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Yield and Quality Response of Two Potato Cultivars to Nitrogen Fertilization

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Abstract Potatoes require high nitrogen (N) fertilizer rates because of their poor N efficiency. Better understanding of N dynamic in potato crops could improve N efficiency and thus enhance crop profitability and reduce N losses. A similar field experiment was conducted in Switzerland in 3 years, from 2009 to 2011, to investigate the yield and quality response to N fertilization of two commercial potato cultivars with different tuber qualities, Bintje and Laura. Five doses of ammonium nitrate were tested: 0, 80, 120, 160 and 200 kg N ha^{-1}. Aboveground and belowground biomass evolution, total yield, starch concentration and tuber sizes were measured annually. In 2011, the total N uptake and the soil mineral N content were also measured during the growing season and at harvest.

The study showed that N fertilization had a positive effect on yield and the percentage of large tubers (> 70 mm) and a negative effect on starch concentration. Both cultivars presented the same potential yield, although cv. Laura's yield was more affected by N fertilization deficiency and more responsive to the late N fertilizer application. At harvest, both cultivars had a similar N uptake efficiency and N utilization efficiency. However, they differed with respect to N uptake dynamics. Nitrogen uptake was slower for cv. Laura than for cv. Bintje due to a longer period required for the development of the belowground biomass. The results provide useful recommendations for improvement of N fertilization practices (e.g. rate and time of application) of these two cultivars in Swiss conditions.

Keywords Belowground biomass · Nitrogen nutrition index · Nitrogen uptake · Nitrogen use efficiency · Starch concentration

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Introduction

Obtaining high yields and quality, while minimizing nitrogen (N) losses, is one of the major challenges for potato producers. Potatoes require high rates of N fertilizers because of their poor N efficiency (Errebhi et al. 1998a). The estimated range of N fertilizer efficiency from the whole plant is broad (29–77%); however, the most common range is from 40 to 60% (Zebarth and Rosen 2007). The low N fertilizer efficiency is partly due to a shallow root system, which is usually confined to the upper 60-cm soil layer, and of which, 90% is in the top 25 cm (Tanner et al. 1982). In addition, the potato is often cultivated on sandy soils and under irrigation, which makes it prone to N losses through nitrate leaching (Hill 1986; Zebarth and Rosen 2007). Davenport et al. (2005) reported that these losses range from 10 to 200 kg N-NO_3 ha^{-1} worldwide.

Thus, improving N use efficiency (*NUE*) of applied N fertilizer is important for increasing crop profitability and reducing N losses. Applying optimum and timely N fertilizer rates is an effective tool for increasing NUE. Studies have shown that the risk of nitrate leaching to groundwater increases rapidly as N fertilizer rates rise above the optimum N rate (Van Es et al. 2002; Houles et al. 2004). In many cases, applying N fertilizers at the optimum N rate may be sufficient to achieve both economic and environmental objectives (Houles et al. 2004). Additionally, application of timely N fertilizer rates according to N uptake demands is commonly proposed as a means of improving NUE in crop production systems (Bundy et al. 1986).

Currently in Switzerland, N fertilizer recommendations do not take into account the differences in NUE between cultivars (Sinaj et al. 2009). However, various studies (Errebhi et al. 1998b, 1999; Sattelmacher et al. 1990a; Sharifi et al. 2007; Zebarth et al. 2004b, 2008) have shown that there are differences in NUE among cultivars. A wider range in NUE has been reported for wild potato accessions than for commercial potato cultivars (Errebhi et al. 1998b). Within commercial cultivars, NUE also varies according to maturity class (Errebhi et al. 1998b, Zebarth et al. 2004b). This emphasizes the importance of comparing cultivars of similar maturity classes when screening for NUE (Zebarth et al. 2004b).

The objective of this study was to investigate the effects of N fertilization on the yield and quality of two potato cultivars with the same maturity class but different tuber characteristics. The study was conducted from 2009 to 2011 in Switzerland on two commercial potato cultivars, Bintje and Laura. The specific aim of the research was to establish whether or not the effects of N fertilizer rates and their time of application depend on the cultivar.

Materials and Methods

Experimental Design

Field experiments were conducted at Agroscope-Changins (16° 24′ E, 06° 13′ N; altitude: 445 m) from 2009 to 2011 on Calcaric Cambisols (FAO classification). Potato cultivars were planted each year on a new field adjacent to the field from the previous year. Soil characteristics of the fields for each year are presented in Table 1. From planting to harvesting of the potato, the total water inputs (sum of precipitations and irrigations) were 402 mm in 2009, 455 mm in 2010 and 481 mm in 2011. During the same period, mean temperatures were 17.3, 16.3 and 17.0 °C in 2009, 2010 and 2011, respectively. The fields were irrigated with 30 mm when the crop hydric deficit reached 40 mm. The deficit was calculated following the model of evapotranspiration of Turc (1961).

Each year before the start of the experiment, the fields were planted with winter cereals followed by an intercrop (fodder radish in 2009 and phacelia plus clover in 2010 and 2011). Crop residues from the winter cereals and the intercrop were incorporated into the soil by ploughing at 20–30 cm deep followed by rotary harrowing at 5 cm deep. Crop management details are described in Table 1. Superphosphate [$Ca(H_2PO_4)_2 \cdot H_2O$], potash salt (KCl) and magnesium chloride ($MgCl_2$) fertilization were applied at planting. Rates of these fertilizers were calculated according to the Swiss

Table 1 Principal physical-chemical soil and crop management characteristics

	Years		
	2009	2010	2011
Soil properties at planting (0–20-cm depth)			
Clay (g kg^{-1})	232	321	273
Sand (g kg^{-1})	330	309	297
Organic matter (g kg^{-1})	20	32	23
pH (H_2O)	7.2	7.3	7.4
Available P (mg kg^{-1})[a]	77	97	130
Available K (mg kg^{-1})[a]	247	234	289
Available Mg (mg kg^{-1})[a]	105	126	116
Mineral N (0–50-cm depth, kg ha^{-1})[b]	34	94	na[c]
Crop management			
Planting date	06.04	19.04	06.04
Desiccation date	27.07	02.08	10.08
First N fertilization date	08.04	19.04	12.04
Second N fertilization date	04.05	17.05	28.04
Third N fertilization date	28.05	26.05	13.05
Harvest date	28.08	24.08	29.08
Amount of fertilizers			
First N fertilization	80 kg ha^{-1} in N80, N120, N160 and N200 treatments		
Second N fertilization	40 kg ha^{-1} in N120 and 80 kg ha^{-1} in N160 and N200 treatments		
Third N fertilization	40 kg ha^{-1} in N200 treatment		
P fertilization (kg ha^{-1})	43	–	–
K fertilization (kg ha^{-1})	247	108	108
Mg fertilization (kg ha^{-1})	30	–	–

[a] Available P, K and Mg are extracted with ammonium acetate + EDTA according to the Swiss standard methods (FAL et al. 2004)

[b] Mineral N is extracted with 0.01 M $CaCl_2$ according to the Swiss standard methods (FAL et al. 2004)

[c] No data available

fertilization guidelines taking into account the available phosphorus (P), potassium (K) and magnesium (Mg) soil contents (Sinaj et al. 2009).

The experimental design was a split-plot with five N fertilizer rates as main treatments and two potato cultivars as sub-treatments and three replications. Each individual plot consisted of four rows of 25 plants surrounded by two rows as buffer zone. The rows were separated by 75 cm and plants spaced at 33 cm. Five N fertilization rates were tested: 0, 80, 120, 160 and 200 kg N ha^{-1}. The mineral N fertilizer used was ammonium nitrate (NH_4NO_3) applied in one to three times during the growing period (Table 1). The N fertilization was divided in three applications as follows: (i) at planting, 80 kg N ha^{-1} for N80, N120, N160 and N200 treatments; (ii) approximately 15 days after planting (dap), 40 kg N ha^{-1} for N120 treatment and 80 kg N ha^{-1} for N160 and N200 treatments; and finally, (iii) 30 dap, 40 kg N ha^{-1} for N200 treatment. The granules were broadcasted on the top of the rows. The first application was incorporated to the soil through hilling, while the following applications remained uncovered. Cultivars Bintje and Laura were selected for this experiment, both of which are industrial cultivars with mid-late maturity but different tuber characteristics. Bintje usually produces more tubers per plant but of smaller size and higher starch concentration than Laura (Schwaerzel et al. 2011).

Biometric Measurements

During plant growth, aboveground (stems and leaves) and belowground (large roots, stolons and tubers) dry matter (DM) were assessed approximately 50 ("D50"), 65 ("D65") and 80 ("D80") dap. The measurements were conducted on N0, N120 and N200 treatments for both cultivars based on a two-plant sample in the first and fourth rows of each plot. The samples were cut into small pieces and dried at 65 °C for at least 48 h before weighing. At harvest, the total dry tuber yield; the small (< to 42.5 mm), marketable (42.5–70 mm) and large (> to 70 mm) fresh tuber yields; and the tuber starch concentration were measured each year on all treatments. The starch concentration was calculated using the underwater weight of the tubers (Haase 2003). The yield measurements were done on the two middle rows of each plot (50 plants per plot). In 2011, a more detailed characterization of the differences between cultivars with respect to N dynamics was performed. The mineral N content ($N\text{-}NO_3$ and $N\text{-}NH_4$) present in the 0–50-cm soil layer was measured at 30, 50, 65 and 80 dap in the N120 treatment for both cultivars according to the Swiss standard methods (FAL et al. 2004). On the N0, N120 and N200 treatments, the dry matter and amount of total N uptake (*Nupt*) by the aboveground and the belowground biomass was quantified at D50, D65 and D80 and at harvest.

Calculations

The quadratic model (Eq. 1) was chosen, among other models (quadratic-plus-plateau, exponential and root-square), to describe the potato yield response to N fertilizer rates.

$$Y = Y\max - A\ (X - X\max)^2 \tag{1}$$

where Y (t FM ha^{-1}) is the total fresh tuber yield; X (kg N ha^{-1}) is the N rate applied; and Ymax, A and Xmax are the parameters to be estimated. The parameter Ymax (t FM ha^{-1}) is the maximum tuber yield, and Xmax is the N fertilizer rate requisite to reach Ymax. A is a parameter without agronomic meaning (t FM kg N^{-1}). These parameter settings determine the optimum N fertilizer rate (*Nopt*, kg N ha^{-1}) that corresponds to the rate of N that provides a yield equal to 95% of Ymax. Thus, Nopt was calculated according to Eq. 2:

$$\mathrm{Nopt} = X\mathrm{max} - \sqrt{0.05 Y\mathrm{max}/A} \tag{2}$$

In 2011, at each plant sampling date during the growing period, the nitrogen nutrition index (*NNI*) was estimated (Lemaire and Gastal 1997; Lemaire et al. 2008). NNI was calculated as the ratio between measured N concentration and predicted critical N concentration (*Nc*). For NNI > 1, the crop N status can be considered as non-limiting, so any increase in N supply would not increase crop biomass, and for NNI < 1, the crop N status can be considered as limited by N supply. In potatoes, the values of the *Nc* and the measured N concentration are estimated using the combined biomass of shoot and tubers (Greenwood et al. 1990; Duchenne et al. 1997; Bélanger et al. 2001). Nc, which represents the minimum N concentration required to achieve maximum growth, was predicted with an allometric function and values of parameters estimated for the potato by Duchenne et al. (1997) in France (Eq. 3).

$$\mathrm{Nc} = 5.21 \times W^{-0.56} \tag{3}$$

where W is the total biomass (aboveground and belowground biomass) expressed in t DM ha^{-1} which is above 1 t DM ha^{-1}. Nc is the N concentration in total biomass expressed in g 100 g^{-1} and is assumed constant, 5.21 g 100 g^{-1} for total biomass less than 1 t DM ha^{-1}.

At harvest, the N use efficiency (NUE) and its components, the N uptake efficiency (*NUpE*) and N utilization efficiency (*NUtE*) were calculated as follows (Errebhi et al. 1999):

$$\mathrm{NUE}\left(\mathrm{t\ (kg\ N)}^{-1}\right) = \mathrm{DM}/X \tag{4}$$

$$\mathrm{NUpE}\left(\mathrm{kg\ N\ (kg\ N)}^{-1}\right) = \mathrm{Nupt}/X \tag{5}$$

$$\mathrm{NUtE}\left(\mathrm{t\ (kg\ N)}^{-1}\right) = \mathrm{DM}/\mathrm{Nupt} \tag{6}$$

Where X (kg N ha^{-1}) is the amount of nitrogen supplied by N fertilizers. DM (t DM ha^{-1}) and Nupt (kg N ha^{-1}) are respectively the total dry matter (above- and belowground biomass) and total N uptake by the crop in treatment with X nitrogen fertilizer rate. The output from a control plot where the soil is the only N source should be included in these efficiency equations for a rough estimate of the efficiency of the soil in relation to fertilizer N and to measure the use efficiency of fertilizer as an input but is not required to measure differences among different crop genotypes (Ladha et al. 2005).

Statistical Analysis

Statistical analyses were performed using R 2.14.1 software (R Development Core Team 2011). Two-way analysis of variance (ANOVA) was conducted each year to test the effects of cultivar, rate and their interactions. Fisher's least significant difference (LSD) test was used for treatment mean comparisons using the R package agricolae.

A principal component analysis (PCA) was performed to investigate the effect of N rates and cultivars on the measured parameters and to identify which parameters most differentiate cultivars. PCA was conducted on data (mean of three replicates) measured for N0, N120 and N200 treatments of both cultivars in 2009, 2010 and 2011. This analysis was done using the R package FactoMineR.

Non-linear regressions were also performed to describe the total tuber yield response to N fertilization rates.

Results

Yield, Starch Concentration and Tuber Size at Harvest

Nitrogen *fertilizer rate* had a highly significant and consistent effect on both tuber yield and quality of the harvest (Table 2). On average for all cultivars and years, the total tuber yield and the percentage of large tubers (> 70 mm) increased with increase in the rate of N applied while the starch concentration and the percentage of small tubers decreased (Fig. 1a, Table 2). As a result, no N fertilization (N0 treatment) and high N fertilization (N200 treatment) had a negative effect on the percentage of marketable tubers (42.5–70 mm) (Table 2). In 2010, the effect of the N *fertilizer rate* was less pronounced than in 2009 and 2011. For example, averaged for both cultivars, the total tuber yields for N0 treatments in 2009, 2010 and 2011 represented respectively 66, 79 and 69% of the N200 treatment (Table 2) and the optimum N rates (Nopt) were 153, 82 and 139 kg N ha^{-1}, respectively (Table 3).

The effect of *cultivar* on tuber quality was also highly significant (Table 2). For all years, averaged over N rates, cv. Laura had lower values of starch concentration and percentage of small tubers (< 42.5 mm) than cv. Bintje, but a higher percentage of marketable tubers (Table 2). The rate × cultivar interaction was only significant in 2009 on the percentage of marketable (42.5–70 mm) and large tubers (> 70 mm) and in 2011 on tuber starch concentration (Table 2). The lowest percentage of large tubers was observed on the N0 treatments for cv. Bintje and the N120 treatments for cv. Laura (Table 2). For total tuber yield, the rate × cultivar interaction was not significant (Table 2) but Bintje was less affected by the absence of N fertilization than Laura (Table 2). On average for all 3 years, the potential yield (*Y*max*)* was the same for both

Table 2 Effects of years, rates and cultivars on tuber yield and quality. Values in parentheses represent the standard deviations. *P* indicate probability of rate × cultivar and year × rate × cultivar interaction

	Total tuber yield (t FM ha^{-1})			Tuber starch concentration (g kg^{-1})			Percentage of tuber sizes (% of total tuber yield) < 42.5 mm			42.5–70 mm			> 70 mm		
	Bintje	Laura	Mean	Bintje	Laura	Mean	Bintje	Laura	Mean	Bintje	Laura	Mean	Bintje	Laura	Mean
2009															
N0	48.2 (2.8)	41.4 (5.8)	44.8 d	160 (2)	149 (4)	155 a	22.5 (3.7)	23.4 (1.8)	23.0 a	75.2 (1.5)	74.7 (1.6)	74.9 b	2.4 (2.2)	1.8 (0.5)	2.1 c
N80	61.6 (6.2)	53.7 (2.7)	57.7 c	149 (9)	143 (2)	146 b	15.0 (2.4)	12.1 (0.4)	13.5 b	83.3 (1.6)	84.6 (1.4)	83.9 a	1.7 (1.5)	3.3 (1.7)	2.5 c
N120	67.0 (2.2)	59.1 (6.5)	63.0 b	137 (6)	136 (6)	137 c	13.8 (0.8)	11.8 (3.4)	12.8 b	81.9 (1.1)	86.5 (2.3)	84.2 a	4.3 (0.6)	1.6 (1.1)	3.0 bc
N160	71.4 (6.1)	63.3 (0.2)	67.3 ab	141 (8)	133 (5)	137 c	13.3 (2.6)	10.4 (0.4)	11.9 b	80.2 (1.3)	86.8 (0.5)	83.5 a	6.5 (2.4)	2.8 (0.7)	4.6 ab
N200	70.0 (7.5)	65.3 (3.4)	67.6 a	127 (8)	129 (5)	128 d	14.5 (0.7)	11.5 (2.2)	13.0 b	79.5 (1.6)	84.1 (2.7)	81.8 a	6.0 (2.3)	4.4 (0.7)	5.2 a
Mean	63.6 A	56.6 B		143 A	138 B		15.8 A	13.8 B		80.0 B	83.3 A		4.2 A	2.8 B	
Rate × cultivar	*P* = 0.95			*P* = 0.47			*P* = 0.40			*P* = **			*P* = *		
2010															
N0	43.9 (2.5)	38.0 (2.7)	41.0 b	166 (4)	151 (1)	159 a	41.7 (2.6)	28.4 (2.0)	35.1 a	58.3 (2.6)	70.7 (2.7)	64.5 b	0.0 (0.0)	0.9 (1.0)	0.5 a
N80	53.0 (1.8)	46.9 (2.4)	50.0 a	160 (2)	143 (3)	152 b	30.1 (2.2)	16.4 (3.0)	23.3 b	69.2 (2.2)	82.2 (2.3)	75.7 a	0.6 (0.7)	1.4 (1.3)	1.0 a
N120	54.3 (2.4)	48.0 (0.2)	51.1 a	154 (2)	136 (3)	145 c	28.9 (1.0)	17.3 (0.8)	23.1 b	70.3 (0.6)	81.7 (0.8)	76.0 a	0.9 (1.0)	1.0 (0.5)	0.9 a
N160	55.7 (0.7)	49.5 (3.7)	52.6 a	146 (5)	133 (4)	140 c	28.1 (0.3)	18.1 (3.3)	23.1 b	70.5 (1.7)	80.8 (3.8)	75.7 a	1.4 (1.9)	1.1 (1.0)	1.2 a
N200	54.3 (4.1)	48.8 (0.9)	51.5 a	148 (7)	133 (4)	140 c	26.8 (3.5)	19.5 (2.5)	23.2 b	72.8 (3.2)	79.0 (1.7)	75.9 a	0.4 (0.3)	1.5 (2.2)	0.9 a
Mean	52.2 A	46.2 B		155 A	139 B		31.1 A	19.9 B		68.2 B	78.9 A		0.7 A	1.2 A	
Rate × cultivar	*P* = 1.00			*P* = 0.75			*P* = 0.15			*P* = 0.31			*P* = 0.74		
2011															
N0	48.7 (8.6)	44.0 (1.5)	46.4 c	178 (6)	163 (4)	170 a	22.9 (2.2)	14.8 (2.1)	18.8 a	76.1 (1.9)	81.4 (0.1)	78.8 c	1.1 (1.5)	3.8 (2.2)	2.4 b
N80	59.0 (1.0)	59.7 (6.7)	59.4 b	159 (7)	153 (7)	156 b	17.2 (1.1)	9.2 (1.7)	13.2 b	81.8 (1.2)	85.3 (3.3)	83.6 ab	1.0 (0.9)	5.5 (4.6)	3.2 b
N120	64.4 (5.3)	58.8 (13.5)	61.6 ab	159 (2)	139 (11)	149 bc	12.2 (2.1)	12.4 (3.8)	13.0 bc	86.0 (2.2)	86.0 (3.3)	86.0 a	1.7 (0.6)	1.7 (1.1)	1.7 b

Table 2 (continued)

	Total tuber yield (t FM ha^{-1})			Tuber starch concentration (g kg^{-1})			Percentage of tuber sizes (% of total tuber yield) < 42.5 mm			42.5–70 mm			> 70 mm		
	Bintje	Laura	Mean	Bintje	Laura	Mean	Bintje	Laura	Mean	Bintje	Laura	Mean	Bintje	Laura	Mean
N160	64.3 (4.5)	63.6 (5.2)	63.9 ab	147 (3)	150 (6)	148 bc	13.9 (2.2)	8.6 (3.8)	11.3 bc	82.2 (4.1)	86.0 (2.5)	84.1 ab	3.9 (2.8)	5.4 (2.7)	4.7 ab
N200	62.1 (8.7)	73.7 (3.5)	67.9 a	146 (5)	140 (5)	143 c	14.5 (1.3)	7.0 (1.2)	10.7 c	80.4 (1.7)	83.7 (1.9)	82.0 b	5.1 (1.1)	9.3 (2.3)	7.2 a
Mean	59.7 A	60.0 A		158 A	149 B		16.1 A	10.4 B		81.3 B	84.5 A		2.6 B	5.1 A	
Rate × cultivar	*P* = *0.18*			*P* = *			*P* = *0.13*			*P* = *0.46*			*P* = *0.38*		
Year × rate × cultivar	*P* = *0.49*			*P* = *0.06*			*P* = *0.05*			*P* = *			*P* = *0.64*		

Different lowercase letters within the same year indicate significant differences between N rates at the 0.05 probability level by Fisher's multiple comparison test. Different uppercase letters within the same year indicate significant differences between cultivars at the 0.05 probability level by Fisher's multiple comparison test. Numbers and letters in italic represent the probability level of Year, Rates and Cultivars effects and their interactions

*, **, and ***Significant at $0.01 \le P < 0.05$, $0.001 \le P < 0.01$ and <0.001, respectively

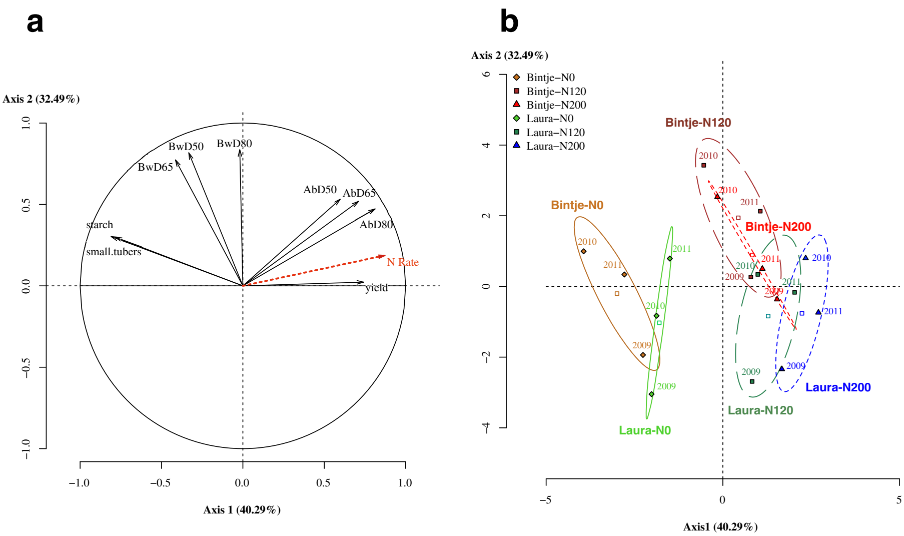

Fig. 1 Principal component analysis for characterization of N rate and cultivar effects: **a** variable factor map and **b** individual factor map. Explanatory variables: yield: total dry tuber yield measured at harvest; starch: starch tuber concentration measured at harvest; small tubers: percentage of tubers < 42.5 mm measured at harvest; Ab50, Ab65 and Ab80: aboveground dry biomass measured at 50, 65 and 80 DAP, respectively; and Bw50, Bw65 and Bw80: belowground dry biomass measured at 50, 65 and 80 DAP, respectively. N fertilization rate is plotted as a supplementary variable without contributing to the PCA axis

cultivars (63.4 t FM ha^{-1}, Table 3) while Nopt was 94 kg N ha^{-1} for Bintje and 155 kg N ha^{-1} for Laura (Table 3).

Biomass Growth Dynamics

Over the 3-year period, rate × cultivar interactions were not significant on either aboveground or belowground biomass at D50, D65 and D80 (Table 4).

Averaged over all years and cultivars, the rate of N fertilizer affected mostly the aboveground biomass at D50, D65 and D80 but had only little effect on the belowground biomass (Fig. 1a). Averaged over both cultivars, an N effect on the aboveground biomass was significant at D65 in 2010 ($P < 0.01$) and 2011 ($P < 0.05$) and at

Table 3 Parameters of the quadratic model describing the relationship between total fresh tuber yields and N fertilization rates

Year	Cultivar	*n*	R^2	*Y*max (t FM ha^{-1})	*A*	*X*max (kg N ha^{-1})	Nopt (kg N ha^{-1})
2009	Bintje	15	0.78***	70.8	5.7E−4	200	121
	Laura	15	0.85***	68.1	3.2E−4	288	185
2010	Bintje	15	0.80***	55.4	4.8E−4	154	78
	Laura	15	0.82***	49.3	4.2E−4	163	86
2011	Bintje	15	0.55**	64.0	6.7E−4	153	83
	Laura	15	0.65**	72.9	3.2E−4	300	194

** and ***Significant at $0.001 \leq P < 0.01$ and < 0.001, respectively

Table 4 Probabilities of N fertilization rate and cultivar effects and their interaction, on aboveground and belowground dry matter measured at D50, D65 and D80. ANOVA was conducted for N0, N120, and N200 treatments of both cultivars and the 3 years

	Aboveground biomass			Belowground biomass		
	D50	D65	D80	D50	D65	D80
2009						
Rates	*0.06*	*0.06*	**	*0.70*	*0.33*	*0.45*
Cultivar	*0.14*	*	*0.64*	*	**	*0.31*
Rates × cultivar	*0.31*	*0.12*	*0.70*	*0.85*	*0.07*	*0.76*
2010						
Rates	*0.08*	**	**	*0.89*	*0.94*	*0.27*
Cultivar	*	*0.08*	*0.054*	**	**	**
Rates × cultivar	*0.18*	*0.39*	*0.06*	*0.15*	*0.61*	*0.18*
2011						
Rates	*0.23*	*	**	*0.47*	*0.12*	*
Cultivar	*0.15*	*0.18*	*0.49*	*0.26*	*	*1.00*
Rates × cultivar	*0.50*	*0.25*	*0.98*	*0.39*	*0.19*	*0.68*
Year × rates × cultivars	*0.61*	*0.13*	*0.63*	*0.83*	*0.15*	*0.89*

*,and ** Significant at $0.01 \leq P < 0.05$ and $0.001 \leq P < 0.01$, respectively

D80 for all 3 years ($P < 0.01$, Table 4). Thus, the aboveground biomass for N0 treatment was less than that for N120 and N200 treatments, while no significant difference ($P > 0.05$) was observed between N120 and N200 treatments (Fig. 2). On the belowground biomass, a significant effect of N rate was observed only at D80 in 2011 (Table 4). At that date, for both cultivars, a negative effect of the highest N rate was observed (Fig. 2). In 2009 and 2010, similar tendencies were noted ($P = 0.45$ and 0.27 respectively, Table 4), and the belowground biomass of N120 treatment was quite higher than that of N0 and N200 treatments (Fig. 2).

Averaged over all years and N rates, cultivars differed mostly in terms of the belowground biomass (Fig. 1). The cultivar had a small effect on the aboveground biomass at the beginning of the growing season (averaged over the three N fertilizer rates at D50 in 2010 and D65 in 2009, Table 4), and thereafter, no further significant difference between cultivars was observed (Table 4 and Fig. 2). On the belowground biomass, the effect of cultivar averaged over all N fertilizer rates was significant at D50 in 2009 and 2010, at D65 each year, and at D80 in 2010 (Table 4). For all 3 years and all three N fertilizer rates, the belowground biomass of cv. Bintje increased faster than that of cv. Laura (Fig. 2).

Nitrogen Uptake and Efficiency in 2011

Averaged over both cultivars, increasing the rate of N had a highly significant and positive effect on the total N uptake at D65, D80 and harvest (Table 5). The N0 treatments absorbed much less N than the other treatments, but the N120 and N200 treatments did not differ significantly from each other (Table 5). The same effect of the

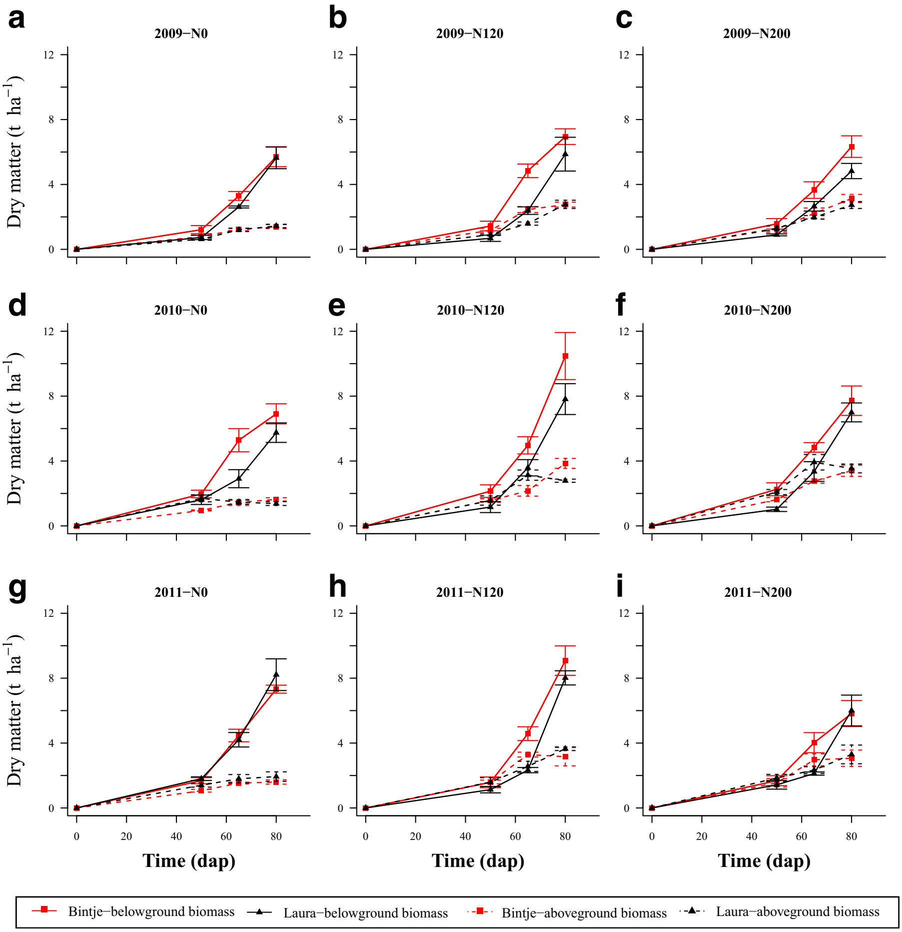

Fig. 2 Effects of cultivar on aboveground (vines) and belowground biomass growth for **a**, **d**, **g** N0, **b**, **e**, **h** N120 and **c**, **f**, **i** N200 treatments in 2009, 2010 and 2011. The red and black lines refer to Bintje and Laura cultivars, respectively. Vertical bars represent the standard errors of mean

rate was observed on the total N concentration and NNI over the whole growing period as well (Table 5).

Averaged over all N rates, the effect of cultivar was significant on total N uptake at D65 and on total N concentration at D50, D65 and D80 (Table 5) while no significant effect was observed on NNI during the growing period (Table 5). For the N120 treatment, cv. Laura absorbed significantly less N than cv. Bintje at D65 but hereafter, the differences disappeared. The same tendency was observed for the N200 treatment while the opposite tendency was observed for the N0 treatment, but the effect of cultivar was not significant. Cv. Laura presented on average significantly higher total N concentration than cv. Bintje at D50, D65 and D80.

Interactions rate × cultivar were not significant for total N uptake, total N concentration nor for NNI during the whole potato cycle (Table 5).

Averaged over both cultivars at harvest, significant differences were observed between rates in NUE, NUpE and NUtE (Table 6). The highest rate of N (N200)

Table 5 N fertilization rate and cultivar effect on total biomass, total N uptake, N concentration and NNI measured at D50, D65, D80 and harvest in 2011. Values in parentheses represented the standard deviations. *P* indicated probability of rate × cultivar interaction

	Total biomass (t DM ha^{-1})			Total N uptake (kg N ha^{-1})			Total N concentration (g 100 g^{-1})			NNI		
	Bintje	Laura	Mean	Bintje	Laura	Mean	Laura	Laura	Mean	Bintje	Laura	Mean
D50												
N0	2.75 (0.52)	3.21 (0.40)	2.98 a	53 (5)	74 (14)	64 b	1.95 (0.20)	2.31 (0.20)	2.13 b	0.65 (0.02)	0.85 (0.12)	0.75 b
N120	3.18 (0.49)	2.72 (0.95)	2.95 a	92 (5)	84 (30)	88 ab	2.92 (0.37)	3.08 (0.06)	3.00 a	1.06 (0.06)	1.03 (0.21)	1.04 a
N200	3.24 (1.10)	3.28 (0.88)	3.26 a	96 (32)	109 (19)	103 a	2.96 (0.09)	3.37 (0.34)	3.17 a	1.09 (0.21)	1.24 (0.08)	1.16 a
Mean	3.06 A	3.07 A		80 A	89 A		2.61 B	2.92 A		0.93 A	1.04 A	
Rate × cultivar	*P* = *0.35*			*P* = *0.26*			*P* = *0.53*			*P* = *0.22*		
D65												
N0	6.02 (0.84)	6.03 (1.38)	6.02 a	79 (9)	89 (14)	83 b	1.31 (0.10)	1.48 (0.11)	1.40 b	0.69 (0.05)	0.77 (0.05)	0.73 b
N120	7.87 (0.76)	4.90 (0.41)	6.38 a	185 (6)	119 (19)	152 a	2.37 (0.20)	2.42 (0.20)	2.39 a	1.44 (0.06)	1.13 (0.15)	1.28 a
N200	6.99 (1.97)	4.48 (0.59)	5.73 a	176 (47)	122 (21)	149 a	2.52 (0.11)	2.72 (0.16)	2.62 a	1.43 (0.20)	1.21 (0.14)	1.32 a
Mean	6.96 A	5.13 B		147 A	110 B		2.07 B	2.21 A		1.18 A	1.04 A	
Rate × cultivar	*P* = *0.20*			*P* = *0.12*			*P* = *0.43*			*P* = *0.11*		
D80												
N0	8.92 (0.71)	10.17 (2.56)	9.54 b	84 (9)	110 (26)	97 b	0.94 (0.06)	1.09 (0.02)	1.01c	0.62 (0.05)	0.76 (0.09)	0.69 b
N120	12.24 (2.94)	11.67 (0.93)	11.96 a	175 (49)	195 (15)	185 a	1.42 (0.06)	1.68 (0.13)	1.55 b	1.10 (0.19)	1.27 (0.08)	1.19 a
N200	8.89 (2.60)	9.29 (3.06)	9.09 b	167 (51)	185 (56)	176 a	1.87 (0.03)	2.01 (0.07)	1.94 a	1.21 (0.21)	1.33 (0.21)	1.27 a
Mean	10.01 A	10.38 A		142 A	164 A		1.41 B	1.59 A		0.98 A	1.12 A	
Rate × cultivar	*P* = *0.87*			*P* = *0.99*			*P* = *0.23*			*P* = *0.97*		
Harvest												
N0	13.02 (2.56)	10.94 (0.57)	11.98 b	104 (25)	94 (5)	99 b	0.80 (0.05)	0.86 (0.01)	0.83 c			
N120	14.41 (0.76)	13.94 (2.73)	14.18 ab	172 (12)	163 (36)	167 a	1.19 (0.02)	1.16 (0.05)	1.18 b			
N200	14.22 (2.39)	16.28 (1.85)	15.25 a	190 (23)	220 (37)	205 a	1.34 (0.08)	1.35 (0.15)	1.35 a			
Mean	13.88 A	13.72 A		155 A	159 A		1.11 A	1.13 A				
Rate × cultivar	*P* = *0.15*			*P* = *0.09*			*P* = *0.71*					

Different lowercase letters within the same row indicate significant differences between N rates at the 0.05 probability level by Fisher's multiple comparison test. Different uppercase letters within the same line indicate significant differences between cultivars at the 0.05 probability level by Fisher's multiple comparison test. Letters in italic represent the probability level of Rate x Cultivar interaction affected negatively NUE and NUpE and, to a lesser extent, the NUtE for both cultivars (Table 6). The rate × cultivar interaction was not significant (Table 6).

Averaged over both N rates, cultivar had no significant effects on NUE and its components at harvest (Table 6). For the N120 treatment, a comparison of cv. Bintje with cv. Laura showed higher but not significant NUpE values for cv. Bintje while the opposite was observed for the N200 treatment.

Discussion

Year Effect

The year 2010 was less favourable for potato growth than 2009 and 2011. The maximum tuber yield (*Y*max) was only 52 t FM ha^{-1} in 2010 and lower than in 2009 (69 t FM ha^{-1}) and 2011 (68 t FM ha^{-1}). Neither water stress nor nitrogen deficiency could explain the lower yields observed in 2010. The total amount of water input (rain and irrigation) and its distribution were similar over the 3 years. Nopt were much lower in 2010 than in 2009 and 2011 (Table 4) which may indicate greater soil N availability in 2010 (Table 1). In addition, the total N uptake measured at D80 on N0 treatment of Bintje was 155 kg N ha^{-1} in 2010 (data not shown) versus 83 (data not shown) and 84 kg N ha^{-1} in 2009 and 2011, respectively (Table 4). However, too much N available early in the growing season leads to delays in tuber growth and physiological maturity, which can be detrimental to production if harvest occurs prior to maturity (Chambenoit et al. 2002). It is thought that under these conditions, desiccation occurred perhaps too early in 2010 compared to 2009 and 2011 (1814 °C d versus 1865 and 2024 °C d in 2009 and 2011, Table 1) and the potato was harvested before maturity. The fact that the percentage of small tubers was higher in 2010 than in 2009 and 2011 seems to support this argument.

Cultivar Effect

Both cultivars showed similar aboveground biomass growth dynamics but differed in their belowground growth dynamics. The allocation of biomass to roots and tubers in cv. Laura was slower than that in cv. Bintje, which resulted in a lower belowground biomass at the beginning of the growing season. At harvest, for the Swiss recommended N fertilizer rate (N120 treatment, Sinaj et al. 2009), cv. Laura had a lower total tuber yield than cv. Bintje, but a higher percentage of marketable tubers (42.5–70 mm) and a lower percentage of small tubers (< 42.5 mm). In addition, cv. Laura tubers had lower starch concentrations than those of cv. Bintje (for the N120 treatment, 13.7 and 15.0%, respectively) and were comparable with those described in the recommended list of Swiss cultivars (Schwaerzel et al. 2011).

N Fertilization Effects

The total biomass responded positively to N fertilization, but the effects of N fertilization on tuber yield and quality were mixed. For example, this study showed an increase in the aboveground biomass with increasing N rate, while the belowground biomass did not increase with N rate above Nopt, resulting in a decrease in harvest index, a phenomenon supported by other studies (Millard and Marshall 1986; Biemond and Vos 1992; Vos 1997). In addition, N fertilization increased the percentage of unmarketable large tubers (> 70 mm) and reduced the starch concentration and the dry matter concentration (data not shown). These results confirmed those reported by other authors (Ojala et al. 1990; Westermann et al. 1994; Bélanger et al. 2002; Kumar et al. 2004) and are related to the effect of N fertilization in delaying tuber maturity and extending the vegetative growth period (Ojala et al. 1990).

In 2011, averaged over both cultivars, fertilizer N recovery (difference in N uptake between an unfertilized and a fertilized treatment, divided by the N fertilizer rate) for the N120 treatment, which is the closest to Nopt (on average 125 kg N ha^{-1}), was 57% at harvest. Fertilizer N recovery of the potato is commonly between 40 and 60% (Zebarth and Rosen 2007). In general, application of N fertilizer rates above the Nopt causes a decrease in the efficiency of N fertilizer (Vos 2009) and an increase in environmental losses during and after the growing season. The results of this study show that in 2011 at the rate of 120 kg N ha^{-1}, the crop nitrogen status was non-limiting (NNI > 1) and that increased N fertilizer rates above 120 kg N ha^{-1} resulted in decreased values of NUE and its components NUpE and NUtE. The decrease in NUtE with increasing N fertilizer rates has been reported by other authors as well (Errebhi et al. 1999; Zebarth et al. 2004a, b). Results, however, for NUpE are less consistent. For example, Zebarth et al. (2004a, b) reported a relative insensitivity of NUpE to N fertilizer rates or crop N supply contrary to previous studies, which found NUpE to decrease with increasing N fertilizer rates (Tyler et al. 1983; Zvomuya and Rosen 2002; Zvomuya et al. 2002). The lack of response of NUpE to N fertilization rates in Zebarth's studies may be due to lower rates of applied N fertilization (Zebarth et al. 2004a). Under such conditions, Zebarth et al. (2004a, b) found that most of the variation in NUE with increasing crop N supply was due to variation in NUtE. In the present study, for N fertilization above Nopt, the NUE decline was largely due to the decrease of NUpE. This is consistent with Moll et al. (1982) who observed that

Table 6 N fertilization rate and cultivar effect on nitrogen use efficiency and its components measured at harvest in 2011. Values in parentheses represented the standard deviations. *P* indicated probability of rate × cultivar interaction

	NUE (t DM kg^{-1})			NUpE (kg kg^{-1})			NUtE (t DM kg^{-1})		
	Bintje	Laura	Mean	Bintje	Laura	Mean	Bintje	Laura	Mean
Harvest									
N120	0.12 (0.01)	0.12 (0.02)	0.12 a	1.43 (0.10)	1.36 (0.30)	1.39 a	0.084 (0.002)	0.086 (0.003)	0.08 a
N200	0.07 (0.01)	0.08 (0.01)	0.08 b	0.95 (0.11)	1.10 (0.19)	1.02 b	0.075 (0.004)	0.075 (0.009)	0.07 b
Mean	0.10 A	0.10 A		1.19 A	1.23 A		0.079 A	0.081 A	
Rate × cultivar	*P* = *0.32*			*P* = *0.15*			*P* = *0.81*		

Different lowercase letters within the same row indicate significant differences between N rates at the 0.05 probability level by Fisher's multiple comparison test. Different uppercase letters within the same line indicate significant differences between cultivars at the 0.05 probability level by Fisher's multiple comparison test. Letters in italic represent the probability level of Rate x Cultivar interaction variation in NUE of corn (*Zea mays*) was primarily determined by variations in NUpE under high N supply and by variation in NUtE under limited N supply. Similarly, Ortiz-Monasterio et al. (1997) showed for wheat (*Triticum aestivum* L.) that the relative importance of NUtE and NUpE was affected by the level of N fertilization.

Did Cultivars Respond Differently to N Fertilization?

Given a non-limited supply of N, total tuber yield was the same for both cultivars (*Y*max = 63.4 t FM ha^{-1}). However, the average optimum (Nopt) rate for cv. Laura was 155 kg N ha^{-1} versus 94 kg N ha^{-1} for cv. Bintje which could suggest lower NUE for cv. Laura. Previous studies have reported significant variation in NUE among commercial potato cultivars (Errebhi et al. 1998b, 1999; Zebarth et al. 2004a), including variation in both NUpE and NUtE (Errebhi et al. 1998b; Zebarth et al. 2004a). Changes in NUpE for potatoes are generally attributed to differences in physiology, for example, N uptake kinetics (Sharifi and Zebarth 2006), and in morphology of the root system (Kamh et al. 2005; Sattelmacher et al. 1990b), while changes in NUtE are mostly attributed to internal plant N demand and the ability to transport and re-mobilize the N (Marschner 1995). Nevertheless, in the present study, no significant differences between cultivars were observed at harvest on NUE and its components. Thus, the differences between cultivars with regard to Nopt may be more related to difference in N uptake dynamic and responsivity to the third N application. Cv. Laura had a lower biomass and N uptake than cv. Bintje early in the growing season, which could be due to a weaker root system and/or a lower N demand in cv. Laura. Indeed, the rate of crop N uptake is co-regulated by soil N availability and crop growth rate (Devienne-Barret et al. 2000). As a result, any genotypic or environmental factor (other than nitrogen supply) enhancing the crop growth rate increases de facto the N uptake capacity of the crop (Sadras and Lemaire 2014). Since crop N uptake reflects crop nitrogen status only if comparisons are made at similar biomass and N supply, Sadras and Lemaire (2014) proposed ranking genotypes on their NNI, thus avoiding this trivial effect of crop size. In this study, during the whole crop cycle, no significant differences between cultivars in NNI and root biomass (data not shown) were observed. Thus, the slower crop growth (and especially belowground biomass growth) of cv. Laura was responsible for the lower plant N uptake demand and the weaker absorption of N available early in the growing season.

Despite lower N uptake by cv. Laura early in the growing season, no significant difference on soil mineral N content was observed between cultivars (Fig. 3). This suggests that N not utilized at the beginning of the growing season by Laura was probably lost by leaching or volatilization. Furthermore, Laura presented a greater capacity to benefit from the third late N instalment of the N200 treatment since N200 treatment had no significant effect on yield of cv. Bintje, while increasing the yield of cv. Laura in 2009 and 2011. This may explain the greater Nopt of Laura in this traditional Swiss split of N fertilization. These results indicate that, perhaps, better N efficiency could be obtained by applying N inputs later in the growing season for cv. Laura than for cv. Bintje.

Conclusion

This study shows that cvs Bintje and Laura react to N fertilization differently, especially with respect to N uptake dynamics. Laura absorbs N slower than Bintje due to a longer

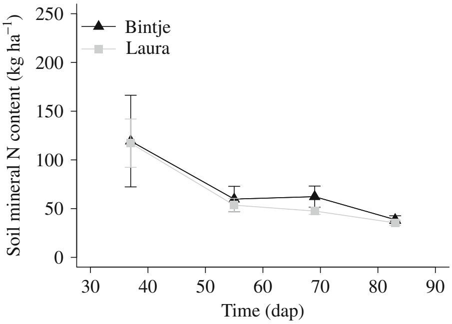

Fig. 3 Effect of cultivar on soil mineral N content (0–50 cm) measured in 2015 during the growing period of N120 treatments

time period required for establishing and developing the belowground biomass. Thus, delaying N fertilization and/or applying slow-release N fertilizers would be beneficial for cv. Laura. It would avoid N deficiencies in the plants while minimizing the negative impacts on the environment due to possible leaching of underutilized N.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

References

Bélanger G, Walsh JR, Richards JE, Milburn PH, Ziadi N (2001) Critical nitrogen curve and nitrogen nutrition index for potato in eastern Canada. Am J Potato Res 78(5):355–364. https://doi.org/10.1007/BF02884344

Bélanger G, Walsh JR, Richards JE, Milburn PH, Ziadi N (2002) Nitrogen fertilization and irrigation affects tuber characteristics of two potato cultivars. Am J Potato Res 79(4):269–279. https://doi.org/10.1007/BF02986360

Biemond H, Vos J (1992) Effects of nitrogen on the development and growth of the potato plant. II. The partitioning of dry matter, nitrogen and nitrate. Ann Bot 70(1):37–45. https://doi.org/10.1093/oxfordjournals.aob.a088437

Bundy LG, Wolkowski RP, Weis GG (1986) Nitrogen source evaluation for potato production on irrigated sandy soils. Am Potato J 63(8):385–397. https://doi.org/10.1007/BF02854101

Chambenoit C, Laurent F, Machet JM, Scheurer O (2002) Fertilisation azotée de la pomme de terre- guide pratique. Published by Agro-Transfert/ITCF-ITPT/INRA, 130 p

Davenport JR, Milburn PH, Rosen CJ, Thornton RE (2005) Environmental impacts of potato nutrient management. Am J Potato Res 82(4):321–328. https://doi.org/10.1007/BF02871962

Devienne-Barret F, Justes E, Machet JM, Mary B (2000) Integrated control of nitrate uptake by crop growth rate and soil nitrate availability under field conditions. Ann Bot 86(5):995–1005. https://doi.org/10.1006/anbo.2000.1264

Duchenne T, Machet JM, Martin M (1997) Potatoes. *In*: Lemaire G(ed), Diagnosis of the nitrogen status in crops. Springer-Verlag, Berlin. pp. 119–130, DOI: https://doi.org/10.1007/978-3-642-60684-7_7

Errebhi M, Rosen CJ, Gupta SC, Birong DE (1998a) Potato yield response and nitrate leaching as influenced by nitrogen management. Agron J 90(1):10–15. https://doi.org/10.2134/agronj1998.00021962009000010003x

Errebhi M, Rosen CJ, Lauer FI, Martin MW, Bamberg JB, Birong DE (1998b) Screening of exotic potato germplasm for nitrogen uptake and biomass production. Am J Potato Res 75:93–100
Errebhi M, Rosen CJ, Lauer FI, Martin MW, Bamberg JB (1999) Evaluation of tuber-bearing Solanum species for nitrogen use efficiency and biomass partitioning. Am J Potato Res 76(3):143–151. https://doi.org/10.1007/BF02853579
FAL, RAC, FAW (2004) Méthodes de référence des stations fédérales de recherches agronomiques. Agroscope, vol. 2, Zurich-Reckenholz
Greenwood DJ, Lemaire G, Gosse G, Cruz P, Draycott A, Neeteson JJ (1990) Decline in percentage N of C3 and C4 crops with increasing plant mass. Ann Bot 66(4):425–436. https://doi.org/10.1093/oxfordjournals.aob.a088044
Haase NU (2003) Estimation of dry matter and starch concentration in potatoes by determination of under-water weight and near infrared spectroscopy. Potato Res 46(3):117–127. https://doi.org/10.1007/BF02736081
Hill AR (1986) Nitrate and chloride distribution and balance under continuous potato cropping. Agric Ecosyst Environ 15(4):267–280. https://doi.org/10.1016/0167-8809(86)90125-8
Houles V, Mary B, Guerif M, Makowski D, Justes E (2004) Evaluation of the ability of the crop model STICS to recommend nitrogen fertilisation rates according to agroenvironmental criteria. Agronomie 24(6-7): 339–349. https://doi.org/10.1051/agro:2004036
Kamh M, Wiesler F, Ulas A, Horst WJ (2005) Root growth and N-uptake activity of oilseed rape (*Brassica napus* L.) cultivars differing in nitrogen efficiency. J Plant Nutr Soil Sci 168(1):130–137. https://doi.org/10.1002/jpln.200421453
Kumar D, Singh BP, Kumar P (2004) An overview of the factors affecting sugar content of potatoes. Ann Appl Biol 145(3):247–256. https://doi.org/10.1111/j.1744-7348.2004.tb00380.x
Ladha JK, Pathak H, Krupnik TJ, Six J, van Kessel C (2005) Efficiency of fertilizer nitrogen in cereal production: retrospects and prospects. Adv Agron 87:85–156. https://doi.org/10.1016/S0065-2113(05)87003-8
Lemaire G, Gastal F (1997) N uptake and distribution in plant canopies. In: Lemaire G (ed) Diagnosis of the nitrogen status in crops. Springer-Verlag, Berlin, pp 3–43. https://doi.org/10.1007/978-3-642-60684-7_1
Lemaire G, Jeuffroy MH, Gastal F (2008) Diagnosis tool for plant and crop N status in vegetative stage theory and practices for crop N management. Eur J Agron 28(4):614–624. https://doi.org/10.1016/j.eja.2008.01.005
Marschner H (1995) Mineral nutrition of higher plants, 2nd edn. San Diego, Academic Press
Millard P, Marshall B (1986) Growth, nitrogen uptake and partitioning within potato in relation to nitrogen application. J Agric Sci Cambridge 107(02):421–429. https://doi.org/10.1017/S0021859600087220
Moll RH, Kamprath EJ, Jackson WA (1982) Analysis and interpretation of factors which contribute to efficiency of nitrogen utilization. Agron J 74(3):562–564. https://doi.org/10.2134/agronj1982.00021962007400030037x
R Development Core Team (2011) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna
Ojala JC, Stark JC, Kleinkopf GE (1990) Influence of irrigation and nitrogen management on potato yield and quality. Am Potato J 67(1):29–43. https://doi.org/10.1007/BF02986910
Ortiz-Monasterio JI, Sayre KD, Rajaram S, McMahon M (1997) Genetic progress in wheat yield and nitrogen use efficiency under four nitrogen rates. Crop Sci 37(3):898–904. https://doi.org/10.2135/cropsci1997.0011183X003700030033x
Sadras VO, Lemaire G (2014) Quantifying crop nitrogen status for comparison of agronomic practices and genotypes. Field Crop Res 164:54–64. https://doi.org/10.1016/j.fcr.2014.05.006
Sattelmacher B, Kuene R, Malagamba P, Moreno U (1990a) Evaluation of tuber bearing Solanum species belonging to different ploidy levels for its yielding potential at low soil fertility. Plant Soil 129(2):227–233. https://doi.org/10.1007/BF00032417
Sattelmacher B, Klotz F, Marschner H (1990b) Influence of the nitrogen level on root growth and morphology of two potato cultivars differing in nitrogen acquisition. Plant Soil 123(2):131–137. https://doi.org/10.1007/BF00011258
Schwaerzel R, Torche JM, Hebeisen T, Ballmer T, Musa T (2011) Liste suisse des variétés de pommes de terre 2012. Recherche Agronomique Suisse 2:11–12
Sharifi M, Zebarth BJ (2006) Nitrate influx kinetic parameters of five potato cultivars during vegetative growth. Plant Soil 288(1-2):91–99. https://doi.org/10.1007/s11104-006-9092-5
Sharifi M, Zebarth BJ, Coleman W (2007) Screening for nitrogen-use efficiency in potato using a recirculating hydroponic system. Commun Soil Sci Plant Anal 38(3-4):359–370. https://doi.org/10.1080/00103620601172357

Sinaj S, Richner W, Flisch R, Charles R (2009) Données de base pour la fumure des grandes cultures et des herbages (DBF-GCH). Revue suisse d'Agriculture 41(1):98 p

Tanner CB, Weis GG, Curwen D (1982) Russet Burbank rooting in sandy soils with pans following deep plowing. Am Potato J 59(3):107–112. https://doi.org/10.1007/BF02866365

Turc L (1961) Evaluation de besoins en eau d'irrigation, ET potentielle. Ann Agron 12:13–49

Tyler KB, Broadbent FE, Bishop JC (1983) Efficiency of nitrogen uptake by potatoes. Am Potato J 60(4):261–269. https://doi.org/10.1007/BF02854276

Van Es HM, Czymmek KJ, Ketterings QM (2002) Management effects on nitrogen leaching and guidelines for a nitrogen-leaching index in New York. J Soil Water Conserv 57:499–504

Vos J (1997) The nitrogen response of potato (*Solanum tuberosum* L.) in the field: nitrogen uptake and yield, harvest index and nitrogen concentration. Potato Res 40(2):237–248. https://doi.org/10.1007/BF02358249

Vos J (2009) Nitrogen responses and nitrogen management in potato. Potato Res 52(4):305–317. https://doi.org/10.1007/s11540-009-9145-2

Westermann DT, James DW, Tindall TA, Hurst RL (1994) Nitrogen and potassium fertilization of potatoes: sugars and starch. Am Potato J 71(7):433–453. https://doi.org/10.1007/BF02849098

Zebarth BJ, Rosen CJ (2007) Research perspective on nitrogen BMP development for potato. Am J Potato Res 84(1):3–18. https://doi.org/10.1007/BF02986294

Zebarth BJ, Leclerc Y, Moreau G, Botha E (2004a) Rate and timing of nitrogen fertilization of Russet Burbank potato: nitrogen use efficiency. Can J Plant Sci 84(3):855–863. https://doi.org/10.4141/P03-123

Zebarth BJ, Tai G, Tarn R, De Jong H, Milburn PH (2004b) Nitrogen use efficiency characteristics of commercial potato cultivars. Can J Plant Sci 84(2):589–598. https://doi.org/10.4141/P03-050

Zebarth BJ, Tarn TR, De Jong H, Murphy AM (2008) Nitrogen use efficiency characteristics of andigena and diploid potato selections. Am J Potato Res 85(3):210–218. https://doi.org/10.1007/s12230-008-9014-6

Zvomuya F, Rosen CJ (2002) Biomass partitioning and nitrogen use efficiency of 'superior' potato following genetic transformation for resistance to Colorado potato beetle. J Am Soc Hortic Sci 127:703–709

Zvomuya F, Rosen CJ, Miller JC (2002) Response of Russet Norkotah clonal selections to nitrogen fertilization. Am J Potato Res 79(4):231–239. https://doi.org/10.1007/BF02986355