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In-Season Nitrogen Status Assessment and Yield Estimation Using Hyperspectral Vegetation Indices in a Potato Crop

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ABSTRACT

The rate and timing of N applications are important issues in precision agriculture because of the within-field spatial and temporal variability of soil N availability. In-season assessment of potato (*Solanum tuberosum* L.) crop N status (CNS) is required to better match N fertilizer supply to crop N demand and improve N use efficiency. The objective of this study was to investigate the ability of hyperspectral vegetation indices (HVIs) to assess the CNS and tuber yield of irrigated 'Russet Burbank' potato at different growth stages. A 2-yr field experiment was conducted near Quebec City, QC, Canada, on plots receiving five different N rates ranging from 0 to 280 kg N ha^{-1}, with 40% applied at planting and 60% at hilling. Entire plant samples were collected biweekly for determination of the N nutrition index (NNI) as the N status reference method. In-field hyperspectral reflectance derived from a handheld spectroradiometer and using two fields of view (FOV; 7.5° and 25°) was obtained on several dates during both growing seasons. The sensitivity of the five HVIs most correlated to the NNI was evaluated by analyses of variance and least significant differences. It was found that HVIs computed from reflectance in the red-edge spectral region and using a wider FOV were the most appropriate indices to detect potato crop N stress. Among these indices, the $CI1_{red\text{-}edge}$ (red-edge chlorophyll index 1) was the most sensitive to potato N content and could explain 76% of the variability in total tuber yield at 55 d after planting (DAP).

It is well known that N is the most limiting nutrient for potato (*Solanum tuberosum* L.) growth. For an irrigated potato crop, adequate N management is required to ensure maximum tuber yield and quality (Vos and MacKerron, 2000). Although excessive N fertilization can delay tuber maturation and reduce quality (Goffart et al., 2008), a N deficiency can significantly reduce tuber size and yield (Bélanger et al., 2000). According to the potato cultivar and irrigation, local N fertilizer recommendations in Quebec, Canada, vary from 125 to 150 kg N ha^{-1} on loamy soils and from 135 to 175 kg N ha^{-1} on sandy soils (Centre de Référence en Agriculture et Agroalimentaire du Québec, 2010). However, potato is characterized by a relatively shallow root system (Stalham and Allen, 2001) and by sensitivity to water stress (Allaire et al., 2014). Moreover, commercial potato production usually occurs on coarse-textured soils with a low cation-exchange capacity and good drainage. In humid climates, high N inputs lead to a low N fertilizer use efficiency, usually below 50% (Cambouris et al., 2008; Tran and Giroux, 1991), and to higher N losses primarily through NO_3^- leaching, which can cause contamination of groundwater (Errebhi et al., 1998). Therefore, appropriate management of N fertilizer is important from both economic and environmental standpoints (Zebarth et al., 2009).

Because it is difficult, at planting, to predict soil mineralization and the potato crop N requirements throughout the growing season, a common and generally accepted agronomic practice is to split N applications (Vos and MacKerron, 2000). Producers need to monitor the N status of both the soil and the crop during the growing season to better match N fertilizer inputs to crop N demand within fields and among years. Instead of predicting soil N supply, the practice of monitoring the crop itself, which is considered a reliable integrator of the soil mineral N supply as well as weather conditions prevailing during the growing season, has been suggested (Schröder et al., 2000).

Therefore, several diagnostic methods have been developed in recent years to assess in-season crop N status (CNS). The N nutrition index (NNI) is a destructive method that relies on the chemical measurement of N concentration on the whole plant and that also considers the weight of aboveground

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Abbreviations: ANOVA, analysis of variance; CNS, crop nitrogen status; DAP, days after planting; FOV, field of view; HVI, hyperspectral vegetation index; LSD, least significant difference; N0, 0 kg N ha^{-1}; N60, 60 kg N ha^{-1}; N120, 120 kg N ha^{-1}; N200, 200 kg N ha^{-1}; N280, 280 kg N ha^{-1}; N_c, critical nitrogen concentration; NIR, near-infrared; NNI, nitrogen nutrition index.

biomass (W) (Lemaire and Gastal, 1997). A critical N concentration (N_c) is thus required to assess CNS at different times during the growing season and ultimately adjust N fertilizer input to crop N demand. The NNI was found to have the ability to assess CNS at different times during the growing season independently of growth stage (Ziadi et al., 2012). This method was first developed for tall fescue by Lemaire et al. (1984) and was successfully adapted to potato by Duchenne et al. (1997). Shortly thereafter, Bélanger et al. (2001) developed a specific N_c for 'Russet Burbank' potato grown under irrigation in eastern Canada. In those conditions, the NNI was proposed as a reliable indicator of the level of N stress in a potato crop during the growing season. The NNI, although considered to be the best indicator of CNS, does not provide recommendations for side-dress N application (Goffart et al., 2008). Because the NNI method requires destructive plant sampling, which is time-consuming and costly, it has been suggested that the NNI could be used as a reference to calibrate faster methods such as remote sensing (Bélanger et al., 2001; Goffart et al., 2008).

Remote sensing is now widely used in a number of disciplines, including precision agriculture. Vegetation indices have been used for a long time to monitor many temporal changes in agricultural crops (Lyon et al., 1998). Although some vegetation indices have been shown to have potential for assessing several crop stresses as well as general plant health (Jackson and Huete, 1991), hyperspectral vegetation indices (HVIs) may provide additional information on a crop's biophysical characteristics in comparison with broad-band vegetation indices (Thenkabail et al., 2000). Assessment of the N status of crops under specific field conditions requires vegetation indices that account for the complex factors that affect the spectral response of vegetation, such as soil background and shadow, which influence the bidirectional reflectance signature (Bannari et al., 1995; Zarco-Tejada et al., 2004). It has been recognized that chlorophyll absorption features have an impact on a larger portion in the spectrum than a width of a few nanometers, and therefore that the optimal wavelengths obtained from a spectroradiometer may be similar to those found in other studies on potato (Jain et al., 2007). However, the optimal wavelengths forming the HVIs that best identify 'Russet Burbank' potato CNS under irrigated fields in eastern Canada are still unknown. Moreover, few studies have reported the effect of a narrower field of view (FOV) on the sensitivity of HVIs in assessing potato crop N status at early stages owing to a reduced soil background effect.

Hyperspectral vegetation indices have been categorized into three groups: structural, chlorophyll, and red-edge indices. Jain et al. (2007) reported that red-edge indices were efficient in detecting variation in a potato crop caused by different N rates. The red-edge is defined by the rapid change in the reflectance spectrum between the red and near-infrared (NIR) regions (i.e., between 680 and 750 nm) and was found to distinctively characterize vegetation (Horler et al., 1983). The red-edge is also known to be correlated to the crop chlorophyll status independently of ground cover and is particularly efficient for the early detection of crop stress (Horler et al., 1983), which is an important consideration in an in-season N management context.

In addition to crop N stress detection, another application of hyperspectral remote sensing in precision agriculture is crop yield estimation (Yao et al., 2011). Yield estimation is one of the most important management aspects for growers (Yao et al., 2011). Zebarth et al. (2003) revealed that the index derived from the N-Sensor (Yara International ASA, Oslo, Norway) was well correlated to tuber yield, but the use of HVIs to predict tuber yield in a potato crop grown in eastern Canada has not been documented.

The objectives of this study were (i) to identify the HVIs that best discriminate 'Russet Burbank' potato CNS, (ii) to study the impact of FOV on the ability of HVIs to detect early crop N stress, (iii) to compare the sensitivity of the most appropriate HVIs with that of a destructive reference method (i.e., the NNI), and (iv) to identify the HVIs that best estimate total tuber yield.

MATERIALS AND METHODS

Study Area and Experimental Design

A 2-yr study was conducted in experiment plots in an irrigated commercial potato field in Sainte-Catherine-de-la-Jacques-Cartier, QC, Canada (46.84°N, 71.64°W, 150 m above mean sea level). The soil series consisted of a Pont-Rouge on the 2011 site and a Morin on the 2012 site, and both soils are classified as Humo-Ferric Podzols in the Canadian System of Soil Classification (Soil Classification Working Group, 1998). The previous crops were oat and corn in the 2011 and 2012 growing seasons, respectively. The 2011 growing season was wetter than normal, and the 2012 growing season was drier than normal (Table 1).

Irrigation was done with a center pivot sprinkler irrigation system. The field was irrigated once in August 2011 (22 mm), three times in July 2012 (66 mm), and three times in August 2012 (66 mm), as recommended by the agronomist in charge (personal communication). The potato crop was planted, hilled, and harvested, respectively, on 25 May, 5 July, and 26 Sept. in 2011 and on 14 May, 21 June, and 24 Sept. in 2012.

Table 1. Monthly normal temperature and rainfall obtained from an Environment Canada weather station and monthly air temperature and rainfall during the 2011 and 2012 growing seasons obtained from an on-site weather station.

	Normal†		2011		2012	
Month	Temperature	Rainfall	Temperature	Rainfall	Temperature	Rainfall
	°C	mm	°C	mm	°C	mm
May	11.2	107	11.0	156	13.4	98
June	16.4	111	16.8	96	17.6	177
July	19.3	125	19.5	152	19.6	44
Aug.	18.1	104	17.6	239	18.9	110
Sept.	12.8	117	15.4	80	13.2	94

† Thirty-year normals (1981–2010) based on data from the Jean-Lesage weather station (≈20 km from the site, 46.80°N latitude, 71.38°W longitude, 74.40 m above mean sea level).

Each experimental plot consisted of six rows, each measuring 0.915 m wide and 8 m long. A randomized complete block design with four replicates was used to maximize N variability to the potato crop (cv. Russet Burbank). The treatments consisted of five N rates, namely 0, 60, 120, 200, and 280 kg N ha^{-1}, which were called N0, N60, N120, N200, and N280, respectively. The N fertilizer used was ammonium sulfate, and 40% of the rate was applied at planting and 60% at hilling (i.e., 41 d after planting [DAP] in 2011 and 38 DAP in 2012). Both P and K were applied based on local recommendations (Centre de Référence en Agriculture et Agroalimentaire du Québec, 2010). Every plot was fertilized with a single uniform rate of 100 kg P_2O_5 ha^{-1} banded at planting as triple superphosphate (0–46–0). Potassium was applied at a rate of 230 kg K_2O ha^{-1} in two applications: 170 kg K_2O ha^{-1} as potassium chloride (0–0–60) was broadcast at preplanting, and the balance was banded at planting in a 50/50 mixture of potassium chloride and Sul-Po-Mag (2 $MgSO_4 \cdot K_2SO_4$).

Nitrogen Nutrition Index and Total Tuber Yield Measurements

Starting at hilling, shoot biomass and tuber biomass were manually harvested biweekly from four whole potato plants in the fifth row of each plot. A representative 550-g sample of shoot biomass from each plot was oven-dried at 55°C and reweighed to determine dry matter content. Because the potato crop nitrogen concentration (N_c) is calculated from the combined biomass of shoots and tubers (Bélanger et al., 2001), a representative sample of six tubers from each plot was sliced into 1 by 1 cm strips, weighed, oven-dried at 55°C, and reweighed to determine dry matter content (Cambouris et al., 2008). The shoot and tuber samples were then ground to pass through a 1-mm sieve. Subsamples of 0.1 g were analyzed separately with an Elementar vario MAX CN analyzer (Elementar Analysensysteme GmbH, Hanau, Germany) to determine total N content in shoots and tubers. Shoot and tuber biomass expressed on a dry matter basis were summed to obtain the combined potato biomass. The following equation was used to calculate the N concentration of the combined biomass of shoots and tubers (N_c) (Eq. [1]):

$$N_c = aW^b \qquad [1]$$

where W is the combined biomass of shoots and tubers (Mg dry matter ha^{-1}), parameter a represents the N concentration for 1 Mg dry matter ha^{-1}, and parameter b represents the coefficient of dilution (Bélanger et al., 2001). Bélanger et al. (2001) set parameter a to 4.57 and parameter b to −0.42 for the Russet Burbank potato cultivar grown under irrigated conditions in eastern Canada. The NNI resulted from the ratio between the measured N_c and the predicted N_c as expressed in Eq. [1]. Vine desiccation was done on 11 Sept. 2011 and 9 Sept. 2012 using the herbicide diquat (1,1′-ethylene-2,2′-bipyridyldiylium dibromide) followed by a second application of diquat 1 wk later. Total tuber yield was determined on 26 Sept. 2011 and 24 Sept. 2012 using one row (6 m long) from each plot.

Hyperspectral Data Collection

Hyperspectral reflectance data were acquired from a FieldSpec HandHeld spectroradiometer (Analytical Spectral Devices [ASD] Inc., Boulder, CO) with a total range of 325 to 1075 nm and a spectral resolution of 3.5 nm at 700 nm. The spectra were sampled according to the device specifications, although after resampling, the data were provided at a 1-nm interval. Two FOVs, 7.5° and 25°, were selected to acquire the spectral measurements with different soil background effects. The readings were collected around midday, between 1000 and 1400 h, and as much as possible under clear sky conditions. The sensor was oriented at nadir over the plant and placed about 1 m above the crop canopy (Fig. 1), resulting in an area of 0.013 and 0.1544 m^2 for the 7.5° and 25° FOVs, respectively. A tripod stabilized the sensor in the proper position, and precautions were taken to not shadow the crop. Fieldwork data were obtained using the RS^3 spectral acquisition software program (ASD Inc.) programmed with a spectrum averaging of 40. Before each measurement, a Spectralon highly Lambertian diffuser (Labsphere, Inc., North Sutton, NH) was used as the white reference. The ViewSpec Pro software program (ASD Inc.) was used to analyze and export the spectral data. The reflectance data were kept at a 1-nm interval and thus were not averaged to a greater spectral interval. A wide range of HVIs and potentially very narrow absorption features specific to the potato crop were therefore fully accessible.

Hyperspectral reflectance measurements were collected at 40, 48, 55, 61, 66, 70, 76, and 84 DAP in 2011 and at 37, 54, and 68 DAP in 2012, on or close to the sampling dates of the N reference method (i.e., NNI), which were 40, 54, 70, and 84 DAP in 2011 and 38, 52, 66, and 80 DAP in 2012. The canopy closure occurred on 3 Aug. 2011 and 23 July 2012 (around 70 DAP).

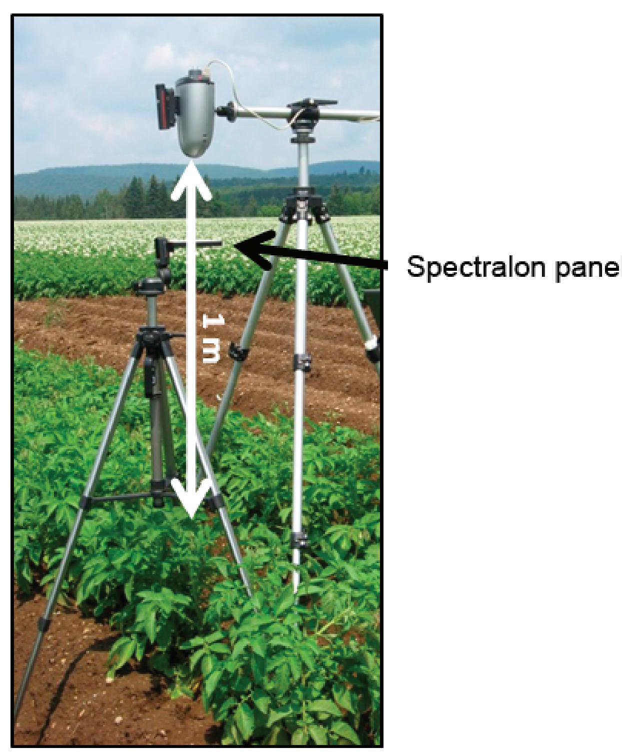

Fig. 1. In-field set-up for hyperspectral proximal sensing of the potato crop.

Table 2. List of hyperspectral vegetation indices used in the study.

Hyperspectral vegetation index	Definition†	Crop studied‡	Origin
Structural indices			
Normalized difference vegetation index (NDVI)	$NDVI=\left[\left(\rho_{800}-\rho_{670}\right)/\left(\rho_{800}+\rho_{670}\right)\right]$	Various crops (Rouse et al., 1974)	Rouse et al. (1974)
Transformed difference vegetation index (TDVI)	$TDVI=1.5\left[\left(\rho_{800}-\rho_{670}\right)/\sqrt{\left(\rho_{800}{}^{2}+\rho_{670}+0.5\right)}\right]$	Balsam fir (Bannari et al., 2002)	Bannari et al. (2002)
Weighted difference vegetation index (WDVI)	$WDVI=\rho_{810(crop)}-\left(\rho_{810(soil)}/\rho_{560(soil)}\right)\times\rho_{560(crop)}$	Potato (van Evert et al., 2012)	Clevers (1989)
Weighted normalized difference vegetation index (WNDVI)	$WNDVI=\dfrac{\left[\rho_{810(crop)}-\left(\rho_{810(soil)}/\rho_{560(soil)}\right)\times\rho_{560(crop)}\right]}{\left[\rho_{810(crop)}+\left(\rho_{810(soil)}/\rho_{560(soil)}\right)\times\rho_{560(crop)}\right]}$	Potato	this study
Soil-adjusted vegetation index L = 1 (SAVIL1)	$SAVIL1=\left(\rho_{800}-\rho_{670}\right)\left(1+L\right)/\left(\rho_{800}+\rho_{670}+L\right)$, where L = 1	Corn, wheat, soybean (Haboudane et al., 2004) potato (Jain et al., 2007)	Huete (1988)
Optimized soil-adjusted vegetation index (OSAVI)	$OSAVI=\left(\rho_{800}-\rho_{670}\right)\left(1+0.16\right)/\left(\rho_{800}+\rho_{670}+0.16\right)$	Corn, wheat, soybean (Haboudane et al., 2004) potato (Jain et al., 2007)	Rondeaux et al. (1996)
Modified soil-adjusted vegetation index (MSAVI)	$MSAVI=\rho_{800}+0.5-\sqrt{\left(\rho_{800}+0.5\right)^{2}-2\times\left(\rho_{800}-\rho_{670}\right)}$	Corn, wheat, soybean (Haboudane et al., 2004) potato (Jain et al., 2007)	Qi et al. (1994)
Chlorophyll indices			
Modified chlorophyll absorption in reflectance index (MCARI)	$MCARI=\left[\left(\rho_{700}-\rho_{600}\right)-0.2\left(\rho_{700}-\rho_{600}\right)\right]\left(\rho_{700}/\rho_{670}\right)$	Corn, wheat, soybean (Haboudane et al., 2004) potato (Jain et al., 2007)	Daughtry et al. (2000)
Modified chlorophyll absorption in reflectance index 1 (MCARI1)	$MCARI1=1.2\left[2.5\left(\rho_{800}-\rho_{670}\right)-1.3\left(\rho_{800}-\rho_{670}\right)\right]$	Corn, wheat, soybean (Haboudane et al., 2004) potato (Jain et al., 2007)	Haboudane et al. (2004)
Modified chlorophyll absorption in reflectance index 2 (MCARI2)	$MCARI2=\dfrac{1.5\left[2.5\left(\rho_{800}-\rho_{670}\right)-1.3\left(\rho_{800}-\rho_{550}\right)\right]}{\left[\left(2\rho_{800}+1\right)^{2}-\left(6\rho_{800}-5\sqrt{\rho_{670}}\right)-0.5\right]}$	Corn, wheat, soybean (Haboudane et al., 2004) potato (Jain et al., 2007)	Haboudane et al. (2004)
Transformed chlorophyll absorption in reflectance index (TCARI)	$TCARI=3\left[\left(\rho_{700}-\rho_{670}\right)-2.0\left(\rho_{700}-\rho_{550}\right)\right]\left(\rho_{700}-\rho_{670}\right)$	Corn (Haboudane et al., 2002) potato (Jain et al., 2007)	Haboudane et al. (2002)
Triangular vegetation index (TVI)	$TVI=0.5\left[120\left(\rho_{750}-\rho_{550}\right)-200\left(\rho_{670}-\rho_{550}\right)\right]$	Corn, wheat, soybean (Haboudane et al., 2004) potato (Jain et al., 2007)	Broge and Leblanc (2001)
Structure-insensitive pigment index (SIPI)	$SIPI=\left(\rho_{770}-\rho_{445}\right)/\left(\rho_{770}+\rho_{680}\right)$	Potato (Jain et al., 2007)	Peñuelas et al. (1995a)
Normalized pigment chlorophyll index (NPCI)	$NPCI=\left(\rho_{680}-\rho_{430}\right)/\left(\rho_{680}+\rho_{430}\right)$	Potato (Jain et al., 2007)	Peñuelas et al. (1995b)

(continued)

Table 2, continued.

Hyperspectral vegetation index	Definition†	Crop studied‡	Origin
Yellowness index (YI)	$YI=(\rho_{582}-2\rho_{626}+\rho_{670})/(0.044^2)$	Soybean (Adams et al., 1999)	adapted from Adams et al. (1999)
<u>Red-edge indices</u>			
Zarco-Tejada and Miller index (ZTM)	$ZTM=\rho_{750}/\rho_{710}$	Sugar maple (Zarco-Tejada et al., 2001) potato (Jain et al., 2007)	Zarco-Tejada et al. (2001)
Red-edge 750/700 index (RE_{750700})	$RE_{750700}=\rho_{750}/\rho_{700}$	Chestnut, Norway maple (Gitelson and Merzlyak 1996) potato (Jain et al., 2007)	Gitelson and Merzlyak (1996)
Red-edge 740/720 index (RE_{740720})	$RE_{740720}=\rho_{740}/\rho_{720}$	Sugar maple potato (Jain et al., 2007)	Vogelmann et al. (1993)
Red-edge chlorophyll index 1 ($CI1_{red\text{-}edge}$)	$CI1_{red\text{-}edge}=\rho_{800}/\rho_{740}-1$	Winter wheat (Li et al., 2012)	Li et al. (2012)
Red-edge chlorophyll index 2 ($CI2_{red\text{-}edge}$)	$CI2_{red\text{-}edge}=\rho_{740}/\rho_{550}-2$	Chestnut, Norway maple (Gitelson and Merzlyak, 1996)	adapted from Gitelson and Merzlyak (1996)
Normalized difference red-edge index (NDRE)	$NDRE=(\rho_{800}-\rho_{720})/(\rho_{800}+\rho_{720})$	Cotton (Barnes et al., 2000) potato (Herrmann et al., 2010)	adapted from Barnes et al. (2000)
Normalized difference nitrogen index (NDNI)	$NDNI=[\log(1/\rho_{740})-\log(1/\rho_{800})]/[\log(1/\rho_{740})+\log(1/\rho_{800})]$	Mediterranean vegetation (Serrano et al., 2002) potato (Herrmann et al., 2010)	Serrano et al. (2002)
Normalized difference index (NDI)	$NDI=(\rho_{850}-\rho_{710})/(\rho_{850}+\rho_{680})$	Eucalyptus (Datt, 1999)	Datt, 1999
<u>Combinations of index categories</u>			
MCARI/SAVIL1	MCARI/SAVIL1	Various tree crops (Zarco-Tejada et al., 2004)	adapted from Zarco-Tejada et al. (2004)
MCARI/OSAVI	MCARI/OSAVI	Various tree crops (Zarco-Tejada et al., 2004)	Zarco-Tejada et al. (2004)
TCARI/SAVIL1	TCARI/SAVIL1	Corn (Haboudane et al., 2002)	adapted from Haboudane et al. (2002)
TCARI/OSAVI	TCARI/OSAVI	Corn (Haboudane et al., 2002)	Haboudane et al. (2002)
Canopy chlorophyll content index (CCCI)	$CCCI = (NDRE - NDRE_{MIN})/(NDRE_{MAX} - NDRE_{MIN})$	Wheat (Fitzgerald et al., 2010)	Fitzgerald et al. (2006, 2010)
Nitrogen planar domain index 1 (NPDI1)	$NPDI1 = (CI1_{red\text{-}edge} - CI1_{red\text{-}edge\ MIN})/(CI1_{red\text{-}edge\ MAX} - CI1_{red\text{-}edge\ MIN})$	Wheat (Li et al., 2012)	Li et al. (2012)
Nitrogen planar domain index 2 (NPDI2)	$NPDI2 = (CI2_{red\text{-}edge} - CI2_{red\text{-}edge\ MIN})/(CI2_{red\text{-}edge\ MAX} - CI2_{red\text{-}edge\ MIN})$	Potato	this study
Hyperspectral two-band vegetation index (HTBVI)	$HTBVI = (\rho_j - \rho_i)/(\rho_j + \rho_i)$	Various agricultural crops (Thenkabail et al., 2011)	Thenkabail et al. (2011)

† ρ stands for the reflectance value, and the subscript indicates the wavelength in nanometers.

‡ Balsam fir [*Abies balsamea* (L.) Mill.], corn (*Zea mays* L.), wheat (*Triticum aestivum* L.), soybean [*Glycine max* (L.) Merr.], sugar maple (*Acer saccharum* M.), chestnut (*Castanea sativa* Mill.), Norway maple (*Acer platanoides* L.), winter wheat (*Triticum aestivum* L.), cotton (*Gossypium hirsutum* L.), eucalyptus (*Eucalyptus* sp.).

Hyperspectral Vegetation Indices

Previous studies have already tested several HVIs on potato crops. Jain et al. (2007) have specifically studied several HVIs on a potato crop (cv. K. Chandramukhi). Herrmann et al. (2010) have also studied some HVIs such as the CCCI, a good chlorophyll index. Overall, a total of 31 HVIs were selected based on previous studies on CNS assessment of the potato crop using HVIs. These indices are defined in Table 2 and will be referred to by their abbreviations in this article. These commonly used and newer HVIs were all computed using the reflectance data exported from the ViewSpec Pro software program. The HVIs were organized into four categories: structural, chlorophyll, red-edge-related, and combination. This fourth group consisted of combinations of the previous index categories.

The combinations of index categories were a more elaborate group. Besides HVIs derived from the simple ratio of two indices from different categories (i.e., MCARI/SAVIL1, MCARI/OSAVI, TCARI/SAVIL1, and TCARI/OSAVI), the other HVIs in this category are based on the theory of planar domain, which requires two indices being related to each other. One index is sensitive to the desired crop property (i.e., CNS) and the other index is sensitive to the crop biomass for estimating fractional vegetation cover (Clarke et al., 2001). The CCCI is thus computed from the relationship between the NDVI and the NDRE according to the method described by Fitzgerald et al. (2006). Following the same principle, Li et al. (2012) developed the NPDI1, which is determined by the relationship between the NDVI and the $CI1_{red\text{-}edge}$. The NPDI2 is in turn obtained from the relationship between the NDVI and the $CI2_{red\text{-}edge}$. The NPDI2 is defined as the ratio of wavelengths in the red-edge and green regions rather than the ratio of wavelengths in the NIR and red-edge regions, as is the case for the $CI1_{red\text{-}edge}$. It is worth noting at this point that a drawback of the planar domain indices is the necessity to access a complete dataset before their calculation.

The hyperspectral two-band vegetation index (HTBVI) (Thenkabail et al., 2011) was found to be a well-suited index for exploiting all the information available in the hyperspectral reflectance data. The HTBVI is constructed with the same equation as that used for the widely used NDVI. However, instead of relying on the reflectance at two predefined wavelengths in the NIR and in the red (chlorophyll absorption maxima) regions, the HTBVI takes information from all possible combinations of wavelengths. In this study, the HTBVI served to identify spectral regions best adapted for CNS assessment at specific times. To that end, correlation contour plots were created in R (R Core Team, 2012). For each wavelength combination, the *cor()* function was selected to fit a linear model between the HTBVI and the N reference method (i.e., NNI) values while storing the result of each coefficient of determination in a matrix. A median filter of 10 by 10 nm was applied to the latter matrix, because some noise in the spectral signal measurements was observed at the beginning and end of the spectrum. Coefficients of determination values were then plotted with the *filled.contour()* function. Lastly, optimization of a selected HVI to detect CNS was performed using the two-wavelength combinations resulting in the highest coefficient of determination.

Statistical Analysis

The statistical analysis for the present article was performed using the SAS software program Statistical Analysis System (SAS Institute, 2004). A preselection of the five most appropriate HVIs to assess potato CNS was conducted using the CORR procedure. Spearman correlation coefficients between the NNI and each HVI from the whole dataset (i.e., available sampling dates in 2011 and 2012, 7.5° and 25° FOVs) were thereafter computed. Moreover, Spearman correlation coefficients between total yield and each HVI from the whole dataset (all eight hyperspectral data collection measurement dates in 2011 and three measurement dates in 2012, 7.5° and 25° FOVs) were computed. Data normality was tested beforehand with the UNIVARIATE procedure, because parametric statistical analyses of variance (ANOVAs) were performed. When normality was rejected, appropriate transformation of explanatory variables was applied to improve distribution normality and homogeneity of variances. For each explanatory variable, ANOVAs were performed using the MIXED procedure with a significance level of 0.05.

The statistical model for ANOVAs used a completely randomized block design with block as a random effect. Differences between means were calculated with the PDIFF option of the LSMEANS statement. Linear and quadratic responses of explanatory variables to fixed effects and their interactions were determined using contrasts. Least significant differences (LSDs) for letter mean separation in the MIXED procedure were assigned using the PDMIX 800 macro (Saxton, 1998) with a significance level of 0.05. More precisely, the NNI was analyzed for each year of the experiment using repeated measures in a two-way ANOVA with N rates and sampling dates as fixed effects. The latter analysis made it possible to compare differences in the NNI response to the five levels of N rates among the sampling dates. For each measurement year, ANOVAs of the five selected HVIs were performed as described for the NNI, with the exception that N rates, sampling dates, and FOVs were considered to be fixed effects.

The MIXED procedure, a priori linear and quadratic contrasts, and the PDMIX 800 macro were used to analyze the total tuber yield as well as the aboveground biomass. The model for total tuber yield response to N rates was created using the NLIN procedure to determine the optimal N rate. Lastly, the REG procedure was used to fit a polynomial regression model of total tuber yield as a function of the most appropriate HVI.

RESULTS AND DISCUSSION

Intraseasonal Monitoring of Crop Nitrogen Status Using the Nitrogen Nutrition Index

For each year, the main effect of the sampling dates (i.e., days after planting) and N rates on the NNI was statistically significant ($\alpha = 0.05$). In addition, a significant quadratic response of the NNI to N rates was tested by a contrast ($p < 0.0001$ in both 2011 and 2012; ANOVA not shown). Therefore, mean NNI values and LSDs were reported among N rates and years (Table 3).

Within sampling dates, NNI values increased as the rate of fertilizer increased, with the exception of the two higher N rates, given that on four of the eight NNI measurements, the N200 rate achieved a higher level of CNS than the N280 rate did.

Table 3. Mean values and least significant differences (LSD) for effect of fertilizer N rate on N nutrition index (Bélanger et al., 2001) of the potato crop measured on different sampling dates in 2011 and 2012.

	N nutrition index values							
	DAP† 2011				DAP 2012			
N rate	40	55	70	84	38	52	66	80
kg N ha^{-1}								
0	0.43a‡	0.54a	0.58a	0.46a	0.39a	0.54a	0.42a	0.41a
60	0.77b	0.83b	0.81b	0.68b	0.57b	na§	0.75b	0.62b
120	0.93c	1.05c	0.88b	0.75bc	0.75c	0.90b	0.86b	0.88c
200	0.97c	1.21c	1.13c	0.89c	0.91c	1.22c	1.19c	1.06c
280	1.01c	1.17c	1.28c	1.16d	0.89c	1.18c	1.30c	0.95c

† DAP, days after planting.

‡ Means followed by the same letter within a sampling date are not significantly different (α = 0.05) using LSD test.

§ na, data not available.

This saturation response of the NNI to N rates was revealed by a significant quadratic contrast in both 2011 and 2012.

Across years, only the N200 and N280 rates consistently matched most of the potato N needs (NNI > 0.9) throughout the entire growing season. The N60 rate did not supply enough N to the crop (NNI < 0.9) on every sampling date of each measurement year, while severe N deficiencies (NNI < 0.6) occurred as expected under the N0 rate. Therefore, soil N mineralization did not provide enough N to fully match the high requirements of the potato crop.

In 2011, the N120 rate matched crop N demand only during the first half of the growing season (i.e., up to 55 DAP). Starting from the second split N application, frequent rainfalls promoted NO_3^- leaching and thus an increase in the potato crop N deficiency level until the last measurement date (i.e., 84 DAP). Higher N rates were then required at later growth stages to reach a sufficient N level. In weather conditions that promote leaching, additional in-season applications of N fertilizer could have been beneficial for maintaining an optimal CNS throughout the growing season. It is worth noting that N fertilizers cost as well as environmental risks related to NO_3^- leaching should also be considered.

In 2012, N stress (NNI < 0.9) was observed under the N120 rate, except at 52 DAP (i.e., 2 wk after the second split N application), when most of the crop N requirements were covered (NNI = 0.90). In comparison with 2011, it was found in 2012 that a higher N rate (i.e., N200) was required in drier conditions to fully meet the crop's N requirements during the first half of the growing season. Higher air temperatures in 2012 early spring may have promoted higher microbial activity and biochemical processes in the soil and thus more N mineralization from soil organic matter (Griffin, 2008; St. Luce et al., 2011). However, a higher N rate on the first measurement date was needed in 2012 than in 2011 to reach a sufficient CNS level. Precipitation of 53 mm occurred 8 d after the first split N application in 2012 and may have caused NO_3^- leaching from the fertilizer applied at planting (40% of the total rate). Plantation in 2011 have been delayed, which may have promoted higher soil temperature and avoided some of the rainfalls that would have contributed to increase N leaching in early May 2011. Therefore, higher N mineralization may have occurred in 2011 because of higher total tuber yield on the control plots in 2011 than in 2012. Bélanger et al. (2000) also reported the complex effects of weather on soil N mineralization, N leaching, and potato crop N uptake.

For each year of the experiment, the NNI discriminated three statistically different groups at the hilling stage as well as throughout the growing season, with the exception of 2011 at the end of the growing season (i.e., at 84 DAP), when four groups were identified (Table 3). Chambenoit et al. (2004) reported that an NNI value higher than 1 ($\approx$1.2) maximized tuber yield, suggesting that the NNI did not distinguish luxury N consumption from N sufficiency level in potato. However, Ziadi et al. (2012) reported the ability of the NNI to monitor the CNS independently of growth stage, which is a prerequisite for calibrating in-season remote sensing measurements.

Total Tuber Yield

Because there was a statistically significant linear interaction between years and N rates (p = 0.0443; ANOVA not shown), the effect of N rates on tuber yield was investigated separately for

Table 4. Mean values and least significant differences (LSD) for effect of N fertilization on total tuber yield and aboveground biomass at canopy closure in 2011 and 2012.

	2011		2012	
N rate	Total tuber yield	Aboveground biomass (DM) at 70 DAP†	Total tuber yield	Aboveground biomass (DM) at 66 DAP
kg N ha^{-1}	Mg ha^{-1}			
0	20.33a‡	1.31a	16.38a	0.67a
60	33.90b	2.13b	31.14b	1.46b
120	37.71b	2.15b	36.10bc	2.08c
200	39.33b	2.89c	41.59c	2.28c
280	37.92b	2.73c	41.25c	2.82d

† DAP, days after planting.

‡ Means followed by the same letter within a measurement year are not significantly different (α = 0.05) using LSD test.

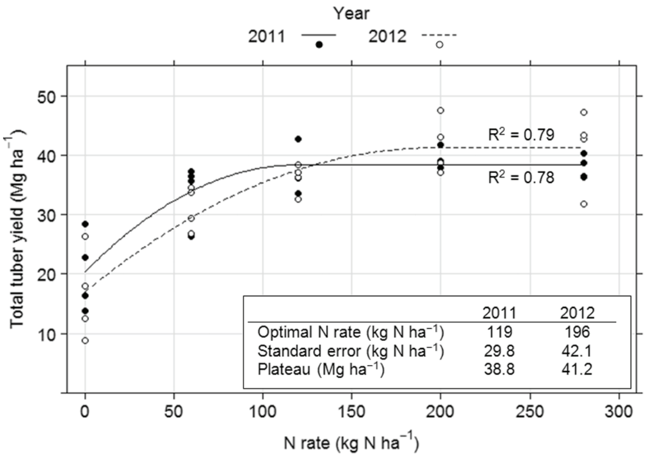

Fig. 2. Response of total tuber yield to N fertilization as determined by a quadratic plateau model in 2011 and 2012.

each measurement year (Table 4). As expected, the lowest yields (20.33 Mg ha^{-1} in 2011 and 16.38 Mg ha^{-1} in 2012) were found when no N fertilizer was applied, confirming that N deficiency significantly reduced tuber yield. Numerically highest total tuber yields (39.33 Mg ha^{-1} in 2011 and 41.59 Mg ha^{-1} in 2012) were observed under the N200 rate for both years of the experiment. Excessive N fertilizer application rates promoted excessive vegetative growth at the expense of tuber production (Table 4). Indeed, under the highest N280 rate, there was no significant increase in tuber yield in comparison with the N200 rate in 2012. In addition, no significant increase in tuber yield was observed under the N60 to N280 rates in comparison with the N0 treatment in 2011. A higher N rate was thus required in 2012 to reach a significantly higher yield.

In this study, yield potential was reduced in leaching conditions such as those prevailing during the 2011 growing season. Moreover, planting occurred 11 d later in 2011 than in 2012, but harvest occurred on nearly the same date, leaving less time for tuber bulking and maturation at the end of the 2011 growing season. Therefore, the highest total tuber yield was observed in 2012 (Table 4).

A significant quadratic contrast of N rates on total tuber yield was observed in 2011 ($p = 0.0006$) and 2012 ($p = 0.0011$), suggesting that total tuber yield varied quadratically with N rates (ANOVA not shown). Therefore, a quadratic plateau model was used to fit total tuber yield response to N fertilizer application (Fig. 2). Optimal N rates of 119 ± 29.8 and 196 ± 42.1 kg N ha^{-1} were obtained in 2011 and 2012, respectively. These optimal N rates are consistent with the LSD results discussed previously and shown in Table 4. A large variation in optimal fertilizer N rate was previously reported to be related to weather conditions (Goffart et al., 2008; Zebarth et al., 2009). Year 2011 was more likely to have been characterized by weather conditions favorable for N leaching; therefore, N requirements could have been lower owing to a later planting date, which resulted in a shorter growing season and lower yield potential. Moreover, the higher yield under the N0 treatment in 2011 suggested that besides the effect of site, more N mineralization from soil organic matter may have occurred after hilling in 2011 than in 2012. The maximum yield response to N fertilizer applications (plateau of 41.2 Mg ha^{-1}) was found in 2012, which is also consistent with the total tuber yield measurements provided in Table 4.

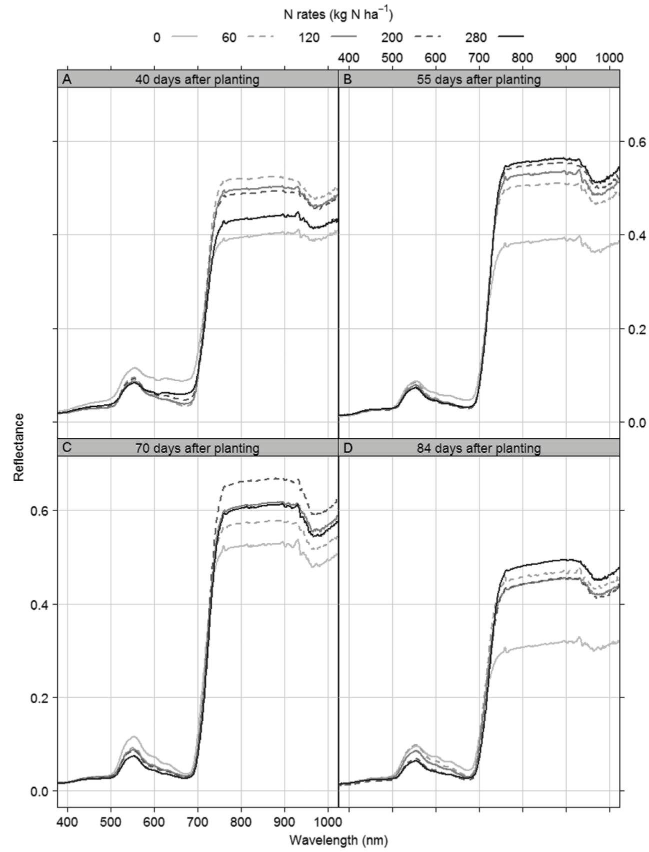

Fig. 3. Hyperspectral signature of a potato crop measured using the 25° field of view under five N rates (0, 60, 120, 200, and 280 kg N ha^{-1}) in 2011 at (A) 40 DAP, (B) 55 DAP, (C) 70 DAP, and (D) 84 DAP.

Intraseasonal Crop Nitrogen Status Assessment Using Hyperspectral Data

Hyperspectral Signatures. Remote sensing of vegetation has shown that a higher crop cover increases scattering in the spongy mesophyll cells and therefore increases reflectance in the NIR (Jensen, 2007). Conversely, chlorophyll pigments absorb visible light and reduce reflectance in the red and blue regions of the spectrum (Jensen, 2007). Typical hyperspectral signatures of the potato crop under different N levels are illustrated in Fig. 3. The hyperspectral signatures in the 2012 growing season (data not shown) were similar to those of 2011 shown in Fig. 3 and are therefore not presented.

At 40 DAP, NIR reflectance, starting at about 790 nm, did not increase as the N application rate increased (Fig. 3). The control, in which no N was applied at planting, showed the lowest NIR plateau value, about 0.40, whereas the maximum, about 0.52, was achieved by the lowest N rate applied, which was the N60 rate. The highest N rate allowed the crop to reflect light in the NIR at about 45% of the incident light, which represented the lowest reflectance value after the control. Lower crop canopy development at hilling and therefore higher soil background effects in the signal, coupled with the fact that the crop had barely begun to take up N from the fertilizer applied at planting (40% of the total N rate), can explain this inconsistent pattern of NIR reflectance at the early growth stage. Therefore, HVIs based only on NIR reflectance may not be sufficient to precisely assess CNS at hilling.

Still at 40 DAP, the reflectance pattern in the visible spectrum (i.e., between 400 and 700 nm), differed more among the five N rates than it did at later dates (Fig. 3). This discrimination of N rates was especially marked around reflectance in the chlorophyll absorption maxima in the red region of the spectrum (i.e., at about ρ_{680}). Indeed, the highest reflectance value, 0.09, was obtained for the control treatment, owing to low chlorophyll content as well as a greater fraction of soil reflectance incorporated into the signal because of less crop development. Because ρ_{680} is effective for chlorophyll-a pigment estimation (Blackburn, 1998), early-stage potato CNS assessment could benefit from the use of visible-based HVIs. Moreover, the greatest soil crop contrast and sensitivity to canopy cover are achieved in the red region at around 680 nm (Thenkabail et al., 2000).

At 55 DAP, the rest of the total N rate had been applied to the crop 15 d earlier. Near-infrared reflectance increased as the applied N rate increased, with an apparent saturation at the two higher N rates. More precisely, the NIR plateau was reached at 0.39, 0.51, 0.53, 0.55, and 0.56 for the N0, N60, N120, N200, and N280 rates, respectively. In the visible portion of the spectrum, the reflectance curves were more or less the same for all N rates, with the exception of the control, for which reflectance was higher. Therefore, CNS discrimination using only visible wavelengths seems less adapted later in the growing season than at 40 DAP.

From 40 to 55 DAP, NIR reflectance of the control treatment remained constant at almost 0.40, whereas reflectance in the visible portion of the spectrum was reduced. From 55 to 70 DAP, each N rate showed to a lesser extent an increase in the NIR reflectance owing to an increase in crop canopy development.

At 84 DAP, the senescence process had begun, and plant sagging was initiated. Consequently, a marked decrease in NIR reflectance of about 0.15 was observed in comparison with the values at 70 DAP. However, N rate differentiation seemed possible in the visible portion of the spectrum, suggesting that chlorophyll-related wavelengths could be used as a good indicator of crop N uptake at the end of the growing season.

Selection of the Most Appropriate Hyperspectral Vegetation Indices for Crop Nitrogen Status Assessment in 2011 and 2012. Spearman correlation coefficients between the NNI and each HVI are shown in Table 5. The NDI was the HVI most correlated to the NNI, with a correlation coefficient of 0.85. Of the 10 HVIs most correlated to the NNI (ranks 1 to 10), 9 are computed from at least one red-edge spectral band. Previous studies also reported that the red-edge region is related to the CNS and chlorophyll content (Daughtry et al., 2000). The WNDVI, a structural index that is calculated without red-edge wavelengths but accounts for soil background effects, ranked in eighth position, with a correlation coefficient of 0.80.

Chlorophyll-based indices such as the MCARI and TCARI alone showed the lowest absolute correlation coefficients ($|r| \approx 0.25$). Shanahan et al. (2008) indicated that a chlorophyll-based index, the transformed soil-adjusted vegetation index, or TSAVI, detected fewer variations in greenness or canopy vigor of cereal crops during early-stage growth. Moreover, Cohen et al. (2010) reported that the TCARI was highly correlated with leaf N concentration of a potato crop only at tuber bulking stage, but not at early growth stage. In contrast, combinations of indices using chlorophyll wavelengths, such as the MCARI/SAVIL1, performed better ($|r| = 0.77$) in predicting NNI values than did the widely used NDVI ($r = 0.61$).

In comparison with the NNI correlations, the HVIs were similarly correlated to total tuber yield (Table 5): four of the five HVIs most correlated to the NNI, namely the $CI1_{red\text{-}edge}$, NDI, NDRE, and RE_{740720}, were also found to be the HVIs most correlated to total tuber yield. In fact, the difference among the NNI correlations with HVI was that the CCCI ranked in the top five HVIs at the expense of the NPDI2. However, the CCCI and NPDI2 are both combinations of index categories that use red-edge wavelengths, validating the reliability of red-edge indices as indicators of general crop productivity. Because N is the most limiting factor for crop growth, after water stress, the four HVIs most correlated to the NNI were also the indices most correlated to tuber yield.

Table 5. Spearman correlation coefficients between the N nutrition index (NNI) and hyperspectral vegetation indices as well as between tuber total yield and hyperspectral vegetation indices regardless of year measurement and field of view.

Rank	Hyperspectral vegetation index	Index category	*r* NNI	*r* Yield
1	NDI	red-edge	0.85	0.64
2	$CI1_{red\text{-}edge}$	red-edge	0.83	0.64
3	NDRE	red-edge	0.83	0.61
4	RE_{740720}	red-edge	0.82	0.60
5	NPDI2	combination	0.82	0.59
6	ZTM	red-edge	0.82	0.60
7	$CI2_{red\text{-}edge}$	red-edge	0.81	0.59
8	WNDVI	structural	0.80	0.58
9	RE_{750700}	red-edge	0.79	0.57
10	CCCI	combination	0.78	0.62
11	MCARI/SAVIL1	combination	–0.77	–0.59
12	WDVI	structural	0.77	0.55
13	NDNI	red-edge	0.77	0.60
14	TCARI/SAVIL1	combination	–0.73	–0.60
15	MCARI/OSAVI	combination	–0.66	–0.51
16	NPDI1	combination	0.64	0.57
17	NDVI	structural	0.61	0.42
18	SIPI	chlorophyll	0.60	0.39
19	OSAVI	structural	0.59	0.45
20	MSAVI	structural	0.59	0.44
21	TCARI/OSAVI	combination	–0.58	–0.50
22	NPCI	chlorophyll	–0.57	–0.47
23	TDVI	structural	0.55	0.42
24	SAVIL1	structural	0.55	0.42
25	MCARI1	chlorophyll	0.54	0.41
26	TVI	chlorophyll	0.44	0.33
27	MCARI2	chlorophyll	0.43	0.25
28	YI	chlorophyll	0.37	0.39
29	TCARI	chlorophyll	–0.26	–0.29
30	MCARI	chlorophyll	–0.25	–0.29

Table 6. Means and least significant differences (LSD) for effect of N fertilization on hyperspectral vegetation indices using the 7.5° and 25° fields of view at 40, 48, 55, 61, 66, 70, 76, and 84 days after planting (DAP) in 2011.

	Hyperspectral vegetation index									
	7.5° field of view					25° field of view				
N rate	NDI	$CII_{red\text{-}edge}$	NDRE	RE_{740720}	NPDI2	NDI	$CII_{red\text{-}edge}$	NDRE	RE_{740720}	NPDI2
kg N ha^{-1}										
40 DAP										
0	0.63a†	0.09a	0.22a	1.44a	0.15a	0.62a	0.09a	0.18a	1.33a	0.14a
60	0.72b	0.14b	0.31b	1.68b	0.35b	0.70b	0.13b	0.29b	1.62b	0.43b
120	0.73b	0.14b	0.32b	1.69b	0.36b	0.72b	0.14b	0.30b	1.63b	0.48b
200	0.71b	0.13b	0.30b	1.64b	0.33b	0.71b	0.13b	0.28b	1.58b	0.43b
280	0.74b	0.14b	0.32b	1.70b	0.40b	0.72b	0.14b	0.28b	1.57b	0.45b
48 DAP										
0	0.67a	0.10a	0.26a	1.55a	0.24a	0.64a	0.09a	0.23a	1.48a	0.27a
60	0.71ab	0.13ab	0.30ab	1.64ab	0.32ab	0.69b	0.12b	0.28b	1.60b	0.40b
120	0.74bc	0.15bc	0.33bc	1.72bc	0.40bc	0.74c	0.15c	0.33c	1.71c	0.56c
200	0.76c	0.17c	0.35c	1.80c	0.44bc	0.76c	0.16cd	0.35c	1.77c	0.64c
280	0.78c	0.18c	0.37c	1.84c	0.50c	0.77c	0.17d	0.36c	1.81c	0.68c
55 DAP										
0	0.67a	0.11a	0.26a	1.54a	0.23a	0.65a	0.11a	0.24a	1.47a	0.29a
60	0.73b	0.15b	0.33b	1.72b	0.40b	0.72b	0.14b	0.31b	1.68b	0.52b
120	0.77bc	0.19bc	0.38b	1.86b	0.52b	0.76c	0.17c	0.35bc	1.77bc	0.62bc
200	0.77bc	0.19c	0.38b	1.86b	0.49b	0.77c	0.18c	0.37c	1.83c	0.71c
280	0.78c	0.19c	0.38b	1.86b	0.49b	0.78c	0.19c	0.38c	1.87c	0.75c
61 DAP										
0	0.68a	0.12a	0.28a	1.59a	0.28a	0.67a	0.12a	0.26a	1.54a	0.36a
60	0.76b	0.18b	0.36b	1.81b	0.49b	0.75b	0.17b	0.35b	1.77b	0.69b
120	0.79bc	0.21bc	0.40bc	1.93bc	0.57bc	0.77bc	0.19bc	0.37bc	1.84bc	0.76bc
200	0.80c	0.22bc	0.42c	2.00c	0.65bc	0.79cd	0.21c	0.39cd	1.90cd	0.86cd
280	0.81c	0.23c	0.42c	2.01c	0.68c	0.80d	0.22c	0.41d	1.96d	0.91d
66 DAP										
0	0.67a	0.12a	0.27a	1.56a	0.26a	0.65a	0.11a	0.25a	1.51a	0.33a
60	0.75b	0.17b	0.35b	1.79b	0.45b	0.75b	0.17b	0.35b	1.76b	0.63b
120	0.77bc	0.20bc	0.38bc	1.88bc	0.52b	0.77bc	0.20c	0.37bc	1.83bc	0.73b
200	0.78bc	0.20bc	0.39bc	1.89bc	0.55bc	0.78cd	0.20cd	0.39cd	1.88cd	0.76b
280	0.81c	0.24c	0.43c	2.03c	0.68c	0.80d	0.23d	0.41d	1.96d	0.89c
70 DAP										
0	0.66a	0.11a	0.26a	1.53a	0.21a	0.64a	0.11a	0.24a	1.49a	0.28a
60	0.73b	0.15b	0.32b	1.70b	0.34b	0.73b	0.15b	0.32b	1.70b	0.53b
120	0.76bc	0.19b	0.37bc	1.84bc	0.36b	0.76bc	0.18c	0.36bc	1.78b	0.63bc
200	0.80cd	0.23c	0.41cd	1.95c	0.57c	0.78cd	0.21d	0.39cd	1.89c	0.73cd
280	0.81d	0.25c	0.43d	1.93c	0.69c	0.79d	0.22d	0.40d	1.91c	0.80d
76 DAP										
0	0.57a	0.08a	0.19a	1.37a	0.09a	0.58a	0.09a	0.20a	1.38a	0.14a
60	0.72b	0.15b	0.32b	1.68b	0.34b	0.70b	0.14b	0.30b	1.63b	0.46b
120	0.73bc	0.16bc	0.33bc	1.72bc	0.37bc	0.73b	0.16bc	0.33bc	1.70b	0.55b
200	0.77c	0.19c	0.38c	1.86c	0.51c	0.76c	0.18cd	0.36cd	1.87c	0.77c
280	0.77c	0.19c	0.37c	1.83c	0.49c	0.78c	0.20d	0.38d	1.84c	0.73c
84 DAP										
0	0.53a	0.08a	0.16a	1.28a	0.02a	0.54a	0.09a	0.16a	1.28a	0.04a
60	0.63b	0.11b	0.24b	1.46b	0.18b	0.65b	0.12b	0.25b	1.49b	0.29b
120	0.69c	0.15c	0.29c	1.60c	0.30c	0.67b	0.14c	0.27b	1.53b	0.38b
200	0.72c	0.16c	0.32c	1.67c	0.37c	0.73c	0.17d	0.33c	1.69c	0.60c
280	0.80d	0.22d	0.41d	1.97d	0.64d	0.77d	0.20e	0.37d	1.82d	0.75d

† Means followed by the same letter within a sampling date and hyperspectral vegetation index are not significantly different (α = 0.05) using LSD test.

Table 7. Means and least significant differences (LSD) for effect of N fertilization on hyperspectral vegetation indices using the 7.5° and 25° fields of view at 37, 54, and 68 days after planting (DAP) in 2012.

	Hyperspectral vegetation index									
	7.5° field of view					25° field of view				
N rate	NDI	$CI1_{red-edge}$	NDRE	RE_{740720}	NPDI2	NDI	$CI1_{red-edge}$	NDRE	RE_{740720}	NPDI2
kg N ha^{-1}										
37 DAP										
0	0.66a†	0.11a	0.22a	1.42a	0.09a	0.64a	0.10a	0.15a	1.23a	0.05a
60	0.67a	0.11a	0.24a	1.48ab	0.16ab	0.66a	0.11ab	0.17a	1.28ab	0.14b
120	0.71b	0.14b	0.29b	1.59bc	0.30bc	0.70b	0.13bc	0.23b	1.43c	0.29c
200	0.74b	0.16b	0.31b	1.65c	0.43c	0.71b	0.14c	0.24b	1.39bc	0.36c
280	0.74b	0.16b	0.31b	1.65c	0.46c	0.73b	0.15c	0.24b	1.43c	0.32c
54 DAP										
0	0.63a	0.09a	0.22a	1.42a	0.04a	0.62a	0.09a	0.18a	1.32a	0.13a
60	0.73b	0.14b	0.32b	1.71b	0.48b	0.71b	0.13b	0.29b	1.60b	0.47b
120	0.75bc	0.17bc	0.35bc	1.78bc	0.55b	0.74bc	0.15bc	0.33bc	1.71bc	0.55bc
200	0.77c	0.19c	0.37c	1.84c	0.69b	0.76cd	0.18cd	0.35c	1.78c	0.68c
280	0.77c	0.19c	0.38c	1.86c	0.69b	0.77d	0.18d	0.36c	1.81c	0.69c
68 DAP										
0	0.63a	0.10a	0.23a	1.45a	0.09a	0.61a	0.09a	0.19a	1.35a	0.13a
60	0.70b	0.13b	0.30b	1.63b	0.33b	0.70b	0.13b	0.29b	1.61b	0.43b
120	0.74c	0.16c	0.34b	1.74b	0.48bc	0.74c	0.16c	0.34c	1.73c	0.59bc
200	0.78d	0.21d	0.39c	1.89c	0.70cd	0.78d	0.21d	0.38d	1.86d	0.79cd
280	0.79d	0.22d	0.40c	1.93c	0.90d	0.79d	0.22d	0.40d	1.90d	0.88d

† Means followed by the same letter within a sampling date and hyperspectral vegetation index are not significantly different (α = 0.05) using LSD test.

Correlations between HVIs and yield were generally lower than those between HVIs and the NNI because of in-season variability of crop growth that could not be accounted for, since yield was measured only at the end of the growing season.

Sensitivity of Selected Hyperspectral Vegetation Indices to Intraseasonal Crop Nitrogen Status. As was the case for the NNI in 2011 and 2012, the main effect of the sampling dates (i.e., days after planting) and N rates on selected HVIs was statistically significant (α = 0.05). For each measurement date, mean HVI values for each FOV are presented with LSDs in Tables 6 and 7 for the 2011 and 2012 growing seasons, respectively. Each HVI increased as the N rate increased, regardless of year, timing, and FOV (Tables 6 and 7), suggesting that HVIs make it possible to monitor the in-season N status of a potato crop. At earlier growth stages, higher index values characterized the 7.5° FOV in comparison with the 25° FOV. Because of lower crop canopy development, soil reflectance was incorporated more into the signal when the 25° FOV was used, as previously discussed (Thenkabail et al., 2000). Despite this difference, the HVIs using the 7.5° FOV did not provide better discrimination of N rates at hilling or within the growing season for both measurement years, resulting in even less capacity to detect significant difference of means than the 25° FOV has at later growth stages. Therefore, the use of a narrower FOV even at early stages, when lower crop development was observed, did not seem conclusive in this study. Moreover, Spearman correlation analysis (Table 5) revealed that soil-adjusted vegetation indices such as the SAVIL1 and MSAVI did not correlate highly to the NNI (ranks 20 and 24, respectively), even though they were developed to minimize the effect of varying background soil reflectance on vegetation index sensitivity (Huete, 1988; Qi et al., 1994). Preference should therefore be given to canopy scale measurements using a wider FOV, especially at later growth stages.

The $CI1_{red-edge}$ using the 25° FOV was found to be the only HVI able to discriminate all five levels of N fertilizer application. This statement was observed only in 2011 at 84 DAP, suggesting that the sensitivity of the index to CNS increased until the end of the growing season. Indeed, the $CI1_{red-edge}$ (25° FOV) discriminated N rates into four groups as early as 48 DAP in 2011 and into three groups at 37 DAP in 2012. However, the $CI1_{red-edge}$ (25° FOV) was not able to maintain the separation of N rates in four groups at 55 and 61 DAP in 2011, although the index still performed at the same level as the NNI at 55 DAP (i.e., discriminated three groups) (Table 3). Partial canopy closure and relatively late N uptake by the potato crop during the first half of the growing season can explain this irregularity in the HVI's sensitivity. Moreover, variability in crop development may be due to the fact that potatoes are grown from tubers. In 2011 at 66 DAP, crop canopy development had stabilized, and the $CI1_{red-edge}$ (25° FOV) discriminated at least four groups of N rates until the end of the season. Therefore, the $CI1_{red-edge}$ (25° FOV) provided the most consistent separation of lower N rates vs. higher N rates across the measurement dates in 2011 and in 2012, even though the NDI (25° FOV) outperformed the $CI1_{red-edge}$ (25° FOV) at 61 DAP in 2011, discriminating N treatments into one more group than the $CI1_{red-edge}$ did. In comparison with the NNI, the $CI1_{red-edge}$ (25° FOV) showed an equal or better ability to discriminate N treatments on all dates (i.e., days after planting) across years, with the exception of 40 DAP in 2011, when the $CI1_{red-edge}$ (25° FOV) discriminated one group fewer than the NNI did. It is worth noting that in 2012, NNI measurements at 38 DAP performed better that $CI1_{red-edge}$ (25° FOV) at 37 DAP.

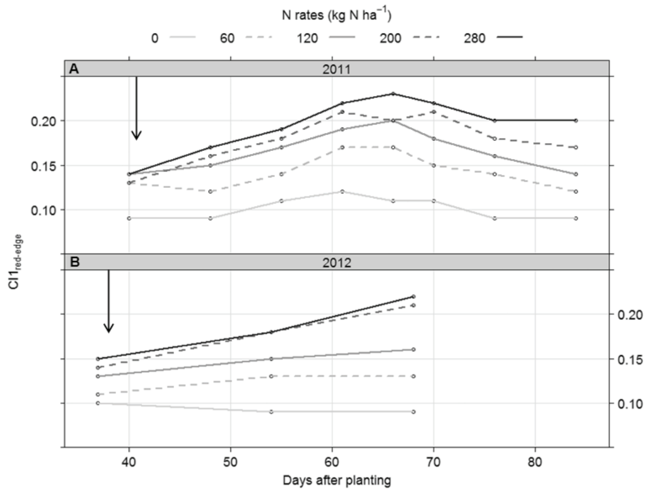

Fig. 4. Intraseasonal evolution of mean CI1$_{red-edge}$ values for the 25° field of view only in (A) 2011 and (B) 2012. The arrows indicates the yearly timing (i.e., at hilling) of the second in-season N fertilizer application.

The CI1$_{red-edge}$ (25° FOV) mean values were plotted in Fig. 4 to illustrate the intraseasonal response of the index to applied N. At 40 DAP in 2011, the CI1$_{red-edge}$ (25° FOV) for the N0 rate differed from the other N rates and had a lower value, about 0.05 (Fig. 4). Before the second N fertilizer application in 2011, the CI1$_{red-edge}$ was able to discriminate only two statistically different groups (i.e., N0 vs. N60 to N280) (Table 6), as clearly illustrated in Fig. 4. Because the optimal N rate was nearly 200 kg N ha^{-1} for tuber yield production in 2012 (Fig. 2), the CI1$_{red-edge}$ response to the two higher N rates (i.e., N200 and N280) was saturated and expressed similar values, especially after the second split N application. The findings in 2012 were globally consistent with that ones in 2011.

During the 2011 growing season, the CI1$_{red-edge}$ followed a quadratic function according to days after planting. For all N rates, the CI1$_{red-edge}$ values followed the same pattern as the intraseasonal distribution of the NNI values (Table 3). The dilution of N concentration in the crop at the end of the season was clearly expressed for both the CI1$_{red-edge}$ and NNI. Among N treatments where N was applied, the CI1$_{red-edge}$ values decreased by about 0.05 from 66 to 84 DAP. As previously reported, the CI1$_{red-edge}$ was efficient in assessing the canopy N content of the crop throughout the growing season (Clevers and Kooistra, 2012). This statement was particularly the case starting at about 50 DAP regardless of year measurement.

Optimization of the CI1$_{red-edge}$ to Assess Early-Stage Crop Nitrogen Status Using the HTBVI. Early-stage CNS assessment is essential to allow farmers to split N fertilizer at a practical time (i.e., at hilling) as well as improve tuber yield and quality. As illustrated in Tables 6 and 7, ANOVAs and LSDs revealed that the CI1$_{red-edge}$ using the 25° FOV was the most appropriate HVI for assessing potato CNS and had N sensitivity at least as good as the sensitivity of the NNI, with the exception of 2011 at 40 DAP, when cooler and humid conditions as compared to 2012 may have reduced the crop growth rate at hilling, delayed N stress symptoms, and reduced the sensitivity of the CI1$_{red-edge}$ to N stress. Moreover, using a passive sensor in variable illumination conditions could have increased variances in hyperspectral data and hindered LSD sensitivity.

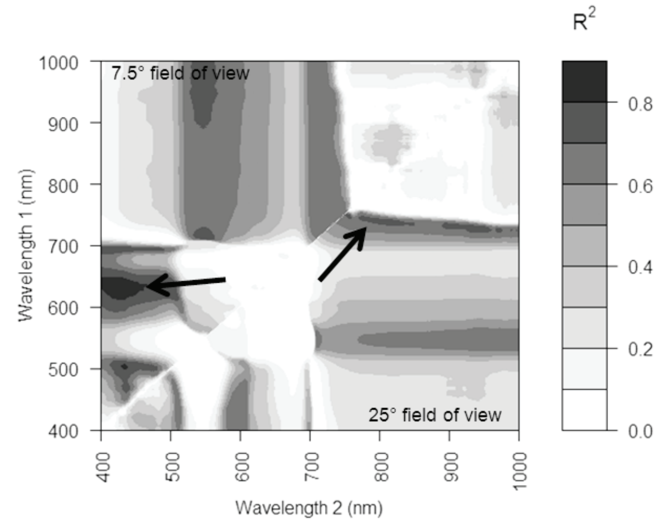

Fig. 5. Contour map of the hyperspectral two-band vegetation index (HTBVI) coefficients of determination (R^2) for the 7.5° (above diagonal) and 25° (below diagonal) fields of view in 2011 at 40 DAP. The contour map shows the coefficients of determination for the linear relationship between the N nutrition index and each wavelength combination forming the HTBVI. The arrows indicate the spectral regions with the highest coefficients of determination.

Therefore, an optimization of the ability of the CI1$_{red-edge}$ to detect N stress at hilling in 2011 was performed using a modified form of the HTBVI (Fig. 5). Based on the parsimony principle (i.e., preference is to be given to the simplest form of an index that can explain the crop N variability), the HTBVI was computed from the ratio of two wavelengths as found in the CI$_{red-edge}$ formula (Table 2). A normalized difference as stated in Thenkabail et al. (2011) was discarded, resulting in a simplified equation for the HTBVI (Eq. [2]):

$$\mathrm{HTBVI}_{i,j} = \frac{\rho_j}{\rho_1} \quad [2]$$

where ρ stands for reflectance at wavelength 1 (i = 400–1000 nm), and wavelength 2 (j = 400–1000 nm).

Figure 5 shows that with the 7.5° FOV, the spectral combination that best explained the NNI variations ($0.8 < R^2 < 0.9$) corresponded to the violet-blue (ρ_{425}) and red (ρ_{630}) spectral regions. Green (ρ_{525}) and NIR (ρ_{950}) combinations as well as green (ρ_{525}) and red-edge (ρ_{720}) combinations had lower but still high coefficients of determination ($0.7 < R^2 < 0.8$). With the 25° FOV, the highest correlations were observed from a combination of red-edge and NIR wavelengths. It is worth noting that the 7.5° FOV using visible wavelengths yielded higher coefficients of determination than did the 25° FOV using red-edge and NIR wavelengths. At earlier growth stages, leaf structure and distribution had less effect on NIR reflectance than they did at later growth stages. Minimizing soil reflection with a narrower FOV allowed the HTBVI based on the visible spectral range to focus on chlorophyll absorption features and better assess CNS.

The optimized CI1$_{red-edge}$ at 40 DAP in 2011 was formed by the highest coefficient of determination: reflectance at 629 and 434 nm (near the red and blue spectral regions, respectively) using the 7.5° FOV. The optimized CI1$_{red-edge}$

Table 8. Means and least significant differences (LSD) for effect of N fertilization on the optimized $CI1_{red\text{-}edge}$ at 40 days after planting in 2011.

N rate	Optimized $CI1_{red\text{-}edge}$
kg N ha^{-1}	
0	2.09a†
60	1.69b
120	1.52c
200	1.56bc
280	1.51c

† Means followed by the same letter are not significantly different (α = 0.05) using LSD test.

was then computed from a formula similar to that of the NPCI (Table 2), which was also obtained from wavelengths in the red (680 nm) and blue (430 nm) spectral regions. However, the NPCI, contrary to the optimized $CI1_{red\text{-}edge}$, used a normalized difference of the reflectance wavelength combination. It is worth noting that the NPCI did not score anywhere close to the five HVIs most correlated to the NNI (i.e., rank 22 in Table 5). This ranking suggests that variations in CNS affected crop biophysical parameters and therefore their optimal estimators. The choice of an HVI for an efficient CNS assessment may depend on climatic conditions and crop growth stage, which can in turn impact the optimal FOV.

The optimized $CI1_{red\text{-}edge}$ in 2011 at 40 DAP decreased from 2.09 to 1.51 as the N rate increased (Table 8). Jain et al. (2007) reported the same behavior for the NPCI. Analysis of variance revealed that the optimized $CI1_{red\text{-}edge}$ achieved the discrimination of three groups, in comparison with only two groups for the non-optimized version. The N200 rate expressed a similar response to the N120 and N280 rates as well as to the lower rate, N60. Therefore, better discrimination was achieved with the optimized version of the $CI1_{red\text{-}edge}$ than with the non-optimized version, but means separation was as not as clearly defined as the means separation of the NNI in 2011 at 40 DAP (Table 3).

Yield Estimation Using the Most Appropriate Hyperspectral Vegetation Index. The $CI1_{red\text{-}edge}$ was found to be highly correlated to total tuber yield in addition to the NNI (Table 5). At about 40 DAP in 2011 and 2012, $CI1_{red\text{-}edge}$ (25° FOV) had the capacity to detect significant differences based on LSD test (Tables 6 and 7) at the same sensibility than the total tuber yield (two groups in 2011 and three groups in 2012; Table 4). At about 65 to 70 DAP in both years, the $CI1_{red\text{-}edge}$ values (25° FOV) were divided into four statistically different groups (Tables 6 and 7). The values of this index under the highest N rate (i.e., N280) were not significantly different from those under the N200 rate, a finding that is consistent with the fact that increasing the N rate above the optimal N rate of about 200 kg N ha^{-1} did not significantly increase yield in 2012 and that the highest tuber yield was found under the N200 rate in 2011 (Table 4). The values of $CI1_{red\text{-}edge}$ under the highest N rate were statistically different from those under the N200 rate at 84 DAP in year 2011 (Table 6), which did not translate in an increased total tuber yield at the N280 rate in 2011 (Table 4). Moreover, as early as 55 DAP, the $CI1_{red\text{-}edge}$ (25° FOV) successfully estimated total tuber yield. A polynomial regression model (Eq. [3]) using the $CI1_{red\text{-}edge}$ (25° FOV) values from both measurement years at about 55 DAP accounted for 76% of the variation in total tuber yield:

$$\text{Total tuber yield (Mg ha}^{-1}) = -60.55 + 1097.37 \times CI1_{red\text{-}edge} - 3004.75 \times (CI1_{red\text{-}edge})^2 \quad [3]$$

It is worth noting that this regression should be considered carefully because the potato total tuber yield occurs only around 125 to 135 DAP. Nevertheless, the $CI1_{red\text{-}edge}$ was found to be an efficient estimator of total tuber yield.

CONCLUSIONS

This study showed that HVIs can be used to assess potato CNS. Among all the HVIs tested in this 2-yr experiment, HVIs based on the reflectance in the red-edge spectral region were found to be the most reliable indicators for detecting in-season N stresses in a potato crop. Red-edge-based HVIs had the ability to correctly detect potato N stress starting at about 50 DAP. The use of a narrower FOV did not improve the discrimination capability of HVIs to detect early N stress in this study. Statistical analyses revealed that the $CI1_{red\text{-}edge}$ predicted the CNS as precisely as the NNI did, with the exception of the hilling stage in 2011. An optimization of this index at 40 DAP showed that optimal wavelengths were 629 and 434 nm. This result suggests that early N stress detection in a potato crop could also benefit from reflectance in the visible range of the spectrum, depending on the contribution of the soil background reflectance in the signal. Further research is required to evaluate the effects of climatic conditions, growth stage, and soil reflectance on the optimal wavelengths for potato CNS assessment. The $CI1_{red\text{-}edge}$ was also highly correlated to total tuber yield starting at 55 DAP. Yield estimation early in the growing season based on HVIs could help farm managers to optimize their storage management and marketing planning for potato processing.

This hyperspectral proximal sensing study will help in the development of future active sensors specific to potato. Those sensors are required to characterize the within-field spatial variability of CNS independently of illumination conditions so that the sensors could be adopted by growers for site-specific N fertilizer management. Furthermore, preference should be given to the use of a specific crop development model based on growing degree days instead of days after planting to better account for inter- and intra-seasonal effects on CNS.

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REFERENCES

Adams, M.L., W.D. Philpot, and W.A. Norvell. 1999. Yellowness index: An application of spectral second derivatives to estimate chlorosis of leaves in stressed vegetation. Int. J. Remote Sens. 20:3663–3675. doi:10.1080/014311699211264

Allaire, S.E., A.N. Cambouris, J.A. Lafond, S.F. Lange, B. Pelletier, and P. Dutilleul. 2014. Spatial variability of potato tuber yield and plant nitrogen uptake related to soil properties. Agron. J. 106:851–859. doi:10.2134/agronj13.0468

Bannari, A., H. Asalhi, and P.M. Teillet. 2002. Transformed difference vegetation index (TDVI) for vegetation cover mapping. Geoscience and Remote Sensing Symposium, 2002. IGARSS '02. 2002 IEEE International, Vol. 5. doi:10.1109/IGARSS.2002.1026867

Bannari, A., D. Morin, F. Bonn, and A.R. Huete. 1995. A review of vegetation indices. Remote Sens. Rev. 13:95–120 doi:10.1080/02757259509532298

Barnes, E.M., T.R. Clarke, S.E. Richards, P.D. Colaizzi, J. Haberland, M. Kostrzewski, P. Waller, C. Choi, E. Riley, and T. Thompson. 2000. Coincident detection of crop water stress, nitrogen status and canopy density using ground based multispectral data. Proceedings of the 5th International Conference on Precision Agriculture. ASA, Madison, WI.

Bélanger, G., J.R. Walsh, J.E. Richards, P.H. Milburn, and N. Ziadi. 2000. Yield response of two potato culivars to supplemental irrigation and N fertilization in New Brunswick. Am. J. Potato Res. 77:11–21. doi:10.1007/BF02853657

Bélanger, G., J.R. Walsh, J.E. Richards, P.H. Milburn, and N. Ziadi. 2001. Critical nitrogen curve and nitrogen nutrition index for potato in eastern Canada. Am. J. Potato Res. 78:355–364. doi:10.1007/BF02884344

Blackburn, G.A. 1998. Spectral indices for estimating photosynthetic pigment concentrations: A test using senescent tree leaves. Int. J. Remote Sens. 19:657–675. doi:10.1080/014311698215919

Broge, N.H., and E. Leblanc. 2001. Comparing prediction power and stability of broadband and hyperspectral vegetation indices for estimation of green leaf area index and canopy chlorophyll density. Remote Sens. Environ. 76:156–172. doi:10.1016/S0034-4257(00)00197-8

Cambouris, A.N., B.J. Zebarth, M.C. Nolin, and M.R. Laverdière. 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. doi:10.4141/CJSS07107

Centre de Référence en Agriculture et Agroalimentaire du Québec. 2010. Guide de référence en fertilization. 2nd edition. CRAAQ, Québec, QC.

Chambenoit, C., F. Laurent, J.M. Machet, and H. Boizard. 2004. Development of a decision support system for nitrogen management on potatoes. In: D.K.L. MacKerron and A.J. Haverkort, editors, Decision support systems in potato production: Bringing models to practice. Wageningen Academic Publishers, the Netherlands.

Clarke, T.R., M.S. Moran, E.M. Barnes, P.J. Pinter, Jr., and J. Qi. 2001. Planar domain indices: a method for measuring a quality of a single component in two-component pixels. Geosci. Remote Sens. Symp., 2001. IGARSS '01. IEEE 2001 International.

Clevers, J.G.P.W. 1989. Application of a weighted infrared-red vegetation index for estimating leaf area index by correcting for soil moisture. Remote Sens. Environ. 29:25–37. doi:10.1016/0034-4257(89)90076-X

Clevers, J.G.P.W., and L. Kooistra. 2012. Using hyperspectral remote sensing data for retrieving canopy chlorophyll and nitrogen content. J. Selected Topics Appl. Earth Obs. Remote Sens., IEEE. 5: 574–583. doi:10.1109/JSTARS.2011.2176468

Cohen, Y., V. Alchanatis, Y. Zusman, Z. Dar, D.J. Bonfil, A. Karnieli, A. Zilberman, A. Moulin, V. Ostrovsky, A. Levi, R. Brikman, and M. Shenker. 2010. Leaf nitrogen estimation in potato based on spectral data and on simulated bands of the VENμS satellite. Precis. Agric. 11:520–537. doi:10.1007/s11119-009-9147-8

Datt, B. 1999. A new reflectance index for remote sensing of chlorophyll content in higher plants: Tests using eucalyptus leaves. J. Plant Physiol. 154:30–36. doi:10.1016/S0176-1617(99)80314-9

Daughtry, C.S.T., C.L. Walthall, M.S. Kim, E.B. de Colstoun, and J.E. McMurtrey, Iii. 2000. Estimating corn leaf chlorophyll concentration from leaf and canopy reflectance. Remote Sens. Environ. 74:229–239. doi:10.1016/S0034-4257(00)00113-9

Duchenne, T., J.M. Machet, and M. Martin. 1997. Potatoes. In: G. Lemaire, editor, Diagnosis of the nitrogen status in crops. Springer, New York. p. 119–130.

Errebhi, M., C.J. Rosen, S.C. Gupta, and D.E. Birong. 1998. Potato yield response and nitrate leaching as influenced by nitrogen management. Agron. J. 90:10–15. doi:10.2134/agronj1998.00021962009000010003x

Fitzgerald, G.J., D. Rodriguez, L.K. Christensen, R. Belford, V.O. Sadras, and T.R. Clarke. 2006. Spectral and thermal sensing for nitrogen and water status in rainfed and irrigated wheat environments. Precis. Agric. 7:233–248. doi:10.1007/s11119-006-9011-z

Fitzgerald, G.J., D. Rodriguez, and G. O'Leary. 2010. Measuring and predicting canopy nitrogen nutrition in wheat using a spectral index—The canopy chlorophyll content index (CCCI). Field Crops Res. 116:318–324. doi:10.1016/j.fcr.2010.01.010

Gitelson, A.A., and M.N. Merzlyak. 1996. Signature analysis of leaf reflectance spectra: Algorithm development for remote sensing of chlorophyll. J. Plant Physiol. 148:494–500. doi:10.1016/S0176-1617(96)80284-7

Goffart, J.P., M. Olivier, and M. Frankinet. 2008. Potato crop nitrogen status assessment to improve N fertilization management and efficiency: Past–present–future. Potato Res. 51:355–383. doi:10.1007/s11540-008-9118-x

Griffin, T.S. 2008. Nitrogen availability. In: J.S. Schepers and W. Raun, editors, Nitrogen in agricultural systems. ASA-CSSA-SSSA, Madison, WI. p. 616–646.

Haboudane, D., J.R. Miller, E. Pattey, P.J. Zarco-Tejada, and I.B. Strachan. 2004. Hyperspectral vegetation indices and novel algorithms for predicting green LAI of crop canopies: Modeling and validation in the context of precision agriculture. Remote Sens. Environ. 90:337–352. doi:10.1016/j.rse.2003.12.013

Haboudane, D., J.R. Miller, N. Tremblay, P.J. Zarco-Tejada, and L. Dextraze. 2002. Integrated narrow-band vegetation indices for prediction of crop chlorophyll content for application to precision agriculture. Remote Sens. Environ. 81:416–426. doi:10.1016/S0034-4257(02)00018-4

Herrmann, I., A. Karnieli, D.J. Bonfil, Y. Cohen, and V. Alchanatis. 2010. SWIR-based spectral indices for assessing nitrogen content in potato fields. Int. J. Remote Sens. 31:5127–5143. doi:10.1080/01431160903283892

Horler, D.N.H., M. Dockray, and J. Barber. 1983. The red edge of plant leaf reflectance. Int. J. Remote Sens. 4:273–288. doi:10.1080/01431168308948546

Huete, A.R. 1988. A soil-adjusted vegetation index (SAVI). Remote Sens. Environ. 25:295–309. doi:10.1016/0034-4257(88)90106-X

Jackson, R.D., and A.R. Huete. 1991. Interpreting vegetation indices. Prev. Vet. Med. 11:185–200. doi:10.1016/S0167-5877(05)80004-2

Jain, N., S. Ray, J.P. Singh, and S. Panigrahy. 2007. Use of hyperspectral data to assess the effects of different nitrogen applications on a potato crop. Precis. Agric. 8:225–239. doi:10.1007/s11119-007-9042-0

Jensen, J.R. 2007. Remote sensing of the environment: An earth resource perspective. second ed. Prentice Hall, Upper Saddle River, NJ.

Lemaire, G., and F. Gastal. 1997. N uptake and distribution in plant canopies. In: G. Lemaire, editor, Diagnosis of the nitrogen status in crops. Springer, Berlin. p. 3–43.

Lemaire, G., J. Salette, M. Sigogne, and J.-P. Terrasson. 1984. Relation entre dynamique de croissance et dynamique de prélèvement d'azote pour un peuplement de graminées fourragères. I. Etude de l'effet du milieu. Agronomie 4:423–430. doi:10.1051/agro:19840503

Li, F., B. Mistele, Y. Hu, X. Yue, S. Yue, Y. Miao, X. Chen, Z. Cui, Q. Meng, and U. Schmidhalter. 2012. Remotely estimating aerial N status of phenologically differing winter wheat cultivars grown in contrasting climatic and geographic zones in China and Germany. Field Crops Res. 138:21–32. doi:10.1016/j.fcr.2012.09.002

Lyon, J.G., D. Yuan, R.S. Lunetta, and C.D. Elvidge. 1998. A change detection experiment using vegetation indices. Photogramm. Eng. Remote Sens. 64:143–150.

Peñuelas, J., F. Baret, and I. Filella. 1995a. Semi-empirical indices to assess carotenoids/chlorophyll α ratio from leaf spectral reflectance. Photosynthetica 31:221–230.

Peñuelas, J., I. Filella, P. Lloret, F. Muñoz, and M. Vilajeliu. 1995b. Reflectance assessment of mite effects on apple trees. Int. J. Remote Sens. 16:2727–2733. doi:10.1080/01431169508954588

Qi, J., A. Chehbouni, A.R. Huete, Y.H. Kerr, and S. Sorooshian. 1994. A modified soil adjusted vegetation index. Remote Sens. Environ. 48:119–126. doi:10.1016/0034-4257(94)90134-1

R Core Team. 2012. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Rondeaux, G., M. Steven, and F. Baret. 1996. Optimization of soil-adjusted vegetation indices. Remote Sens. Environ. 55:95–107. doi:10.1016/0034-4257(95)00186-7

Rouse, J.W., Jr., R.H. Haas, J.A. Schell, D.W. Deering, and J.C. Harlan. 1974. Monitoring the vernal advancement and retrogradation (greenwave Effect) of natural vegetation. Texas A&M Univ., College Station, TX. http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19750020419.pdf (accessed 1 Apr. 2015).

SAS Institute. 2004. SAS user's guide. SAS Inst., Cary, NC.

Saxton, A. 1998. A macro for converting mean separation output to letter groupings in Proc Mixed. Proceedings of the 23rd SAS Users Group International: 1243–1246.

Schröder, J.J., J.J. Neeteson, O. Oenema, and P.C. Struik. 2000. Does the crop or the soil indicate how to save nitrogen in maize production?: Reviewing the state of the art. Field Crops Res. 66:151–164. doi:10.1016/S0378-4290(00)00072-1

Serrano, L., J. Peñuelas, and S.L. Ustin. 2002. Remote sensing of nitrogen and lignin in Mediterranean vegetation from AVIRIS data: Decomposing biochemical from structural signals. Remote Sens. Environ. 81:355–364. doi:10.1016/S0034-4257(02)00011-1

Shanahan, J.F., N.R. Kitchen, W.R. Raun, and J.S. Schepers. 2008. Responsive in-season nitrogen management for cereals. Comput. Electron. Agric. 61:51–62. doi:10.1016/j.compag.2007.06.006

Soil Classification Working Group. 1998. The Canadian system of soil classification, third edition. Publ. 1646. Agriculture and Agri-Food Canada, Ottawa, ON.

St. Luce, M., J.K. Whalen, N. Ziadi, and B.J. Zebarth. 2011. Nitrogen dynamics and indices to predict soil nitrogen supply in humid temperate soils. Adv. Agron. 112:55–102. doi:10.1016/B978-0-12-385538-1.00002-0

Stalham, M.A., and E.J. Allen. 2001. Effect of variety, irrigation regime and planting date on depth, rate, duration and density of root growth in the potato (Solanum tuberosum) crop. J. Agric. Sci. 137:251–270. doi:10.1017/S0021859601001332

Thenkabail, P.S., J.G. Lyon, and A. Huete. 2011. Advances in hyperspectral remote sensing of vegetation and agricultural croplands. Hyperspectral remote sensing of vegetation. CRC Press, Boca Raton, FL. p. 3–36.

Thenkabail, P.S., R.B. Smith, and E. De Pauw. 2000. Hyperspectral vegetation indices and their relationships with agricultural crop characteristics. Remote Sens. Environ. 71:158–182. doi:10.1016/S0034-4257(99)00067-X

Tran, T.S., and M. Giroux. 1991. Effects of N rates and harvest dates on the efficiency of 15N-labeled fertilizer on early harvested potatoes (*Solanum tuberosum* L.). Can. J. Soil Sci. 71:519–532. doi:10.4141/cjss91-050

van Evert, F.K., R. Booij, J.N. Jukema, H.F.M. ten Berge, D. Uenk, E.J.J. Meurs, W.C.A. van Geel, K.H. Wijnholds, and J.J. Slabbekoorn. 2012. Using crop reflectance to determine sidedress N rate in potato saves N and maintains yield. Eur. J. Agron. 43:58–67. doi:10.1016/j.eja.2012.05.005

Vogelmann, J.E., B.N. Rock, and D.M. Moss. 1993. Red edge spectral measurements from sugar maple leaves. Int. J. Remote Sens. 14:1563–1575. doi:10.1080/01431169308953986

Vos, J., and D.K.L. MacKerron. 2000. Basic concepts of the management of supply of nitrogen and water in potato production. In: A.J. Havekort and D.K.L. MacKerron, editors, Management of Nitrogen and Water in Potato Production. Wageningen Academic Publisher, the Netherlands. p. 15–33.

Yao, H., L. Tang, L. Tian, R. Brown, D. Bhatnagar, and T. Cleveland. 2011. Using hyperspectral data in precision farming applications. Hyperspectral remote sensing of vegetation. CRC Press, Boca Raton, FL. p. 591–608.

Zarco-Tejada, P.J., J.R. Miller, A. Morales, A. Berjón, and J. Agüera. 2004. Hyperspectral indices and model simulation for chlorophyll estimation in open-canopy tree crops. Remote Sens. Environ. 90:463–476. doi:10.1016/j.rse.2004.01.017

Zarco-Tejada, P.J., J.R. Miller, T.L. Noland, G.H. Mohammed, and P.H. Sampson. 2001. Scaling-up and model inversion methods with narrowband optical indices for chlorophyll content estimation in closed forest canopies with hyperspectral data. IEEE Trans. Geosci. Rem. Sens. 39:1491–1507 doi:10.1109/36.934080.

Zebarth, B.J., C.F. Drury, N. Tremblay, and A.N. Cambouris. 2009. Opportunities for improved fertilizer nitrogen management in production of arable crops in eastern Canada: A review. Can. J. Soil Sci. 89:113–132. doi:10.4141/CJSS07102

Zebarth, B.J., H. Rees, N. Tremblay, P. Fournier, and B. Leblon. 2003. Mapping spatial variation in potato nitrogen status using the N Sensor. Acta Hortic. 627:267–273.

Ziadi, N., B. Zebarth, G. Bélanger, and A. Cambouris. 2012. Soil and plant tests to optimize fertilizer nitrogen management of potatoes. In: Z. He, R. Larkin, and W. Honeycutt, editors, Sustainable potato production: Global case studies. Springer, the Netherlands. p. 187–207.