Chapter 11
Soil and Plant Tests to Optimize Fertilizer Nitrogen Management of Potatoes

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Abstract Appropriate fertilizer nitrogen (N) management can optimize tuber yield and quality, and reduce the risk of environmental N losses. However, the optimal fertilizer N management can vary among fields and years. Plant- and soil-based tests are examined in this chapter as diagnostic tools to improve fertilizer N management in rain-fed potato production in eastern Canada. Plant-based diagnostic tests assess potato N sufficiency and can be used to guide in-season fertilizer N management. The nitrogen nutrition index (NNI) based on whole plants, the petiole nitrate concentration, and the leaf chlorophyll meter reading (SPAD) have been shown to successfully diagnose the level of potato N nutrition during the growing season in eastern Canada. The use of gene expression, a promising tool for a direct measurement of potato N sufficiency compared with chemical or optical methods, is also examined. Soil-based tests can be used to provide an estimate of soil N supply to adjust the at-planting fertilizer N rate. The use of pre-plant and in-season soil nitrate tests, ion exchange membranes, indices of soil mineralizable N, and near-infrared reflectance spectroscopy (NIRS) are examined. A combination of a soil-based test to guide at-planting fertilizer N application and a plant-based test to guide in-season N management may be most effective.

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11.1 Introduction

Potato (S*olanum tuberosum* L.) crops frequently require high applications of fertilizer nitrogen (N) to achieve high tuber yield and quality. In eastern Canada, general fertilizer N recommendations vary between 125 and 200 kg N ha^{-1} (NBDAFA 2001; CRAAQ 2010). The apparent recovery of applied fertilizer N in the growing crop, however, may average less than 50% (Cambouris et al. 2008; Ziadi et al. 2011). Management of this fertilizer N is important from both economic and environmental standpoints (Zebarth et al. 2009). Nitrogen deficiency results in poor crop growth, small tuber size, and low tuber yield (Bélanger et al. 2000) while excessive N can lead to poor tuber quality, delayed crop maturity, increased N_2O emissions, and excessive nitrate leaching (Ojala et al. 1990; Bélanger et al. 2000; Burton et al. 2008). However, the optimal fertilizer N rate can vary widely among fields and among years (Zebarth et al. 2009). This variation results from variation in both the crop N demand and the soil N supply. As a result, the development of tools which predict more precisely the fertilizer N requirement on an individual field basis in potato production can be used as a strategy to optimize tuber yield and quality and to minimize the risk of N losses to the environment.

In this chapter, we examine plant- and soil-based tests which can be used as diagnostic tools to improve fertilizer N recommendations for potato production on an individual field basis. Plant-based diagnostic tests have an advantage in that they commonly assess plant N sufficiency (i.e. the balance between crop N demand and N supply), whereas soil-based tests commonly assess only soil N supply. However, plant-based tests can often only be used later in the growing season whereas soil-based tests are commonly used early in the growing season. As a result, use of a combination of soil- and plant-based tests may be most effective in optimizing fertilizer N management.

11.2 Plant-Based Diagnostic Methods

Several plant-based diagnostic methods have been developed over the last 20 years. These methods use either whole plants or specific plant parts (e.g. leaf or petiole) and they can include either chemical or optical measurements.

11.2.1 Nitrogen Nutrition Index (NNI)

The N concentration on a whole plant basis can be used as a diagnostic tool to assess crop N nutrition during the growing season. To do so, a critical N concentration (N_c), that is the minimum N concentration required for maximum crop growth, must be defined. Crop N concentration decreases over time as crop biomass increases

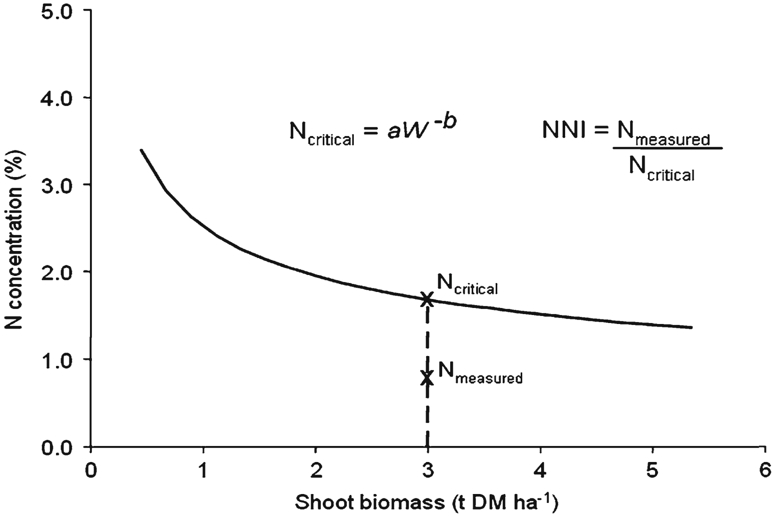

Fig. 11.1 General concept of critical N concentration. W is the total shoot biomass expressed in t dry matter (DM) ha^{-1}, $N_{critical}$ is the total N concentration in shoots expressed in % of DM, and *a* and *b* are estimated parameters. NNI is the N nutrition index

because of an increased proportion of the structural and storage components that contain little N. Consequently, N_c also decreases over time during the growing season. For that reason, N_c is commonly expressed as a function of crop biomass with critical N curves.

The concept of a critical N curve, based on the N concentration of whole plants, was first developed in France for tall fescue by Lemaire and Salette (1984) and has been successfully applied in eastern Canada to other perennial crops [timothy (Bélanger and Ziadi 2008)] and annual crops [wheat (Ziadi et al. 2010a); corn (Ziadi et al. 2008a)], including potatoes (Bélanger et al. 2001b). For the majority of crops, the N_c can be represented by the following allometric function:

$$N_c = aW^{-b} \tag{11.1}$$

where W is the total shoot biomass expressed in t dry matter (DM) ha^{-1}, N_c is the total N concentration in shoots expressed in % of DM, and *a* and *b* are estimated parameters (Fig. 11.1). The parameter *a* represents the N concentration with 1 t DM ha^{-1} and the parameter *b* represents the coefficient of dilution which describes the relationship of decreasing N concentration with increasing shoot biomass. For potatoes, the function is applied to the vines plus tubers rather than to the above-ground plant for other crop species. Therefore, the values of the parameters *a* and *b* are estimated using the combined biomass of shoots and tubers, and the N concentration of this combined biomass.

The critical N curve can then be used to calculate the N nutrition index (NNI) as the ratio between the measured N concentration of the shoot biomass and the

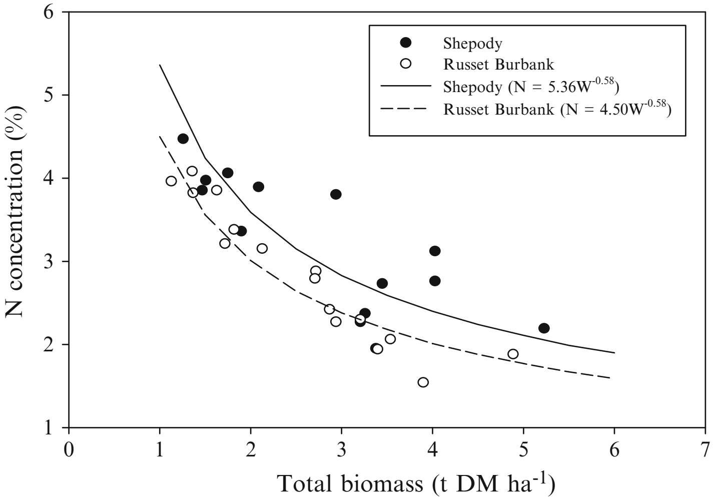

Fig. 11.2 Critical N curves for two potato cultivars under rain-fed conditions; data points correspond to maximum total biomass for each combination of site and cultivar (Bélanger et al. 2001b)

predicted N_c. This NNI describes the N nutrition status of a crop at different times during the growing season, independently of the stage of development. The critical N curve (Eq. 11.1; Fig. 11.1) discriminates three different types of N status. Data points below the curve (i.e. $NNI < 1$) indicate situations where N is limiting growth and additional N fertilizer would therefore increase growth. Data points above the curve (i.e. $NNI > 1$) indicate situations of excessive N nutrition where additional N fertilization would not increase growth. Data points located on or near the curve (i.e. $NNI \approx 1$) correspond to situations where N does not limit growth and N nutrition is not excessive.

In potatoes, critical N curves were first proposed in France, Scotland, and the Netherlands (Greenwood et al. 1990; Duchenne et al. 1997). In eastern Canada, the critical N curve of potato was determined for the cultivars Russet Burbank and Shepody under rain-fed and irrigated conditions (Bélanger et al. 2001b). Critical N curves were found to be specific to cultivars and water conditions. Parameters of the critical N curves are:

$$\text{Shepody } N_c = 5.36W^{-0.58} \tag{11.2}$$

$$\text{Russet Burbank } N_c = 4.50W^{-0.58} \tag{11.3}$$

under rain-fed conditions (Fig. 11.2) and:

$$\text{Shepody } N_c = 5.04W^{-0.42} \tag{11.4}$$

$$\text{Russet Burbank } N_c = 4.57W^{-0.42} \tag{11.5}$$

under irrigated conditions.

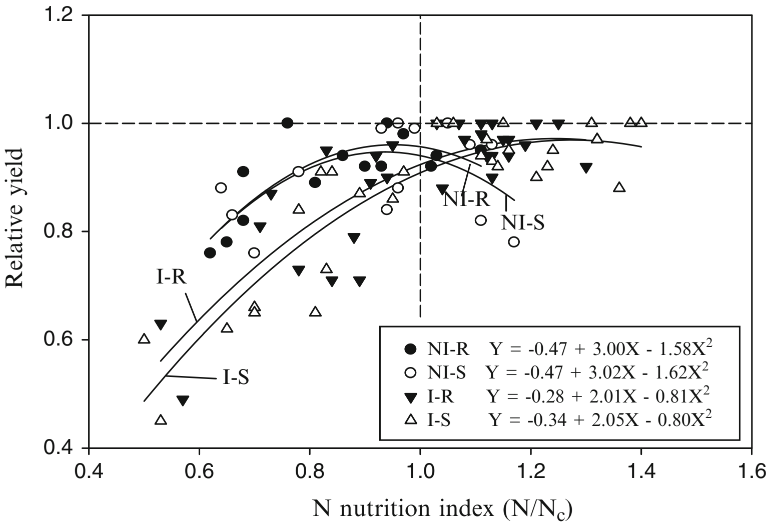

Fig. 11.3 Relationship between relative yield and the N nutrition index (NNI) of two potato cultivars (R: Russet Burbank; S: Shepody) with (I) and without (NI) irrigation (Bélanger et al. 2001b)

Using the NNI concept, relationships between potato relative yield and NNI were established for potatoes produced at six site-years in eastern Canada by Bélanger et al. (2001b) (Fig. 11.3). For a NNI equal to or greater than 1.0, the relative yield was near 1.0. In eastern Canada, there is limited evidence of yield depression at higher fertilizer N rates (Bélanger et al. 2000; Cambouris et al. 2007).With decreasing NNI below 1.0, the relative yield decreased. These results indicate that the NNI is a reliable indicator of the level of N sufficiency during the potato growing season.

The concept of N_c and the resulting NNI effectively identified situations of deficient and non-deficient N nutrition making it possible to quantify the level of potato N sufficiency. A major difficulty in using the NNI at the farm level, however, is the need to determine the actual crop biomass and its N concentration. For this reason, it may be more practical to use the NNI as a reference for calibration of simpler procedures (e.g. leaf chlorophyll measurements, petiole nitrate concentration) to determine the potato N status as described in the following sections.

11.2.2 Petiole Nitrate Concentration

Petiole nitrate concentration is one of the most widely used diagnostic tools to assess potato N sufficiency. Petiole nitrate concentration may be measured on a dry plant tissue basis or on freshly expressed petiole sap (Errebhi et al. 1998). The former is commonly done using a water extraction followed by colorimetric determination of nitrate concentration in the extract in a laboratory (Porter and Sisson 1991) whereas the latter can be measured either by a Nitrate Specific Electrode (Waterer 1997; Errebhi et al. 1998) or a combination of nitrate test strips with a hand-held reflectometer (Goffart et al. 2008). Significant relationships between petiole sap nitrate concentrations and petiole nitrate concentrations on a dry matter basis have been attained (Waterer 1997; Errebhi et al. 1998). Petiole dry matter content can vary widely among sampling dates in rain-fed potato production (Zebarth et al., unpublished data) and consequently petiole nitrate concentration on a dry tissue basis is likely more reliable in rain-fed production systems.

The concentration of nitrate in the petiole reflects the balance between nitrate reduction in the leaf and recent plant nitrate uptake from soil (Zebarth et al. 2009). Petiole nitrate concentration can be influenced by several factors including the stage of development or days after planting (DAP), fertilizer N application, water availability, and potato cultivar. Similar to the N concentration of whole plants, the petiole nitrate concentration decreases over time (Bélanger et al. 2003). Nitrogen fertilization consistently increases petiole nitrate concentration. For example in a study conducted at six sites and with two cultivars, the average petiole nitrate concentration at 63 DAP increased from 0.69% with no N applied to 2.60% when 250 kg N ha^{-1} was applied (Bélanger et al. 2003). A quadratic response to N application was reported (Porter and Sisson 1991; Bélanger et al. 2003) which is attributed to the saturation of the plant uptake capacity at high N rates.

Petiole nitrate concentration was reported to be influenced by water availability during the growing season. Insufficient water may result in the accumulation of nitrate in potato petioles (Meyer and Marcum 1998) whereas excessive water may reduce petiole nitrate concentration (Stark et al. 1993). Irrigation, however, had no consistent effect on petiole nitrate concentration in study conducted at several site-years in New Brunswick (Bélanger et al. 2003) where the level of water stress might have been insufficient to influence petiole nitrate concentration. The petiole nitrate concentration also varies with cultivars (Lewis and Love 1994; Bélanger et al. 2003). Greater petiole nitrate concentrations were reported for Shepody than for Russet Burbank on all sampling dates and all sites in a study conducted in New Brunswick (Bélanger et al. 2003).

Critical values or ranges of petiole nitrate concentrations have been suggested for potatoes in several producing areas of the world (Porter and Sisson 1991; Waterer 1997; Bélanger et al. 2003). The critical petiole nitrate concentration, that is the petiole nitrate concentration required to reach maximum yield, has most often been established using the relationship between petiole nitrate concentration and tuber yield or relative tuber yield. This relationship varies with sampling dates (DAP) and cultivars. In eastern Canada, petiole nitrate concentration increased linearly with relative yield for Russet Burbank ($R^2=0.60$) and Shepody ($R^2=0.53$) at approximately 59 DAP (Bélanger et al. 2003). However, the use of relative yield to determine the critical petiole concentration has one major limitation. Petiole nitrate concentration keeps increasing even when relative yield has reached its maximum value, that is, with no corresponding increase in tuber yield.

A novel approach to defining critical petiole concentrations was proposed by Bélanger et al. (2003) in which the NNI is used to determine critical petiole nitrate

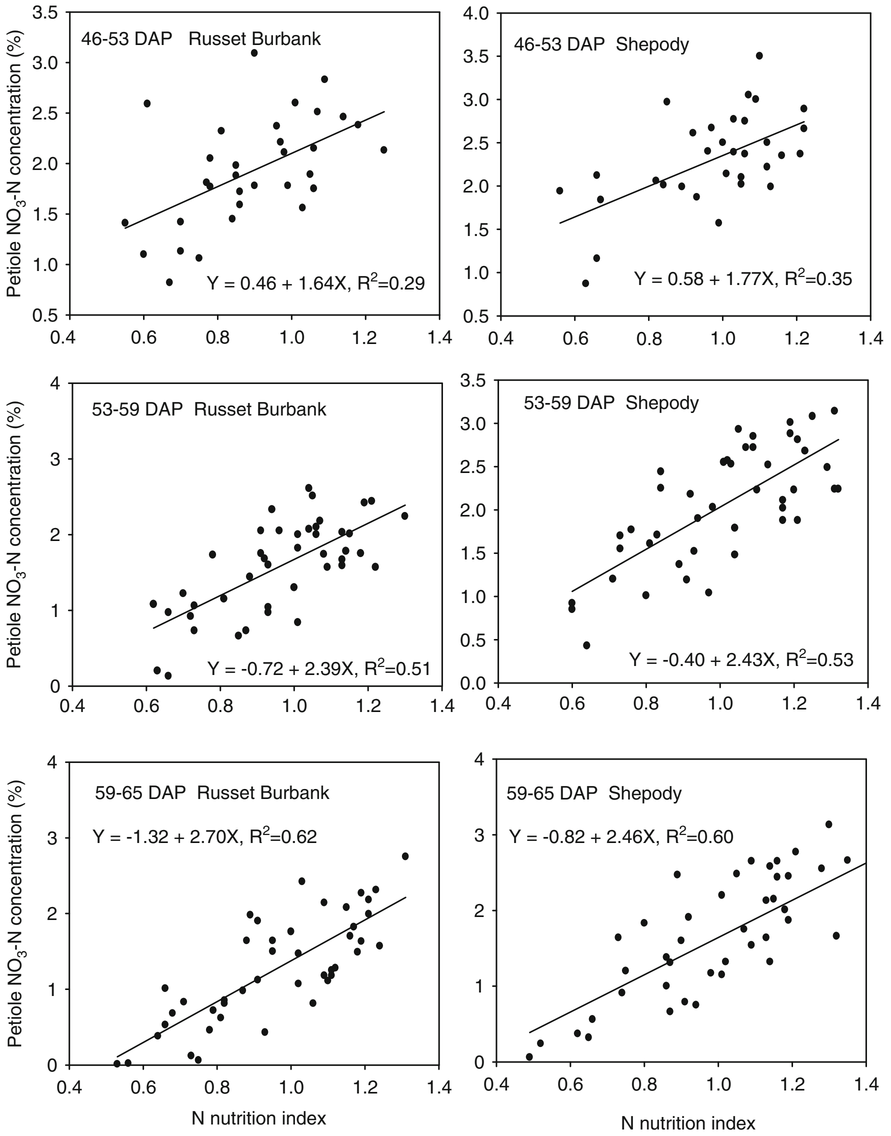

Fig. 11.4 Petiole NO$_3$-N concentration as a function of the N nutrition index on three sampling intervals based on the number of days after planting (DAP) and for two potato cultivars (Bélanger et al. 2003)

concentrations. They confirmed that the relationship between petiole nitrate concentration and NNI was specific to each cultivar and that it changed during the growing season (Fig. 11.4). Consequently, separate critical petiole nitrate concentrations for Russet Burbank and Shepody were proposed, taking the number of days

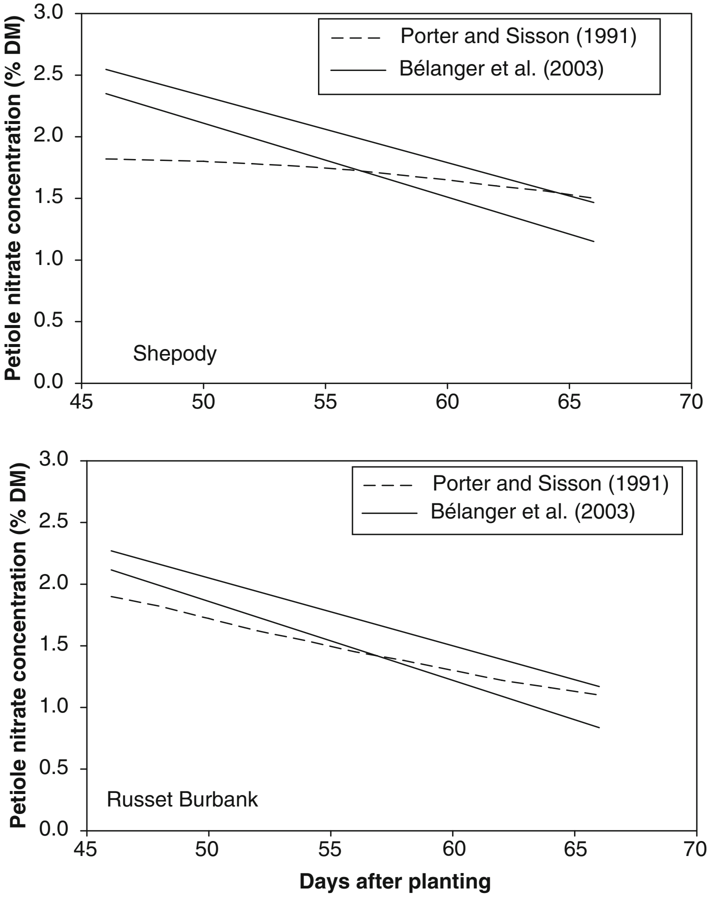

Fig. 11.5 Critical petiole nitrate concentration curves for potato cultivars Shepody and Russet Burbank as a function of the number of days after planting from two independent studies conducted in Maine (Porter and Sisson 1991) and New Brunswick (Bélanger et al. 2003). For Bélanger et al. (2003), the estimation of critical concentrations is based on the relationship with the N nutrition index (NNI) with the upper limit corresponding to NNI = 1.0 and the lower limit to NNI = 0.90

after planting into account (Fig. 11.5). These critical values are relatively close to those reported by Porter and Sisson (1991) in Maine, which were based on tuber yield (Fig. 11.5).

11.2.3 Chlorophyll Content and Chlorophyll Fluorescence

Optical methods of quantifying plant N sufficiency have been developed. Most of these methods are based on quantification of leaf chlorophyll content, which in turn is well correlated with leaf N concentration (Vos and Bom 1993). The SPAD-502 meter (Minolta Camera Co., Osaka, Japan) is the most commonly used optical instrument to measure the leaf chlorophyll content of potatoes (Vos and Bom 1993; Minotti et al. 1994). The SPAD values are the ratio of the intensities of the transmitted light at two wavelengths: red at 640 nm and near infrared at 940 nm (Spectrum Technologies Inc 2009).

Several factors, including cultivar, soil type, and climatic conditions, influence the SPAD values for potato (Gianquinto et al. 2004). This problem can be resolved by using reference plots that can be either over-fertilized or under-fertilized (i.e. no N applied). Denuit et al. (2002) concluded that over-fertilized plots were not effective for potatoes because the SPAD values were relatively insensitive to N rate at high N rates, and it was difficult to discriminate between the fertilized and over-fertilized plots. Olivier et al. (2006) compared both over-fertilized and under-fertilized reference plots and concluded that the zero-N plots discriminated well which potato fields responded to a second N application. Goffart et al. (2008) concluded that SPAD readings do not respond to potato N uptake when fertilizer N rates are above optimal and consequently can only be used to detect N deficiency.

In New Brunswick, for each date of measurements of SPAD values, relatively good positive correlations ($0.45 < r < 0.79$) between SPAD values and total tuber yield were obtained whereas SPAD values were poorly correlated with relative yield when all sampling dates were included (Zebarth et al. 2003b). Those results indicate that the relationship between SPAD measurements and tuber yield are specific to development stages (Zebarth and Rosen 2007). More recently, the lack of sensitivity of the SPAD values to fertilizer N rate near the optimal rate during crucial development stage for in-season N fertilization were demonstrated (Zebarth et al. 2011). Similar to petiole nitrate concentration, expressing the chlorophyll readings or the relative chlorophyll readings as a function of NNI might provide a more reasonable approach to determine critical values. This has not yet been tested in potatoes, but it has proved useful in corn (Ziadi et al. 2008b) and wheat (Ziadi et al. 2010b).

The popularity of the SPAD meter is linked to the fact that it is easier to use, faster and less costly than the current plant N tissue analyses which require destructive plant sampling. SPAD measurements are, however, still limited to small sampling areas because they require physical contact (near sensing approach) with the leaves (Botha et al. 2007). In addition, SPAD has been shown to detect N deficiency later than petiole nitrate diagnostic tool. Indeed, Wu et al. (2007) reported that N deficiency could be detected about 1 month and 2 weeks after emergence with SPAD and petiole nitrate concentrations, respectively.

Chlorophyll fluorescence analysis is another technique that can be used to determine the plant N status. It is based on the measurement of polyphenolics (Phen), which are secondary metabolites affected by stress factors (Goffart et al. 2008). A N-stressed plant has a higher content of Phen than non-stressed plants. The Phen compounds have typical ultraviolet (UV) absorption peaks in the UV-A and UV-B region (Cerovic et al. 2002) and the value of leaf UV absorbance is directly correlated with the concentration of polyphenolics in leaf tissues.

The Dualex, a portable leaf-clip tool, has been developed by Goulas et al. (2004) in France (Force-A, Orsay, France) to measure Phen contents. The Dualex provides an estimation of the absorbance by the leaf epidermis using two excitation wavelengths, one in the ultraviolet (375 nm) and one red 650 nm where the former is directly related to the concentration of Phen (Goulas et al. 2004). Cartelat et al. (2005) showed that with increasing N fertilization in wheat, leaf chlorophyll content increased and leaf polyphenolics content decreased. They further suggested that the ratio of leaf chlorophyll to polyphenolics is potentially a better indicator of leaf N concentration at the canopy level than either individual measurement. Tremblay et al. (2007) reported similar results for corn produced in eastern Canada. The Dualex has been successfully used in eastern Canada for corn (Tremblay et al. 2007), wheat (Tremblay et al. 2010) and strawberry (Fan et al. 2011). However, this technique is still under investigation for potatoes.

11.2.4 Multispectral Leaf Reflectance Measurements

Light reflectance-based measurements are an alternative approach to measuring leaf chlorophyll content, and have the advantage of being suitable for use at both the leaf and canopy scales (Botha et al. 2006, 2007). Reflectance measurements do not need a contact with the leaves and these measurements can be done with proximal or remote sensors. Reflectance measurements are therefore more suitable for measurement over larger areas. Tractor-mounted sensors such as “Greenseeker” or “Hydro N Sensor” are commercially available to map spatial variability of crop N status in a field (Zebarth et al. 2003b).

Recent studies had shown that hyperspectral leaf reflectance and transmittance measurements using a portable spectroradiometer and inverted analytical models such as PROSPECT or PROSAIL can be used to assess potato N status by estimating leaf or canopy chlorophyll contents (Botha et al. 2006, 2007). When used at the canopy level, hyperspectral reflectance measurements with the inverted PROSAIL model were most effective when the canopy structure was homogenous, and was less effective before canopy closure or after vine collapse (Botha et al. 2007). Spatial variability of potato N status in a field in New Brunswick was effectively mapped using the Hydro N Sensor (Zebarth et al. 2003b). While light reflectance-based approaches are generally effective in assessing relative potato N sufficiency, practical means of using this information to guide in-season fertilizer N management are currently lacking.

11.2.5 Use of Gene Expression

A novel approach to quantification of potato N sufficiency using gene expression is currently being evaluated. Plant responses to their environment, including abiotic stresses, are mediated through changes in gene expression (Hazen et al. 2003). Consequently, quantification of gene expression may provide a more direct measure of plant N sufficiency than current chemical or optical methods. Several studies have identified stress-specific plant gene expression profiles in response to single and combined abiotic stresses including nutrient deficiency (Hazen et al. 2003; Bohnert et al. 2006; Swindell 2006), suggesting it may be possible to use this approach to identify and distinguish among multiple abiotic stresses.

Quantitative assessment of plant N status by gene expression was first done by Li et al. (2010) using potato plants from three potato cultivars grown in a hydroponic system in the greenhouse. Although the conditions of the study were somewhat artificial, it demonstrated that a nitrate reductase gene could be used to quantitatively assess a change in potato N sufficiency within a few days of imposition of N deficiency stress. Subsequently, Zebarth et al. (2011) examined response of expression for 22 genes in leaf tissue of Shepody potatoes grown in the field at six fertilizer N rates. An ammonium transporter gene was identified which was as good as or better than petiole nitrate concentration and SPAD-502 meter readings for quantifying potato N status. While preliminary information on use of gene expression to quantify potato N status is promising, further information is required to determine the potential of this approach. In addition, practical application of this approach is currently limited by economics and by requirements for sample collection and handling protocols (Luo et al. 2011).

11.3 Soil-Based Diagnostic Methods

In most cases, soil-based tests provide an estimate of soil N supply that can be used to adjust the at-planting fertilizer N rate of a given field. Alternatively, soil-based tests can be taken in-season to estimate crop N supply (i.e. soil N supply plus applied fertilizer N). Such tests do not, however, consider crop N demand, and consequently it may be useful to utilize plant-based tests to refine in-season N management.

11.3.1 Soil Mineral Nitrogen Tests

Spring soil mineral N tests are the most commonly used soil-based diagnostic tests. In most cases, these tests are used to quantify the residual soil nitrate from the previous cropping season. Different terminology may be used to describe these tests such as the pre-plant nitrate test or the Nmin test. Such tests have been widely adopted for use in predicting fertilizer N requirements in North America (Hergert 1987) and Europe (Greenwood 1986) of several annual crops, including potatoes.

In humid regions such as eastern Canada, most residual soil nitrate from the previous growing season is lost over the autumn and winter period (Zebarth et al. 2009). Despite this, spring soil nitrate concentration is often well correlated with soil N supply because it reflects early season soil N mineralization (McTaggart and Smith 1993; Sharifi et al. 2008). Spring soil nitrate used alone, however, is not suitable as the basis for making fertilizer N recommendations for potatoes in eastern Canada (Bélanger et al. 2001a). Soil nitrate concentrations change rapidly over time when sampling would occur, and the quantity of soil nitrate in spring is relatively small compared with soil N supply (Zebarth et al. 2005). Therefore, the spring soil nitrate is not a reliable predictor of soil N supply. This is particularly true in some years when significant residual nitrate from the previous growing season is present (Zebarth et al. 2003a). As a result, it may be more appropriate in these humid environments to use spring soil mineral N as a N credit to adjust the fertilizer N recommendations (Zebarth et al. 2009).

An alternative approach is to use a mid-season nitrate test done at 32–47 DAP as a measure of crop N supply from the soil and spring-applied fertilizer to determine if supplemental N fertilizer is required. Bélanger et al. (2001a) suggested that a critical mid-season value of 80 mg NO_3-N kg^{-1} soil, measured at the 0–30 cm depth in the potato ridge following banded at-planting fertilizer application, above which additional N fertilizer may not be needed. The high spatial variability in nitrate concentration within the potato ridge/furrow system, the presence of a significant proportion of soil mineral N as ammonium at this time (Zebarth and Milburn 2003), and the variable geometry of the ridge/furrow system among grower fields may, however, complicate practical application of this approach.

11.3.2 Ion Exchange Membranes

Ion exchange membranes placed in soil have been used as an alternative to measurement of soil mineral N concentration. Both anionic and cationic exchange membranes have been used to measure nitrate and ammonium, respectively, and are commercially available as “Plant Root Simulators” (PRS). These membranes accumulate N from soils through exchange reactions by a similar mechanism to the soil-root system (Yang et al. 1991; Sharifi et al. 2009a). Thus, these membranes detect soil mineral N present at the time of insertion, plus net soil N mineralization during the period during which they are deployed, and N adsorbed on the membranes are not subject to loss through leaching or denitrification. Results from a number of field studies across Canada suggest that ion exchange membranes provide a better index of plant N availability than measurements of soil mineral N alone (Paré et al. 1995; Qian and Schoenau 1995; Ziadi et al. 1999; Nyiraneza et al. 2009). These membranes can be used to measure soil N supply when used on unfertilized plots, or crop N supply (i.e. soil N supply plus applied fertilizer N) when used on fertilized plots.

In potatoes grown in Prince Edward Island and Nova Scotia, Sharifi et al. (2009a) used PRS probes to measure soil N supply following different spring-applied organic amendments. Cumulative N supply measured over a 31 day period after planting was closely related to plant (vines plus tubers) N uptake measured at vine mechanical removal ($R^2 = 0.60$), and plant N uptake plus soil mineral N (0–30 cm depth) at harvest ($R^2 = 0.60$).

In Quebec, Ziadi et al. (2011) used anion exchange membranes (PRS-N) during three consecutive growing seasons in potatoes grown under different mineral fertilizer treatments. They concluded that PRS-N measured 40 to 50 DAP can be used as a tool to determine the need for additional N. A significant linear-plus-plateau relationship between relative yield and PRS-N was obtained indicating a critical value of 15 μg PRS-N cm^{-2} d^{-1} above which no additional N application may be required.

Ion exchange membranes can be an effective means of quantifying crop N supply, particularly in the presence of an active crop root system (Zebarth et al. 2009). Duration of deployment of the membranes should be limited to avoid the risk of saturation of the membranes (Qian and Schoenau 2002). Given the high spatial variation in soil mineral N in the potato ridge/furrow system (Zebarth and Milburn 2003), the location of placement of the ion exchange membranes should be carefully selected. In addition, the units of measurement for ion exchange membranes (i.e. flux values) cannot be converted directly to units of concentration or mass, which makes it more difficult to use them for making fertilizer N recommendations. While there has been increased interest in use of ion exchange membranes in research studies, their use in commercial potato production is limited.

11.3.3 Mineralizable Soil Nitrogen

The N mineralized from soil organic matter, organic amendments, and crop residues represents a significant proportion (between 20% and 80%) of crop N requirement (Broadbent 1984). However, estimating this source remains a challenge because of the complex soil, management and environmental controls on the N mineralization process (Dessureault-Rompré et al. 2010a, 2011a; Nyiraneza et al. 2010).

The standard laboratory-based method to quantify soil mineralizable N was developed by Stanford and Smith (1972) to estimate soil potentially mineralizable N (N_0). The N_0 is determined using a long-term aerobic incubation, and therefore this approach is not feasible for practical use. Consequently, a number of indices of soil N availability have been evaluated as predictors of N_0 (St. Luce et al. 2011). In many cases, these indices are chemical tests that target various mineralizable N pools or are biological assays of soil mineralizable N.

A number of studies have evaluated the indices of soil N availability by comparison with N_0 (Sharifi et al. 2007a; Schomberg et al. 2009). Some of the better predictors of N_0 included UV absorbance of a 0.01 *M* $NaHCO_3$ extract at 205 nm or 260 nm (Fox and Piekielek 1978; Hong et al. 1990), direct distillation with NaOH (50%) (Sharifi et al. 2009b), Illinois soil N test (ISNT) for amino sugar N (Khan et al. 2001), particulate organic matter C or N (Gregorich and Beare 2007), hot KCl extractable NH_4-N (Gianello and Bremner 1986), and hot KCl hydrolysable NH_4-N (Wang et al. 2001) (Table 11.1). However in some cases, simple soil properties, for example soil organic C or clay content, may be almost as effective in predicting N_0 as these indices of soil N availability (Simard et al. 2001).

Table 11.1 Proportion of variation in N_0 (i.e. r^2 values from linear regressions) explained by different indices of soil N availability

N availability index^Z	r^{2Y}
$NaHCO_3$-260	0.74
NaOH-DD	0.61
ISNT	0.51
POMC	0.47
$NaHCO_3$-205	0.47
$HKCl_{HYDR}$	0.46
POMN	0.39
HKCl-NH_4	0.26
PBN_{HYDR}	0.13
PBN	0.11
MBC	0.11
Total organic C	0.60
Total organic N	0.67
Clay	0.46

Adapted from Sharifi et al. (2007a)

$^Y r^2 \geq 0.26$ were significant $P \leq 0.001$; $n = 39$

^{Z}KCl-NH_4 = extractable NH_4 with 1.7 M KCl; HKCl-NH_4 = extractable NH_4N with 2 M 100 °C KCl; $HKCl_{HYDR}$ = HKCl-NH_4 - KCl-NH_4; $NaHCO_3$-205 = UV absorbance of 0.01 M $NaHCO_3$ extract at 205 nm; $NaHCO_3$-260 = UV absorbance of 0.01 M $NaHCO_3$ extract at 260 nm; ISNT = Illinois Soil N Test for amino sugar-N; NaOH-DD = direct distillation with NaOH (50%); MBC = microbial biomass C by fumigation extraction method; PBN = direct distillation with phosphate-borate buffer (pH = 11.2); PBN_{HYDR} = PBN – (KCl-NH_4); POMC = particulate organic matter C; POMN = particulate organic matter N

Some studies compared indices of soil N availability with field-based measures of soil N supply, most commonly for corn. For example, Hong et al. (1990) found strong positive correlations between soil N supplying capacity (N uptake in the above-ground plant less 75% of starter N) with spring soil nitrate, spring soil nitrate plus hot KCl extractable NH_4-N, spring soil nitrate plus distillation with a phosphate-borate buffer solution (pH 11.2), and ultraviolet absorbance of a 0.01 M $NaHCO_3$ extract at 200 nm. The ISNT was highly correlated with check-plot corn yield (r = 0.79) and fertilizer N response (r = 0.82) of corn in Illinois (Mulvaney et al. 2001), however, Barker et al. (2006) concluded that the ISNT is not a good predictor of corn relative grain yield. No single index of soil N availability has gained widespread adoption.

Few studies compared indices of soil N availability with field-based measures of soil N supply in potatoes. Sharifi et al. (2007b) compared potato plant (vines plus tubers) uptake and tuber relative yield against a series of indices of N availability for sites in New Brunswick, Canada and Maine, USA under rain-fed production from 2000 to 2005. Spring soil mineral N was one of the best predictors of soil N supply, however, Sharifi et al. (2007b) recommended use of spring soil N plus Pool I (a labile pool of mineralizable N measured using a 14 day aerobic incubation) as a

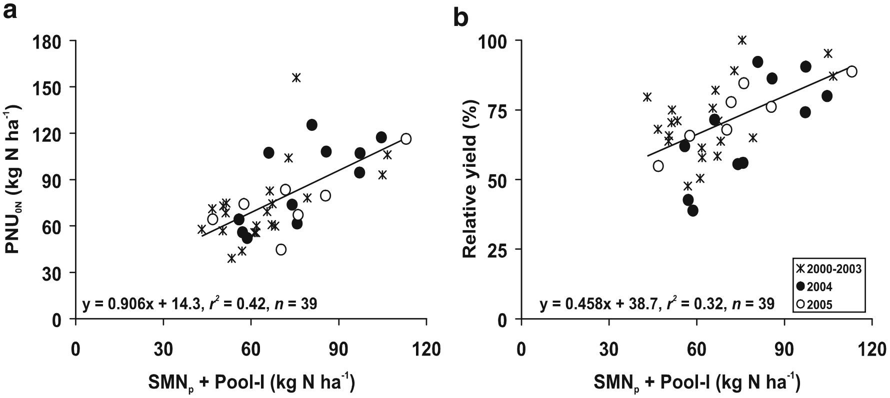

Fig. 11.6 Relationships between spring soil mineral N (0–30 cm depth) (SMN$_p$) plus Pool-I (a labile mineralizable N pool) and (**a**) soil N supply as estimated by plant (vines plus tubers) N uptake measured at vine desiccation with no fertilizer N application (PNU$_{0N}$) and (**b**) relative yield in field experiments in New Brunswick, Canada and Maine, USA in 2000–2005 (Sharifi et al. 2007b)

more robust predictor of soil N supply (Fig. 11.6). Interestingly, N_0 was a poor predictor of soil N supply. This was attributed at least in part to the exclusion of the labile mineralizable N pool in estimating the value of N_0.

Soil N availability indices provide a measure of the potential for soil N mineralization to occur, but they do not account for the effects of environmental conditions in influencing actual soil net N mineralization. One option is to predict soil N supply using simple first order kinetic models of soil N mineralization:

$$\mathrm{N}_{\min} = N_0\left[1-\mathrm{e}^{-kt}\right] \tag{11.6}$$

where $\mathrm{N}_{\min}$ is the cumulative amount of N mineralized at time t, N_0 is potentially mineralizable N, and k is the mineralization rate coefficient (Stanford and Smith 1972; Curtin and Campbell 2007). The value of the mineralization rate constant, k, can be modified based on soil temperature (Dessureault-Rompré et al. 2010b) or soil water content (Paul et al. 2003; Dessureault-Rompré et al. 2011b) to reflect changes in environmental conditions. In some cases, satisfactory predictions of net N mineralization in the field have been achieved using a kinetic model (Stanford et al. 1977; Marion et al. 1981; Campbell et al. 1984) whereas in other cases soil N supply has been overestimated (Verstraete and Voets 1976; Griffin and Laine 1983; Cabrera and Kissel 1988; Mikha et al. 2006). In eastern Canada, Dessureault-Rompré et al. (2011a) compared estimates of soil N supply from a kinetic model with plant (vines plus tubers) N uptake in unfertilized potato plots in New Brunswick, Canada and Maine, USA. Direct application of the kinetic model significantly underestimated field measured soil N supply, however when the model considered soil mineral N and the labile mineralizable pool (i.e. Pool-I), satisfactory results were obtained. However, practical application of kinetic models is currently limited by the requirement for long-term laboratory incubations to obtain estimates of the values of N_0 and k.

Substantial effort has been made to improve understanding and prediction of soil N mineralization, and promising progress has been made. However to date, there is limited use of soil mineralizable N tests in making fertilizer N recommendations for potato production.

11.3.4 Near-Infrared Reflectance Spectroscopy

Near-infrared reflectance spectroscopy (NIRS) is a rapid, non-destructive technique which can be used for soil analyses (Dunn et al. 2002). The NIRS is commonly used in plant analysis, specifically to determine the nutritive value of feedstuffs, but its application in soil analysis is still under investigation (Malley et al. 2002; Nduwamungu et al. 2009a, b). The soil N availability as measured by NIRS was previously demonstrated to be closely related to soil N supply as measured by crop N uptake in unfertilized plots for corn ($R^2 = 0.49$; Fox et al. 1993) and winter wheat ($R^2 = 0.81$; Börjesson et al., 1999). In eastern Canada, Nduwamungu et al. (2009a) accurately predicted potentially mineralizable N calculated from soil organic matter and clay content (Simard et al. 2001) under corn production. The NIRS is a technique which merits further examination as a measure of soil N availability.

11.4 Agronomic Applications

Soil- and plant-based diagnostic tests have the potential to improve the efficiency of N utilization, and hence provide economic benefits to growers and environmental benefits to society. It is necessary for test results to be interpreted and converted into N recommendations in order for them to be effective for action (Vos 2009).

Some plant-based tests have been successfully used as a diagnostic of crop N status (e.g. petiole nitrate concentration in potatoes) or in crop models of several crops (e.g. NNI) to account for the effect of N on growth and yield. At the farm level, however, there are some limitations to their adoption by growers. Although, the NNI has been shown to have the potential to successfully diagnose the N status for different crops including potatoes, this tool requires the determination of the shoot biomass during the growing season and its N concentration, which is time-consuming for growers. Furthermore, the critical N curve is only valid for shoot biomass greater than 1.0 Mg DM ha^{-1}. The window of opportunity for a remedial action is then limited in a relatively short season. The NNI could, however, be used as a reference for simpler procedures such as the chlorophyll meter readings and petiole nitrate concentration to determine the crop N status. These simpler procedures are currently available but they are still not widely used in eastern Canada. The benefits of multi or hyperspectral measurements have not yet been demonstrated at the farm scale whereas further research is required to determine if gene expression can be used to reliably assess potato N sufficiency.

Soil tests based on residual nitrate are most commonly used world-wide, but are not as effective in eastern Canada because most residual nitrate is lost over the fall and winter period. Significant progress has been made in use of ion exchange membranes and in soil mineralizable N tests. However, further work is required before such approaches can be used as the basis of fertilizer N recommendations.

It is proposed that the most effective strategy will be the use of a combination of soil- and plant-based diagnostic tools. Soil-based tests can be used to predict soil N supply, and to adjust at-planting fertilizer N rates whereas plant-based tests can be used to assess crop N sufficiency as a guide to in-season fertilizer N management. Such an approach will facilitate the matching of the N supply to the crop N demand on an individual field basis and yield economic and environmental benefits.

References

Barker DW, Sawyer JE, Al-Kaisi MM, Lundvall JP (2006) Assessment of the amino sugar-nitrogen test on Iowa Soils: II. Field correlation and calibration. Agron J 98:1352–1358

Bélanger G, Ziadi N (2008) Phosphorus and nitrogen relationships during spring growth of an aging timothy sward. Agron J 100:1757–1762

Bélanger G, Walsh JR, Richards JE, Milburn PH, Ziadi N (2000) Yield response of two potato cultivars to supplemental irrigation and N fertilization in New Brunswick. Am J Potato Res 77:11–21

Bélanger G, Walsh JR, Richards JE, Milburn PH, Ziadi N (2001a) Predicting nitrogen fertilizer requirements of potatoes in Atlantic Canada with soil nitrate determinations. Can J Soil Sci 81:535–544

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

Bélanger G, Walsh JR, Richards JE, Milburn PH, Ziadi N (2003) Critical petiole nitrate concentration of two processing potato cultivars in eastern Canada. Am J Potato Res 80:251–262

Bohnert HJ, Gong Q, Li P, Ma S (2006) Unraveling abiotic stress tolerance mechanisms – getting genomics going. Curr Opin Plant Biol 9:180–188

Börjesson T, Stenberg B, Linden B, Jonsson A (1999) NIR spectroscopy, mineral nitrogen analysis and soil incubations for the prediction of crop uptake of nitrogen during the growing season. Plant Soil 214:75–83

Botha EJ, Zebarth BJ, Leblon B (2006) Non-destructive estimation of potato leaf chlorophyll and protein contents from hyperspectral measurements using the PROSPECT radiative transfer model. Can J Plant Sci 86:279–291

Botha EJ, Leblon B, Zebarth BJ, Watmough J (2007) Non-destructive estimation of potato leaf chlorophyll from canopy hyperspectral reflectance using the inverted PROSAIL model. Intern J Appl Earth Observ Geoinform 9:360–374

Broadbent FE (1984) Plant use of soil nitrogen. In: Hauck RD (ed) Nitrogen in crop production. ASA, CSSA, and SSSA, Madison, pp 171–182

Burton DL, Zebarth BJ, Gillam KM, MacLeod JA (2008) Effect of split application of fertilizer nitrogen on N_2O emissions from potatoes. Can J Soil Sci 88:229–239

Cabrera ML, Kissel DE (1988) Evaluation of a method to predict nitrogen mineralized from soil organic matter under field conditions. Soil Sci Soc Am J 52:1027–1031

Cambouris AN, Zebarth BJ, Nolin MC, Laverdière MR (2007) Response to added nitrogen of a continuous potato sequence as related to sand thickness over clay. Can J Plant Sci 87:829–839

Cambouris AN, Zebarth BJ, Nolin MC, Laverdière MR (2008) Apparent fertilizer nitrogen recovery and residual soil nitrate under continuous potato cropping: effect of N fertilization rate and timing. Can J Soil Sci 88:813–825

Campbell CA, Jame YW, Winkleman GE (1984) Mineralization rate constants and their use for estimating nitrogen mineralization in some Canadian prairie soils. Can J Soil Sci 64:333–343

Cartelat A, Cerovic ZG, Goulas Y, Meyer S, Lelarge C, Prioul JL, Barbottin A, Jeuffroy MH, Gate P, Agati G, Moya I (2005) Optically assessed contents of leaf polyphenolics and chlorophyll as indicators of nitrogen deficiency in wheat (*Triticum aestivum* L.). Field Crops Res 91:35–49

Cerovic ZG, Ounis A, Cartelat A, Latouche G, Goulas Y, Meyer S, Moya I (2002) The use of chlorophyll fluorescence excitation spectra for the non-destructive *in situ* assessment of UV-absorbing compounds in leaves. Plant Cell Environ 25:1663–1676

CRAAQ (2010) Centre de Références en Agriculture et Agroalimentaire du Québec. Fertilisation reference guide. (In French.) 2nd ed. ISBN 978-2-7649-0231-8, 473pp

Curtin D, Campbell CA (2007) Mineralizable nitrogen. In: Carter MC, Gregorich EG (eds) Soil sampling and methods of analysis, 2nd edn. CRC press, Boca Raton, FL, pp 599–606

Denuit JP, Olivier M, Goffaux MJ, Herman J, Goffart JP, Destain JP, Frankinet M (2002) Management of nitrogen fertilization of winter wheat and potato crops using the chlorophyll meter for crop nitrogen status assessment. Agronomie 22:847–853

Dessureault-Rompré J, Zebarth BJ, Burton DL, Sharifi M, Cooper J, Grant CA, Drury CF (2010a) Relationships among mineralizable soil nitrogen, soil properties and climatic indices. Soil Sci Soc Am J 74:1218–1227

Dessureault-Rompré J, Zebarth BJ, Georgallas A, Burton DL, Grant CA, Drury CF (2010b) Temperature dependence of soil nitrogen mineralization rate: comparison of mathematical models, reference temperatures and origin of the soils. Geoderma 157:97–108

Dessureault-Rompré J, Zebarth BJ, Burton DL, Georgallas A, Sharifi M, Porter GA, Moreau G, Leclerc Y, Arsenault WJ, Chow TL, Grant CA (2011a) Prediction of soil nitrogen supply in potato fields in a cool humid climate. Soil Sci Soc Am J 75:626–637

Dessureault-Rompré J, Zebarth BJ, Georgallas A, Burton DL, Grant CA (2011b) A biophysical water function to predict the response of soil nitrogen mineralization to soil water content. Geoderma 167–168:214–227

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

Dunn BW, Batten GD, Beecher HG, Ciavarella S (2002) The potential of near-infrared reflectance spectroscopy for soil analysis – a case study from the Riverine Plain of south-eastern Australia. Aust J Exp Agric 42:607–614

Errebhi M, Rosen CJ, Birong DE (1998) Calibration of a petiole sap nitrate test for irrigated Russet Burbank potato. Commun Soil Sci Plant Anal 29:23–25

Fan L, Fang C, Dubé C, Tremblay N, Khanizadeh S (2011) A non-destructive method to predict polyphenol content in strawberry. J Food Agric Environ 9:59–62

Fox RH, Piekielek WP (1978) A rapid method for estimating the nitrogen supplying capability of a soil. Soil Sci Soc Am J 42:751–753

Fox RH, Shenk JS, Piekielek WP, Westerhaus MO, Toth JD, Macneal KE (1993) Comparison of near-infrared spectroscopy and other soil nitrogen availability quick tests for corn. Agron J 85:1049–1053

Gianello C, Bremner JM (1986) A simple chemical method of assessing potentially available organic nitrogen in soil. Commun Soil Sci Plant Anal 17:195–214

Gianquinto G, Goffart JP, Olivier M, Guarda G, Colauzzi M, Dalla Costa L, Delle Vedove G, Vos J, Mackerron DKL (2004) The use of hand-held chlorophyll meters as a tool to assess the nitrogen status and to guide nitrogen fertilization of potato crop. Potato Res 47:35–80

Goffart JP, Olivier M, Frankinet M (2008) Potato crop nitrogen status assessment to improve N fertilization management and efficiency: past-present-future. Potato Res 51:355–383

Goulas Y, Cerovic ZG, Cartelat A, Moya I (2004) Dualex: a new instrument for field measurements of epidermal UV-absorbance by chlorophyll fluorescence. Appl Opt 43:4488–4496

Greenwood DJ (1986) Prediction of nitrogen fertilizer needs of arable crops. Adv Plant Nutr 2:1–61

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 66:425–436

Gregorich EG, Beare MH (2007) Physically uncomplexed organic matter. In: Carter MR, Gregorich EG (eds) Soil sampling and methods of analysis, 2nd edn. CRC Press, Boca Raton, FL, pp 607–616

Griffin GF, Laine AF (1983) Nitrogen mineralization in soils previously amended with organic wastes. Agron J 75:124–129

Hazen SP, Wu Y, Kreps JA (2003) Gene expression profiling of plant responses to abiotic stress. Funct Integr Genomics 3:105–111

Hergert GW (1987) Status of residual nitrate-nitrogen soil tests in the United States of America. In: Brown JR (ed) Soil testing: sampling, correlation, calibration, and interpretation. SSSA, Madison, pp 73–78

Hong SD, Fox RH, Piekielek WP (1990) Field evaluation of several chemical indexes of soil nitrogen availability. Plant Soil 123:83–88

Khan SA, Mulvaney RL, Hoeft RG (2001) A simple soil test for detecting sites that are nonresponsive to nitrogen fertilization. Soil Sci Soc Am J 65:1751–1760

Lemaire G, Salette J (1984) Relationship between growth and nitrogen uptake in a pure grass stand. I. Environmental effects. Agronomie 4:423–430, In French

Lewis RJ, Love SL (1994) Potato genotypes differ in petiole nitrate-nitrogen concentrations over time. HortSci 29:175–179

Li X-Q, Sveshnikov D, Zebarth BJ, Tai H, De Koeyer D, Millard P, Haroon M, Singh M (2010) Detection of nitrogen sufficiency in potato plants using gene expression markers. Am J Potato Res 87:50–59

Luo S, Tai H, Zebarth BJ, Li X-Q, Millard P, De Koeyer D, Xiong X (2011) Sample collection protocol effects on quantification of gene expression in potato leaf tissue. Plant Molec Biol Reporter 29:369–378

Malley DF, Yesmin L, Eilers RG (2002) Rapid analysis of hog manure and manure-amended soils using near-infrared spectroscopy. Soil Sci Soc Am J 66:1677–1686

Marion GM, Kummerow J, Miller PC (1981) Predicting nitrogen mineralization in Chaparral soils. Soil Sci Soc Am J 45:956–961

McTaggart IP, Smith KA (1993) Estimation of potentially mineralisable nitrogen in soil by KCl extraction. II. Comparison with soil N uptake in the field. Plant Soil 157:175–184

Meyer RD, Marcum DB (1998) Potato yield, petiole nitrogen, and soil nitrogen response to water and nitrogen. Agron J 90:420–429

Mikha MM, Rice CW, Benjamin JG (2006) Estimating soil mineralizable nitrogen under different management practices. Soil Sci Soc Am J 70:1522–1531

Minotti PL, Halseth DE, Sieczka JB (1994) Field chlorophyll measurements to assess the nitrogen status of potato varieties. HortSci 29:1497–1500

Mulvaney RL, Khan SA, Hoeft RG, Brown HM (2001) A soil organic nitrogen fraction that reduces the need for nitrogen fertilization. Soil Sci Soc Am J 65:1164–1172

NBDAFA (2001) Crop fertilization guide. Dept. Agriculture, Fisheries and Aquaculture, New Brunswick

Nduwamungu C, Ziadi N, Tremblay GF, Parent LE (2009a) Near-infrared reflectance spectroscopy prediction of soil properties: effects of sample cups and preparation. Soil Sci Soc Am J 73:1896–1903

Nduwamungu C, Ziadi N, Parent LE, Tremblay GF, Thuriès L (2009b) Opportunities for, and limitations of, near infrared reflectance spectroscopy applications in soil analysis: a review. Can J Soil Sci 89:531–541

Nyiraneza J, N'Dayegamiye A, Chantigny MH, Laverdiere MR (2009) Variations in corn yield and nitrogen uptake in relation to soil attributes and nitrogen availability indices. Soil Sci Soc Am J 73:317–327

Nyiraneza J, N'Dayegamiye A, Gasser MO, Giroux M, Grenier M, Landry C, Guertin S (2010) Soil and crop parameters related to corn nitrogen response in Eastern Canada. Agron J 102:1478–1490

Ojala JC, Stark JC, Kleinkopf GE (1990) Influence of irrigation and nitrogen management on potato yield and quality. Am Potato J 67:29–43

Olivier M, Goffart JP, Ledent JF (2006) Threshold values for chlorophyll meter as decision tool for nitrogen management of potato. Agron J 98:496–506

Paré T, Gregorich EG, Ellert BH (1995) Comparison of soil nitrate extracted by potassium chloride and adsorbed on an anion exchange membrane in situ. Commun Soil Sci Plant Anal 26:883–898

Paul KI, Polglase PJ, O'Connell AM, Carlyle JC, Smethurst PJ, Khanna PK (2003) Defining the relation between soil water content and net nitrogen mineralization. Eur J Soil Sci 54:39–47

Porter GA, Sisson JA (1991) Petiole nitrate content of Maine grown Russet Burbank and Shepody potatoes in response to varying nitrogen rate. Am Potato J 68:493–505

Qian P, Schoenau JJ (1995) Assessing nitrogen mineralization from soil organic matter using anion exchange membranes. Fert Res 40:143–148

Qian P, Schoenau JJ (2002) Practical applications of ion exchange resins in agricultural and environmental soil research. Can J Soil Sci 82:9–21

Schomberg HH, Wietholter S, Griffin TS, Reeves DW, Cabrera ML, Fisher DS, Endale DM, Novak JM, Balkcom KS, Raper RL, Kitchen NR, Locke MA, Potter KN, Schwartz RC, Truman CC, Tyler DD (2009) Assessing indices for predicting potentially nitrogen mineralization in soils under different management systems. Soil Sci Soc Am J 73:1575–1586

Sharifi M, Zebarth BJ, Burton DL, Grant CA, Cooper JM (2007a) Evaluation of some indices of potentially mineralizable nitrogen in soil. Soil Sci Soc Am J 71:1233–1239

Sharifi M, Zebarth BJ, Burton DL, Grant CA, Porter GA, Cooper JM, Leclerc Y, Moreau G, Arsenault WJ (2007b) Evaluation of laboratory-based measures of soil mineral nitrogen and potentially mineralizable nitrogen as predictors of field-based estimates of soil nitrogen supply in potato production. Plant Soil 301:203–214

Sharifi M, Zebarth BJ, Burton DL, Grant CA, Porter GA (2008) Organic amendment history and crop rotation effects on soil nitrogen mineralization potential and soil nitrogen supply in a potato cropping system. Agron J 100:1562–1572

Sharifi M, Lynch DH, Zebarth BJ, Zheng Z, Martin RC (2009a) Evaluation of nitrogen supply rate measured by in situ placement of Plant Root Simulator probes as a predictor of nitrogen supply from soil and organic amendments in potato crop. Am J Potato Res 86:356–366

Sharifi M, Zebarth BJ, Burton DL, Grant CA, Hajabbasi MA, Abbassi-Kalo G (2009b) Sodium hydroxide direct-distillation: a method for estimating total nitrogen in soil. Commun Soil Sci Plant Anal 40:2505–2520

Simard RR, Ziadi N, Nolin MC, Cambouris AN (2001) Prediction of nitrogen responses of corn by soil nitrogen mineralization indicators. In: Optimizing nitrogen management in food and energy production and environmental protection: Proceedings of 2nd international nitrogen conference on science and policy. Scientific World 1(S2):135–141

Spectrum Technologies Inc. (2009) SPAD 502 Plus Chlorophyll Meter Product Manual Item # 2900P, 2900PDL. 24pp

St. Luce M, Whalen JK, Ziadi N, Zebarth BJ (2011) Nitrogen dynamics and indices to predict soil nitrogen supply in humid temperate soils. Adv Agron 112:55–102

Stanford G, Smith SJ (1972) Nitrogen mineralization potentials of soils. Soil Sci Soc Am J 36:465–472

Stanford G, Carter JN, Westermann DT, Meisinger JJ (1977) Residual nitrate and mineralizable soil nitrogen in relation to nitrogen uptake by irrigated sugarbeets. Agron J 69:303–308

Stark JC, McCann IR, Westermann DT, Izadi B, Tindall TA (1993) Potato response to split nitrogen timing with varying amounts of excessive irrigation. Am Potato J 70:765–777

Swindell WR (2006) The association among gene expression responses to nine abiotic stress treatments in *Arabidopsis thaliana*. Genetics 174:1811–1824

Tremblay N, Wang Z, Bélec C (2007) Evaluation of the Dualex for the assessment of corn nitrogen status. J Plant Nutr 30:1355–1369

Tremblay N, Wang Z, Belec C (2010) Performance of Dualex in spring wheat for crop nitrogen status assessment, yield prediction and estimation of soil nitrate content. J Plant Nutr 33:57–70

Verstraete W, Voets JP (1976) Nitrogen mineralization tests and potentials in relation to soil management. Pedologie 26:15–26

Vos J (2009) Nitrogen responses and nitrogen management in potato. Potato Res 52:305–317

Vos J, Bom M (1993) Hand-held chlorophyll meter: a promising tool to assess the nitrogen status of potato foliage. Potato Res 36:301–308

Wang W, Smith CJ, Chalk PM, Chen D (2001) Evaluating chemical and physical indices of nitrogen mineralization capacity with an unequivocal reference. Soil Sci Soc Am J 65:368–376

Waterer D (1997) Petiole sap NO_3-N testing as a method of monitoring nitrogen nutrition of potato crops. Can J Plant Sci 77:273–278

Wu J, Wang D, Rosen CJ, Bauer ME (2007) Comparison of petiole nitrate concentrations, SPAD chlorophyll readings, and QuickBird satellite imagery in detecting nitrogen status of potato canopies. Field Crops Res 101:96–103

Yang JE, Skogley EO, Georgitis SJ, Schaff BE, Ferguson AH (1991) Phyto-availability soil test: development and verification of theory. Soil Sci Soc Am J 55:85–1365

Zebarth BJ, Milburn PH (2003) Spatial and temporal distribution of soil inorganic nitrogen concentration in potato hills. Can J Soil Sci 83:183–195

Zebarth BJ, Rosen CJ (2007) Research perspective on nitrogen BMP development for potato. Am J Potato Res 84:3–18

Zebarth BJ, Leclerc Y, Moreau G, Gareau R, Milburn PH (2003a) Soil inorganic nitrogen content in commercial potato fields in New Brunswick. Can J Soil Sci 83:425–429

Zebarth BJ, Rees H, Tremblay N, Fournier P, Leblon B (2003b) Mapping spatial variation in potato nitrogen status using the “N Sensor”. Acta Hort (ISHS) 627:267–273

Zebarth BJ, Leclerc Y, Moreau G, Sanderson JB, Arsenault WJ, Botha E, Wang-Pruski G (2005) Estimation of soil nitrogen supply in potato fields using a plant bioassay approach. Can J Soil Sci 85:377–386

Zebarth BJ, Drury CF, Tremblay N, Cambouris AN (2009) Opportunities for improved fertilizer nitrogen management in production of arable crops in eastern Canada: a review. Can J Soil Sci 89:113–132

Zebarth BJ, Tai H, Luo S, Millard P, De Koeyer D, Li X-Q, Xiong X (2011) Differential gene expression as an indicator of nitrogen sufficiency in field-grown potato plants. Plant Soil 345:387–400

Ziadi N, Simard RR, Allard G, Lafond J (1999) Field evaluation of anion exchange membranes as a N soil testing method for grasslands. Can J Soil Sci 79:281–294

Ziadi N, Brassard M, Bélanger G, Cambouris AN, Tremblay N, Nolin MC, Claessens A, Parent LE (2008a) Critical nitrogen curve and nitrogen nutrition index for corn in eastern Canada. Agron J 100:271–276

Ziadi N, Brassard M, Bélanger G, Claessens A, Tremblay N, Cambouris AN, Nolin MC, Parent LE (2008b) Chlorophyll measurements and nitrogen nutrition index for the evaluation of corn nitrogen status. Agron J 100:1264–1273

Ziadi N, Bélanger G, Claessens A, Lefebvre L, Cambouris AN, Tremblay N, Nolin MC, Parent LE (2010a) Determination of a critical nitrogen dilution curve for spring wheat. Agron J 102:241–250

Ziadi N, Bélanger G, Claessens A, Lefebvre L, Tremblay N, Cambouris AN, Nolin MC, Parent LE (2010b) Plant-based diagnostic tools for evaluating wheat nitrogen status. Crop Sci 50:2580–2590

Ziadi N, Grant C, Samson N, Nyiraneza J, Bélanger G, Parent LE (2011) Efficiency of controlled-release urea for a potato production system in Quebec, Canada. Agron J 103:60–66