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Remote estimation of crop and grass chlorophyll and nitrogen content using red-edge bands on Sentinel-2 and -3

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ABSTRACT

Sentinel-2 is planned for launch in 2014 by the European Space Agency and it is equipped with the Multi Spectral Instrument (MSI), which will provide images with high spatial, spectral and temporal resolution. It covers the VNIR/SWIR spectral region in 13 bands and incorporates two new spectral bands in the red-edge region, which can be used to derive vegetation indices using red-edge bands in their formulation. These are particularly suitable for estimating canopy chlorophyll and nitrogen (N) content. This band setting is important for vegetation studies and is very similar to the ones of the Ocean and Land Colour Instrument (OLCI) on the planned Sentinel-3 satellite and the Medium Resolution Imaging Spectrometer (MERIS) on Envisat, which operated from 2002 to early 2012. This paper focuses on the potential of Sentinel-2 and Sentinel-3 in estimating total crop and grass chlorophyll and N content by studying in situ crop variables and spectroradiometer measurements obtained for four different test sites. In particular, the red-edge chlorophyll index ($CI_{red-edge}$), the green chlorophyll index (CI_{green}) and the MERIS terrestrial chlorophyll index (MTCI) were found to be accurate and linear estimators of canopy chlorophyll and N content and the Sentinel-2 and -3 bands are well positioned for deriving these indices. Results confirm the importance of the red-edge bands on particularly Sentinel-2 for agricultural applications, because of the combination with its high spatial resolution of 20 m.

1. Introduction

In vegetation studies actual information on canopy chlorophyll or nitrogen (N) content, in addition to properties like leaf area index, biomass and fraction of absorbed photosynthetically active radiation, is important in understanding plant functioning and status. Photosynthesis is one of the key processes in plants that is responsible for the energy and carbon balance. The photosynthesis occurs in so-called reaction centers containing chlorophyll. Since N is a key element in chlorophyll and in enzymes needed for photosynthesis, N shortage in plants will result in non-optimal photosynthesis. A strong correlation between foliar N and chlorophyll has been found for various plant species (Baret et al., 2007; Oppelt, 2002; Oppelt and Mauser, 2004; Vos and Bom, 1993; Yoder and Pettigrew-Crosby, 1995). Actual N and/or chlorophyll estimates are important for a range of applications such as precision agriculture and the global carbon cycle.

Since chlorophyll is the main plant constituent determining the reflectance in the visible region of the spectrum, optical remote sensing techniques have great potential in providing information on canopy chlorophyll and N content. At the moment, most sensors on board of satellite systems are not specifically tailored for this application. Currently a multitude of satellite data is available already, and this availability will increase enormously in the near future. The European Space Agency (ESA) is developing five new missions called Sentinels specifically for the operational needs of the "Global Monitoring for Environment and Security" (GMES) program (Aschbacher and Milagro-Pérez, 2012). For land applications using the solar reflective domain, in particular two systems are relevant. Sentinel-2 (equipped with the Multi Spectral Instrument, MSI), which will provide images with high spatial, spectral and temporal resolution, aims at ensuring continuity of Landsat and SPOT (Système Pour l'Observation de la Terre) observations. It covers the visible and near-infrared (VNIR) and the shortwave-infrared (SWIR) spectral region in 13 bands, incorporating two new spectral bands in the so-called red-edge region, which are very important for retrieval of chlorophyll content (Dash and Curran, 2004; Delegido et al., 2011; Gitelson et al., 2005). It will carry 4 bands at 10 m (cf. SPOT), 6 bands at 20 m and 3 bands at 60 m spatial resolution. The latter are dedicated to atmospheric corrections and cloud screening (Drusch et al., 2012).

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Sentinel-3 is a medium resolution land and ocean mission, to be seen as a continuation of the Envisat mission. The Ocean and Land Colour Instrument (OLCI) has similar specifications as the Medium Resolution Imaging Spectrometer (MERIS) on Envisat (Rast et al., 1999), and, thus, will provide data continuity of MERIS (Donlon et al., 2012). Since it also has red-edge bands, it can be used for the retrieval of chlorophyll content, albeit at a different scale as Sentinel-2 (Clevers et al., 2002; Dash and Curran, 2004). Both Sentinel-2 and Sentinel-3 missions are based on a constellation of two satellites each in order to fulfill revisit and coverage requirements, providing robust datasets for GMES services.

For estimating chlorophyll content the red-edge region has shown to be highly significant (Clevers et al., 2001; Curran, 1989; Dash and Curran, 2004). Recently, the significance of the red-edge bands on Sentinel-2 for estimating LAI and chlorophyll content has been shown through simulation studies (Delegido et al., 2011; Herrmann et al., 2011). In this paper, we will further elaborate on the potential of Sentinels for retrieving crop and grass canopy chlorophyll and N content by paying special attention to the suitability of the band positions for use in vegetation indices.

Several vegetation indices (VIs) have been proposed for estimating canopy chlorophyll or N content (Clevers and Kooistra, 2012). In particular, the red-edge region has often been used for estimating chlorophyll and N content. VIs often combine a near-infrared (NIR) spectral band, representing scattering of radiation by a canopy, with a visible spectral band, representing absorption by chlorophyll. Problem with using, e.g., a red spectral band is the strong absorption by chlorophyll resulting into less sensitivity of such indices. Due to lower absorption by chlorophyll in the red-edge region, the use of such a band reduces the saturation effect, and the reflectance still remains sensitive to chlorophyll absorption at its moderate-to-high values (Gitelson and Merzlyak, 1996). Horler et al. were amongst the first to show the importance of the position of the red-edge inflection point for detecting plant stress (Horler et al., 1983). Since this first publication, the red-edge position (REP) has often been used as an estimate for chlorophyll content. With the limited number of red-edge bands of MERIS and the proposed Sentinel-2 and Sentinel-3 bands, the REP can be derived by applying a simple linear model to the red-infrared slope (Guyot and Baret, 1988). Another type of index based on the MERIS red-edge bands is the MERIS terrestrial chlorophyll index, MTCI (Dash and Curran, 2004). This index has been applied successfully for many applications. As heritage of MERIS, this MTCI is the basis of one of the Level 2B main terrestrial products of Sentinel-3, called the OLCI Terrestrial Chlorophyll Index (OTCI) (Vuolo et al., 2012). Therefore, this index will also get explicit attention in this paper.

Wu et al. also stressed the importance of the red-edge bands (Wu et al., 2008). They suggested to replace the red and NIR spectral bands in the MCARI/OSAVI (Daughtry et al., 2000) and TCARI/OSAVI (Haboudane et al., 2002) by bands at 705 nm and 750 nm, respectively. Indeed these adapted indices showed better linearity with canopy chlorophyll and N content (Clevers and Kooistra, 2012). We will quote these indices as MCARI/OSAVI[705,750] and TCARI/OSAVI[705,750].

It has been shown in various studies that ratio indices and/or normalized difference indices using red-edge bands perform very well in estimating chlorophyll or N content. Gitelson (Gitelson et al., 2003, 2006) presented a ratio index based on a NIR band (e.g., at 800 nm) and a red-edge band (e.g., at 710 nm) for estimating chlorophyll content: the so-called red-edge chlorophyll index ($CI_{red\text{-}edge} = R_{800}/R_{710} - 1$). Similarly, a so-called green chlorophyll index ($CI_{green} = R_{800}/R_{550} - 1$) has been proposed. Major advantages are their linearity with chlorophyll content and absence of the saturation effect. In literature, various ratio indices can be found with slightly different band settings, often depending on the available sensor.

Table 1
Specifications of the Multi Spectral Instrument (MSI) on the Sentinel-2 satellite system.

Spectral band	Center wavelength (nm)	Band width (nm)	Spatial resolution (m)
B1	443	20	60
B2	490	65	10
B3	560	35	10
B4	665	30	10
B5	705	15	20
B6	740	15	20
B7	783	20	20
B8	842	115	10
B8a	865	20	20
B9	945	20	60
B10	1380	30	60
B11	1610	90	20
B12	2190	180	20

Normalized difference indices using the red-edge bands mostly are called "normalized difference red-edge" (NDRE or red-edge NDVI). A version 1 using 750 nm and 705 nm (Gitelson and Merzlyak, 1994; Sims and Gamon, 2002) is presented in literature, whereas also a version 2 using 790 nm and 720 nm (Barnes et al., 2000) can be found. Sometimes, also deviating names are used in literature. The $CI_{red\text{-}edge}$ with MERIS spectral bands was able to accurately estimate chlorophyll content in maize and soybean (Gitelson et al., 2005). Moreover, the $CI_{red\text{-}edge}$ with reflectance in the band 720–730 nm (in denominator) was found to be universal for maize and soybean, crops with contrasting leaf structures and canopy architectures, and it did not require re-parameterization of the algorithm for chlorophyll estimation.

In a previous study, we obtained best results in estimating either canopy chlorophyll or N content using the indices $CI_{red\text{-}edge}$ and CI_{green} (Clevers and Kooistra, 2012). In this paper, we will first study which band setting is best for the $CI_{red\text{-}edge}$, since many variants have been used in literature. Subsequently, we will compare this with using the band setting of Sentinel-2, -3 and MERIS. Finally, we will study the performance of the other indices mentioned using the Sentinel-2 band setting. We will use a number of different case studies for this analysis. Since the band positions of all three sensors relevant for land applications are very similar and the spatial resolution of Sentinel-2 is the more appropriate for agricultural applications at the field scale, we will mainly present results for Sentinel-2.

2. Materials and methods

2.1. Satellite sensors

ESA is planning to launch the first Sentinel-2 polar-orbiting satellite in 2014. It carries the MSI (Multi Spectral Instrument), having four bands at 10 m, six bands at 20 m and three bands at 60 m spatial resolution (Drusch et al., 2012). It has a swath width of 290 km by applying a total field-of-view of about 20°. It incorporates two spectral bands in the red-edge region, which are centered at 705 nm and 740 nm at a band width of 15 nm and a spatial resolution of 20 m (Table 1).

Sentinel-3 is being developed to provide continuity to some key Envisat capabilities, in particular the Radar Altimeter (RA), the Advanced Along Track Scanning Radiometer (AATSR) and the Medium resolution Imaging Spectrometer (MERIS), with a planned launch of the first satellite late 2013 and a second one late 2014 (Donlon et al., 2012). The OLCI imaging spectrometer has a swath width of 1270 km (FOV of 68°, but slightly tilted) and a spatial resolution of 300 m. The sensor (5 cameras) is tilted 12.6° westwards to avoid sun-glint over water, which may have some effects over land

Table 2
Specifications of the Ocean and Land Colour Instrument (OLCI) on the Sentinel-3 satellite system.

Spectral band	Center wavelength (nm)	Band width (nm)
O1	400	15
O2	412.5	10
O3	443	10
O4	490	10
O5	510	10
O6	560	10
O7	620	10
O8	665	10
O9	673.75	7.5
O10	681	7.5
O11	709	10
O12	754	7.5
O13	761	2.5
O14	764.375	3.75
O15	767.5	2.5
O16	779	15
O17	865	20
O18	885	10
O19	900	10
O20	940	20
O21	1020	40

too. It will provide data continuity of MERIS on Envisat. In principle, OLCI has the same spectral band definitions as MERIS, although OLCI has a few additional bands, mainly for a more accurate atmospheric correction. Whereas, the spatial resolution is worse than the one of Sentinel-2, the spectral resolution is better than the one of Sentinel-2 (Table 2).

MERIS (Medium Resolution Imaging Spectrometer) was one of the payload components of ESA's Envisat satellite, which was launched in March 2002. MERIS was designed for monitoring marine phenomena and processes. It also contributed significantly to atmospheric investigations and to land surface process studies. MERIS was a 15 band, programmable imaging spectrometer, which allowed for changes in band position and band widths throughout its lifetime. It was designed to acquire data at variable band widths between 1.25 nm and 30 nm over the spectral range of 390–1040 nm. For land applications data were acquired at 300 m or 1200 m spatial resolution, thus vegetation monitoring was performed at regional to global scales. MERIS was mostly operated with a standard band setting as shown in Table 3. Operation of Envisat ended April 2012.

Table 3
Specifications of the Medium Resolution Imaging Spectrometer (MERIS) on the Envisat system.

Spectral band	Center wavelength (nm)	Band width (nm)
1	412.5	10
2	442.5	10
3	490	10
4	510	10
5	560	10
6	620	10
7	665	10
8	681.25	7.5
9	708.75	10
10	753.75	7.5
11	760	2.5
12	778.75	15
13	865	20
14	890	10
15	900	10

2.2. Experimental data

A number of experimental data sets have been used for performing the study described in this paper.

The first data sets concern maize and soybean data. The study area is located at the University of Nebraska-Lincoln (UNL) Agricultural Research and Development Center near Mead, Nebraska, U.S.A. It consists of three 65-ha fields under different management practices. During the 3 years of study (2001–2003), one field was under continuous irrigated maize while two other fields were under a maize/soybean rotation, with maize during 2001 and 2003 and soybean during 2002. One of these fields was irrigated, while another one received only rainfall (Gitelson et al., 2005; Viña et al., 2011). Leaf chlorophyll content was measured spectrophotometrically in the laboratory and also using leaf reflectance applying a leaf clip with an Ocean Optics USB2000 spectroradiometer in the laboratory (Ciganda et al., 2008; Gitelson et al., 2003). Canopy reflectance was collected using an all-terrain sensor platform (called "Goliath"), equipped with a dual-fiber system and two Ocean Optics USB2000 spectroradiometers, with a spectral range of 400–1100 nm and a spectral resolution of 1.25 nm (Rundquist et al., 2004). One fiber was fitted with a cosine diffuser to measure incoming downwelling irradiance, while the second one measured upwelling radiance. The field of view of the downward-pointing sensor was kept constant along the growing season (approximately 2.4 m in diameter) by placing the spectroradiometer at a height of 5.5 m above the top of the canopy. Six randomly selected plots were established per field, each with six randomly selected sampling points. Ten reflectance spectra were measured at each collection point and computed average reflectance represented each collection point. Thus, a total of 36 points within these areas were sampled per field at each data acquisition, and their median per date was used as the overall field reflectance. This resulted in a total of 169 reflectance spectra for maize (47 in 2001, 30 in 2002, 92 in 2003) and 54 spectra for soybean in 2002, which were representative of a wide range of chlorophyll and green leaf area variation in maize and soybean cropping systems.

Sentinel-2 bands were simulated by calculating the average reflectance over the band width of the respective Sentinel-2 bands. This approximation was applied since the spectral response functions of the Sentinel-2 spectral bands are close to rectangular (Drusch et al., 2012). The average reflectance over the 697.5–712.5 nm interval was used to simulate the 705 nm Sentinel-2 band. Similarly, the 773.5–792.5 nm interval was used to simulate the 783 nm band.

The third data set is a grassland site where 40 plots were destructively sampled in 2008 (Clevers and Kooistra, 2012). It is an extensively grazed fen meadow acting as a buffer zone around a protected bog ecosystem in the east of the Netherlands. Ground sampling took place in June 2008. Plots of 3 by 3 m were randomly distributed over the study area. Per plot 3 subsamples were taken. In addition to fresh and dry weight, leaf N content was determined using the Kjeldahl method (AOAC, 1990). Before harvesting the plots the spectral reflectance was measured with an ASD FieldSpec 3 spectroradiometer with a 1 nm sampling interval. Measurement height was about 1.5 m and the instrument field of view was 25°. As a result, at the plot level a circular area of about 0.35 m^2 was measured and each spectral measurement represented the average of 50 readings. Calibration was done by using a Spectralon white reference panel. Finally, average data per plot were calculated. Sentinel-2 bands were simulated by assuming a rectangular filter response and calculating the average reflectance over the band width of the respective Sentinel-2 bands. For instance, the average reflectance over the 698–712 nm interval was used to simulate the 705 nm Sentinel-2 band. Similarly, the 773–793 nm interval was used to simulate the 783 nm band.

Table 4
Specifications of the Cropscan MSR16R system.

Center wavelength (nm)	Band width (nm)
490	7.3
530	8.5
550	9.2
570	9.7
670	11
700	12
710	12
740	13
750	13
780	11
870	12
940	13
950	13
1000	15
1050	15
1650	200

The fourth data set was obtained from a field experiment conducted at a potato field in the south of the Netherlands in 2010 (Clevers and Kooistra, 2012). Plots of 30 m by 30 m were planted with four levels of N fertilization in two replicates, yielding eight plots in total. Crop status was measured monthly by sampling and wet-chemistry analysis. Plant fresh and dry weight and N content were determined. The latter was based on the Dumas method (Hansen, 1989). The plots were also measured monthly with a Cropscan Multispectral Radiometer (MSR16R). This is a 16-band radiometer measuring simultaneously reflected and incoming radiation in narrow spectral bands (Table 4). Reflected radiance was measured at about 1.5 m height through a 28° field of view aperture and incoming downwelling irradiance was measured through a cosine diffuser. On four dates during the 2010 growing season (23 June, 14 July, 19 August and 6 September) 36 samples per plot were measured and subsequently average reflectances per plot were calculated. Since the Cropscan does not provide a very high spectral resolution, the Cropscan bands located close to the Sentinel-2 bands (Table 1) were used to simulate Sentinel-2. In addition, the average of the Cropscan bands at 700 nm and 710 nm was used to simulate the 705 nm band of Sentinel-2.

2.3. Vegetation indices

In this study the performance of the $CI_{red\text{-}edge}$, CI_{green}, REP, MTCI, MCARI/OSAVI[705,750], TCARI/OSAVI[705,750], NDRE1 and NDRE2 for the estimation of canopy chlorophyll and N content has been evaluated. Many of them used red-edge bands and definitions using the Sentinel-2 spectral bands are provided in Table 5.

Table 5
Vegetation indices evaluated in this study.

Index	Formulation	Reference
$CI_{red\text{-}edge}$	$\left(\frac{R_{783}}{R_{705}}\right)-1$	Gitelson et al. (2003, 2006)
CI_{green}	$\left(\frac{R_{783}}{R_{560}}\right)-1$	Gitelson et al. (2003, 2006)
REP	$705+35\frac{(R_{665}+R_{783})/2-R_{705}}{R_{740}-R_{705}}$	Guyot and Baret (1988)
MTCI	$\frac{R_{740}-R_{705}}{R_{705}-R_{665}}$	Dash and Curran (2004)
MCARI/OSAVI[705,750]	$\frac{[(R_{740}-R_{705})-0.2(R_{740}-R_{560})](R_{740}/R_{705})}{(1+0.16)(R_{740}-R_{705})/(R_{740}+R_{705}+0.16)}$	Wu et al. (2008)
TCARI/OSAVI[705,750]	$\frac{3[(R_{740}-R_{705})-0.2(R_{740}-R_{560})(R_{740}/R_{705})]}{(1+0.16)(R_{740}-R_{705})/(R_{740}+R_{705}+0.16)}$	Wu et al. (2008)
NDRE1	$\frac{R_{740}-R_{705}}{R_{740}+R_{705}}$	Gitelson and Merzlyak (1994), Sims and Gamon (2002)
NDRE2	$\frac{R_{783}-R_{705}}{R_{783}+R_{705}}$	Barnes et al. (2000)

R_λ refers to the reflectance factor at wavelength λ nm.

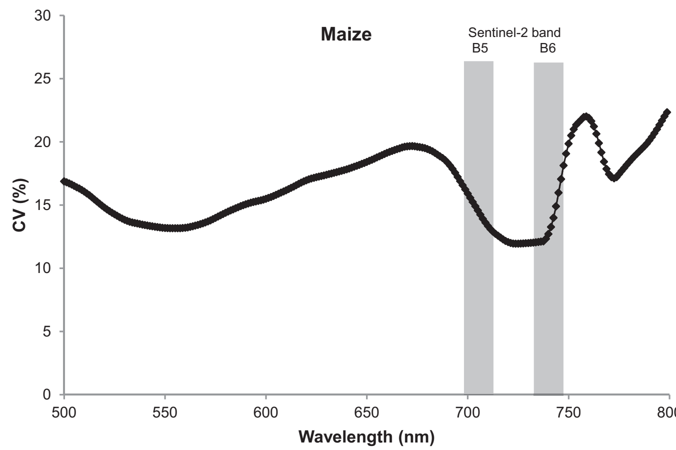

Fig. 1. Coefficient of variation (%) of canopy chlorophyll content estimation for maize by the R_{800}/R_{xxx} index, with R_{xxx} as the reflectance of a spectral band in the 500–800 nm interval.

Testing the optimal band setting in using the $CI_{red\text{-}edge}$ for estimating canopy chlorophyll or N content has been performed by comparing coefficients of variation (CV%) for all possible positions of reflectance wavelength in the denominator of the CI. The original band settings for the instruments used at the various test sites were used for this analysis. Since the reference band in the numerator is not that critical, 800 nm has been used initially, as suggested in Gitelson et al. (2005). The CV is calculated as the ratio of the root-mean-square-error of chlorophyll or nitrogen content estimation using a linear regression and the average content value. Subsequently, other reference NIR bands have been tested (in the range 780–900 nm). Intercomparison of the various vegetation indices using the Sentinel-2 spectral bands has been performed by comparing the coefficients of determination (R^2 values) of linear estimators. The predictive power of the best indices has been assessed by estimating the root mean square error of prediction (RMSEP) using the leave-one-out cross-validation approach.

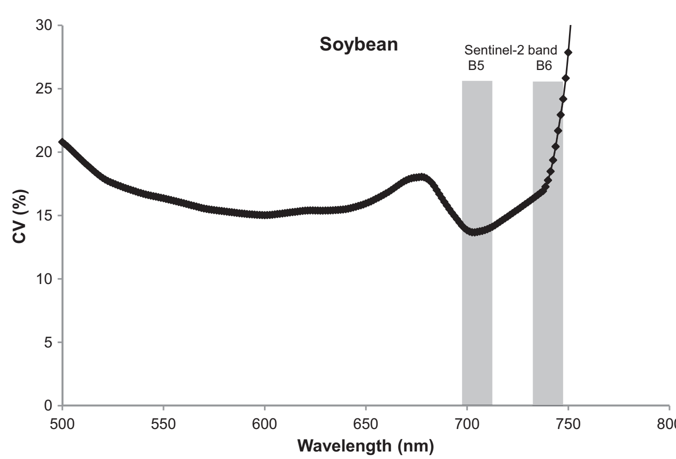

Fig. 2. Coefficient of variation (%) of canopy chlorophyll content estimation for soybean by the R_{800}/R_{xxx} index, with R_{xxx} as the reflectance of a spectral band in the 500–800 nm interval.

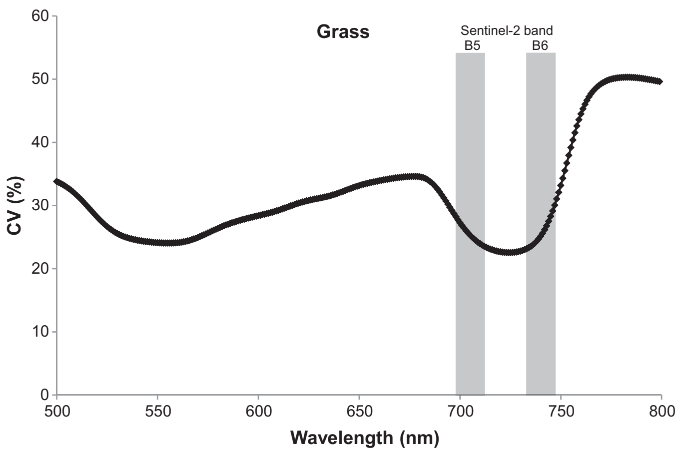

Fig. 3. Coefficient of variation (%) of canopy N content estimation for grass by the R_{800}/R_{xxx} index, with R_{xxx} as the reflectance of a spectral band in the 500–800 nm interval.

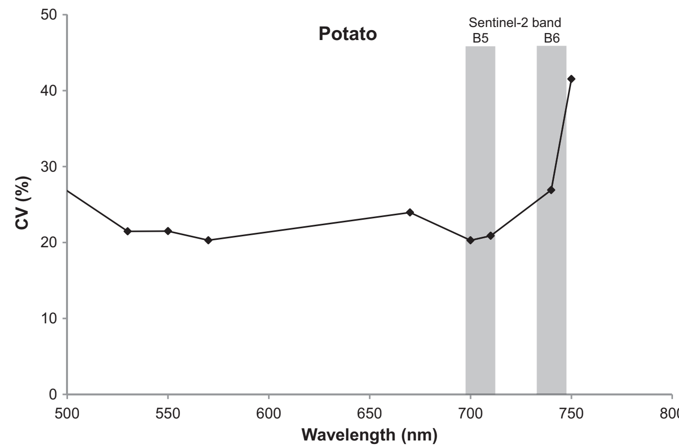

Fig. 4. Coefficient of variation (%) of canopy N content estimation for potatoes by the R_{780}/R_{xxx} index, with R_{xxx} as the reflectance of a spectral band in the 500–800 nm interval.

3. Results and discussion

3.1. Optimal band selection for $CI_{red\text{-}edge}$

By taking a wavelength at 800 nm in the numerator and varying the wavelength in the denominator between 500 nm and 800 nm, the optimal CI could be obtained. Results for the coefficient of variation, CV (%), in the maize experiment are shown in Fig. 1. Since the Ocean Optics instrument had a sampling interval of 1.25 nm, the indices have been calculated at steps of 1.25 nm. The CV had a minimal value below 12% in the red-edge range from 720 nm to 740 nm. The best result was obtained at about 724 nm (meaning optimal $CI_{red\text{-}edge} = R_{800}/R_{724} - 1$). This $CI_{red\text{-}edge}$ yields a coefficient of determination, R^2, of 0.94. Another local minimum of CV was in the green range from 550 nm to 560 nm where CV was below 13.5%.

Similarly, Fig. 2 provides the results of the soybean experiment. Minimum in the red-edge range was between 700 nm and 710 nm with a CV below 14%. The minimum was much narrower than in maize. Here the best result is obtained for a wavelength at 704 nm ($CI_{red\text{-}edge} = R_{800}/R_{704} - 1$) with an R^2 also of 0.94. In the green part of the spectrum, a band in the 570–640 nm interval provided best results with CV below 16%.

In the grassland experiment, an ASD FieldSpec Pro has been used with a 1 nm sampling interval. Results for the CV using 800 nm wavelength in numerator of the CI, as a reference wavelength, were shown in Fig. 3. In the red-edge range CV dropped below 24% in a wide range from 705 nm to 735 nm. The best result was obtained for wavelength 720 nm ($CI_{red\text{-}edge} = R_{800}/R_{720} - 1$). This best $CI_{red\text{-}edge}$ yields an R^2 value of 0.80. Fig. 3 also shows that a band in the 530–570 nm range may be used, but the CV is slightly higher as compared to the red-edge region.

Table 6
Overview of R^2 values of the linear relationships between indices based on Sentinel-2 spectral bands and chlorophyll (maize and soybean) and nitrogen (grass and potato) content.

Index	Maize	Soybean	Grass	Potato
Best $CI_{red\text{-}edge}$ from Section 3.1	0.94	0.94	0.80	0.89
$CI_{red\text{-}edge}$	0.92	0.94	0.75	0.89
CI_{green}	0.93	0.92	0.77	0.89
REP	0.92	0.70	0.79	0.85
MTCI	0.92	0.87	0.78	0.86
MCARI/OSAVI[705,750]	0.86	0.92	0.51	0.83
TCARI/OSAVI[705,750]	0.85	0.91	0.72	0.85
NDRE1	0.83	0.81	0.62	0.71
NDRE2	0.83	0.81	0.67	0.73

Finally, for the potato plots the Cropscan radiometer has been used, which has more irregularly spaced spectral bands since they are already tuned to the most common wavelength positions used in VIs. Results for the CV using 780 nm as reference band were shown in Fig. 4. The best result was obtained for bands centered at 700 nm and 710 nm, meaning $CI_{red\text{-}edge} = R_{780}/R_{700} - 1$ and $CI_{red\text{-}edge} = R_{780}/R_{710} - 1$. Taking into account the width of Cropscan bands, minimum CV values were obtained between 694 nm and 716 nm (CV about 20%). Both best $CI_{red\text{-}edge}$ yielded an R^2 value of

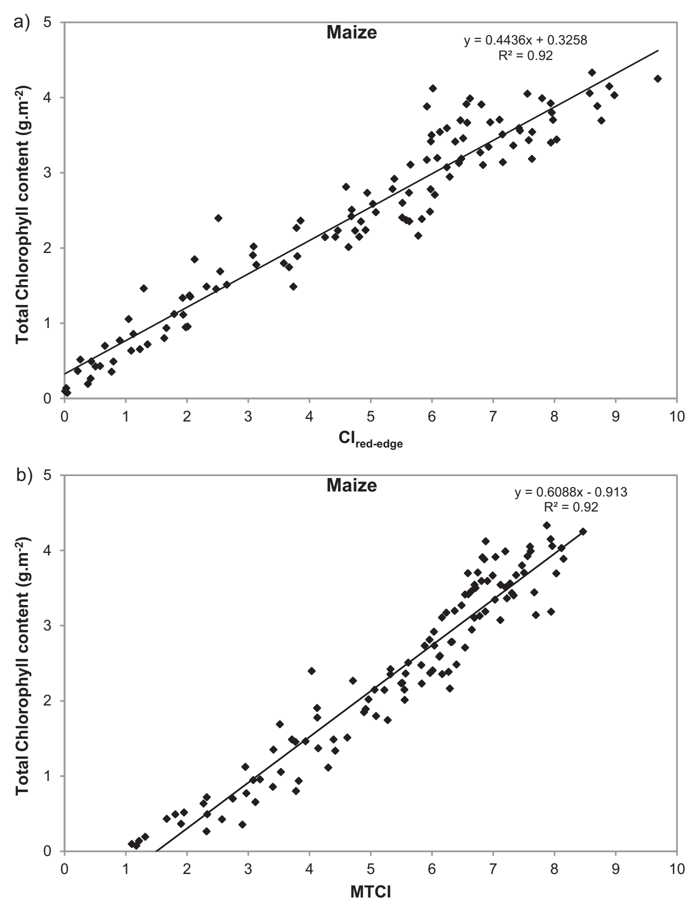

Fig. 5. Relationship between $CI_{red\text{-}edge}$ (a) or MTCI (b), based on the Sentinel-2 spectral bands, and chlorophyll content for the maize experimental data.

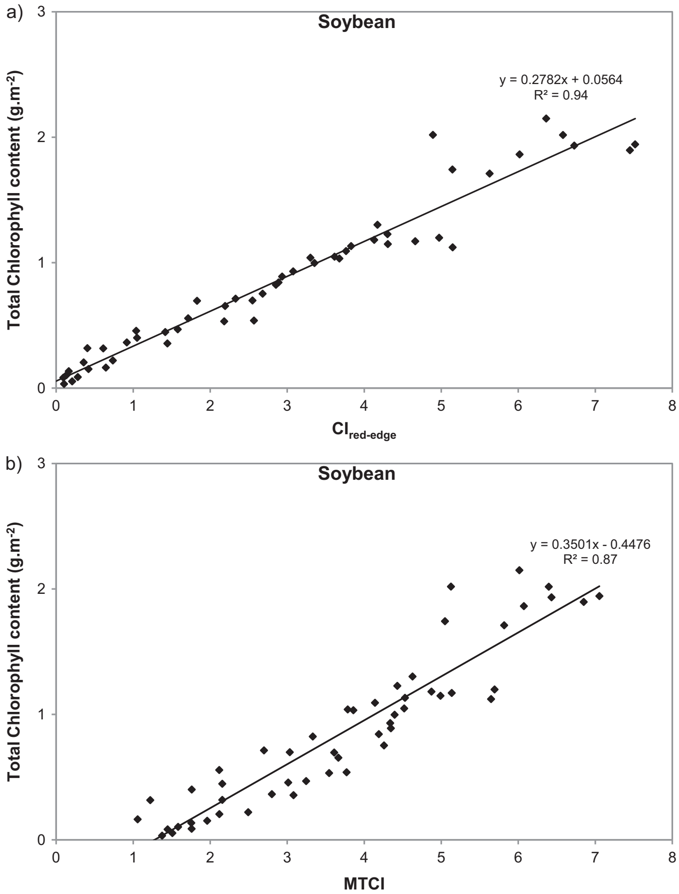

Fig. 6. Relationship between $CI_{red-edge}$ (a) or MTCI (b), based on the Sentinel-2 spectral bands, and chlorophyll content for the soybean experimental data.

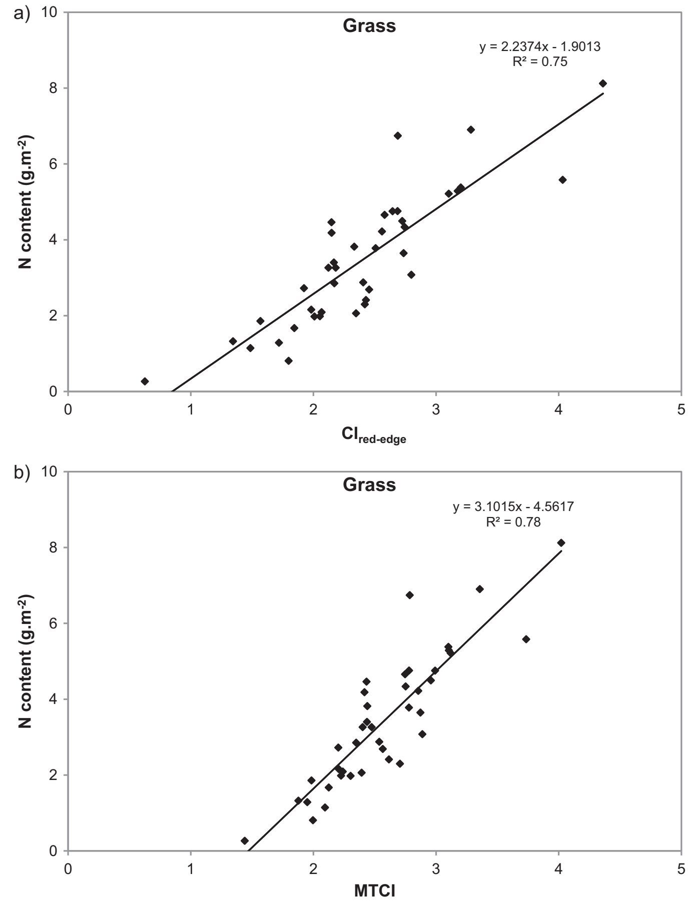

Fig. 7. Relationship between $CI_{red-edge}$ (a) or MTCI (b), based on the Sentinel-2 spectral bands, and N content for the grass experimental data.

0.89. Fig. 4 also shows that a band at 530–570 nm may be used for the CI_{green}, a result that is similar as found for the grassland and maize experiments.

In addition to using 800 nm in the numerator, also other available bands in the NIR, ranging between 780 nm and 900 nm, have been tested. Results (not shown) were not significantly different from the ones presented here.

Importantly, coefficient of variation spectra (Figs. 1–4) of three crops and grass showed a very similar shape with two distinguished minima in the green and red-edge ranges. The difference in width of CV minima between maize and soybean is due to very different crop chlorophyll content: in maize, it was twofold higher than in soybean (Gitelson et al., 2005). Thus, maximal sensitivity of $CI_{red-edge}$ to soybean chlorophyll content was obtained around 705 nm and sensitivity decreased toward longer wavelength. In maize, chlorophyll content was so high that reflectance in the range 700–715 nm (positioned 30–40 nm far from main in situ chlorophyll absorption band) was saturated. Thus, a linear relationship of chlorophyll versus $CI_{red-edge}$ was obtained at much longer wavelength than in soybean – above 720 nm.

Almost the same position of CV minimum in the red-edge as in maize was found in grass. We do not have data on grass chlorophyll content, likely it was comparable to that of maize. The much lower spectral resolution of the Cropscan did not allow defining the position of the minimum at CV spectra for potato accurately. Taking into account that potato nitrogen content was almost twice higher than in grass, the position of red-edge minimum of CV spectra was likely very close to that of maize and grass. Thus, CV of $CI_{red-edge}$ in crops and grass with high chlorophyll and nitrogen content had minimal values in the range 720–740 nm. Both shortwave and longwave red-edge bands of Sentinel-2 are off the range of optimal wavelength. In addition to a red-edge band, also a green band may be used in the chlorophyll index, called CI_{green}. For all four test sites, the performance of the best CI_{green} was worse than the performance of the best $CI_{red-edge}$ (Figs. 1–4).

3.2. Performance of VIs based on Sentinel-2 data

When calculating all mentioned indices (Table 5) using the simulated Sentinel-2 bands for the four experiments, all these indices were related in a linear way with canopy chlorophyll content (for maize and soybean) and with canopy N content (for grass and potato). Results are summarized as coefficients of determination, R^2 values, in Table 6. The first line with numbers in Table 6 offers the $CI_{red-edge}$ with optimal position of reflectance in the red-edge range (denominator of $CI_{red-edge}$ from Section 3.1). Subsequently, results for the simulated indices based on the Sentinel-2 band positions are given and they can be compared with the “optimal index”.

For the maize the $CI_{red-edge}$, CI_{green}, REP and MTCI, based on the Sentinel-2 band positions, all had a similar performance in terms of R^2 values, and they were only slightly less accurate than the optimal $CI_{red-edge} = R_{800}/R_{724} - 1$. Fig. 5a shows the relationship of total canopy chlorophyll content versus the $CI_{red-edge}$ with simulated bands of Sentinel-2. The resulting RMSE of the estimate compared to the measured values was 0.32 g m^{-2}. In testing the predictive power of the $CI_{red-edge}$ for the maize data the leave-one-out cross validation resulted in an RMSEP of 0.32 g m^{-2} too (as relative to an average measured chlorophyll content of 2.4 g m^{-2}). Since the MTCI

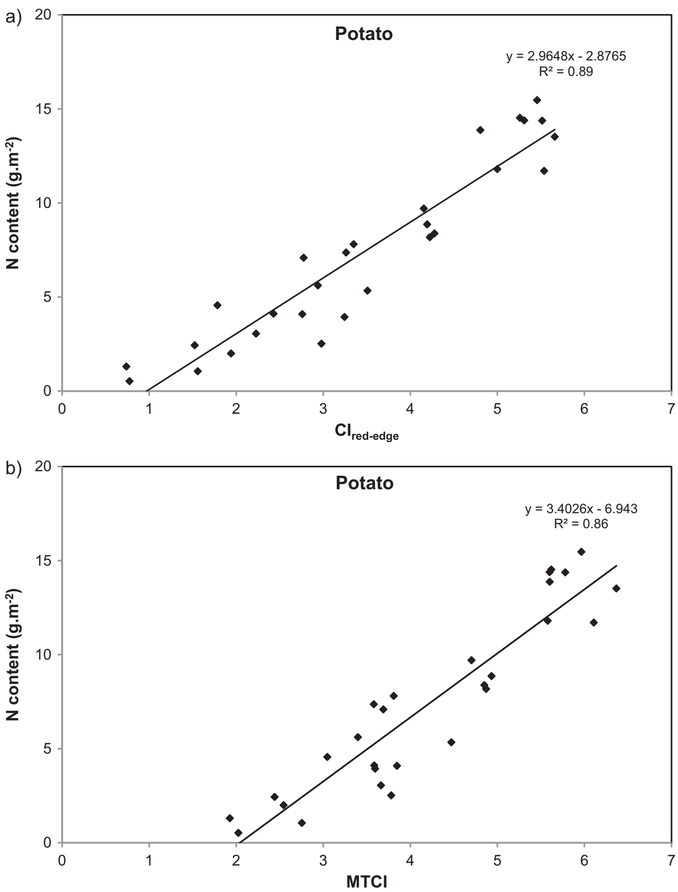

Fig. 8. Relationship between $CI_{red\text{-}edge}$ (a) or MTCI (b), based on the Sentinel-2 spectral bands, and N content for the potato experimental data.

also showed a good performance and it will be an important Level 2b product of Sentinel-3, it is also worthwhile showing its results for Sentinel-2 in this paper (Fig. 5b). Performance for the MTCI was very similar to the one for the $CI_{red\text{-}edge}$.

For the soybean experiment the $CI_{red\text{-}edge}$, CI_{green}, MTCI, MCARI/OSAVI[705,750] and the TCARI/OSAVI[705,750], based on the Sentinel-2 band positions, all had a similar performance in terms of R^2 values, and the $CI_{red\text{-}edge}$ with Sentinel simulated bands had a similar R^2 value as the optimal $CI_{red\text{-}edge} = R_{800}/R_{704} - 1$. This could be expected because the denominators are nearly equal. Fig. 6a shows the result for the $CI_{red\text{-}edge}$ simulating Sentinel-2. The resulting RMSE of the estimate compared with the input values was 0.16 g m^{-2}. The RMSEP was 0.19 g m^{-2} (as relative to an average measured chlorophyll content of 0.86 g m^{-2}). In comparison, results for the MTCI are illustrated in Fig. 6b showing a larger scatter around the regression line than for the $CI_{red\text{-}edge}$.

For the grassland the $CI_{red\text{-}edge}$, CI_{green}, REP, MTCI and TCARI/OSAVI[705,750], based on the Sentinel-2 band positions, all had a similar performance in terms of R^2 values, and they were only slightly less accurate than the optimal $CI_{red\text{-}edge} = R_{800}/R_{720} - 1$. Fig. 7a shows the result for the $CI_{red\text{-}edge}$ simulating Sentinel-2. The resulting RMSE of the estimate compared to the measured values was 0.78 g m^{-2}. In testing the predictive power of the $CI_{red\text{-}edge}$ for the grass data the RMSEP was 0.87 g m^{-2} (as relative to an average measured N content of 2.44 g m^{-2}). Fig. 7b shows the result for the MTCI, which for this test site is slightly better than the one for the $CI_{red\text{-}edge}$.

For the potato site the $CI_{red\text{-}edge}$ and CI_{green}, based on the Sentinel-2 band positions, had a similar performance. Since the optimal indices were $CI_{red\text{-}edge} = R_{780}/R_{700} - 1$ and $CI_{red\text{-}edge} = R_{780}/R_{710} - 1$ with an equal R^2 (cf. Fig. 4), the $CI_{red\text{-}edge}$ based on the Sentinel-2 band positions had the same R^2 value. This one namely is using R_{780} and the average of R_{700} and R_{710}. The relationship between this $CI_{red\text{-}edge}$ simulating Sentinel-2 and N content is shown in Fig. 8a. For this experiment, the REP, MTCI, MCARI/OSAVI[705,750] and TCARI/OSAVI[705,750] also performed well. The resulting RMSE of the estimate compared with the input values was 1.55 g m^{-2} based on the $CI_{red\text{-}edge}$. The RMSEP was 1.61 g m^{-2} (as relative to an average measured N content of 7.41 g m^{-2}). Fig. 8b gives the result for the MTCI, showing a performance not much worse than the one for the $CI_{red\text{-}edge}$.

The band settings used in calculating the indices of Table 6 are very similar for the MSI, MERIS and OLCI instruments. For example, both MERIS and MSI have a spectral band centered at 705 nm (with band width of 10 nm and 15 nm, respectively). OLCI has a band centered at 709 nm (width of 10 nm). With respect to the 780 nm band, MSI has a band at 783 nm (width of 20 nm), whereas MERIS and OLCI have a band centered at 775 nm and 779 nm, respectively (both with a width of 15 nm). Testing the different band settings of the MSI, MERIS and OLCI sensors in the used indices did not yield significantly different results from the ones given in Table 6.

4. Conclusions

This paper presents the significance of the red-edge bands of the MSI sensor on Sentinel-2 for estimating chlorophyll and N contents in crops and grasslands. These narrow MSI spectral bands (15 nm width) are centered at 705 nm and 740 nm, and they have good potential for retrieving canopy chlorophyll and N content. In combination with the high spatial resolution (20 m) and short revisit time (about weekly due to a constellation of two identical satellites), it offers improved applications in fields like precision farming. Similar band positions have been applied for the MERIS sensor on board of ESA's Envisat satellite (which stopped operation early 2012) and will be available on the upcoming OLCI sensor on the Sentinel-3 satellite constellation. However, both MERIS and OLCI combine a worse spatial resolution (300 m) with a better spectral resolution (about 10 nm), making it applicable at other spatial scales than Sentinel-2 data.

In a previous study, it has been shown that the $CI_{red\text{-}edge}$ is one of the best indices for estimating canopy chlorophyll or N content (Clevers and Kooistra, 2012) and that the precise position of the spectral bands in the $CI_{red\text{-}edge}$ is not very critical. In this study, this was further elaborated by studying the spectral bands to be used in the $CI_{red\text{-}edge}$ in order to get the minimum RMSE (or CV) in estimating canopy chlorophyll or N content for three crop species and grasslands. Although results varied for the various experiments, optimal results were obtained using a spectral band around 800 nm in the numerator of the $CI_{red\text{-}edge}$ and a spectral band in the range 705–740 nm in the denominator. The choice of the denominator waveband was more critical than the choice of the numerator. For maize and grass (erectophile canopies) this was in a wide range of 720–740 nm as band for the denominator, whereas for soybean and potato (planophile canopies) this band was around 705–710 nm.

Subsequently, the Sentinel-2 spectral bands have been simulated using the data of the four experiments, and the $CI_{red\text{-}edge}$, CI_{green}, REP, MTCI, MCARI/OSAVI[705,750], TCARI/OSAVI[705,750], NDRE1 and NDRE2 (cf. Table 5) were calculated. The NDVI-type of indices (NDRE1 and NDRE2) were the worst for all test sites in this study. The MCARI/OSAVI[705,750] and TCARI/OSAVI[705,750] performed well for the soybean test site, but less for the other test sites. The REP index on the other hand performed less for the soybean experiment and well for the other three experiments. Considering all four experiments, best results in estimating canopy chlorophyll and N content were obtained for the $CI_{red\text{-}edge}$, CI_{green}

and MTCI. Moreover, results using the Sentinel-2 band positions were quite similar to the optimal band positions for the $CI_{red\text{-}edge}$. This confirms the importance of the red-edge bands on Sentinel-2. However, using the green band in the CI_{green} also seems very promising and requires further research.

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