010) Reducing unavoidable nutrient losses from Florida's horticultural crops. HortTechnology 20:52–66
Stanley CD, Toor G (2010) Florida commercial horticultural production: constraints limiting water and nutrient use efficiency. HortScience 20:89–93
U.S. Department of Agriculture (1981) Soil survey of St. Johns County, Florida. Soil conservation service. U.S. Department of Agriculture, Washington
USDA-NASS (2014) Potatoes 2013 Summary. United States, National Agricultural Statistics Service. https://www.census.gov/history/pdf/idahopotatoes2014.pdf. Accessed 06 February 2016
Vos J (2009) Nitrogen responses and nitrogen management in potato. Potato Res 52(4):305–317
Westermann D, Kleinkopf G, Porter L (1988) Nitrogen fertilizer efficiencies on potatoes. Am Potato J 65:377–386
Worthington CM, Hutchinson CM (2006) Yield and quality of "Atlantic" and "Harley Blackwell" potatoes as affected by multiple planting dates, nitrogen rates and growing degree days. Proc Fla State Hortic Soc 119:275–278
Worthington CM, Portier KM, White JM, Mylavarapu RS, Obreza TA, Stall WM, Hutchinson CM (2007) Potato (*Solarium tuberosum* L.) yield and internal heat necrosis incidence under controlled-release and soluble nitrogen sources and leaching irrigation events. Am J Potato Res 84:403–413
Zotarelli L, Rens LR, Cantliffe DJ, Stoffella PJ, Gergela D, Fourman D (2014) Nitrogen fertilizer rate and application timing for chipping potato cultivar Atlantic. Agron J 106:2215–2226
Zotarelli L, Rens LR, Cantliffe DJ, Stoffella PJ, Gergela D, Burhans D (2015) Effect of rate and timing of nitrogen fertilizer application on potato 'FL1867' part i: nitrogen uptake and soil nitrogen availability. Field Crops Res 183: 246–256