USING THE RED-EDGE BANDS ON SENTINEL-2 FOR RETRIEVING CANOPY CHLOROPHYLL AND NITROGEN CONTENT

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ABSTRACT

Sentinel-2 is planned for launch in 2013 and it is equipped with the Multi Spectral Instrument (MSI), which will provide images with high spatial, spectral and temporal resolution. It incorporates two new spectral bands in the red-edge region, which can be used to derive red-edge type of vegetation indices. These are particularly suitable for deriving estimates of canopy chlorophyll and nitrogen (N) content. In this paper, the potential of Sentinel-2 in estimating canopy chlorophyll and N content is evaluated by studying data obtained for a number of different test sites. In particular, the red-edge chlorophyll index was found to be an accurate and linear estimator of canopy chlorophyll and N content and the Sentinel-2 bands are well positioned for deriving this index. Results stress the importance of the red-edge bands on Sentinel-2 for agricultural applications.

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 centres 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 (e.g., [1-5]). Actual N and/or chlorophyll estimates are important for applications ranging from precision agriculture to the global carbon cycle.

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 have not yet been developed 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) programme. For land applications using the solar reflective domain, in particular two systems are relevant. Sentinel-2 (equipped with the Multi Spectral Instrument MSI) will provide images with high spatial, spectral and temporal resolution and it aims at ensuring continuity of Landsat and SPOT observations. In addition, it incorporates two new spectral bands in the so-called red-edge region, which are very important for retrieval of chlorophyll content [6]. 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 MERIS on Envisat, and, thus, will provide data continuity of MERIS. Since it also has red-edge bands, it can be used for the retrieval of chlorophyll content, albeit at a different scale level as Sentinel-2 [7]. 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.

To estimate chlorophyll content the red-edge region is highly significant [8, 9]. Recently, the significance of the red-edge bands on Sentinel-2 for estimating LAI and chlorophyll content has been shown through simulation studies [6, 10]. In this paper, we will further elaborate on the potential of Sentinel-2 for retrieving 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 [9]. 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 a quick saturation of the signal. 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 is sensitive to chlorophyll absorption at its moderate-to-high values [11]. Horler et al. were

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amongst the first to show the importance of the position of the red-edge inflection point for detecting plant stress [12]. 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 [13]. Another type of index based on the MERIS red-edge bands is the MERIS terrestrial chlorophyll index, MTCI [14].

Wu et al. also stressed the importance of the red-edge bands [15]. They suggested to replace the red and NIR spectral bands in the MCARI/OSAVI [16] and TCARI/OSAVI [17] by bands at 705 nm and 750 nm, respectively. Indeed these adapted indices showed better linearity with canopy chlorophyll and N content [9]. We will quote these indices as MCARI/OSAVI[705,750] and TCARI/OSAVI[705,750].

It has been shown in various studies that simple ratio indices or normalized difference indices using red-edge bands perform very well in estimating chlorophyll or N content. Gitelson [18, 19] presented a simple 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 ($CI_{red-edge} = R_{800}/R_{710} - 1$). 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.

Normalized difference indices using the red-edge bands mostly are called “normalized difference red-edge” (NDRE or red-edge NDVI). A version 1 using 740 nm and 705 nm [20, 21] is presented in literature, whereas also a version 2 using 780 nm and 705 nm [22] can be found. Sometimes, also deviating names are used in literature.

In a previous study, we obtained best results for the ratio indices $CI_{red-edge}$ and CI_{green} in estimating either canopy chlorophyll or N content [9]. We will first study which band setting is best for the $CI_{red-edge}$, since many variants have been used in literature. Subsequently, we will compare this with using the band setting of Sentinel-2. 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.

2. MATERIAL AND METHODS

2.1. Sentinel-2

ESA is planning to launch the first Sentinel-2 polar-orbiting satellite in 2013. 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 [23]. 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 centred at 705 and 740 nm at a band width of 15 nm and a spatial resolution of 20 m (Tab. 1).

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

Spectral band	Centre 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	1375	30	60
B11	1610	90	20
B12	2190	180	20

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 a maize data set and a soybean data set collected at the research facilities of the University of Nebraska-Lincoln [24]. Data were collected in the 2001 through 2003 growing seasons. Leaf chlorophyll content was measured analytically and also using leaf reflectance applying a leaf clip with an Ocean Optics USB2000 spectroradiometer in the laboratory [18]. Relationship between leaf chlorophyll content and $CI_{red-edge}$ was calibrated two-three times per growing season and then used for retrieval of leaf chlorophyll content from measured reflectance spectra [18]. Leaf area index was determined destructively by harvesting leaves [25]. Canopy spectral reflectance measurements were carried out by using a dual-fiber system with two intercalibrated Ocean Optics USB2000 radiometers, mounted on an all-terrain platform. Reflectance measurements were obtained in the range 400 – 900 nm with a spectral sampling interval of 10 nm. Sentinel-2 bands were simulated by selecting the best matching spectral bands of the Ocean Optics instrument. For the Sentinel-2 band at 783 nm the Ocean Optics band at 780 nm was used. The 705 nm band was simulated by averaging the 700 nm and 710 nm band of the Ocean Optics. Similarly the 665 n m band of Sentinel-2 was simulated by averaging the 660 nm and 670 nm band.

The third data set is a grassland site where in 2008 40 plots were destructively sampled [9]. In addition to fresh and dry weight, leaf N content was determined using the Kjeldahl method. Before harvesting the plots the spectral reflectance was measured with an ASD FieldSpec 3 spectroradiometer with a 1 nm sampling interval. Sensinel-2 bands were simulated by calculating the average reflectance over the band width of the respective Sentinel-2 bands. For instance, the average reflectance over the 698 nm – 712 nm interval was used to simulate the 705 nm Sentinel-2 band. Similarly, the 773 nm – 793 nm interval was used to simulate the 783 nm band.

The fourth data set was obtained from a field experiment conducted at a potato field in 2010 [9]. 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. 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 (Tab. 2). In this study, the observations of potential "luxury" N consumption, identified before [9], were omitted. The Cropscan bands located close to the Sentinel-2 bands (Tab. 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.

Table 2. Specifications of the Cropscan MSR16R system.

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

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. All are mainly based on red-edge bands and definitions using the Sentinel-2 spectral bands are provided in Tab. 3.

The relationship of both $CI_{red\text{-}edge}$ and CI_{green} with chlorophyll content runs through the origin [18, 19], meaning that the actual ratio of R_{783}/R_{705} or R_{783}/R_{560} for bare soil should be used in the respective equations for these two indices in Tab. 3 instead of the value "1", which assumes a co nstant soil spectral reflectance. Actual values for the slope of the soil lines at the individual test sites have been used.

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 combinations. This CV is calculated as the ratio of the root-mean-square-error of content estimation using a l inear regression and the average content value. Since the reference band in the nominator is not that critical, 800 nm has been used initially as suggested in Gitelson et al. [24]. Subsequently, a few other reference bands have been tested (like 780 nm and 820 nm). In the denominator all available bands between 500 nm and 800 nm have been tested.

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.

3. RESULTS AND DISCUSSION

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

By taking a band at 800 nm in the nominator and varying the band in the denominator between 500 n m and 800 nm, the optimal ratio index could be obtained. Results for the coefficient of variation, CV (%), in the maize experiment are shown in Fig. 1. Since the Ocean Optics instrument has a sampling interval of 10 nm, the indices have been calculated at steps of 10 nm. The best result is obtained for 720 nm (meaning ratio R_{800}/R_{720} as index), but using 720 nm or 730 nm in the $CI_{red\text{-}edge}$ also provides good results. The R_{800}/R_{720} index yields a coefficient of determination, R^2, of 0.94. In addition, it can be concluded from Fig. 1 that the CI_{green} also yields good results. As a green band, a band in the 530 – 570 nm interval may be used. Similarly, Fig. 2 provides the results of the soybean experiment. Here the best result is obtained for 700 nm (index R_{800}/R_{700} with an R^2 also of 0.94), but 710 n m also provides good results. In the green part of the spectrum, a band in the 580 – 610 nm interval provides best results, but the red-edge bands perform better.

Table 3. Vegetation indices evaluated in this study.

Index	Formulation	Reference
$CI_{red\ edge}$	$(R_{783}/R_{705})-1$	[18, 19]
CI_{green}	$(R_{783}/R_{560})-1$	[18, 19]
REP	$705+35\frac{(R_{665}+R_{783})/2-R_{705}}{R_{740}-R_{705}}$	[13]
MTCI	$(R_{740}-R_{705})/(R_{705}-R_{665})$	[14]
MCARI/OSAVI[705,750]	$\frac{[(R_{740}-R_{705})-0.2(R_{740}-R_{560})](R_{740}/R_{705})}{(1+0.16)\,(R_{740}-R_{705})/(R_{740}+R_{705}+0.16)}$	[15]
TCARI/OSAVI[705,750]	$\frac{3[(R_{740}-R_{705})-0.2(R_{740}-R_{560})(R_{740}/R_{705})]}{(1+0.16)\,(R_{740}-R_{705})/(R_{740}+R_{705}+0.16)}$	[15]
NDRE1	$(R_{740}-R_{705})/(R_{740}+R_{705})$	[20, 21]
NDRE2	$(R_{783}-R_{705})/(R_{783}+R_{705})$	[22]

R_λ refers to the reflectance factor at wavelength λ nm.

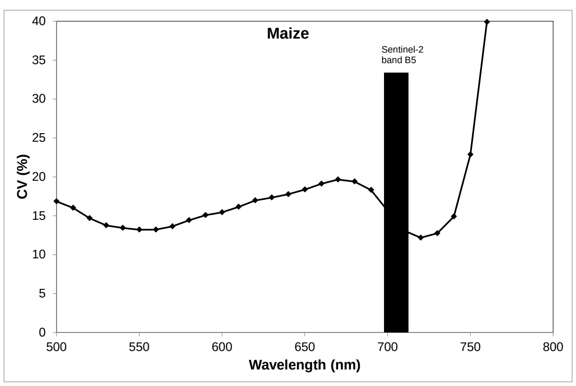

Figure 1. Coefficient of variation (%) of canopy chlorophyll content estimation for maize by the R_{800}/R_{xxx} index, with R_{xxx} as the reflectance of a spectral band in the 500 – 800 nm interval.

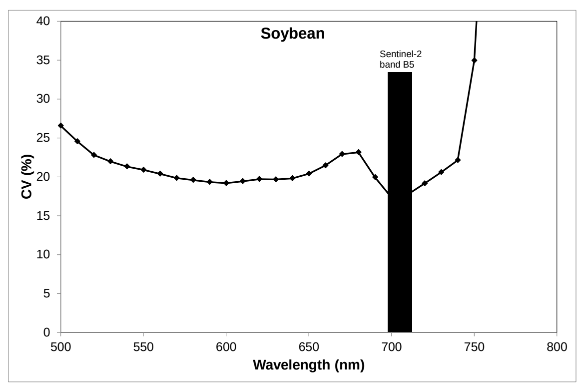

Figure 2. Coefficient of variation (%) of canopy chlorophyll content estimation for soybean by the R_{800}/R_{xxx} index, with R_{xxx} as the reflectance of a spectral band in the 500 – 800 nm interval.

In the grassland experiment, an ASD FieldSpec Pro has been used with a 1 nm sampling interval. Results for the CV using 800 nm as a reference band are shown in Fig. 3. The best result is obtained for 720 nm (meaning the ratio R_{800}/R_{720}), but using a wavelength in the interval 705 – 735 nm also provides good results. Using the above-mentioned best $CI_{red-edge}$ index yields an R^2 value of 0.80. Fig. 3 also shows that we may use a band in the 530 – 570 nm interval for the CI_{green}. Again, the $CI_{red-edge}$ performs better.

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 are shown in Fig. 4. The best result is obtained for 700 nm and 710

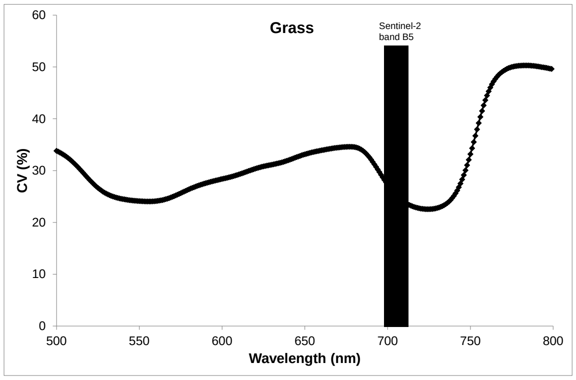

Figure 3. Coefficient of variation (%) of canopy N content estimation for grass by the R_{800}/R_{xxx} index, with R_{xxx} as the reflectance of a spectral band in the 500 – 800 nm interval.

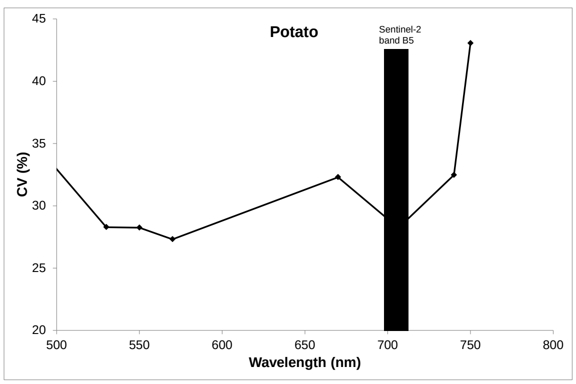

Figure 4. Coefficient of variation (%) of canopy N content estimation for potatoes by the R_{780}/R_{xxx} index, with R_{xxx} as the reflectance of a spectral band in the 500 – 800 nm interval.

nm, meaning ratios of R_{780}/R_{700} and R_{780}/R_{710}. Using the above-mentioned best $CI_{red\text{-}edge}$ indices both yield an R^2 value of 0.89. Fig. 4 also shows that we again may use a band in the 530 – 570 nm interval for the CI_{green}, a result that is similar as found for the grassland, soybean, and maize experiments.

In addition to using 800 nm in the nominator, also a few other bands in the NIR have been tested as denominator, like 780 nm and 820 nm. Results are not significantly different from the ones presented here.

3.2. Performance of VIs based on Sentinel-2 data

When calculating all mentioned indices (Tab. 3) using the simulated Sentinel-2 bands for the four experiments, we can relate these indices in a linear way with canopy chlorophyll content (for maize and soybean) or with canopy N content (for grass and potato). Results are summarized as coefficients of determination, R^2 values, in Tab. 4. The first line with numbers in Tab. 4 offers the 'best' $CI_{red\text{-}edge}$ from section 3.1. Subsequently, results for the indices based on the Sentinel-2 band positions are given and they can be compared with the 'best' index.

For the maize the $CI_{red\text{-}edge}$, CI_{green}, REP and MTCI, based on the Sentinel-2 band positions, all have a similar performance in terms of R^2 values, and they are only slightly worse than the best $CI_{red\text{-}edge}$ index using the R_{800}/R_{720} ratio. Fig. 5 shows the result for the $CI_{red\text{-}edge}$ simulating Sentinel-2.

For the soybean experiment the $CI_{red\text{-}edge}$, CI_{green}, MCARI/OSAVI[705,750] and the TCARI/OSAVI[705, 750], based on the Sentinel-2 band positions, all have a similar performance in terms of R^2 values, and the $CI_{red\text{-}edge}$ has a similar R^2 value as the best $CI_{red\text{-}edge}$ index using the R_{800}/R_{700} ratio. This could be expected because the denominators are nearly equal. Fig. 6 shows the result for the $CI_{red\text{-}edge}$ simulating Sentinel-2.

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 have a similar performance in terms of R^2 values, and they are only slightly worse than the best $CI_{red\text{-}edge}$ index using the R_{800}/R_{720} ratio. The MTCI has a similar performance, whereas the $CI_{red\text{-}edge}$ is slightly worse. Fig. 7 shows the result for the $CI_{red\text{-}edge}$ simulating Sentinel-2.

For the potato site the $CI_{red\text{-}edge}$ and CI_{green}, based on the Sentinel-2 band positions, have a similar performance. Since the best indices were R_{780}/R_{700} and R_{780}/R_{710} with an equal R^2 (cf. Fig. 4), the $CI_{red\text{-}edge}$ based on the Sentinel-2 band positions has 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. 8. For this experiment, the REP, MTCI, MCARI/OSAVI[705,750] and TCARI/OSAVI[705, 750] also performed well.

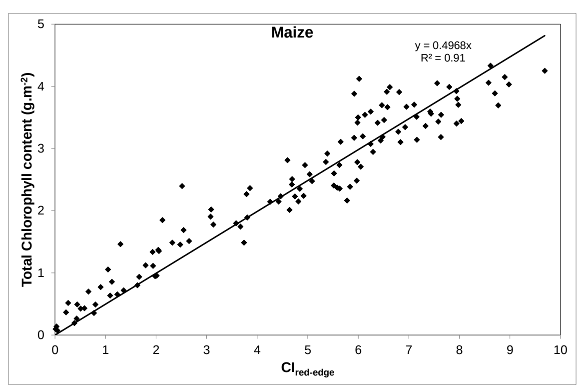

Figure 5. Relationship between $CI_{red\text{-}edge}$, based on the Sentinel-2 spectral bands, and chlorophyll content for the maize experimental data.

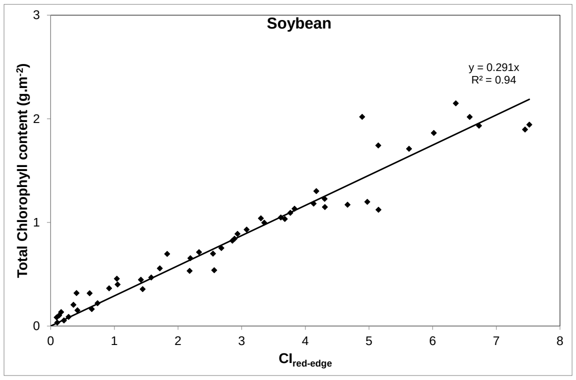

Figure 6. Relationship between $CI_{red\text{-}edge}$, based on the Sentinel-2 spectral bands, and chlorophyll content for the soybean experimental data.

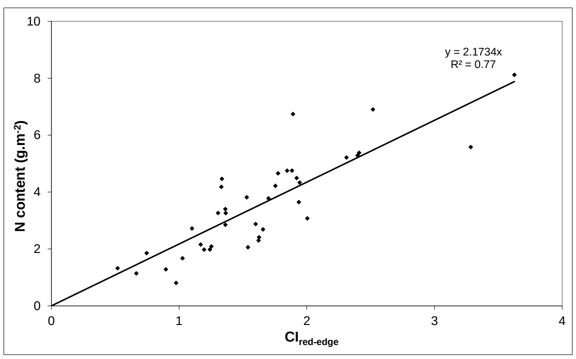

Figure 7. Relationship between $CI_{red\text{-}edge}$, based on the Sentinel-2 spectral bands, and N content for the grass experimental data.

4. CONCLUSIONS

This paper studies the significance of the so-called red-edge bands on Sentinel-2. These narrow Sentinel-2 spectral bands are located 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.

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 [9] 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 in estimating canopy chlorophyll or N content for four experiments. Although results varied for the various experiments, optimal results were obtained using a spectral band around 800 nm in the nominator of the $CI_{red\text{-}edge}$ and a spectral band in the range 700 nm – 720 nm in the denominator. The choice of the denominator waveband was more critical than the choice of the nominator. For maize and grass (erectophile canopies) this was around 720 nm as band for the denominator, whereas for soybean and potato (planophile canopies) this band was around 700 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 3) were calculated. Best results in estimating canopy chlorophyll and N content were obtained for the $CI_{red\text{-}edge}$. Moreover, results using the Sentinel-2 band positions were similar to the optimal band positions for the $CI_{red\text{-}edge}$. This confirms the importance of the red-edge bands on Sentinel-2.

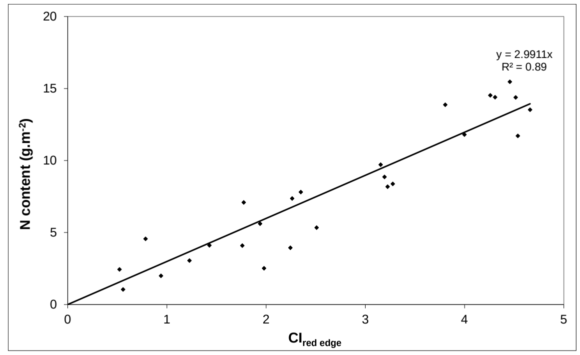

Figure 8. Relationship between $CI_{red\text{-}edge}$, based on the Sentinel-2 spectral bands, and N content for the potato experimental data.

Table 4. 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 $CI_{\mathbf{red\text{-}edge}}$ from §3.1	0.94	0.94	0.80	0.89
$CI_{red\ edge}$	0.92	0.94	0.77	0.89
CI_{green}	0.93	0.92	0.77	0.88
REP	0.92	0.70	0.79	0.85
MTCI	0.92	0.87	0.80	0.86
MCARI/OSAVI[705,750]	0.86	0.92	0.57	0.83
TCARI/OSAVI[705,750]	0.85	0.91	0.75	0.85
NDRE1	0.83	0.81	0.63	0.71
NDRE2	0.83	0.81	0.67	0.73

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