Impacts of interactions between soil water and mineral nitrogen resources on potato productivity and nitrogen fertilizer needs

Project # 6592

irda

Final report

Christine Landry, agr., Ph.D. – IRDA
Carl Boivin, agr., M.Sc. – IRDA

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Project team:

IRDA

Christine Landry	Research scientist
Carl Boivin	Research scientist
Luc Belzile	Research scientist
Paul Deschênes	Research Professional
Michèle Grenier	Statistician
Julie Mainguy	Research Associate
Laurence Simard-Dupuis	Research Associate
Danièle Pagé	Agricultural technician
Stéphane Nadon	Agricultural technician
François Charrier	Agricultural technician

Summer students

Éloïse Bastien, David Bilodeau, Jessie Caron, Maxime Delisle-Houde, Paul Harrison, Bruno Lavallée, Michaël Lemay, Alain Marcoux, Jean-François Plourde, Julien Vachon and Nicolas Watters.

MAPAQ DRBSL

Serge Bouchard	Farm production advisor specializing in potatoes

Table of Contents

List of figures

List of tables

1 SUMMARY OF PROJECT ACHIEVEMENTS

In the form of nitrate (NO_3^-), its most common form in soils, nitrogen (N) is distinctive among crop nutrients in not binding to soil particles, resulting in its subsurface transport being closely tied to soil water fluxes. This situation results in a less than optimal nitrogenous fertilizer use efficiency and greater risk of NO_3^- losses through leaching. The present project sought to document interactions between the availability of nitrogenous nutrients (primarily NO_3^-) and water under potato (*Solanum tuberosum* L.) cultivation. Experimental potato (cv. 'Goldrush') field trials were undertaken at the Deschambault Agricultural Experiment Station (Deschambault, QC) in 2011 and 2012. These included 10 treatment combinations, arrayed in a split-plot design with (i) 2 main plot irrigation treatments (none *vs.* triggered when soil available water depletion exceeded a threshold of 50%) arrayed in 4 randomized complete blocks, and (ii) 5 sub-plots of N fertilization rate treatments (0, 50, 100, 150 or 200 kg ha^{-1}), randomized within the main plots. With respect to plants' N nutritional status, their development and the fresh weight basis (f.w.b.) marketable tuber yield, no advantage was gained by exceeding 100 kg N ha^{-1}, with the exception of 2011 yields which were greatest at an N fertilization rate of 150 kg N ha^{-1}. Plant and tuber N-uptake levelled off around 73 days after planting (DAP), indicating that the bulk of crop development had occurred by then. Moreover, in both years, soil NO_3^--N levels were lowest when N-uptake rates levelled off. The best N use efficiencies (73% in 2011, and 71% in 2012) occurred under the 100 kg N ha^{-1} fertilization rate, whereas for the 200 kg N ha^{-1} fertilization rate these efficiencies dropped to 55% and 46%, respectively. While irrigation had no effect on tuber yield (f.w.b.) in 2011, in 2012 yields across all fertilization rates were significantly higher in irrigated than non-irrigated plots. While irrigation did not influence the most cost-effective N fertilization rate (185 kg N ha^{-1}) in either year, the rate of N fertilization influenced the demand for water, more irrigations being required at the 200 kg N ha^{-1} fertilization rate than at lower rates. Furthermore, the soil organic matter (SOM) content appeared to have an impact on tuber yields (f.w.b.) and on the benefits derived from irrigation, particularly in the drought-stress-prone 2012 growing season. Indeed, soils with SOM <1.4% (*vs.* those where SOM > 1.6%) showed greater and more uniform yields, and a greater number of subplots with yields between 15 and 30 Mg ha^{-1} (6.7-13.4 ton ac^{-1}). Moreover, in the absence of irrigation the subplots with the highest SOM performed best. A similar tendency was found for tuber specific gravity. This project highlighted the advantages of maintaining good soil health and quality given its significant contribution to available N levels, in this case an amount equivalent to a quarter of the most cost-effective N fertilization rate. Cultural practices ensuring long term soil health can contribute to reducing the consumption of inputs, and thereby, any negative impacts crop production could have on the environment.

PROJECT DESCRIPTION

1.1 Introduction

Canada is an important potato-producing nation, producing 4.28 Tg y^{-1} (FPPTQ 2010a). In 2010, Prince Edward Island, Nova Scotia and Quebec alone had 740 km^2 devoted to potato production (Statistics Canada 2010). Under recommended fertilisation rates (CRAAQ 2003), these areas receive 13 Gg of nitrogen. Nitrogen inputs to the receiving environment are therefore rather large and that much more difficult to manage given that potatoes are grown on well-drained sandy soils. In the form of nitrate (NO_3), its most common form in soils, nitrogen (N) is distinctive among crop nutrients in not binding to soil particles, resulting in its subsurface transport being closely tied to soil water fluxes. This situation results in a less than optimal N fertilizer use efficiency and a greater risk of NO_3 losses through leaching. Potatoes N use efficiency is known to be poor, rarely reaching 60% and being as low as 30% under unfavourable soil or weather conditions (Gasser and Laverdière 2000; CRAAQ 2003). These numbers were confirmed by studies undertaken since 2007 on the sandy soils of the National Capital Region's Portneuf district (Boivin and Landry 2008, 2011, 2012; Landry 2011). These studies showed that while mean applied N fertilizer use efficiency was under 60%, excess water from natural sources (*e.g.*, rainfall) or applied in irrigation not only reduced this efficiency below 50%, but also led to yield reductions of several tonnes per hectare. Excess water also increased leachate NO_3 -N concentrations (NO_3 -N) up to five-fold during the growing season. These observations are all the more troubling in that (i) potato production acreage in Canada is significant, (ii) the use of irrigation is increasing, and (iii) costs for N-fertilizers are rising since their prices follows trends in oil prices. The Quebec Federation of Potato Producers (FPPTQ) has developed a response-plan prioritizing a move towards integrated fertilization and the reduction of non-point source N pollution risks (FPPTQ 2010b), to be achieved through a better understanding of the agronomic potential of cultural practices.

Significant economic impacts can indeed arise from a non-integrated management of N fertilization. The drop in profitability can be very significant since the greatest costs incurred by the producers are those for fertilization. These can vary between 17% and 21% of variable costs, and between 12% and 16% of total operating costs (Fortier et al. 2010). On a typical 104 ha farm, fertilizing fields at a rate of 175 kg N ha^{-1} at a price of \$2 kg^{-1} N, will result in an expenditure of \$36 400 for N fertilizer alone, not taking into account the time and expenditures involved in its application. Determining the ideal combination of irrigation and fertilization is therefore likely to provide substantial dividends to potato producers. On the environmental level, for the same 104 ha farm, if the N use efficiency is 55 %, then 8190 kg of the 18 200 kg applied are not taken up by the crop and remain in the receiving environment. This N can then migrate to surface and sub-surface waters. Indeed several studies have clearly shown intensive NO_3 leaching to occur under commercial potato production (Richards *et al*. 1990), and highlighted its implications on drinking water quality and human health (Kenney and Hatfield 2001). After a well sampling campaign in Quebec's potato production regions between 1999 and 2001; Giroux (2003) reported that 42% wells tested showed [NO_3 -N] exceeding the drinking water standard of 10 mg L^{-1} NO_3 -N. As a matter of fact, NO_3 leaching is the primary mechanism through which N is lost from potato production systems (Zebarth and Rosen 2007).

Estimates of NO_3 leached from different potato production regions range from 10 to 200 kg NO_3 -N ha^{-1} (*e.g.*,. Milburn et al. 1990; Errebhi et al. 1998). In Quebec, Gasser et al. (2002) reported a NO_3 leaching rate of 116 kg NO_3 -N ha^{-1}. To the NO_3 leached in the year of N application is accrued that remaining in the soil after the previous season's harvest. Particularly prone to leaching during the lengthy autumnal rains and spring snowmelt events typical of Eastern Canada's humid climate, minimizing this residual nitrate's can prove to be a key factor in limiting its downward migration through the soil profile (Bélanger et al. 2003). Consequently, an optimized N fertilization program could help in reducing residual N after harvest. It is therefore fitting to determine potato N use dynamics from the onset of the growing season through to harvest.

Potato producers will benefit as well from extending their understanding of the relationship between N fertilization and irrigation, thereby gaining the opportunity to take advantage of the synergy existing between soil N and soil moisture, which modulates the former's transport in the soil, and thereby influences the relative amounts allocated to potential crop uptake and leaching.

1.2 General objective

The general objective was to detail the interaction between the potato crop's nitrogen and water statuses, so as to provide the tools necessary to maximize N use efficiency and sector profitability, while reducing environmental pressures.

1.3 Specific objectives

1. Measure the effect of increasing N inputs, in the presence or absence of irrigation, on soil N availability, as well as plant nutrition and growth.

2. Monitor the evolution in the rate of fertilizer-contributed N uptake over the season, depending on the rate of N applied, with or without irrigation.

3. Monitor the potato crops' evolving phenological stages over the season and their chronology's dependence on the rate of N fertilization in the presence or absence of irrigation.

4. Determine if irrigation alters the N application rate offering the best yield (*i.e.*, is there an irrigation × N rate interaction)

5. Determine to what extent increasing the N fertilization rate modifies water demand under a regime where irrigation is triggered at a threshold of 50% loss in soil available water.

6. Evaluate the potential economic benefits to be derived from the synergy between N fertilization and irrigation. Analyse the potato production process to determine the best combination of inputs (*i.e.*, the combination of irrigation and N fertilisation rate which maximizes producer profit).

2 MATERIALS AND METHODS

2.1 Study site characteristics

Undertaken at the Deschambault Experiment Station (Deschambault, QC, Canada; 46° 40’ 26.5” N, 71° 54’ 54.8” W) on a loamy sand (Table 1), the study’s field trials extended over two years (2011, 2012). Dates for the major cultivation operations are summarized in Table 2. Whole 40-225 g (1½–8 oz) Elite-4-certified seed potatoes (cv. ‘Goldrush’) were cut to a size of 40-112 g (1½–4 oz) and planted at a density of 32 584 plants ha^{-1}. Within-row spacing was 0.33 m, while between-row spacing was 0.93 m.

Table 1. Soil Characteristics.

Parameters	**2011**
pH_{sw}	6,14
Soil organic matter (% w/w)	1,12
N_{tot} (mg kg^{-1} d.w.b.)	640
Mehlich-3 Nutrients (mg kg^{-1} d.w.b.)	
P	204
K	94
Ca	565
Mg	23
Al	1076
P/Al (%)	19

Table 2. Dates of main cultivation operations at the study site in 2011 and 2012.

	Year	
	2011	**2012**
Initial fertilization, at planting (N, P, K)	1 June	14 May
Second of split fertiliser applications (N)	8 July	28 June
Top-killing	16 September*	29 August
Harvest	19 October	25 September

*Top-killing of plants did not require dessicant treatment in 2011.

At planting, inorganic fertilizers were hand-banded in a row-centered furrow, a few centimeters under the seed, with a thin layer of soil separating them. The full phosphate and potash applications were made at this time. The fertilizers employed for N, P, and K inputs were, respectively, 27-0-0, 0-46-0, and 0-0-60 or 0-0-22-11. The plants thus received 100 kg P_2O_5 ha^{-1} and 150 kg K_2O ha^{-1} in both years. Nitrogen fertilizer was given in a split application, one at planting and one at hilling. The second N application was also hand-banded, half on either side of the plants. The fertilizer application rates were set according to the recommendation grids for potatoes in the CRAAQ's (2003) Quebec Fertilization Guide.

Prior to emergence, a sprinkler irrigation system was installed (Figure 1). To allow subplot irrigation on an individual basis, each subplot was equipped with a single sprinkler head linked to an on-off valve. To achieve a more even flow rate (22 L min^{-1}) when multiple sprinkler heads were operating, sprinkler heads were each linked to a 172 kPa (25 psi) pressure regulator.

Each subplot was equipped with a HORTAU Tx-80 tensiometer in order to manage irrigation inputs on an individual basis. In certain subplots, additional HORTAU tensiometer (models T-80 and Tx-80) were installed to depths of 0.30 and 0.60 m in order to confirm the duration of irrigations and the direction of soil water fluxes.

Figure 1**.** Sprinkler irrigation system, summer 2011.

2.2 Experimental treatment factors

The present study compared ten treatment combinations: two irrigation regimes (non-irrigated and irrigation at a 50% soil available water depletion threshold), and five N fertilization rates (0, 50, 100, 150, 200 kg N ha^{-1}). The latter included irrigated and non-irrigated unfertilized controls (0 kg N ha^{-1}), which served to assess the site's natural N contribution and irrigation's impact thereon (**Erreur ! Source du renvoi introuvable.**). The drop in soil water tension below a threshold equivalent to a 50% in soil available water (SAW) triggered irrigation. In a study with 'Russet Burbank' potatoes, Boivin and Landry (2011) identified this method as leading to greater economic and environmental gains than those achieved in a non-irrigated control, or a regime under which the SAW depletion threshold was 65%. The soil water tension equivalent to the 50% SAW depletion threshold was determined using the soil's water retention curve. The duration of the irrigation was adjusted over the season according to the crop's rooting depth.

Table 3. Irrigation and N fertilization treatments under study.

Treatment No.	kg N ha^{-1}		Irrigation	Treatment designation
	at planting	at hilling		
1	0	0	No	N_0I_0
2	0	0	Yes	$N_0I_{50\%}$
3	50	0	No	$N_{50}I_0$
4	50	0	Yes	$N_{50}I_{50\%}$
5	50	50	No	$N_{100}I_0$
6	50	50	Yes	N_{100}-$I_{50\%}$
7	75	75	No	$N_{150}I_0$
8	75	75	Yes	$N_{150}I_{50\%}$
9	100	100	No	$N_{200}I_0$
10	100	100	Yes	$N_{200}I_{50\%}$

2.3 Experimental design and statistical analysis

A split-plot design with two main plot irrigation treatments (I_0 and $I_{50\%}$) randomized in four complete blocks, and five N fertilization rate (N_0, N_{50}, N_{100}, N_{150}, N_{200}) subplots, randomized within the main plots, resulted in a total of 40 sub-plots (Figure 2). Each variable investigated was subject to an ANOVA in order to assess the effects of irrigation and nitrogen fertilization rate on these variables.

A normalized mixed model was fitted using PROC MIXED in SAS (Littell et al. 2006). The fixed effects were Irrigation, N rate, and their interaction (IRRIG × NRATE), while the random effects were BLOCK and the BLOCK × IRRIG interaction. For certain variables monitored over a number of dates, fixed effects of DATE and the interactions of DATE × IRRIG, DATE × NRATE, and DATE × IRRIG × NRATE, were added to the model. The random effect of BLOCK × IRRIG × NRATE also had to be added, and a variance-covariance matrix was modelled in order to address autocorrelation between repeated measures in time on the same sub-plots. Satterthwaite's approximation was employed in determining the degrees of freedom. A graphical analysis of residuals served to confirm the hypotheses underpinning the model's validity. When the *F* test confirmed a factor or an interaction to be significant, differences between means were explored through *t* tests. Further contrasts were also implemented to study the linear and quadratic effects of N rates.

2.4 Soil physical and chemical analysis

Except for soil bulk density (ρ) measurements, done in triplicate, all soil analyses were done on composite samples made up of six subsamples drawn from the 0-0.30 m soil layer of each subplot. Each year, upon setting up the experimental site, the top 0.30 m of soil was sampled to allow the characterization of its soil parameters: soil water pH (pH_{sw}), Mehlich-3 macronutrients, total soil C and N content (% w/w; C_{tot} and N_{tot}). In order to monitor mineral N (N_{min}) during the production season, soil sampling was repeated on a further six occasions: before the second N fertilizer application, when 50-75% of flowers had bloomed, early August, mid-August, at top-killing and at harvest, when C_{tot} and N_{tot} were once again measured. At each sampling, soil samples were placed in a cooler and maintained at 4°C until analysis. Soils were sieved (2 mm mesh), then air dried at 21°C. Nutrient levels were reported in kg ha^{-1} (d.w.b.), using ρ values measured simultaneously with soil sampling by inserting copper cylinders into the soil. The soil in the cylinders was then dried at 105ºC to remove water, then weighed. Soil particle size distribution was determined by the hydrometer method, using six points, followed by a sieving of the sand fraction (Gee and Bauder 1986). The pH_{sw} was measured in a 1:1 (w/w) soil: water slurry (Conseil des productions végétales du Québec 1988). The C_{tot} and N_{tot} were measured using a LECO induction furnace, while N_{min} as NO_3 -N was extracted with 2M KCl (Isaac et Johnson 1976) and determined colorimetrically (Technicon AA-II). Micronutrients, P and K were extracted in Mehlich-3 solution (Tran and Simard 1993) and quantified by coupled plasma optical emission spectroscopy. In the first year, undisturbed soil samples were also taken in each of the four blocks in order to develop soil moisture characteristic curves in the laboratory (Topp et al. 1993).

Treatments: 1. N_0I_0 2. $N_0I_{50\%}$ 3. $N_{50}I_0$ 4. $N_{50}I_{50\%}$ 5. $N_{100}I_0$ 6. $N_{100}I_{50\%}$ 7. $N_{150}I_0$ 8. $N_{150}I_{50\%}$ 9. $N_{200}I_0$ 10. $N_{200}I_{50\%}$

Subplot No. shown in small numbered inserts.

Figure 2. Experimental layout of the study site in 2011 and 2012.

2.5 Potato development and nutrient uptake

The progression of potato phenological stages was monitored throughout the growing season, as recommended by the local phytosanitary alert net. The stages monitored, numbered 0 through 8 (Sparks 1982), corresponded to the following developmental stages: emergence, plant differentiation, floral buds, pedunculated floral buds, onset of flowering, full flowering, end of flowering, adult plant, senescent plant.

Analysis of N_{tot} in the plant's youngest fully-expanded leaf (4th from the apex), recognized as a reliable indicator of plant nutritional status in potato, was done from samples taken just prior to the second N fertilizer application and at 50-75% flowering. Plant N levels being much influenced by light levels, the sampling of 10 such leaves per subplot was done in the morning. The samples were kept in a cooler at 4°C during their transport to the laboratory, where they were dried at 65°C, then ground to pass a 100 mesh sieve. Extracted by the Kjehdahl method (Isaac and Johnson 1976), N_{tot} content of leaves ($[N_{tot}^{leaf4}]$) was then quantified by automated colorimetry (Technicon AA-II autoanalyzer).

On six occasions over the growing season (prior to fertilization, at hilling, 50-75% flowering, early August, mid-August, top-killing, harvest) three vines per subplot were cut off at the soil surface and taken for plant biomass and N_{tot} (d.w.b.) analysis. Vine dry matter (DM^{vine}) was measured after 48 hr drying at 65°C. Following vine drying, vine N_{tot} content ($[N_{tot}^{vine}]$) was measured in the same manner as the leaves. Plant nitrogen uptake (N_{tot}^{vine}) into above-ground biomass was calculated as :

$$N_{tot}^{vine} = DM^{vine} \times [N_{tot}^{vine}] \quad (1)$$

In addition, tubers of three adjacent plants were harvested on five individual occasions during the season (50-75% flowering, early August, mid-August, top-killing, harvest), not in order to determine yield per hectare, but rather to better characterize tuber development over the season. These repeated harvests over time also allowed a more complete picture of plant N uptake at these developmental stages by making it possible to combine vine and tuber N uptake. For each harvest, tubers were classified by fresh weight. A composite sample of healthy tubers, unpeeled but washed, was then taken, cut into sticks, dried at 65°C, and ground to pass a 100 mesh sieve. Extraction and quantification of N_{tot} followed the same method as was used for the leaves. Plant nitrogen uptake by tubers (N_{tot}^{tuber}) was then calculated as the product of tuber N_{tot} content ($[N_{tot}^{tuber}]$) and tuber matter (DM^{tuber}):

$$N_{tot}^{tuber} = DM^{tuber} \times [N_{tot}^{tuber}] \quad (2)$$

and the full potato plant's above- and below-ground N_{tot} (N_{tot}^{t+v}) is given as

$$N_{tot}^{t+v} = N_{tot}^{vine} + N_{tot}^{tuber} \quad (3)$$

At season's end, a much more extensive harvest (4 m in each of two rows, for a total of 8 linear meters) served to determine total and marketable yield per hectare. Size classification of tubers followed Canadian Food Inspection Agency criteria (Canada #1 : 51 mm < diam. < 89 mm, and Canada #1 large : 89 mm < diam. < 114 mm) (ACIA 2013). Twenty-five randomly selected tubers were drawn from each subplot's harvest, and assessed for black scurf (*Rhizoctonia* sp.) symptom severity and percent tuber surface affected. A roughly 3 kg sub-sample was taken for each subplot, weighed in the air (TW_{air}), then weighed in water (TW_{water}), and tuber specific gravity (T_{sg}) calculated as:

$$T_{sg} = \frac{TW_{air}}{TW_{air} - TW_{water}} \tag{4}$$

In addition, a composite sample of five healthy tubers, unpeeled but washed, were drawn from each subplot, and prepared for N_{tot} analysis as described for the periodic harvests. The total tuber yield (d.w.b.) per plot/subplot (DM^{tuber*}) and [N_{tot}^{tuber}] were used to calculate total plot/subplot crop N_{tot} exports through tubers (N_{tot}^{tuber*}; *i.e.*, all N_{tot} removed from the plot/subplot with harvested tubers), as well as in determining total seasonal per plot/subplot N uptake (N_{tot}^{t+v*}).

$$N_{tot}^{tuber*} = DM^{tuber*} \times [N_{tot}^{tuber}] \tag{5}$$

$$N_{tot}^{t+v*} = N_{tot}^{tuber*} + (N_{tot}^{vine}@top\text{-}killing \times no.\frac{vines}{plot}) \tag{6}$$

Once the N_{tot}^{t+v*} values were calculated for all treatment combinations, the apparent nitrogen use coefficient (C_{ANU}) was calculated. This compares the total seasonal per plot/subplot applied fertilizer N uptake at a given fertilization rate expressed with respect to the N fertilization rate [e.g., $(N_{tot}^{t+v*}\ under\ N_{150}I_0) - (N_{tot}^{t+v*}\ under\ N_0I_0)$]. To obtain the irrigation efficiency coefficient (C_{IRR}) for the different irrigation regimes tested, the C_{ANU} for that treatment combination was compared to the C_{ANU} obtained at the same time, under the same fertilization regime, but in the absence of irrigation (control). For example, the C_{ANU} and C_{IRR} calculations for an N fertilization rate of 150 kg ha^{-1} are as follows (Giroux et al. 2007):

$$C_{ANU(N_{150}I_0)} = \frac{(N_{tot}^{t+v*}\ under\ N_{150}I_0) - (N_{tot}^{t+v*}\ under\ N_0I_0)}{Fertilizer\ N\ applied\ per\ plot\ for\ N_{150}I_0} \tag{7}$$

$$C_{IRR(N_{150})} = \frac{C_{ANU(N_{150}I_{50\%})}}{C_{ANU(N_{150}I_0)}} \tag{8}$$

This coefficient allowed one to compare the fertilization efficiency of fertilizer N according to the irrigation regimes tested.

2.6 Weather conditions and estimation of potential evapotranspiration (ET_p)

A weather station set up on the site served to monitor temperature and relative humidity (HC2-S3, Campbell Scientific), solar radiation (LI-200SZ, LI-COR), wind speed and direction (Wind monitor, Young Model 05103-10), along with rainfall (TE525WS, Campbell Scientific). Data were recorded on a CR1000 datalogger (Campbell Scientific) at hourly intervals. Potential evapotranspiration (ET_p) was calculated using the Penman-Montheith equation (Allen et al. 2005).

2.7 Economic analysis

The method employed in developing an economic analysis is discussed in the results to render its discussion more transparent (section 3.7).

3 RESULTS AND ANALYSIS

3.1 Weather conditions

Rainfalls, along with minimum, maximum and mean air temperatures, were measured on a daily basis in both 2011 and 2012 (Figure 3 and Figure 4). Daily ET_p, derived from weather station data (Figure 5 and Figure 6) represents the depth of water lost from the soil through surface evaporation and by transpiration through plants. The volume of water lost is a function of the intensity of the weather conditions. When the evapotranspirative demand exceeds what the plant can easily use, the latter can find itself in conditions of water or heat stress.

It is apparent in comparing both seasons' daily ET_p that, given a greater number of days where 2 mm < ET_p < 4 mm in 2012 than 2011, plants were more likely to have suffered water stress in 2012 than 2011. Moreover, from mid-July onward, the number of days when 4 mm < ET_p < 6 mm was also greater in 2012. Finally, there were almost no rainfall events in July 2012.

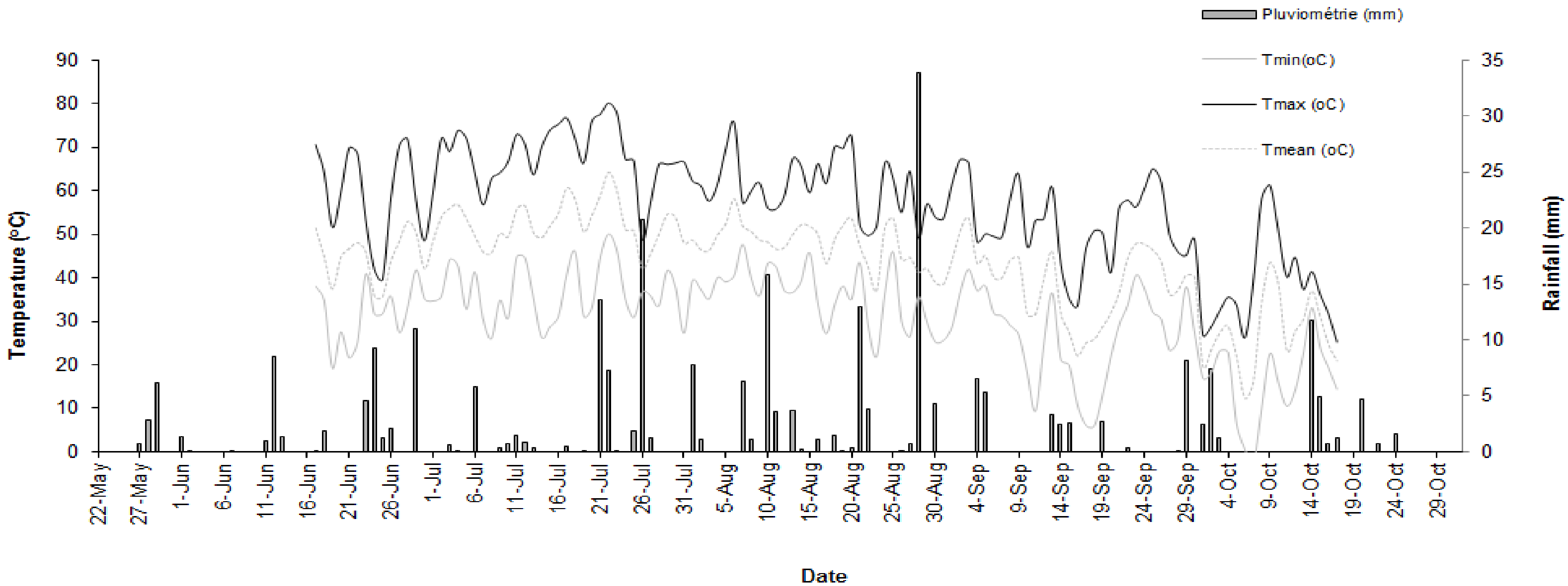

Figure 3. Daily rainfall (mm) and daily minimum, maximum and mean air temperatures (T_{min}, T_{max} and T_{mean}; °C), 2011.

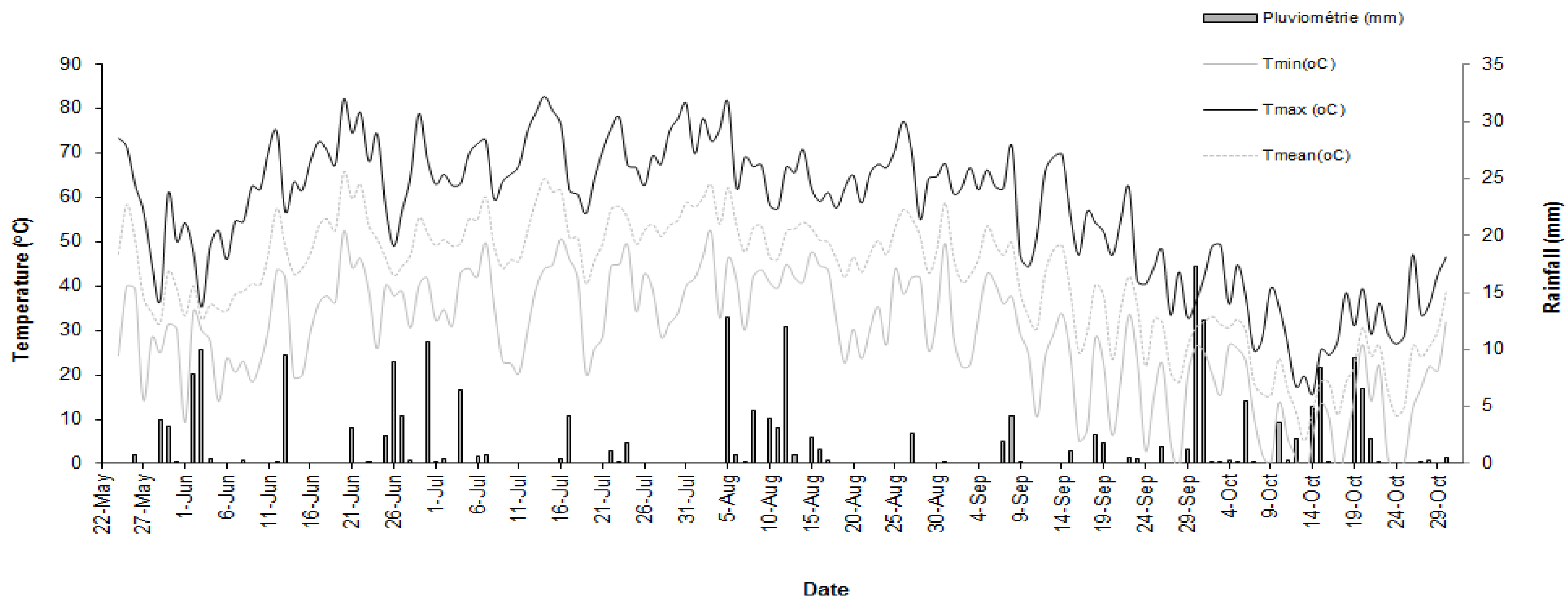

Figure 4. Daily rainfall (mm) and daily minimum, maximum and mean air temperatures (T_{min}, T_{max} and T_{mean}; °C), 2012.

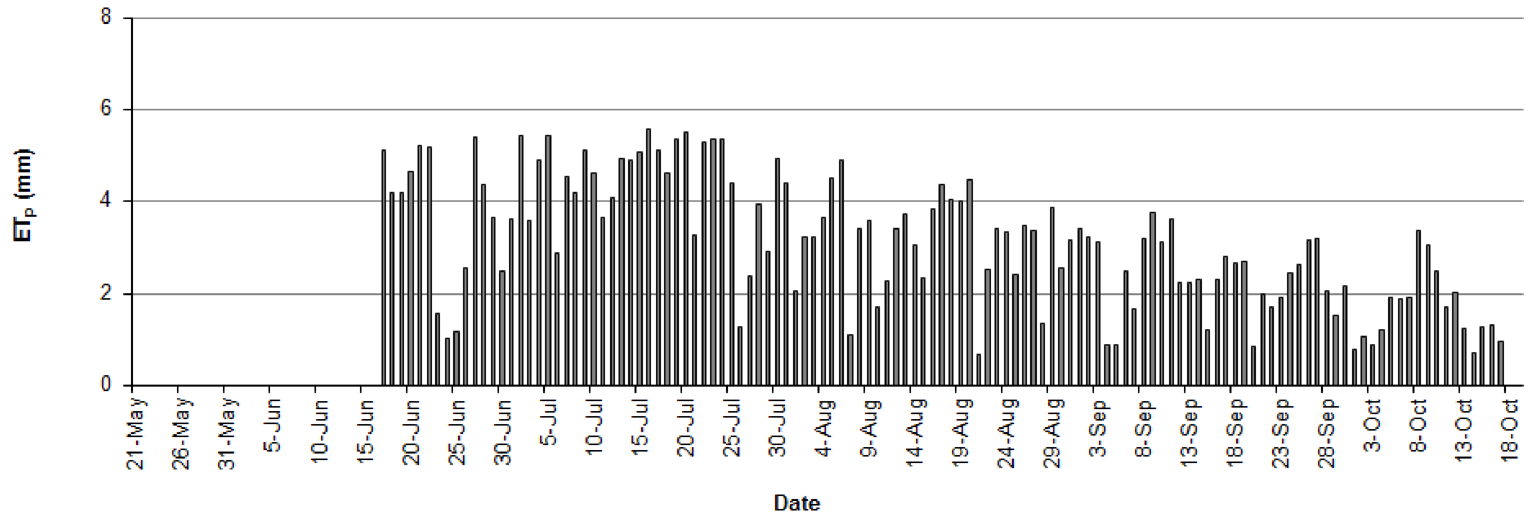

Figure 5. Daily potential evapotranspiration (ET_p; mm) - 2011.

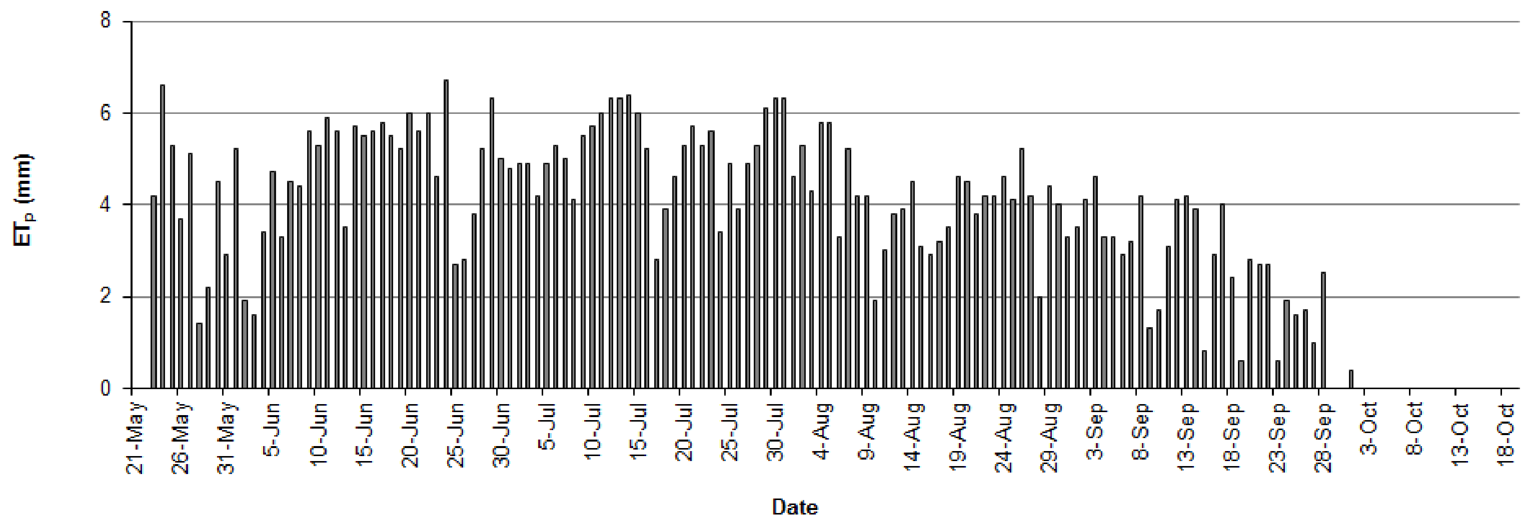

Figure 6. Daily potential evapotranspiration (ET_p; mm) – 2012.

3.2 Assessing the impact of increasing N inputs, with or without irrigation, on plant nutrient status and growth, as well as soil N availability.

3.2.1 Plant nutrient status

As expected, in both years N fertilization rate strongly influenced potato plant N status, both at the flower bud (NRATE × DATE, $P = 0.0009$) and full flowering (NRATE × DATE, $P < 0.0001$) stages (Figure 7). In both seasons, at the flower bud stage (7 July 2011 and 22 June 2012), prior to the second split N application, leaf N was significantly greater in N_{50} plots than in N_0, but minimal additional improvement in leaf N status occurred when N application rates at planting were 100 kg N ha^{-1} or greater. At the flowering stage (*i.e.*, after the second N fertilizer application), the N_{50} subplots showed no better plant nutrient status than the N_0 subplots. In addition, plant N statuses for N_{100}, N_{150} and N_{200} fertilization rate treatments were superior to those for the N_0 and N_{50} treatments, but did not differ significantly among themselves. In terms of reaching the potato plant's N sufficiency threshold, a total N application of 100 kg N ha^{-1} was sufficient in both years (Figure 7).

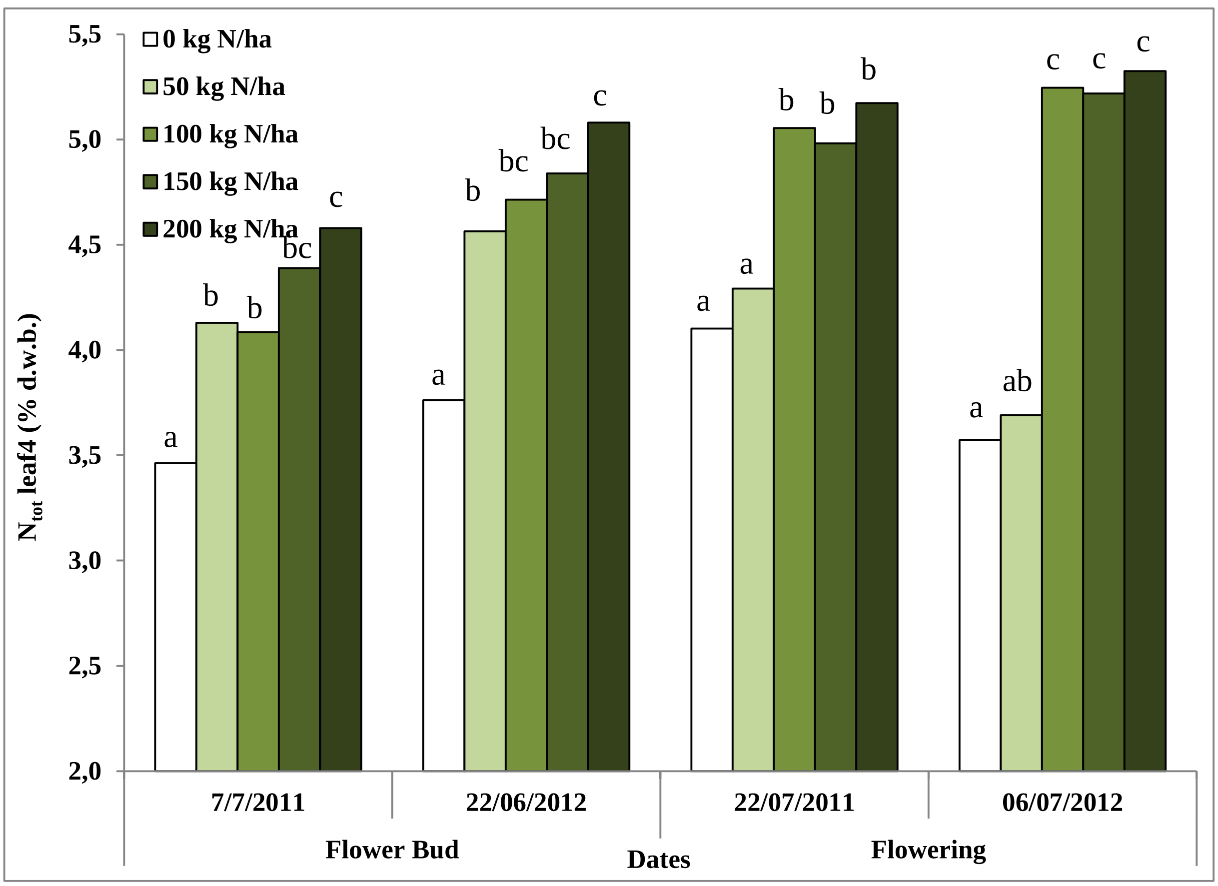

Figure 7. Total first mature leaf (4th leaf from apex) nitrogen (% d.w.b., $[N_{tot}^{leaf4}]$) for potato plants in 2011 and 2012. Bars for a common date bearing different letters are significantly different, $P \leq 0.05$.

3.2.2 Plant development

Nitrogen fertilizer inputs strongly influenced plant development in both years (NRATE×DATE, P < 0.0001). Monitoring plant development on a dry weight basis showed it to peak within 70 days after planting (DAP) in both years (2011: 78 DAP, Figure 8; 2012: 70 DAP, Figure 9). The marked difference in the rate of development between the N_0 and N_{50} fertilization rate treatments and those receiving 100 kg N ha^{-1} of more is highlighted in Figures 8 and 9. In both years, at peak development the weight of N_{50} plants were not significantly different from those of N_0 plants; only at N fertilization rates of N_{100}, N_{150} and N_{200} was plant development significantly greater than that of their N_0 counterparts. Moreover, the three top fertilization rates resulted in similar plant weights. Unlike the nutritional status, at this stage there was no gain in going beyond the 100 kg N ha^{-1} in either year; thereafter plants entered senescence until their tops died off or were killed off.

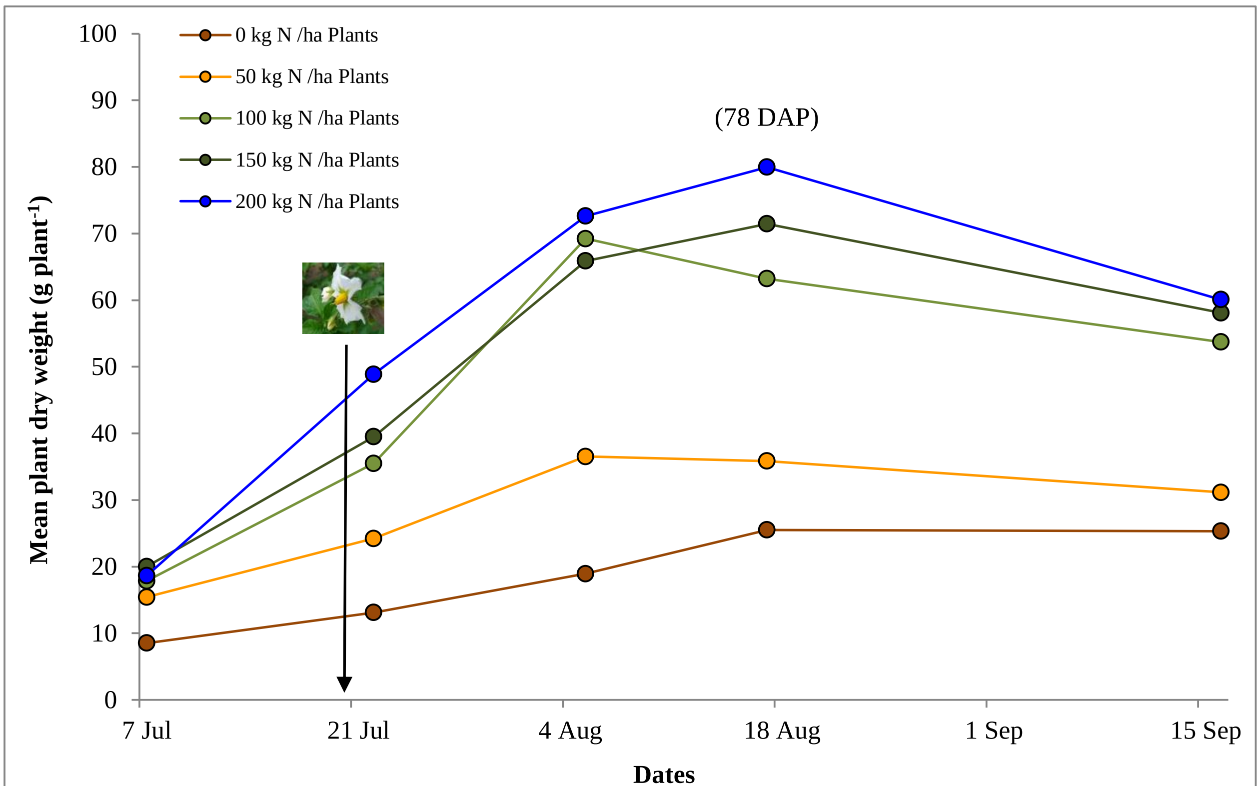

Figure 8. Progression in mean plant dry weight (g plant^{-1}) over the 2011 season.

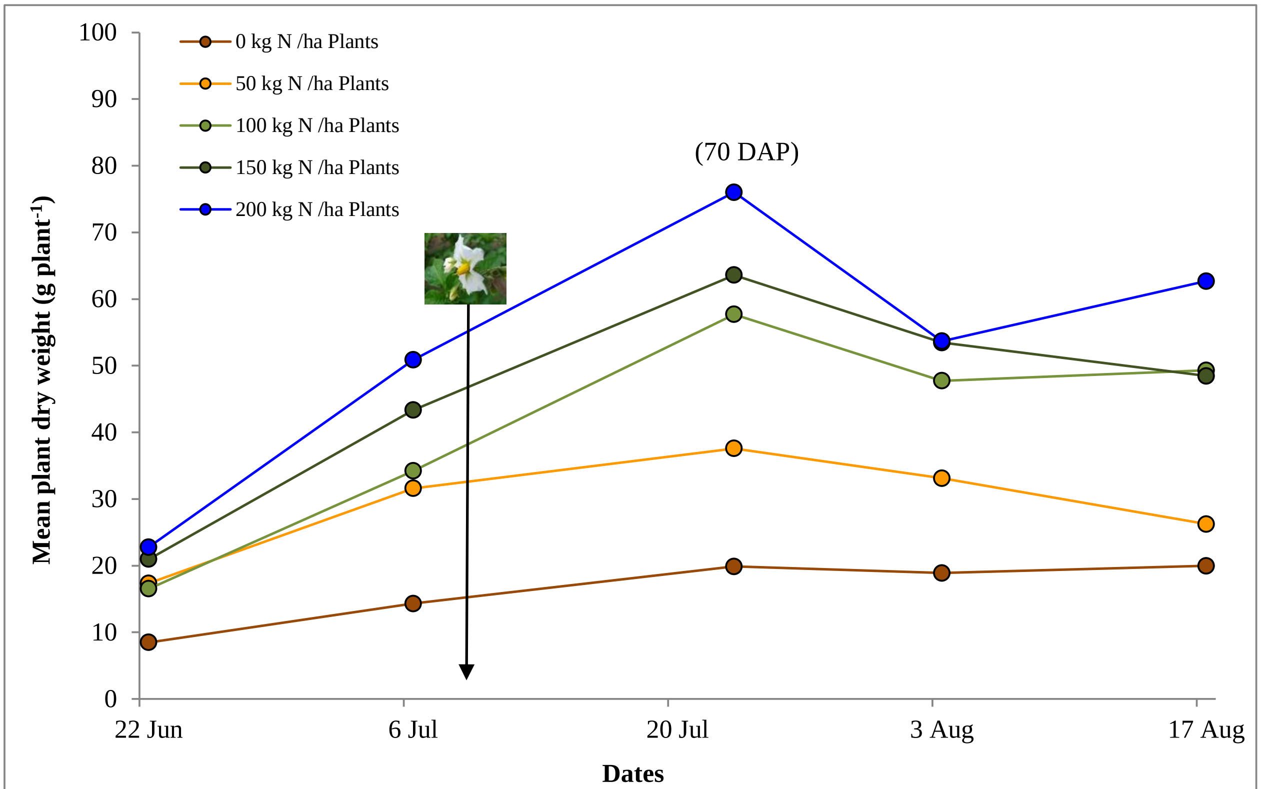

Figure 9**.** Progression in mean plant dry weight (g plant^{-1}) over the 2012 season.

3.2.3 Repeated tuber harvests over the season

Tuber weights per hectare, assessed on four occasions during the growing season and a fifth time at harvest, are shown by year, irrigation treatment and N application rate (Figure 10 through 13). Along previously lines, this graphic representation of total tuber weight allows one to visualize the temporal evolution in tuber weight, and the impact of N fertilization rate thereon. The weight of tubers measured in plots receiving less than 100 kg N ha^{-1} was clearly less than that measured for the other N fertilization treatments [2011 and 2012 NRATE : P = 0.1006 and $P < 0.0001$, respectively; no NRATE × DATE interaction ($P > 0.05$)]. It should be noted that these necessarily represent total yield, since these tubers were harvested prior to reaching maturity. Similarly, end of season tuber weight was also expressed as a total weight. Nonetheless, the same conclusions can be applied to marketable tuber yield (f.w.b.).

Overall, the different treatment combinations' tuber weights were lower in 2012 than 2011. While the statistical analysis of 2011 results showed no effect of irrigation, in 2012, irrigation ($I_{50\%}$) significantly improved tuber weight compared to non-irrigated treatments (I_0). Another way of presenting results for I_0 and $I_{50\%}$ treatments individually is to average tuber weights across all N fertilization rates, as shown in Figure 14 (2011) and Figure 15 (2012). The lack of irrigation treatment effect in 2011 is shown by the superimposition of the I_0 and $I_{50\%}$ curves, whereas in 2012, the curve for $I_{50\%}$ treatments across all N fertilization rates shows tuber weight values significantly higher than those of non-irrigated plots (I_0).

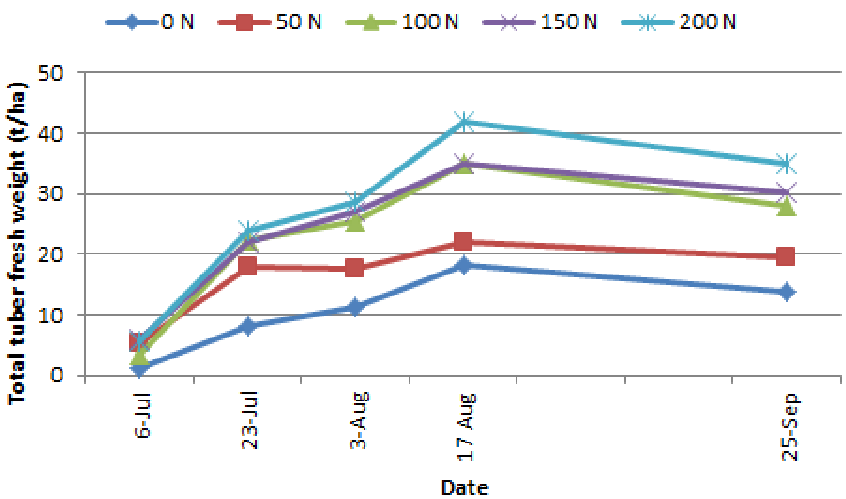

Figure 10. Total tuber fresh weight (t/ha) by harvest date and N fertilization rate (kg/ha), no water inputs from irrigation (I_0), 2011 season.

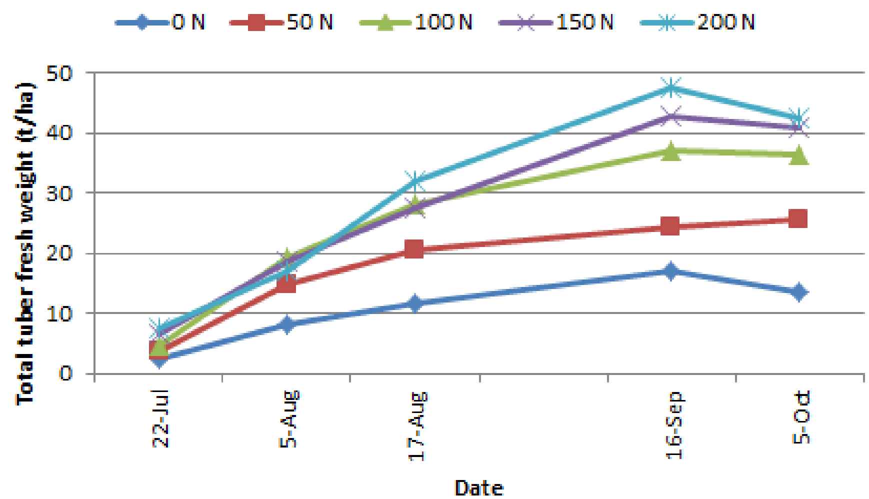

Figure 12. Total tuber fresh weight (t/ha) by harvest date and N fertilization rate (kg/ha), no water inputs from irrigation (I_0), 2012 season.

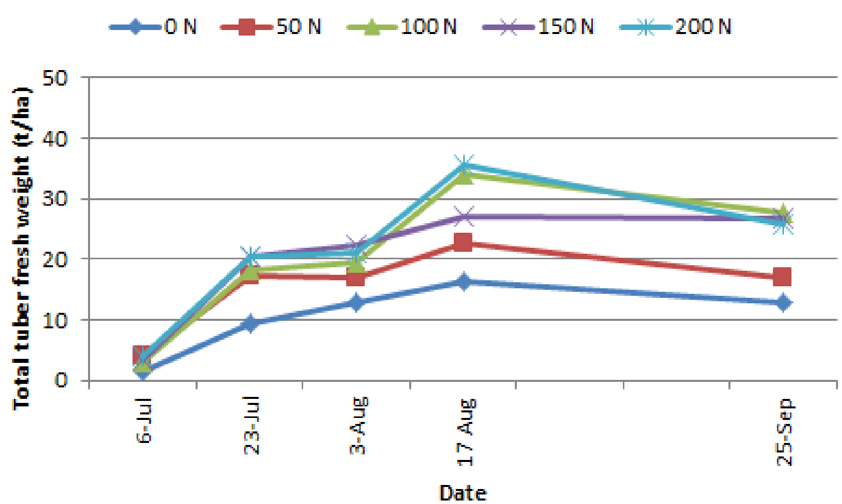

Figure 11. Total tuber fresh weight (t/ha) by harvest date and N fertilization rate (kg/ha), irrigated ($I_{50\%}$), 2011 season.

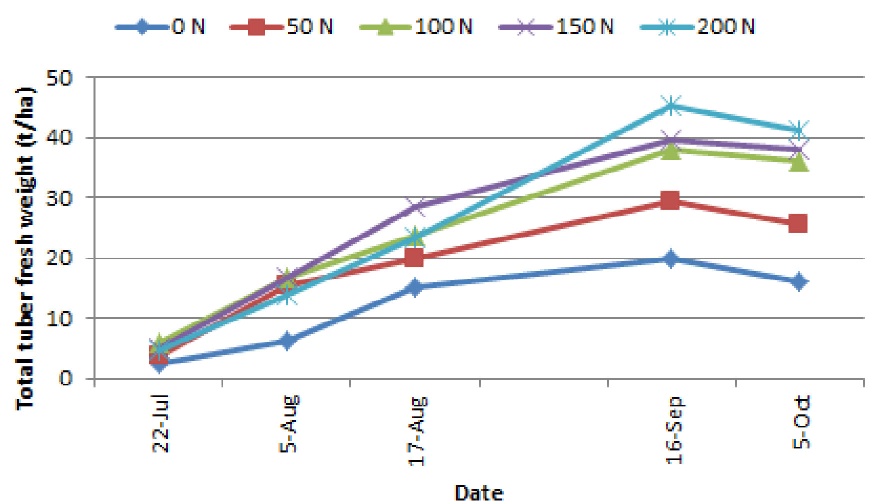

Figure 13. Total tuber fresh weight (t/ha) by harvest date and N fertilization rate (kg/ha), irrigated ($I_{50\%}$), 2012 season.

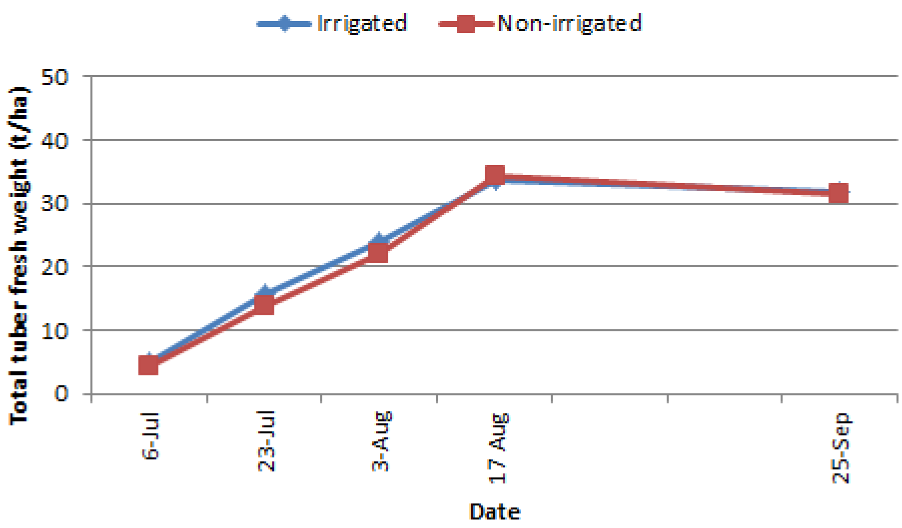

Figure 14. Total tuber fresh weight (t/ha) by harvest date across all N fertilization rates, with ($I_{50\%}$) or without (I_0) irrigation, 2011 season.

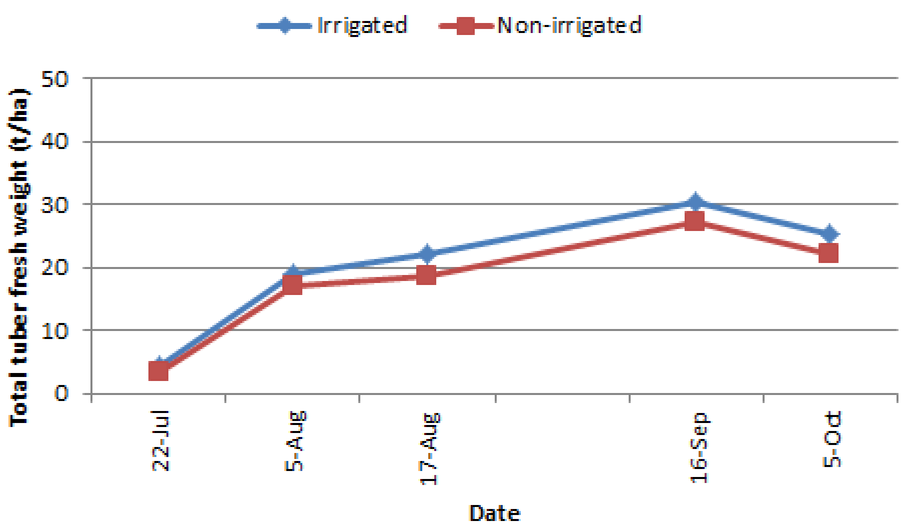

Figure 15. Total tuber fresh weight (t/ha) by harvest date across all N fertilization rates, with ($I_{50\%}$) or without (I_0) irrigation, 2011 season.

Why then are irrigation effects more difficult to detect than those of N fertilization rate? From a statistical point of view, the number of harvests (5 dates) increases the power of the ANOVA to discriminate between treatments. Moreover, in the split plot design technical limitations encountered in the field led to a layout where irrigation and N fertilization rate were implemented as main plot and subplot effects, respectively, heightening discrimination among the latter (NRATE) over the former (IRRIG).

3.2.4 Nitrogen uptake by vines and tubers

In both years, across both irrigation treatments, the impact of N fertilization on vine development and tuber production was directly reflected by plant N uptake (vines and tubers: NRATE, $P < 0.0001$; interaction NRATE × DATE, $P < 0.0001$) (Figure 16 and Figure 17). In both years, levels of N taken up into vines and tubers (N_{tot}^{vine} and N_{tot}^{tuber}) reached roughly equal levels at 70 DAP (2011 : 78 DAP; 2012 : 70 DAP), prior to which N uptake was greater in the vines. In 2011 N_{tot}^{vine} reached 42% to 71% of N fertilizer applied, while in 2012 this proportion was 37% to 61%. Therefore, great part of N uptake had occurred at this point. Thereafter N_{tot}^{tuber} exceeds N_{tot}^{vine}, reaching a peak at 108 and 95 DAP, in 2011 and 2012, respectively. They then each remain largely unchanged until harvest. In 2011, at its peak, N_{tot}^{tuber} increased progressively with fertilization rates from 50 to 200 kg N ha^{-1}, thereby representing 111%, 98%, 78% and 66% of the N application rates. In 2012, these proportions relative to N application rate, were 89%, 81%, 52% and 51%, respectfully. Thus, for N fertilization rates of 100 kg N ha^{-1} or greater and considering the full season, averages of 40% and 60% of the N taken up by the crop will have gone to vines and tubers, respectively.

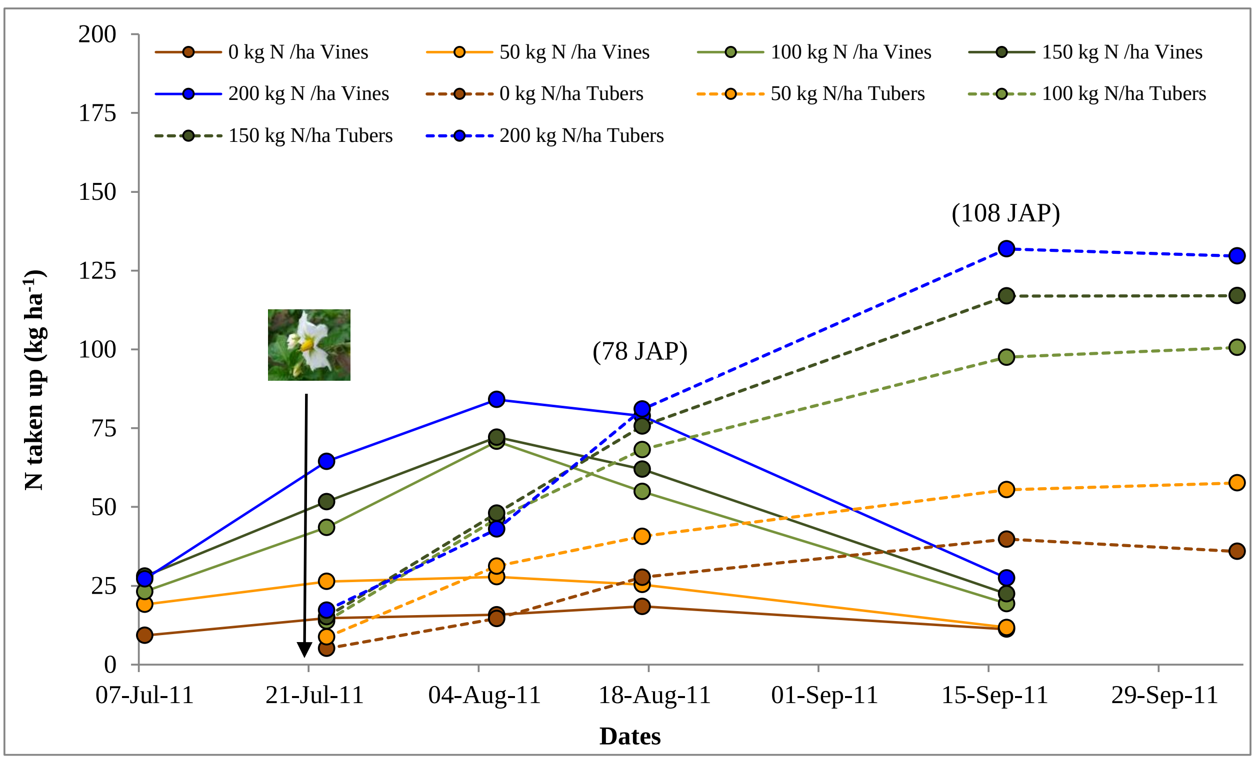

Figure 16**.** Nitrogen taken up by vines and tubers according to N fertilization rate across both irrigation treatments, 2011 season.

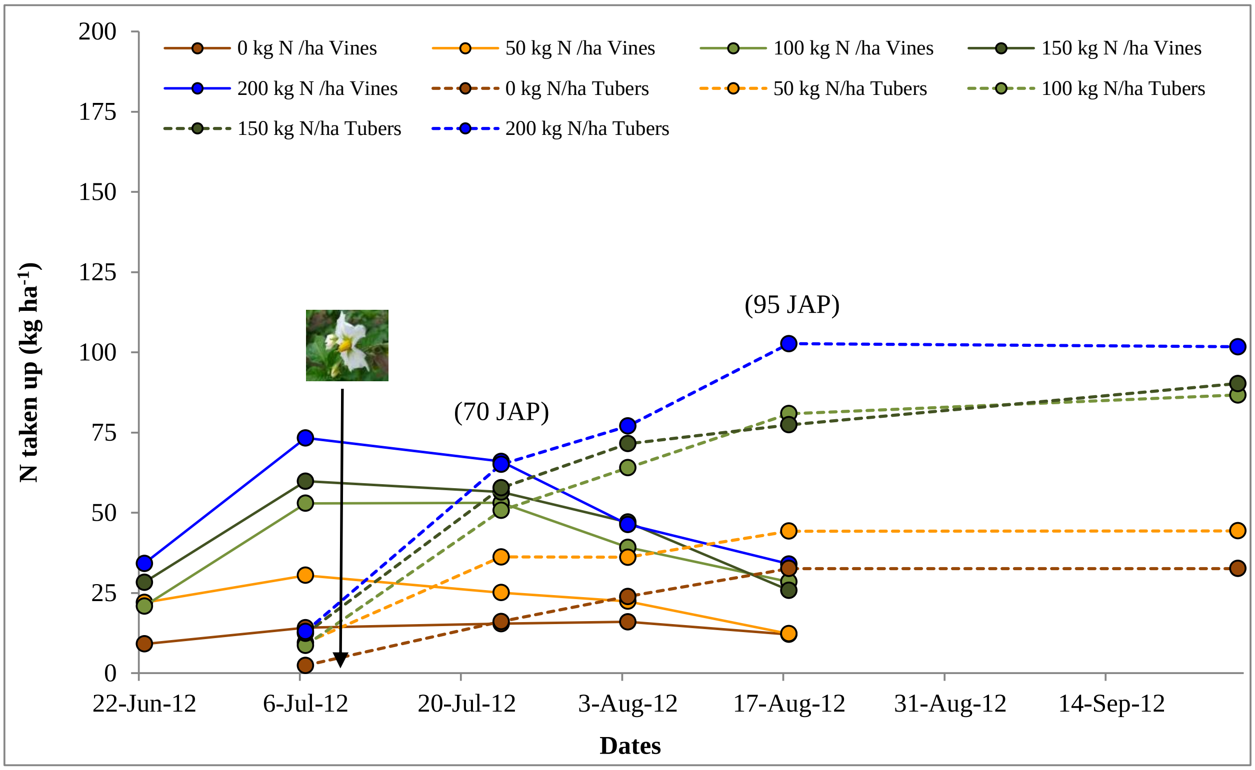

Figure 17. Nitrogen taken up by vines and tubers according to N fertilization rate, across both irrigation treatments, 2012 season.

3.2.5 Overall crop N uptake

As seen in Figure 18 et Figure 19, if N_{tot}^{vine} and N_{tot}^{tuber} (averaged across irrigation treatments) are added to obtain the overall N uptake, N_{tot}^{v+t}, the N fertilization rate was found to have a significant effect in both years ($P < 0.0001$) as did the NRATE × DATE interaction ($P < 0.0001$). This shows that in both years 55% of the final N uptake was completed by flowering, indicating that the pre-flowering period is key to the crop's fertilizer N use. Moreover, from 70 DAP (17 August 2011 and 23 July 2012) onward, N_{tot}^{v+t}levels off right through to harvest. The crop thus used an average of 74 days to take up its N. For the N_{200} application rate this means that, averaged across the two years, the crop had taken up the equivalent of 2 kg N ha^{-1} d^{-1} from planting to 74 DAP. Once levelled off, the N_{tot}^{v+t} values for fertilization rates of 50 through 200 kg N ha^{-1} represented, respectively, 132%, 123%, 92% and 80% of the N applied under these rates in 2011, while for 2012 these proportions were 123%, 104%, 76% and 66 %. The quantity of N taken up per kilogram of N applied varies significantly, decreasing as the N application rate rises. For a given N fertilization rate, crop N uptake differs from year to year, being least in the year when yields were poorest. Moreover, in the N_0 subplots the soil supplied 51 and 45 kg N ha^{-1} in 2011 and 2012, respectively, representing, on average, a third of the recommended N application rate (CRAAQ 2010) of 150 kg N ha^{-1}. This observation highlights the importance of maintaining a healthy soil, since its contribution can be rather significant. In the case of N application rates of 50, 100, 150 and 200 kg ha^{-1}, maximum N_{tot}^{v+t} values were roughly 70, 123, 139 and 160 kg N ha^{-1} in 2011, and 61, 115, 119 and 137 kg N ha^{-1} in 2012.

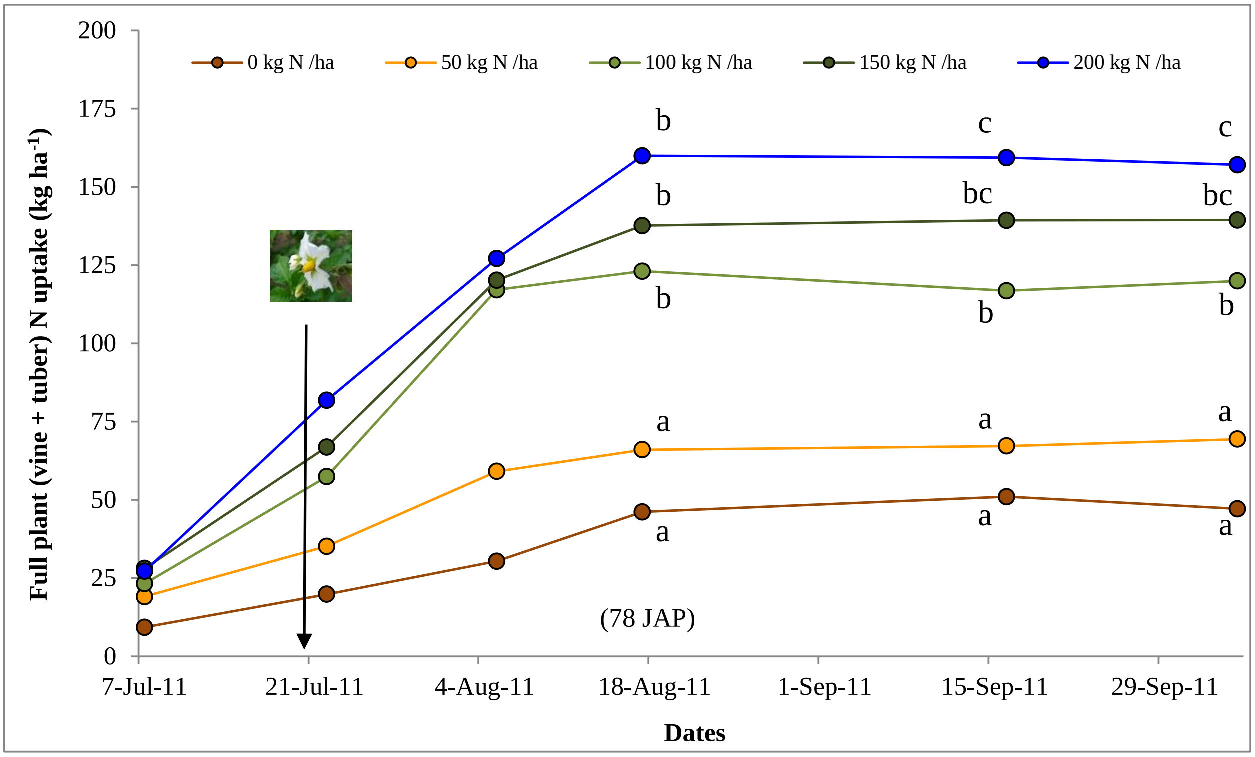

Figure 18. Total (vine + tuber) N uptake, across both irrigation treatments, 2011 season.

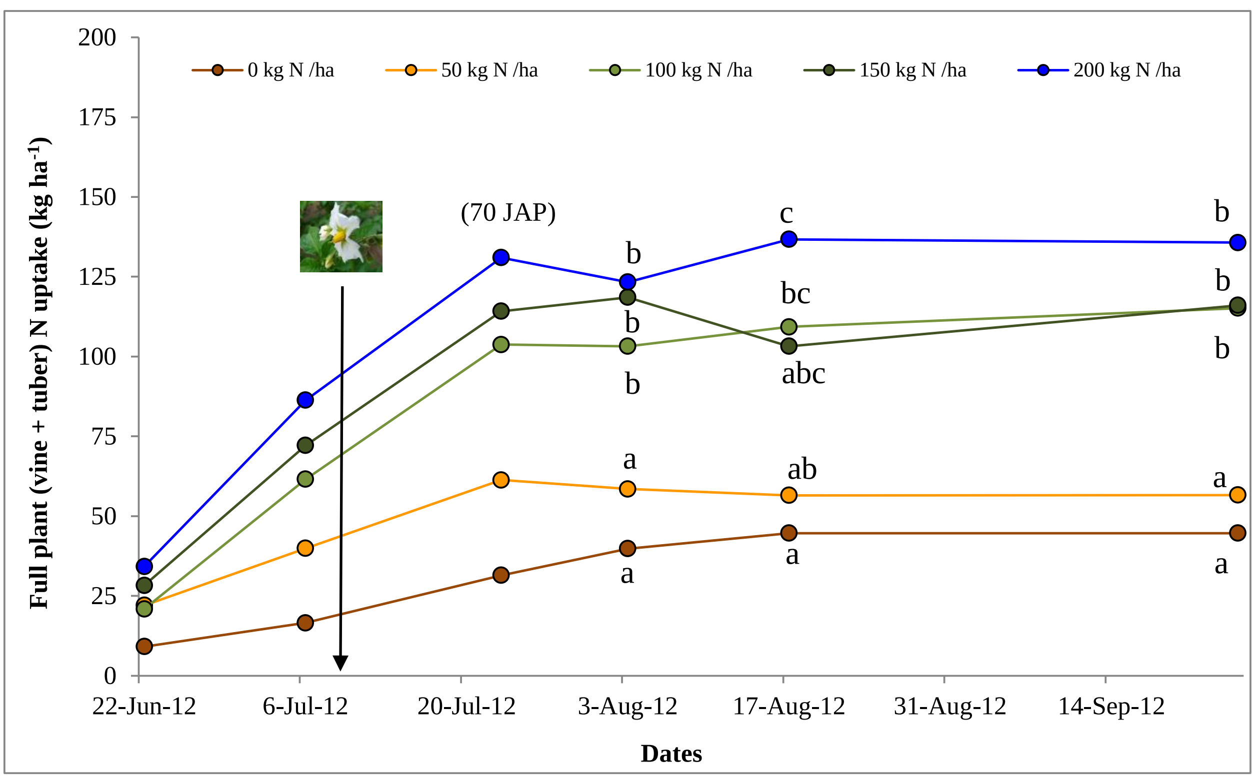

Figure 19. Total (vine + tuber) N uptake, across both irrigation treatments, 2012 season.

3.2.6 Soil N availability

In both years, both N fertilisation rate (2011 and 2012: P < 0,001) and irrigation (2011: P = 0.0369; 2012: P = 0.0017) influenced the plant available N (as NO_3 -N) in the first 0.30 m of topsoil (Figure 20 and Figure 21). In 2011, across irrigation treatments, N fertilization influenced NO_3 -N for the period preceding August 5 (DAP 66; NRATE × DATE, P < 0,001). At that point the soils of N_0 and N_{50} subplots together had 2- and 8-fold less soil NO_3 -N than the N_{150} and N_{200} treatments, respective. However, at all times soil NO_3 -N levels in the N_{100}, N_{150} and N_{200} subplots did not differ significantly. Across all N fertilization rates, for the dates of 22 July (52 DAP) and 5 August (66 DAP), the topsoil of $I_{50\%}$ plots bore 1.16- to 1.46-fold less NO_3 -N than I_0 plots (IRRIG × DATE, P = 0.0204). In 2012, (DATE × NRATE × IRRIG, P < 0,001) the impact of irrigation on soil NO_3 -N levels was even greater, which is in keeping with the much greater number of irrigations having taken place. Thus from July 6 (53 DAP), not only did the soil of N_0 and N_{50} subplots bear less NO_3 -N than the N_{100}, N_{150} and N_{200} subplots, but the difference was much greater in the absence of irrigation. In other words, under irrigation a portion of the additional N contributed by the higher fertilization rates was lost, reducing the differences between the subplots receiving high and low N fertilizer applications.

In 2011, NO_3 -N levels in N-fertilized subplots ranged from 50 to 105 kg ha^{-1} (d.w.b.) just before the second of the split N applications (37 DAP), and between 11 and 151 kg ha^{-1} at the peak of N availability (52 DAP). In 2012, prior to the second fertilization NO_3 -N levels ranged between 16 and 29 kg ha^{-1} and between 11 and 117 kg ha^{-1} at the peak of N availability. In general, for both years: (i) the soil of N_{50} subplots was quickly lost as NO_3 -N after the second fertilization event. (ii) for N_{100}, N_{150}, N_{200} subplots the soil bore between 50 and 79 % of what was provided at the peak of soil N availability, and (iii) the difference between the N input and measured NO_3 -N was always greatest in the N_{200} subplots. Finally, in both years, soil NO_3 -N bottomed out when crop N uptake levelled out, leaving one to wonder whether crop N uptake would not have been greater if NO_3 -N availability had been maintained longer.

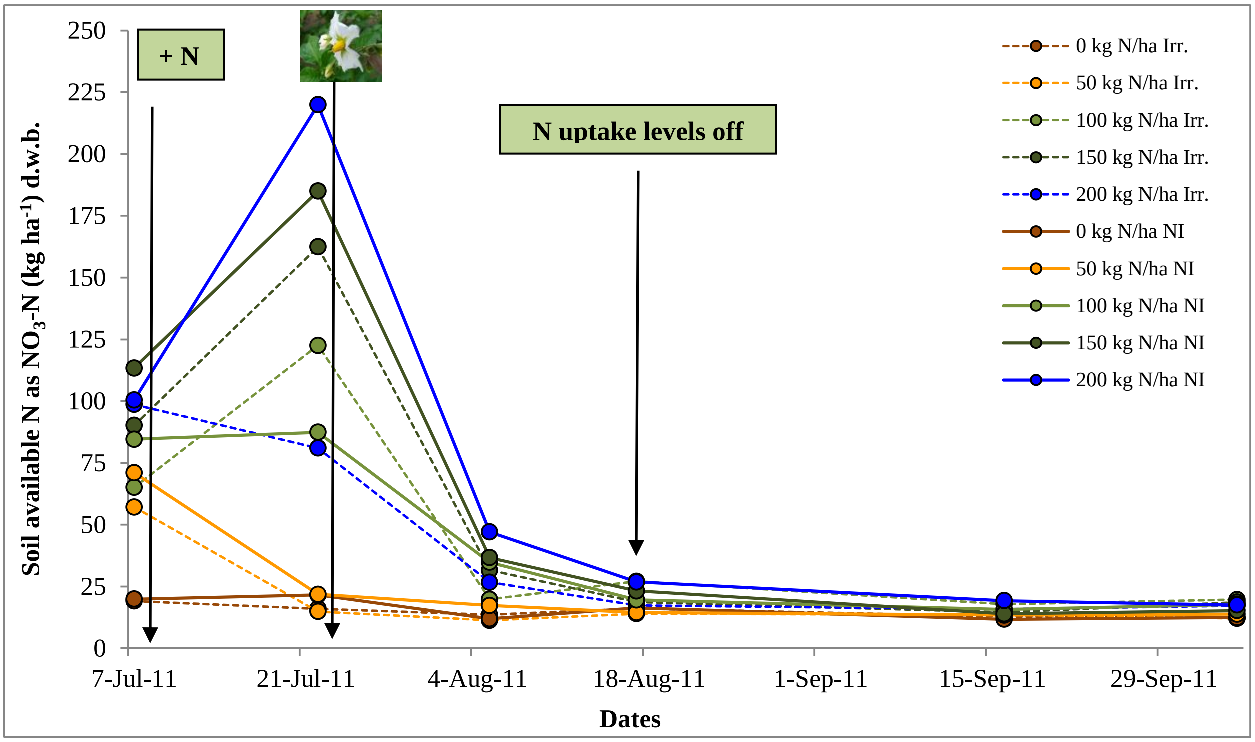

Figure 20. Plant available N (as NO_3 -N) in topsoil (0-0.30 m depth) over the 2011 season, by treatment.

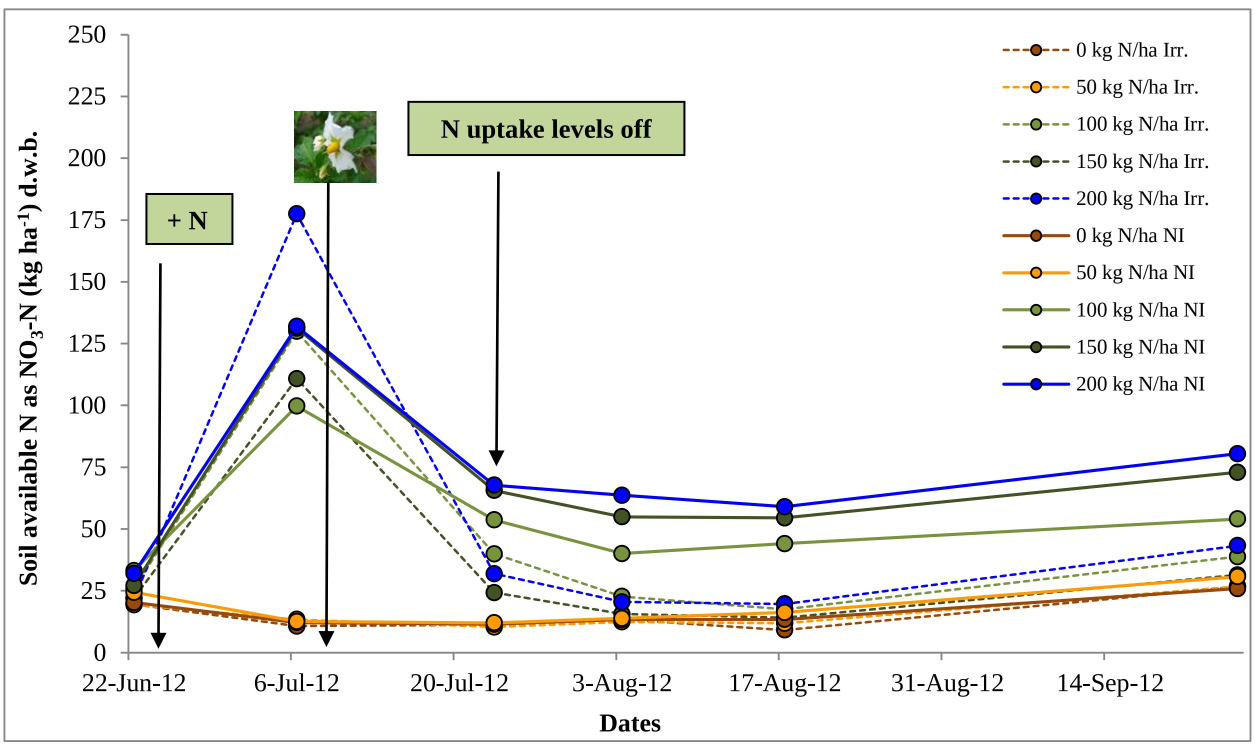

Figure 21. Plant available N (as NO_3 -N) in topsoil (0-0.30 m depth) over the 2012 season, by treatment.

3.2.7 Residual soil N at harvest

Residual NO_3 -N levels at harvest were quite different in 2011 and 2012 (Figure 22 and Figure 23). Indeed, residual NO_3 -N levels were much higher at the end of the poor yielding 2012 season; yields were then 1.4- to 1.7-fold less, and residual NO_3 -N 2- to 6-fold greater, than in 2011. This concurs with the observation that a lesser tuber production entails a lesser N uptake, leaving a greater portion of fertilizer N unused. Moreover, in 2011, neither fertilization rate nor irrigation influenced residual NO_3 -N levels (13 kg ha^{-1}, on average), which is small compared to most of the fertilizer input treatments tested. In contrast, in 2012, both N fertilization rate and irrigation had a significant impact on residual NO_3 -N. In the $I_{50\%}$ plots (*vs.* I_0 plots) residual NO_3 -N levels were much more similar between N fertilization treatments, and much lower overall. Thus, on average, the soil of subplots which were both fertilized and irrigated bore 8 kg ha^{-1} of residual NO_3 -N, while in non-irrigated subplots residual levels were much higher: for N_{50}, N_{100}, N_{150} and N_{200}, residual NO_3 -N exceeded its level in the non-fertilized (N_0) soil by 5, 28, 47 and 54 kg ha^{-1}, respectively. Therefore, for the N_{100}, N_{150} and N_{200} treatments the total measured residual NO_3 -N represented 50%, 46% and 38%, respectively, of the N application rate.

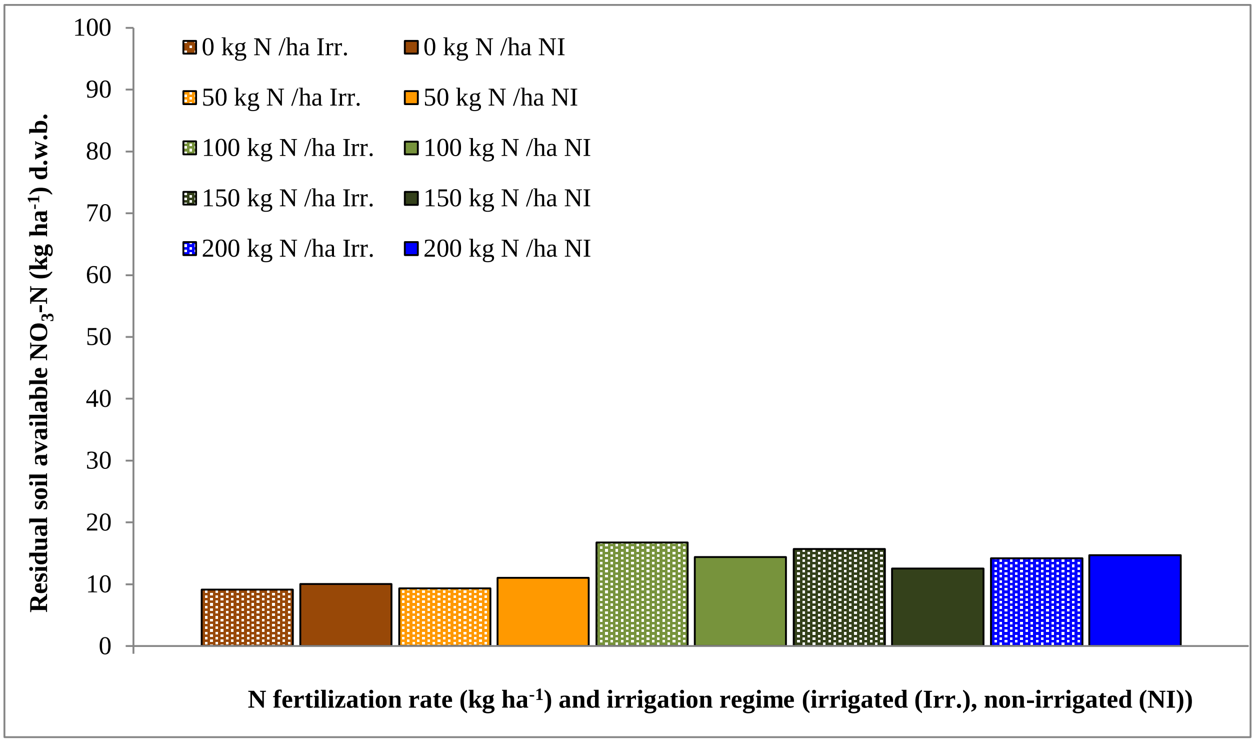

Figure 22. Residual NO_3 -N levels in the top 0.30 m of soil at harvest for different combinations of N fertilization rate and irrigation regime, 2011 season.

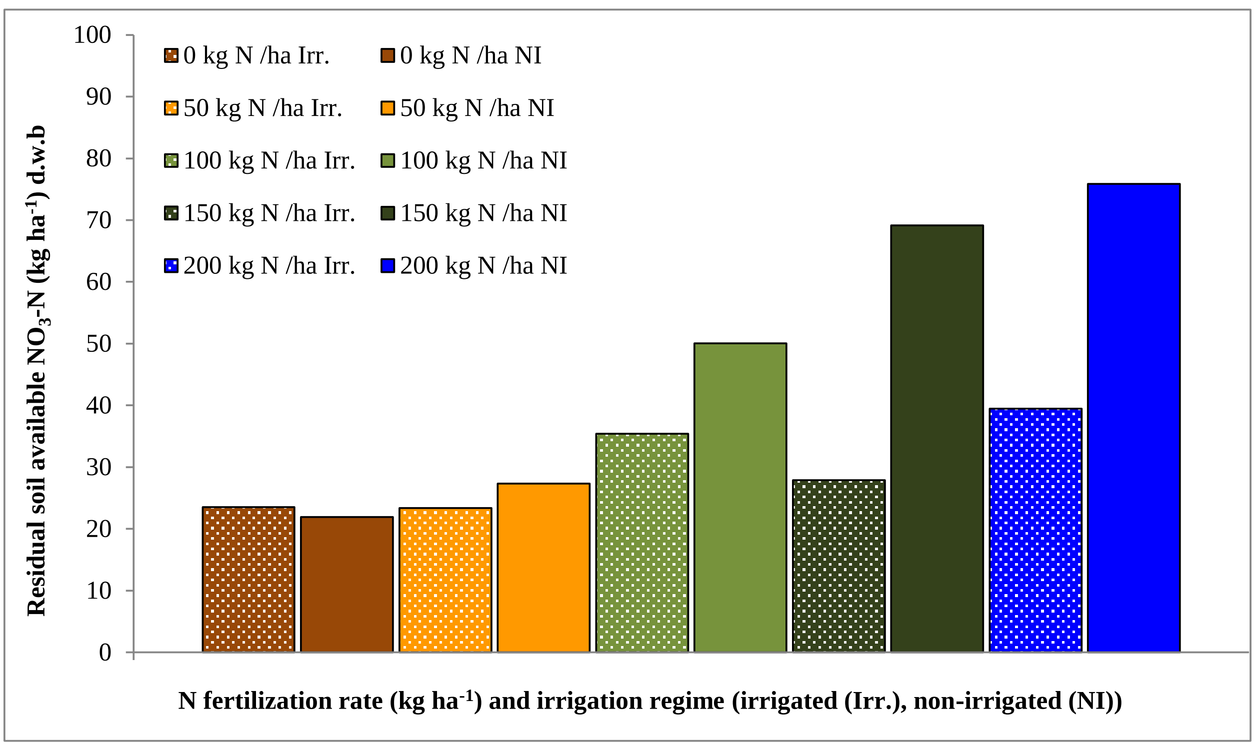

Figure 23. Residual NO_3 -N levels in the top 0.30 m of soil at harvest for different combinations of N fertilization rate and irrigation method, 2012 season.

3.3 Monitoring evolving apparent nitrogen use coefficients (C_{ANU}) over the growing season, according to N inputs with or with irrigation.

The assessment of C_{ANU} values' evolution over the growing season revealed that as early as the flowering stage, 31% to 47% of fertilizer N had already been used (Table 4). Thereafter, this rate increases in magnitude to a greater or lesser extent according to the N fertilization rate. Thus, in the end, the C_{ANU} varies between 24% and 73% depending on the N fertilization rate and year. The variation in yields largely explains the year-to-year differences, with a lesser C_{ANU} occurring when few tubers are produced. As for the influence of N fertilization rate, C_{ANU} in the N_{50} subplots was lowest, even if these subplots received the least N (besides non-fertilized plots). This likely was the result of plants being underdeveloped and therefore having smaller root systems, and thus a lesser access to soil N.

For fertilization rates between 100 and 200 kg ha^{-1}, C_{ANU} declines as fertilization rate increases. The best C_{ANU} was therefore associated within N_{100} subplots: 73% and 71% in 2011 and 2012, respectively. Roughly 30% of the N input was therefore never taken up, which nonetheless represents a good C_{ANU} since this parameter can never reach a value of 100% in practice. Indeed, on average in Quebec, crop C_{ANU} is on the order of 50% in the year of application (N'Dayegamiye and Seydoux 2008). For potato production (vines and tubers) the C_{ANU} rarely exceeds 60% and can drop as low as 30% under unfavourable weather or soil conditions (Tran and al. 1992; CRAAQ 2003). At the recommended rate of N_{150} the C_{ANU} values were 62% and 42% in 2011 and 2012, respectively. At a rate of N_{200}, the C_{ANU} were lower, at 55% and 46% in 2011 and 2012, respectively. When one exceeds the recommended N fertilization rate, the portion of fertilizer inputs not taken up by the crop becomes rather significant. For example, in 2012, in I_0 plots the N_{200} subplots bore NO_3 -N levels of 76 kg ha^{-1} compared to 50 kg ha^{-1} in N_{100} subplots.

Therefore, when the recommended N fertilization rate of 150 kg ha^{-1} was employed (CRAAQ 2010), 57 and 79 kg ha^{-1} remained untapped in the soil medium in 2011 and 2012, respectively. Given an annual average of 68 kg ha^{-1} and 17 000 ha of potato production acreage in Quebec in 2012 (ISQ 2013), this represents 1.2 Gg N remaining untapped in the soil medium. Such quantities are not negligible, and highlight the importance of using the most cost effective N application rate in order to best limit losses, since once this optimal rate is exceeded, the C_{ANU} drops rapidly. For example, in this study the NO_3 -N losses at the N_{200} fertilization rate would theoretically be 1.7 Gg for the same acreage, or 0.5 Gg more than at the recommended N fertilization rate (N_{150}).

Table 4. Apparent fertilizer-nitrogen use coefficients (C_{ANU}) by N fertilization rate, 2011 and 2012 growing seasons.

Years	**Fertilization Rate (kg N ha^{-1})**	**C_{ANU} (%)**†					
		Before 2nd N application ‡	Flowering	Early August	Mid-August	Top-killing	Harvest
		37 DAP 8 July	52 DAP 23 July	66 DAP 6 August	78 DAP 18 August	108 DAP 17 Sept.	140 DAP 19 Oct.
	0	-	-	-	-	-	-
2011	50	20	31	57	40	32	45
	100	28	38	87	77	66	73
	150	25	31	60	63	59	62
	200	18	31	48	57	54	55
		39 DAP 22 June	53 DAP 6 July	70 DAP 23 July	81 DAP 3 August	107 DAP 17 August	134 DAP 25 Sept.
	0	-	-	-	-	-	-
2012	50	26	47	60	37	24	24
	100	24	45	72	63	65	71
	150	26	37	55	53	39	48
	200	25	35	50	42	46	46

† The C_{ANU} takes into account the sum of N taken up by vines and tubers when both were present at the developmental stage listed.
‡ The C_{ANU} calculated prior to the second N application only takes into account the portion of the fertilization applied at planting.

3.4 Monitoring the timing of different potato (cv. Goldrush) crop phenological stages, according to N inputs with or with irrigation.

The rate of N fertilization affected the date at which different phenological stages were reached (**Erreur ! Source du renvoi introuvable.** and 6). In 2011, for the emergence and plant differentiation stages the N_0 plants showed a delay compared to fertilized plants. However, from the floral bud stage onward, the more heavily fertilized plants were, the more advanced their development. The situation in 2012 was similar (Table 6), except that differences were of a lesser magnitude between the N_{100}, N_{150} and N_{200} treatments.

Table 5. Effect of N fertilization rate on occurrence of potato crop phenological stages at four dates in the 2011 season.

	Stage	**Dates**	**Fertilization rate (kg N ha^{-1})**				
			0	**50**	**100**	**150**	**200**
Percent of plants having reached stage on each date	0. Emergence	23 June	46	54	56	59	51
		4 July	93	38	38	31	29
		8 July	0	0	0	0	0
		14 July	0	0	0	0	0
	1. Plant differentiation	23 June	0	0	0	0	0
		4 July	7	61	61	68	69
		8 July	97	53	41	31	19
		14 July	22	3	1	1	0
	2. Floral buds	23 June	0	0	0	0	0
		4 July	0	1	1	1	1
		8 July	3	48	59	69	81
		14 July	73	41	23	26	1
	3. Pedunculated floral buds	23 June	0	0	0	0	0
		4 July	0	0	0	0	0
		8 July	0	0	0	0	0
		14 July	4	53	74	69	91
	4. Flowering Onset	23 June	0	0	0	0	0
		4 July	0	0	0	0	0
		8 July	0	0	0	0	0
		14 July	1	3	3	4	8

Table 6. Effect of N fertilization rate on occurrence of potato crop phenological stages at six dates in the 2012 season.

	Stage	Date	Fertilisation rate (kg N ha^{-1})				
			0	**50**	**100**	**150**	**200**
Percent of plants having reached stage on each date	0. Emergence	6 June	24	46	51	50	50
		14 June	99	69	54	58	58
		20 June	0	0	0	0	0
		4 July	0	0	0	0	0
		12 July	0	0	0	0	0
	1. Plant differentiation	6 June	0	0	0	0	0
		14 June	1	31	46	42	43
		20 June	100	81	71	72	57
		4 July	0	0	0	0	0
		12 July	0	0	0	0	0
	2. Floral buds	6 June	0	0	0	0	0
		14 June	0	0	0	0	0
		20 June	0	19	29	28	43
		4 July	0	0	0	0	0
		12 July	0	0	0	0	0
	3. Pedunculated floral buds	6 June	0	0	0	0	0
		14 June	0	0	0	0	0
		20 June	0	0	0	0	0
		4 July	98	89	91	91	86
		12 July	0	0	0	0	0
	4. Onset of flowering	6 June	0	0	0	0	0
		14 June	0	0	0	0	0
		20 June	0	0	0	0	0
		4 July	2	11	9	9	14
		12 July	0	0	0	0	0
	5. Full flowering	6 June	0	0	0	0	0
		14 June	0	0	0	0	0
		20 June	0	0	0	0	0
		4 July	0	0	0	0	0
		12 July	100	100	75	88	75
	6. Flowering Ended	6 June	0	0	0	0	0
		14 June	0	0	0	0	0
		20 June	0	0	0	0	0
		4 July	0	0	0	0	0
		12 July	0	0	25	13	25

3.5 Assessing if irrigation alters the N fertilization rate needed to achieve an optimal yield.

In this study, neither marketable yields nor the crop's response to N fertilization was affected by irrigation. In 2011 marketable yields were greatest under the N_{150} fertilization rate, while in 2012 no gain in yield was achieved with N fertilization rates above 100 kg N ha^{-1}. The significantly lower yields in 2012 suggest that yield in that year was limited by factors other than the fertilization rate. The most cost effective N fertilization rate was similar in both years, averaging 185 kg N ha^{-1} (Figure 24). However, as previously mentioned, on the one hand the best C_{ANU} was achieved for the N_{100} fertilization treatment, while, on the other hand, at least for 2012, the largest quantity of residual NO_3 -N was measured under the N_{200} treatment. The most cost effective N fertilization rate therefore offers a compromise between the two.

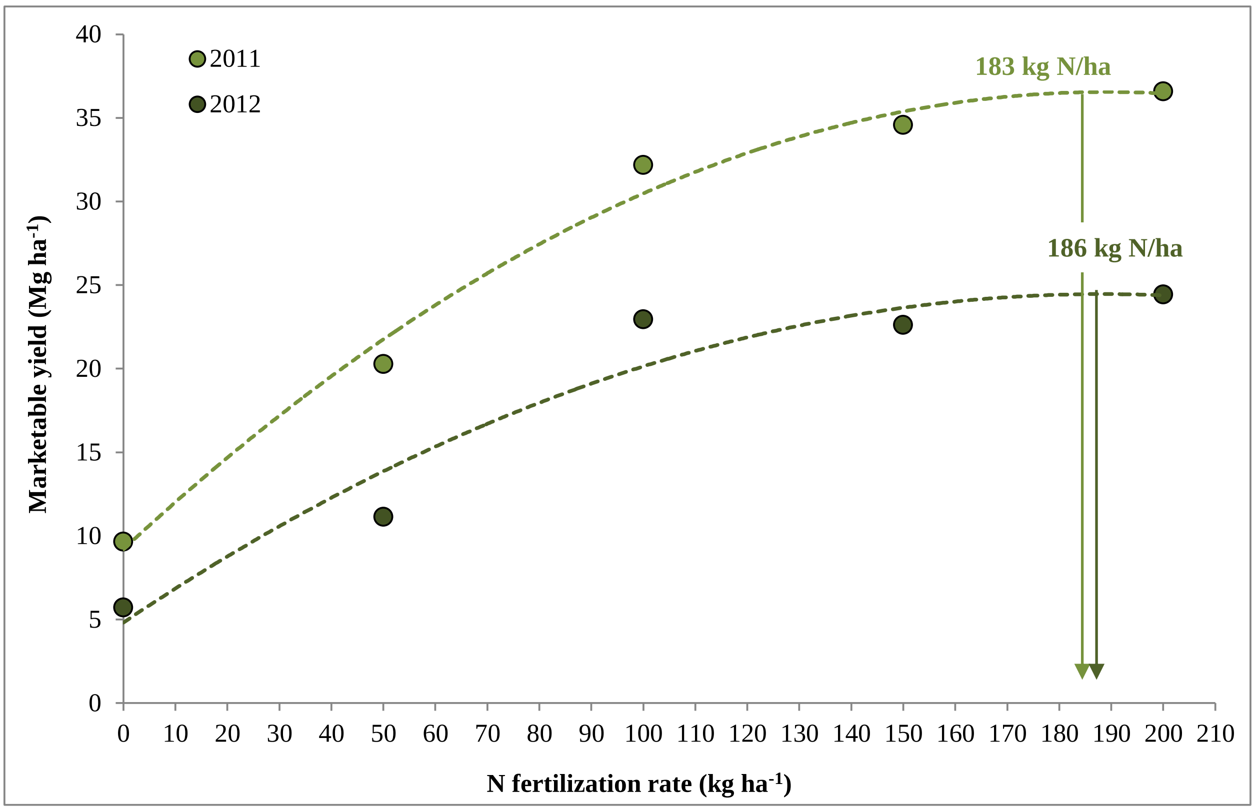

Figure 24. Effect of N fertilization rate on marketable yields in 2011 and 2012.

3.6 Assessing at which point increasing N fertilization alters water demand under an irrigation system triggered when soil available water depletion exceeds 50%.

Table 7 shows the number of irrigations triggered by a 50% soil available water depletion in 2011 and 2012, depending on the N fertilization rate. The fact that in 2012 the number of irrigations needed to maintain the soil's moisture status within the parameters set was twice that required in 2011, can be explained in part by the occurrence of weather conditions more conducive to water stress in 2012 than 2011 (Figure 3–6). In 2011, all irrigation water inputs occurred before 23 July (53 DAP), a period in which less than 25% of final tuber weight had been achieved (Figure 10 and 11), the remaining tuber development occurring under conditions where rainfall was sufficient in maintaining available soil moisture below the irrigation triggering threshold. In 2012, irrigation water inputs occurred between June 23 and 3 August (40-81 DAP), when 75% of final tuber weight had been achieved (Figure 12 and 13).

Now, across both years, it was in N_0 subplots receiving no N-fertilization (*vs*. those receiving 50-200 kg ha^{-1}) that the fewest number of irrigations occurred: 2 and 6 in 2011 and 2012, respectively. The number of irrigations necessary in the N_{50}, N_{100} and N_{150} subplots was similar; however, N_{200} subplots required an additional irrigation. The N_0 subplots might have required fewer irrigations were it not that the poor vegetative development of their plants left the soil surface exposed longer and over a greater area than in fertilized subplots, leading to greater evaporative losses.

Table 7. Number of irrigations applied in 2011 and 2012 by treatment and developmental period.

Year	Treatments	Number of irrgations						Total
		Prior to 2nd fertilizer applic.	**50-75% flowering**	**Early August**	**Mid-August**	**Top-killing**	**Harvest**	
2011	DAP	**0-37**	**38-52**	**53-66**	**67-78**	**79-108**	**109-127**	
	End date	8 July	23 July	6 Aug.	18 Aug.	17 Sept.	19 Oct.	
	$N_0I_{50\%}$	0	2	0	0	0	0	2
	$N_{50}I_{50\%}$	0	3	0	0	0	0	3
	$N_{100}I_{50\%}$	0	3	0	0	0	0	3
	$N_{150}I_{50\%}$	0	2	0	0	0	0	2
	$N_{200}I_{50\%}$	0	4	0	0	0	0	4
2012	DAP	**0-39**	**40-53**	**54-70**	**71-81**	**82-107**	**108-134**	
	End date	22 June	6 July	23 July	3 Aug.	17 Aug.	25 Sept.	
	$N_0I_{50\%}$	0	1	3	2	0	0	6
	$N_{50}I_{50\%}$	0	1	4	2	0	0	7
	$N_{100}I_{50\%}$	0	1	4	2	0	0	7
	$N_{150}I_{50\%}$	0	1	4	2	0	0	7
	$N_{200}I_{50\%}$	0	1	4	3	0	0	8

3.7 Assessing the potential economic return to be drawn from the synergy between N fertilization and irrigation. Generating a production function for potato production in order to determine the best combination of inputs (*i.e.*, the combination of irrigation and N fertilization) which maximizes farmer profits.

The economic analysis consisted in determining the optimal N fertilizer application rates while taking irrigation into account. These optimal rates were derived by maximizing the profit function, which defines the process whereby inputs (irrigation and N fertilizer) are converted into outputs (potato production). In more generic terms, the production function is defined as (Debertin 1986):

$$y = f\ (\mathrm{X}) \tag{9}$$

where :
y is the marketable yield in potatoes (kg ha^{-1}), and
X is the vector of inputs, in the present case irrigation and N fertilization rate.

In econometric terms, the production function can be written in the following quadratic form:

$$y = \alpha + \beta_1 N + \beta_2 N^2 + \beta_3 I + \epsilon \tag{10}$$

where :
N is the N fertilization rate (N_0, N_{50}, N_{100}, N_{150}, or N_{200}),
I is a binary variable indicating whether or not irrigation was applied (I = 0,1);
α, β_k are the coefficients to be estimated; and
ϵ is an error term.

Several other forms of the production function were tested; for example, a variable taking into account the interaction between irrigation and the rate of the second N application was introduced into the model. However, other formulations than the one shown (Eq. 10) did not provide any advantages in terms of coefficient of determination (R^2), coefficient (β_k) t statistics, or in the power to forecast marketable yields (y) from the different treatment factors tested. Consequently, the adoption of the form shown in Eq. 10 was maintained. This equation, besides including fertilizer and irrigation inputs, takes into account the declining marginal return of N inputs, thereby establishing a profit function maxima which follows the production function. This profit function is determined by attributing prices to the appropriate inputs and outputs. Thus the profit function takes on the following form:

$$\pi = p\,.\,f\ (\mathrm{X}) - w(\mathrm{X}) \tag{11}$$

where,
π is the profit,
p is the price of white-fleshed potatoes[1], and
w is the cost of inputs

[1] Average bulk white potato prices between July 2011 and June 2012, for the 2011 production year, and from July 2012 to May 2013, for the 2012 production year. Prices are as published by the Quebec Potato Growers Federation (http://www.fpptq.qc.ca/prix.htm, accessed 29 October 2013).

The profit function is then maximized by obtaining its first derivative and making it equal to zero; optimal N fertilization rates can then be determined.

$$\text{Max. } \pi = \frac{d\pi}{dN}[p \,.\, f\ (\mathrm{X}) - \ w(\mathrm{X})] = 0 \qquad (12)$$

$$p. f_1 = w \ \Rightarrow \ f_1 = \frac{w}{p} \qquad (13)$$

where :

f_1 is the first derivative of the production function on *N*, the N fertilization rate.

Data from the agronomic measurements made in the present study made it possible to develop production functions for both 2011 and 2012. This step was completed using Stata (ver. 12) econometrics and statistics software. From these production functions, the profit function was maximized for each year and the optimal N fertilization rates determined.

<u>The production functions for 2011 and 2012 were.</u>

i) Production function – 2011 production season :

$$y = \underset{(P<0.001)}{9.204429} + \underset{(P<0.001)}{(0.2893579N)} + \underset{(P<0.001)}{(-0.0007652N^2)} + \underset{(\mathrm{P}=0.990)}{(-0.0179997I)} \qquad (14)$$

ii) Production function – 2012 production season :

$$y = \underset{(P=0.117)}{2{,}734286} + \underset{(P<0{,}001)}{(0{,}2085261N)} + \underset{(P=0.037)}{(-0{,}0005534N^2)} + \underset{(P=0.055)}{(4.1685I)} \qquad (15)$$

In Eqs. 14 and 15, the *P* values presented beneath the coefficients refer to their statistical significance, where values of $P \leq 0.05$ indicate the coefficient to be significant at a 95% confidence level. On this basis, irrigation is shown not to have had a significant effect on yields ($P > 0.05$).

<u>Maximization of profit functions</u>

In the present context, the maximization of the profit function (Eq. 12) for the two years of production, leads to the most cost effective N application rates (N^*_{2011} and N^*_{2012})

iii) Most cost effective N fertilization rate for the 2011 production season :

$$f_1 = \frac{w}{p} \qquad \Rightarrow \qquad 0.2893579 + (2\,x \ \ -0.0007652N) = \frac{w}{p} \qquad (16a)$$

$$N^*_{2011} = \frac{\left(\frac{w}{p} - 0.2893579\right)}{(2\,x \ -0.0007652)} \qquad (16b)$$

i) Most cost effective N fertilization rate for the 2012 production season :

$$f_1 = \frac{w}{p} \qquad \Rightarrow \qquad 0.2085261 + (2\,x \ \ -0.0005534N) = \frac{w}{p} \qquad (17a)$$

$$N^*_{2012} = \frac{\left(\frac{w}{p} - 0.2085261\right)}{(2\,x \ -0.0005534)} \qquad (17b)$$

The values of N^*_{2011} and N^*_{2012} can therefore be derived from current potato and N fertilizer prices. Mean bulk white potato prices were \$399.12 Mg^{-1} for the 2011 production season. The cost of N fertilizers were drawn from Quebec's Reference Centre on the Agricultural and Agri-food Industry (CRAAQ 2013) and based on a kilogram of N drawn from a 27-0-0 fertilizer. The average price of N was \$2.28 kg^{-1} for 2011 and 2012.[2] However, as the CRAAQ makes clear, this price does not take into account discounts for advanced payment or volume purchasing. Therefore, the N^*_{2011} and N^*_{2012} values were calculated for three N price levels (Table 8): \$1.75 kg^{-1}, \$2.00 kg^{-1} and 2.25 kg^{-1}.

Table 8. Most cost effective N fertilizer application rate as a function of potato and N fertilizer prices, in 2011 and 2012.

Year	**Price of potatoes (\$ Mg^{-1})**	**Price of nitrogen (\$ kg^{-1})**	**Most cost effective N fertilizer application rate (kg ha^{-1})**
2011	399.12	1.75	186
		2.00	186
		2.25	185
2012	350.59	1.75	184
		2.00	183
		2.25	183

From the results presented in Table 8 it is evident that the most cost effective N fertilizer application rate varies little. Indeed, based on 2011 and 2012 white potatoes sales prices, the most cost effective N fertilizer application rate varies little, remaining around 185 kg ha^{-1}. The slight variations observed depend more on changes in potato prices than changes in N fertilizer prices.

These results are based on agronomic outcomes and prices in the production years 2011 and 2012. Obviously, the most cost effective N fertilizer application rate could be quite different depending on market conditions. In the case where the price of N fertilizers proportionally follows that of potatoes, the most cost effective N fertilizer application rates would show little variation. For example, at the time of writing this report the price of 27-0-0 fertilizer was \$624 Mg^{-1} before discounts (CRAAQ 2013), or \$2.31 kg^{-1} N, while the mean price for the 2013 white potato harvest was around \$500 Mg^{-1}. Substituting these prices in Eqs. 16b and 17b, the N^*_{2013} still remains around 185 kg ha^{-1}.

Based on the results of the present project it therefore seems that the most cost effective N fertilizer application rate diverges little from 185 kg ha^{-1}. Obviously, this ideal fertilization level can vary from one farm to another, according to soil and weather conditions. The rate of N fertilization must therefore take into account the agroenvironmental risks that may arise under these conditions.

[2] [(\$578 Mg^{-1} + \$651 Mg^{-1}) ÷ 2] ÷ (270 kg Mg^{-1})

3.8 Influence of soil organic matter on weight and quality of tubers grown in the presence or absence of irrigation

3.8.1 Tuber yield by weight

In 2011 and 2012, the soil organic matter content (SOM) was measured in each of the experimental field's 40 subplots. For each of the two seasons the total tuber weight (yield by weight) per subplot is known. Total tuber yield by weight and SOM are shown for 2011 and 2012, according to whether subplots did not receive any irrigation (Figure 25 and 27, respectively), or did receive water inputs through irrigation (Figure 26 and 28). For each of these two irrigation regimes, the 20 subplots shown, were further sub-grouped by their N fertilization rate, and, finally, their individual SOM contents are shown.

In 2011, the results in the I_0 and $I_{50\%}$ plots are similar (Figure 25 and Figure 26). With respect to fertilization, besides the yield of tubers measured in N_0 subplots (<15 t/ha), the tuber yields by weight measured for the other N fertilization rates (N_{50}–N_{200}) varied from rate to rate and within a given rate. In 2012, a similar situation ensued, but the variation in tuber yields between subplots, while not evaluated statistically, seemed strongly influenced by the SOM, regardless of the subplot's irrigation status. Indeed, overall, in the absence of irrigation, the tuber yield was lower in subplots where SOM<1.4% than in subplots where SOM> 1.6% (Figure 27). However, under irrigation these differences in tuber yield were obscured (Figure 28) and more of the subplots had yields under 15 t/ha. The subplots where lower tuber yields and SOM were measured seemed to profit more from irrigation than did other subplots. In so doing, irrigation contributed to reducing yield variability.

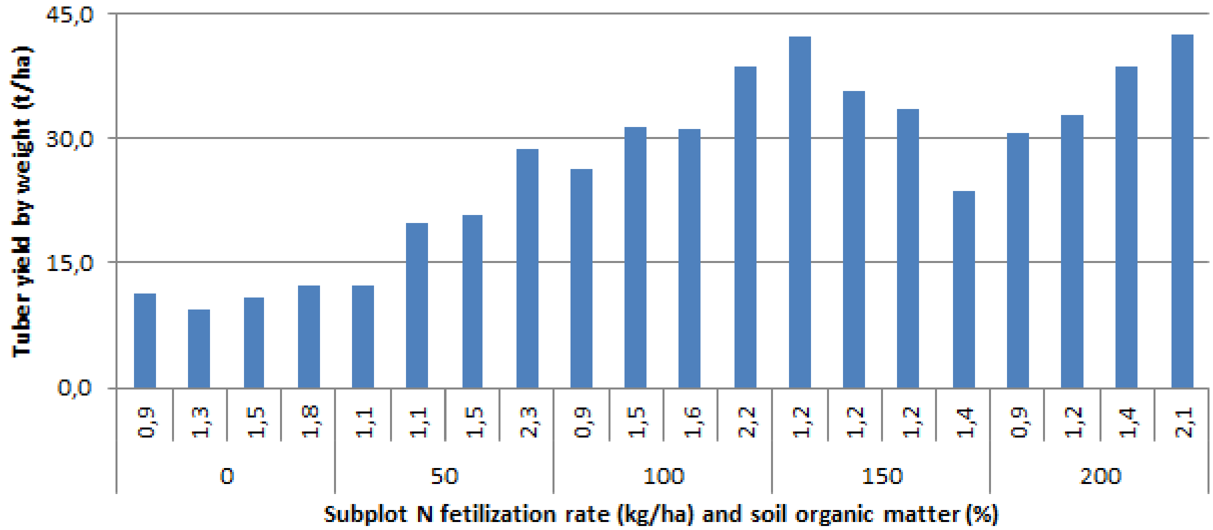

Figure 25. Tuber yield by weight (t/ha) by N fertilization rate (kg/ha) and soil organic matter (%) – no irrigation, 2011 season.

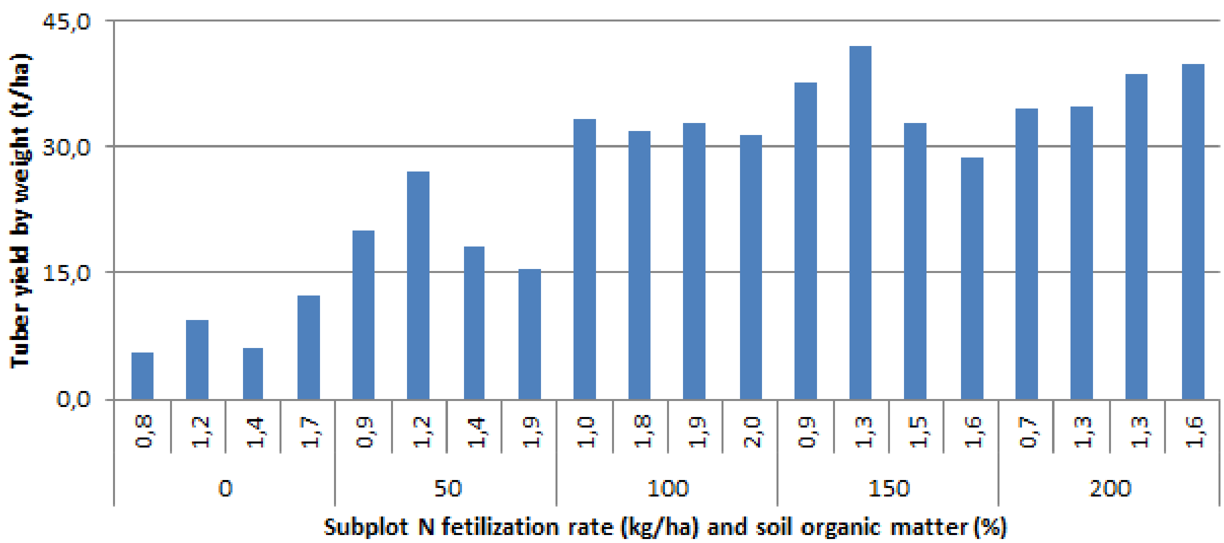

Figure 26. Tuber yield by weight (t/ha) by N fertilization rate (kg/ha) and soil organic matter (%) – irrigated, 2011 season.

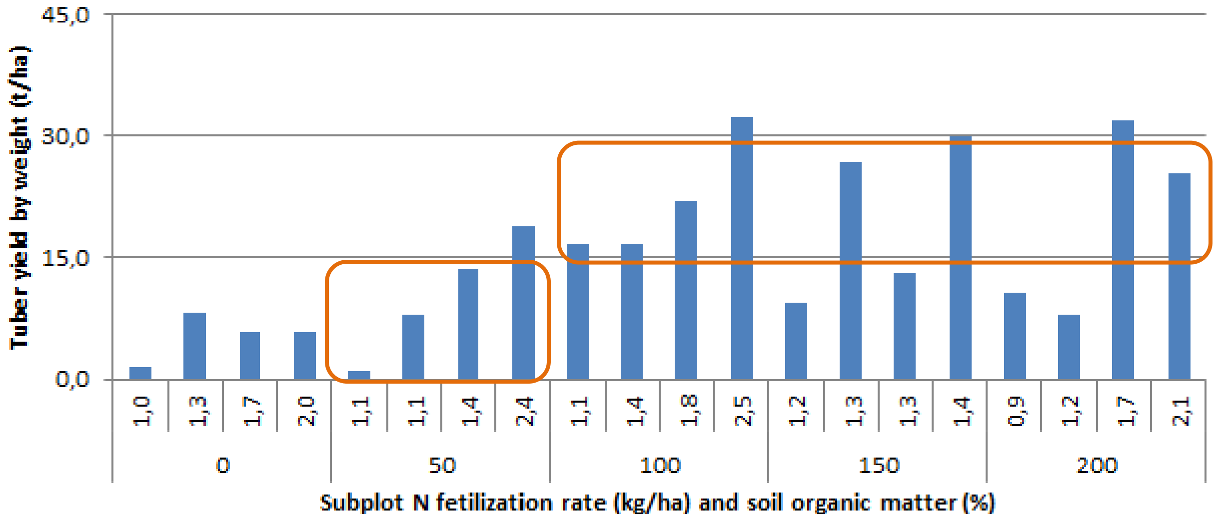

Figure 27. Tuber yield by weight (t/ha) by N fertilization rate (kg/ha) and soil organic matter (%) – no irrigation, 2012 season.

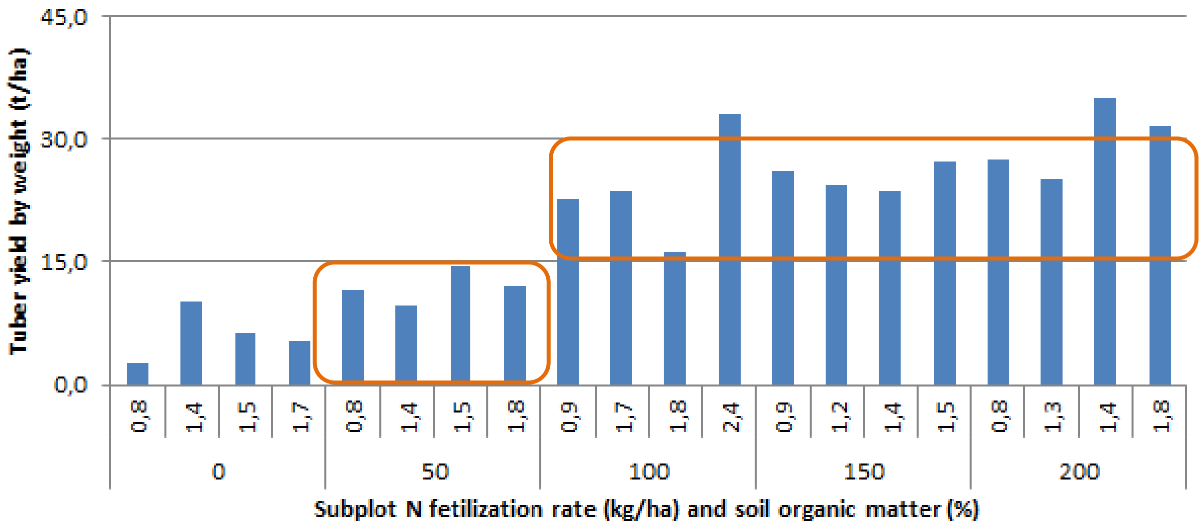

Figure 28. Tuber yield by weight (t/ha) by N fertilization rate (kg/ha) and soil organic matter (%) – irrigated, 2012 season.

3.8.2 Tuber specific gravity

For each subplot the mean specific gravity of tubers harvested at the end of the season is presented by year, N fertilization rate and SOM, according to whether these were irrigated or not (Figures 29 and 30). A relationship between tuber specific gravity and SOM is apparent in 2012, the specify gravity being greater in subplots richer in SOM. However, under irrigated conditions, as observed for tuber yield by weight, the specific gravity of tubers was greater and showed fewer variations.

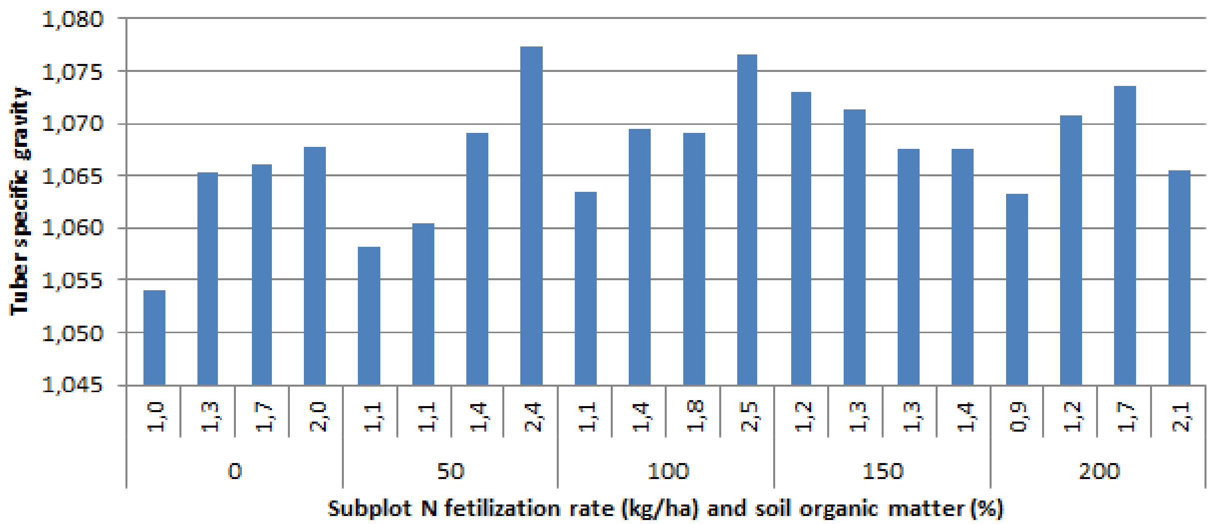

Figure 29. Mean tuber specific gravity by N fertilization rate (kg/ha) and soil organic matter (%) – subplots receiving no irrigation, 2012 season.

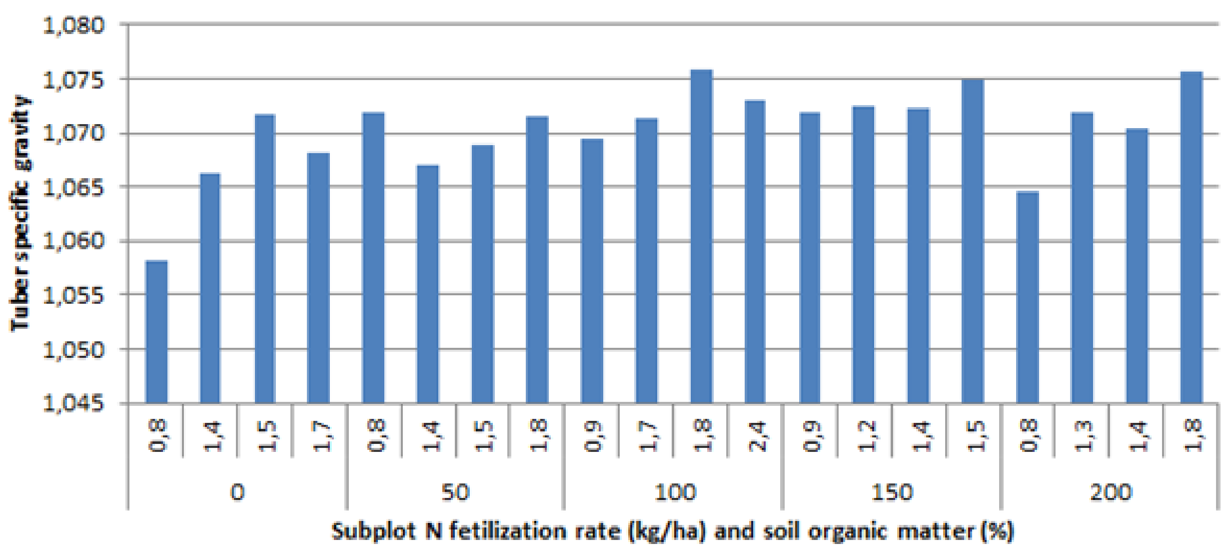

Figure 30. Mean tuber specific gravity by N fertilization rate (kg/ha) and soil organic matter (%) –irrigated subplots, 2012 season

4 CONCLUSIONS

Monitoring crop N uptake showed that by the flowering stage 55% of the seasonal total N uptake had occurred. Some 20 days later the total (vine + tubers) N taken up levelled off. The crop therefore takes up N for an average of 74 days, with the period prior to flowering being crucial. At the same time soil NO_3 -N levels reached their lowest level. This leads one to wonder if crop N uptake might not have levelled off later if the availability of NO_3 -N had been maintained longer. With respect to plant nutrition and development, nothing was gained by exceeding the 100 kg N ha^{-1} fertilization rate. However, while marketable yields were higher at 150 kg N ha^{-1} fertilization rate in 2011, this was not the case in 2012, when yields for N fertilization rates of 100 kg N ha^{-1} and up were largely the same. Yields in 2012 were much lower than in 2011, suggesting that in that year yield was limited by conditions other than fertilization. While, for its part, irrigation did not affect N fertilization impacts on yield, N fertilization rate did indeed alter the crop's water needs, with a greater number of irrigations being required at the higher N fertilization rates. While irrigation generally had little impact on the production parameters measured, in 2012 the tuber yield across all N fertilization rates was greater in irrigated (*vs*. non-irrigated) plots. However this was not the case for marketable yields, and was not observed in 2011. Irrigation's limited impact can nonetheless be explained by the number and timing of the irrigations. In 2011, all water inputs occurred prior to a quarter of the tubers' final weight having been reached (23 July), the remainder of water requirements having been supplied by rainfall. In 2012, twice as many irrigations were applied as in 2011, with the greater portion of water inputs occurring between 23 June and 3 August, when nearly 75% of final tuber weight had been achieved.

At harvest, the best apparent nitrogen use coefficients (C_{ANU}) were found for the N_{100} subplots, with C_{ANU} values of 73% and 71% in 2011 and 2012, respectively. At the high N fertilization rate of N_{200}, the C_{ANU} dropped substantially to 55 % and 46% in 2011 and 2012, respectively. Using the most cost effective N fertilizer application rate (185 kg N ha^{-1} in both years) presents an interesting compromise between maximizing revenue and environmental protection. Indeed, in N_{200} subplots, 90 and 108 kg ha^{-1} of fertilizer N remained untapped in 2011 and 2012, respectfully. These non-negligeable quantities highlight the importance of fertilizing in an optimal manner in order to limit, as much as possible, levels of leaching-prone residual NO_3 -N. In this case, irrigation management is also key, as in both years irrigation has a significant effect on soil NO_3 -N. Depending at what point of the season it was measured, the rise in soil NO_3 -N which occurred with a rise in N fertilization rate was of lesser magnitude under irrigation than in its absence. A portion of the surplus N supplied by the higher fertilizer rates therefore seem to have been lost. Indeed, for the 2012 season, which was subject to a greater number of irrigations than 2011, residual NO_3 -N levels at harvest were much inferior in irrigated plots than non-irrigated plots, where residual NO_3 -N levels reached 50 to 76 kg NO_3 -N ha^{-1} for the N_{100} and N_{200} fertilization rates. Therefore, in irrigated plots a substantial portion of residual NO_3 -N appears to have been lost by leaching. Moreover, the substantial difference of 26 kg NO_3 -N ha^{-1} between the N_{100} and N_{200} subplots highlights the importance of not exceeding the ideal N fertilization rate, since residual NO_3 -N can be very high, particularly in years with poor yields, when plant N uptake has been limited.

Lastly, this study's results demonstrate the importance of having a good knowledge of one's soil so as to avoid inputs (N, water) unnecessary to a healthy soil. Indeed, in the absence of N fertilization, the soil alone supplied 51 and 45 kg N ha^{-1} in 2011 and 2012, respectively. A healthy soil's N contribution can therefore be quite significant. An analysis of results with respect to SOM content showed that in a drier year like 2012 the level of SOM had an impact on total tuber weight at harvest, with lesser weights when SOM < 1.4%, compared to plots where SOM > 1.6 %. In soils poorest in SOM, irrigation did indeed help in raising total tuber weight and reducing its variability, with a number of subplots producing between 15 and 30 Mg ha^{-1}. Similar observations were made for tuber specific gravity. In conclusion, it would be particularly relevant to assess the gains in marketable potato yield to be made through N fertilization and irrigation, in the light of soil available water and other soil parameters such as SOM and compaction rate, in order to avoid compensating for soil degradation by increasing inputs.

5 BIBLIOGRAPHY

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6 DISSEMINATION OF RESULTS

- On IRDA's website http://www.irda.qc.ca, since April 2011.
- Information Day: *Water and mineral nutrition of potato: A unified management to increase productivity!* Organised by IRDA, 29 November 2013, in Quebec (QC).