RETRIEVING CANOPY CHLOROPHYLL CONTENT OF POTATO CROPS USING SENTINEL-2 BANDS

J.G.P.W. Clevers [(1)], L. Kooistra [(1)]

[(1)] *Laboratory of Geo-Information Science and Remote Sensing, Wageningen University, P.O. Box 47, 6700 AA Wageningen, the Netherlands, Email: jan.clevers@wur.nl*

ABSTRACT

In this paper the potential of Sentinel-2 for estimating canopy chlorophyll content is evaluated. First, the PROSAIL radiative transfer model was used to study the relationship between reflectance and canopy chlorophyll content. Subsequently, relationships were tested for potato crops by studying in-situ crop variables and radiometer measurements obtained for three different growing seasons (2010 – 2012). Finally, results were evaluated using spaceborne RapidEye and WorldView-2 images obtained in the 2010 growing season for the potato field studied. Results show that the optimal wavelength position for the denominator in the red-edge chlorophyll index ($CI_{red\text{-}edge}$) is between 695 nm and 725 nm. The red-edge band of Sentinel-2 at 705 nm is optimally located. In addition to the $CI_{red\text{-}edge}$, the green chlorophyll index (CI_{green}) had a similar performance in estimating canopy chlorophyll content. Finally, these results were confirmed using a WorldView-2 image acquired June 2010.

1. INTRODUCTION

Sentinel-2 is planned for launch in 2014 by the European Space Agency. 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 centred at 705 and 740 nm, which can be used to derive vegetation indices using red-edge bands. These are particularly suitable for estimating vegetation chlorophyll content, which is a key parameter for understanding plant functioning and status. The band setting in this region is also 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 until early 2012. In this paper, we will further elaborate on the potential of Sentinel-2 for retrieving canopy chlorophyll 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 content [1]. In particular, the red-edge region has often been used for estimating chlorophyll 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 [2]. Horler et al. [3] were amongst the first to show the importance of the position of the red-edge inflection point for detecting plant stress. 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 [4]. Another type of index based on the MERIS red-edge bands is the MERIS terrestrial chlorophyll index, MTCI [5].

Wu et al. also stressed the importance of the red-edge bands [6]. They suggested to replace the red and NIR spectral bands in the MCARI/OSAVI [7] and TCARI/OSAVI [8] by bands at 705 nm and 750 nm, respectively. Indeed these adapted indices showed better linearity with canopy chlorophyll content [1]. 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 or normalized difference indices using red-edge bands perform very well in estimating chlorophyll content. Gitelson [9, 10] 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.

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 [11, 12] is presented in literature, whereas also a version 2 using 790 nm and 720 nm [13] can be found. Sometimes, also deviating names are used in literature.

Proc. ‘ESA Living Planet Symposium 2013’, Edinburgh, UK
9–13 September 2013 (ESA SP-722, December 2013)

In a previous study, we obtained best results for the ratio indices $CI_{red\text{-}edge}$ and CI_{green} in estimating either canopy chlorophyll or N content [1]. 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. 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 using potato crops for this analysis.

2. MATERIAL AND METHODS

2.1. Sentinel-2 system

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 [14]. 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. PROSAIL radiative transfer model

First, the optimal band setting for the $CI_{red\text{-}edge}$ will be studied from simulated spectra using the PROSAIL radiative transfer (RT) model. PROSAIL is a combination of the PROSPECT leaf RT model [15] and the SAIL canopy RT model [16], which has been used extensively over the past few years for a variety of applications [17]. At the leaf level, PROSAIL is using leaf chlorophyll concentration (C_{ab}), equivalent leaf water thickness (EWT), leaf structure parameter (N) and leaf dry matter (C_m) as inputs. At the canopy level, input parameters are LAI, leaf angle distribution (LAD), soil brightness, ratio diffuse/direct irradiation, solar zenith angle, view zenith angle and sun-view azimuth angle. It also includes a parameter describing the hot-spot effect [18]. Recently, version 5 of PROSPECT has been released, simulating leaf reflectance and transmittance at a 1 nm spectral sampling interval and using updated values for the specific absorption coefficients of leaf constituents [19]. The inputs for the PROSAIL simulations were varied according to the values given in Tab. 2. Subsequently, 5% of Gaussian noise has been added to all simulated reflectances in order to better mimic realistic spectra.

Table 2. Nominal values and range of parameters used for the canopy simulations with the PROSAIL model.

PROSAIL parameters	Nominal values
Chlorophyll concentration (C_{ab})	10 / 20 / 30 / 40 / 50 / 60 / 70 /80 μg.cm^{-2}
Leaf area index	0.5/ 1.0 / 1.5 / 2 / 3 / 4 / 5 / 6
Equivalent water thickness	0.0137 g.cm^{-2}
Leaf dry matter	0.005 / 0.010 g.cm^{-2}
Leaf structure parameter	1.0 / 1.8 / 2.5
Leaf angle distribution	Spherical / Planophile / Erectophile
Hot-spot parameter	0.05 / 0.10
Soil reflectance	0.0 / 0.1 / 0.2
Diffuse/direct radiation	0
Solar zenith angle	30° / 45° / 60°
View zenith angle	0°
Sun-view azimuth angle	0°

2.3. Potato study sites

Three data sets were obtained from field experiments conducted at different potato fields in 2010, 2011 and 2012, respectively, located in the South of the Netherlands. In 2010, 10 plots were prepared with five levels of nitrogen (N) fertilization (0, 190, 290, 320 and 390 kg N/ha) in two replicates [1]. Plots were 30 by 30 m. The field used in the 2011 growing season consisted of 12 experimental plots. Each plot was 30 by 30 m in size and received four levels of initial N fertilizer (0, 161, 242 and 322 kg N/ha). In addition, three types of treatment have been applied over the growing period based on the recommendations from sensor readings. The field used in the 2012 growing season consisted of 8 experimental plots where 2 plots were 13 m by 30 m and the rest of the plots were 30 by 30 m. The 2012 experimental plots involved four levels of only initial N fertilization (0, 43, 117 and 218 kg N/ha) in the form of liquid organic fertilizer and organic fertilizer from stable manure.

Leaf area index (LAI) was collected weekly using a Plant Canopy Analyser (LAI-2000, LI-COR, Lincoln, NE). Leaf chlorophyll concentration was measured using a handheld chlorophyll meter (SPAD-502, Minolta Osaka Company Ltd., Japan), by clamping the instrument on randomly selected leaves from the top of the plant. Each reading per plant was the averaged result of three leaf chlorophyll readings. Per plot six LAI and chlorophyll estimates per row for four rows (24 values per plot) were taken biweekly. SPAD measurements during the growing season were converted to leaf C_{ab} (g.m^{-2}) using the model suggested by [20], which is used specifically for potatoes. The product of leaf chlorophyll concentration and LAI yielded the canopy chlorophyll content used in this study.

2.4. Field radiometry

The study sites were measured biweekly with a Cropscan Multispectral Radiometer (MSR16R). This is a 16-band radiometer measuring simultaneously reflected and incoming radiation in narrow spectral bands (Tab. 3). 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.

2.5. Vegetation indices

In this study the performance of the REP, MTCI, MCARI/OSAVI[705,750], TCARI/OSAVI[705,750], $CI_{red\text{-}edge}$, CI_{green}, NDRE1 and NDRE2 for the estimation of canopy chlorophyll content has been evaluated. All are mainly based on red-edge bands and definitions using the Sentinel-2 spectral bands are provided in Tab. 4.

Table 3. 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

Testing the optimal band setting in using the $CI_{red\text{-}edge}$ for estimating canopy chlorophyll content has been performed by comparing coefficients of variation (CV%) for all combinations. Since the reference band in the numerator is not that critical, 800 nm has been used initially as suggested in [21]. 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.

Table 4. Vegetation indices based on the Sentinel-2 spectral band settings evaluated in this study.

Index	Formulation	Reference
$CI_{red\text{-}edge}$	$(R_{783}/R_{705})-1$	[9, 10]
CI_{green}	$(R_{783}/R_{560})-1$	[9, 10]
REP	$705+35\dfrac{(R_{665}+R_{783})/2-R_{705}}{R_{740}-R_{705}}$	[4]
MTCI	$(R_{740}-R_{705})/(R_{705}-R_{665})$	[5]
MCARI/OSAVI[705,750]	$\dfrac{[(R_{740}-R_{705})-0.2(R_{740}-R_{560})](R_{740}/R_{705})}{(1+0.16)\,(R_{740}-R_{705})/(R_{740}+R_{705}+0.16)}$	[6]
TCARI/OSAVI[705,750]	$\dfrac{3[(R_{740}-R_{705})-0.2(R_{740}-R_{560})(R_{740}/R_{705})]}{(1+0.16)\,(R_{740}-R_{705})/(R_{740}+R_{705}+0.16)}$	[6]
NDRE1	$(R_{740}-R_{705})/(R_{740}+R_{705})$	[11, 12]
NDRE2	$(R_{783}-R_{705})/(R_{783}+R_{705})$	[13]

R_{λ} refers to the reflectance factor at wavelength λ 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.

2.6. Other satellite data

Currently, the only satellite systems with spectral bands in the red-edge region are MERIS (shut down), Hyperion, CHRIS/PROBA, WorldView-2 and RapidEye. Only RapidEye and WorldView-2 are operational satellites with a spatial resolution useful for precision farming applications and having a red-edge band.

DigitalGlobe has launched WorldView-2 (WV2) in October 2009. It has a 46 cm panchromatic band and 8 multispectral bands at 1.84 m (Tab. 5). The orbit has an altitude of 770 km and a swath width of 15 km. The revisit time is about 3 days depending on latitude. For this study two recordings are available, one from 3 June 2010 and one from 22 June 2010. As a result, only the 2010 potato experiment can be used for this analysis. Field measurements obtained 11 June and 23 June, respectively, are available for the analysis. Digital numbers have been converted to top-of-canopy reflectances by applying a radiometric and an atmospheric correction. For the atmospheric correction the solar spectral irradiance and actual solar zenith angle were taken into account. In addition, a darkest pixel correction was applied.

WV2 does not have a red-edge band close to one of the Sentinel-2 bands. The centre wavelength of the red-edge band of WV2 is at 725 nm. This band was used for calculating the $CI_{red\text{-}edge}$, MCARI/OSAVI, TCARI/OSAVI and NDRE indices. For the MCARI/OSAVI and TCARI/OSAVI no specific red-edge version could be calculated, but band 5 and 6 in addition to band 3 and 7 were used. In addition, CI_{green} was calculated. WV2 does not have sufficient bands to calculate the REP and MTCI.

Table 5. Specifications of the WorldView-2 spectral bands.

Band	Wavelength interval (nm)
1	400 – 450
2	450 – 510
3	510 – 580
4	585 – 625
5	630 – 690
6	705 – 745
7	770 – 895
8	860 – 1040
Panchromatic	400 – 900

The RapidEye constellation of five satellites can acquire high-resolution, large-area image data on a daily basis. The five satellites have been launched in 2008. Data are provided with a pixel size of 5 m and a swath width of 77 km. Spectral specifications are given in Tab. 6. For this study only one image from 5 June 2010 is available. Digital numbers have been converted to top-of-canopy reflectances by applying a similar radiometric and atmospheric correction as described for the WorldView-2 data. RapidEye has a red-edge band centred at 710 nm, which is very close to band B5 of Sentinel-2. Basically, the same indices were calculated as for WV2, although band 3 and 4 in addition to band 2 and 5 were used. Major difference is the location of the red-edge band, which is at 710 nm for RapidEye and at 725 nm for WV2.

Table 6. Specifications of the RapidEye spectral bands.

Band	Wavelength interval (µm)
1	440 – 510
2	520 – 590
3	630 – 685
4	690 – 730
5	760 – 850

3. RESULTS AND DISCUSSION

3.1. Optimal red-edge band selection

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 chlorophyll index (CI) could be obtained. Results for the coefficient of variation (CV%) for the dataset simulated with PROSAIL are shown in Fig. 1. Results show that the optimal wavelength position for the denominator in the $CI_{red\text{-}edge}$ is between 695 nm and 710 nm, whereas an extension of the upper limit to 725 nm still seems acceptable. The red-edge bands of Sentinel-2 and RapidEye are optimally located according to this result, whereas the red-edge band of WV2 is located sub-optimally. Fig. 1 also indicates that the CI_{green} yields similar accuracies, whereby a denominator in the interval between 500 nm and 640 nm seems useful. Results also confirm that the use of red reflectance is less suitable in such an index due to the saturation effects with increasing chlorophyll content. Beyond 740 nm the index loses sensitivity to chlorophyll content.

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.

For the potato plots in the 2010, 2011 and 2012 growing seasons the Cropscan radiometer has been used for determining the optimal CI. The Cropscan has more

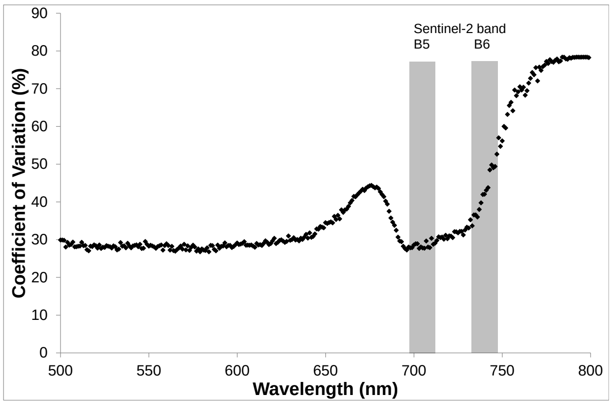

Figure 1. Coefficient of variation (%) of canopy chlorophyll content estimation for PROSAIL simulated data by the R_{800}/R_{xxx} index, with R_{xxx} as the reflectance of a spectral band in the 500 – 800 nm interval.

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. 2 for all three growing seasons. The best result was obtained for bands centered at 710 nm, meaning $CI_{red\text{-}edge} = R_{780}/R_{710} - 1$. Taking into account the width of Cropscan bands, minimum CV values were obtained between 694 and 716 nm. The best $CI_{red\text{-}edge}$ yielded an R^2 value of 0.89, 0.88 and 0.76 for the years 2010, 2011 and 2012, respectively. Crop growth in the 2012 growing season was worse than those in the other two years, yielding lower biomass levels and yields. As a result, the CV% was rather high. Fig. 2 also shows that a band at 530 – 570 nm may be used for the CI_{green}. These results for the potato experiments are similar to those obtained for the PROSAIL simulated dataset.

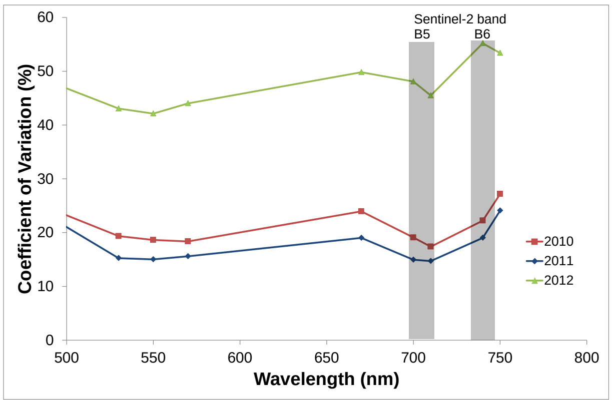

Figure 2. Coefficient of variation (%) of canopy chlorophyll content estimation for potatoes in 2010, 2011 and 2012 by the R_{780}/R_{xxx} index, with R_{xxx} as the reflectance of a spectral band in the 500 – 800 nm interval.

3.2. Performance of VIs based on simulated S2 data

When calculating all mentioned indices (Tab. 4) using the simulated Sentinel-2 bands for the three potato experiments, all these indices were related in a linear way with canopy chlorophyll content. Results are summarized as coefficients of determination, R^2 values, in Tab. 7. The first line with numbers in Tab. 7 offers the $CI_{red\text{-}edge}$ with optimal position of reflectance in the red-edge range (denominator of $CI_{red\text{-}edge}$ at 710 nm 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 potato experiments the $CI_{red\text{-}edge}$ and CI_{green}, based on the Sentinel-2 band positions, had a similar performance almost equal to the 'optimal index' using 710 nm as red-edge band. The calculated $CI_{red\text{-}edge}$ based on the Sentinel-2 band positions 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 canopy chlorophyll content for potatoes in the three years is shown in Fig. 3. 2012 shows a slightly deviating relationship, which can be explained by use of a different cultivar, different field and particularly different growing conditions yielding lower canopy chlorophyll contents than in 2010 and 2011. The other indices also performed well in comparison to the $CI_{red\text{-}edge}$ for most situations, but overall $CI_{red\text{-}edge}$ and CI_{green} had the highest R^2 values.

Table 7. Overview of R^2 values of the linear relationships between indices based on Sentinel-2 spectral bands and canopy chlorophyll content.

Index	2010	2011	2012
Best $CI_{red\text{-}edge}$ from §3.1	0.89	0.88	0.76
$CI_{red\text{-}edge}$	0.88	0.88	0.74
CI_{green}	0.87	0.88	0.75
REP	0.84	0.81	0.17
MTCI	0.84	0.73	0.73
MCARI/OSAVI[705,750]	0.82	0.81	0.62
TCARI/OSAVI[705,750]	0.88	0.85	0.69
NDRE1	0.75	0.76	0.64
NDRE2	0.78	0.79	0.68

3.3. Results for WorldView-2 and RapidEye data

Potato crops in the Netherlands normally are emerging by the end of May (to diminish chances of frost damage). As a result, beginning of June 2010 at the acquisition moment of the first WV2 image and the only RapidEye image crop development was still small and soil background was still governing the signal. First extensive field sampling on LAI and chlorophyll content occurred on 11 June 2010. Therefore, the WV2

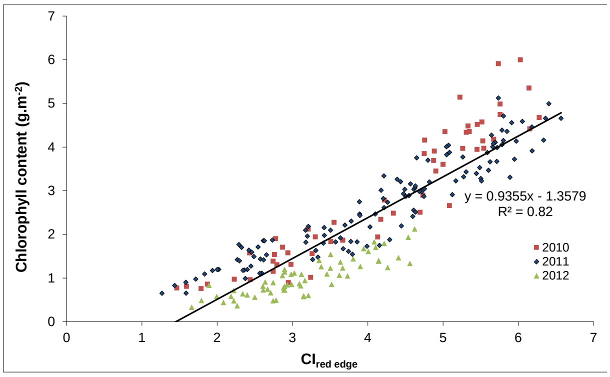

Figure 3. Relationship between $CI_{red-edge}$ based on the Sentinel-2 spectral bands and chlorophyll content for the three potato experiments.

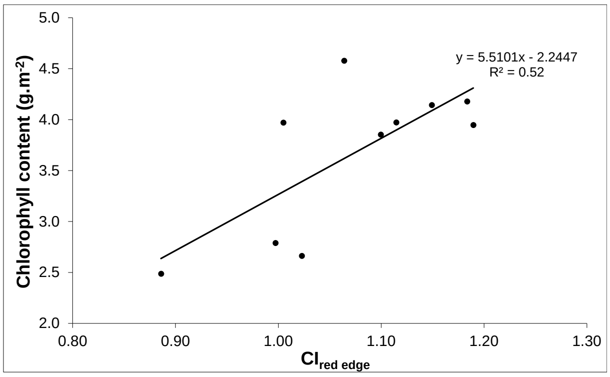

Figure 4. Relationship between $CI_{red-edge}$ and chlorophyll content for the 2010 potato experiment. WorldView-2 TOC reflectances acquired 22 June 2010.

image of 22 June 2010 is more promising for analysis, moreover since a second field sampling date occurred on 23 June 2010.

Tab. 8 shows results for the red-edge indices that could be calculated for the WV2 bands. R^2 values for the WV2 image of 3 June are low. Major reason is that this image has been acquired early in the life cycle of the potato crop, when plants are still small. As a result, no field measurements were performed yet that early. The first field measurements available are from 11 June 2010, being more than one week later in time than the first WV2 image. This constitutes a second reason for the low R^2 values.

R^2 values for the WV2 image of 22 June yield better results, except for the MCARI/OSAVI (Tab. 8). Best results were obtained for the $CI_{red-edge}$, being $R_{830}/R_{725} - 1$ for WV2. This is illustrated in Fig. 4. The relationship shown in Fig. 4, however, deviates a lot from the relationship shown in Fig. 3. Reason is that different spectral bands were used for calculating the $CI_{red-edge}$. In particular the red-edge band in the denominator was located at significantly different wavelength locations. WV2 has a red-edge band at 725 nm, whereas the red-edge band of Sentinel-2 is located at 705 nm. This explains the different relationships. Unfortunately, the number of experimental plots was limited.

Table 8. Overview of R^2 values of the linear relationships between indices based on WorldView-2 spectral bands and chlorophyll content.

Index	WV2 03-06-2010	WV2 22-06-2010
$CI_{red-edge}$	0.26	0.52
CI_{green}	0.12	0.47
MCARI/OSAVI	0.05	0.03
TCARI/OSAVI	0.00	0.46
NDRE	0.26	0.53

R^2 values for the RapidEye image of 5 June are very low and all close to 0.0. In addition to the remarks made before for the WV2 image of 3 June, the pixel size of RapidEye of 5 m will also have contributed to the worse results.

4. CONCLUSIONS

This paper presents the significance of the red-edge bands of the MSI sensor on Sentinel-2 for estimating chlorophyll content in potato crops. 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 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 $CI_{red-edge}$ is one of the best indices for estimating canopy chlorophyll or N content [1] and that the precise position of the spectral bands in the $CI_{red-edge}$ is not very critical. In this study, this was further elaborated by studying the spectral bands to be used in the $CI_{red-edge}$ in order to get the minimum CV in estimating canopy chlorophyll content for potato crops in three different growing seasons. Optimal results were obtained using a spectral band around 800 nm in the numerator of the $CI_{red-edge}$ and a spectral band in the range 695 nm – 725 nm in the denominator. The choice of the denominator waveband was more critical than the choice of the numerator. This optimal band position was also confirmed by results of the PROSAIL RT model simulations.

Subsequently, the Sentinel-2 spectral bands have been simulated using the data of the three experiments, and the $CI_{red-edge}$, CI_{green}, REP, MTCI, MCARI/OSAVI[705,750], TCARI/OSAVI[705,750], NDRE1 and NDRE2 (cf. Tab. 4) were calculated. Best results in estimating canopy chlorophyll content were obtained for the $CI_{red\text{-}edge}$ and CI_{green}. 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.

Finally, these results were confirmed using real satellite data, in particular a WorldView-2 image of the beginning of the 2010 growing season. Unfortunately, availability of satellite data (e.g., WorldView-2 or RapidEye images) was very limited, preventing a thorough analysis with satellite data including red-edge bands. Moreover, the red-edge band of WV2 was far off the one anticipated for Sentinel-2.

5. REFERENCES

[1] Clevers, J.G.P.W. & Kooistra, L. (2012). Using hyperspectral remote sensing data for retrieving canopy chlorophyll and nitrogen content. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* **5**(2), 574-583.

[2] Gitelson, A.A. & Merzlyak, M.N. (1996). Signature analysis of leaf reflectance spectra: Algorithm development for remote sensing of chlorophyll. *Journal of Plant Physiology* **148**(3-4), 494-500.

[3] Horler, D.N.H., Dockray, M. & Barber, J. (1983). The red edge of plant leaf reflectance. *International Journal of Remote Sensing* **4**(2), 273-288.

[4] Guyot, G. & Baret, F. (1988). Utilisation de la haute resolution spectrale pour suivre l'etat des couverts vegetaux. In Proceedings 4th International Colloquium 'Spectral Signatures of Objects in Remote Sensing', Aussois, France, pp. 279-286.

[5] Dash, J. & Curran, P.J. (2004). The MERIS terrestrial chlorophyll index. *International Journal of Remote Sensing* **25**(23), 5403-5413.

[6] Wu, C., Niu, Z., Tang, Q. & Huang, W. (2008). Estimating chlorophyll content from hyperspectral vegetation indices: Modeling and validation. *Agricultural and Forest Meteorology* **148**(8-9), 1230-1241.

[7] Daughtry, C.S.T., Walthall, C.L., Kim, M.S., Brown de Colstoun, E. & McMurtrey III, J.E. (2000). Estimating corn leaf chlorophyll concentration from leaf and canopy reflectance. *Remote Sensing of Environment* **74**(2), 229-239.

[8] Haboudane, D., Miller, J.R., Tremblay, N., Zarco-Tejada, P.J. & Dextraze, L. (2002). Integrated narrow-band vegetation indices for prediction of crop chlorophyll content for application to precision agriculture. *Remote Sensing of Environment* **81**(2-3), 416-426.

[9] Gitelson, A.A., Gritz, Y. & Merzlyak, M.N. (2003). Relationships between leaf chlorophyll content and spectral reflectance and algorithms for non-destructive chlorophyll assessment in higher plant leaves. *Journal of Plant Physiology* **160**(3), 271-282.

[10] Gitelson, A.A., Keydan, G.P. & Merzlyak, M.N. (2006). Three-band model for noninvasive estimation of chlorophyll, carotenoids, and anthocyanin contents in higher plant leaves. *Geophysical Research Letters* **33, L11402** (doi: 10.1029/2006GL026457).

[11] Sims, D.A. & Gamon, J.A. (2002). Relationships between leaf pigment content and spectral reflectance across a wide range of species, leaf structures and developmental stages. *Remote Sensing of Environment* **81**(2-3), 337-354.

[12] Gitelson, A. & Merzlyak, M.N. (1994). Spectral reflectance changes associated with autumn senescence of Aesculus hippocastanum L. and Acer platanoides L. leaves. Spectral features and relation to chlorophyll estimation. *Journal of Plant Physiology* **143**(3), 286-292.

[13] Barnes, E.M., Clarke, T.R., Richards, S.E., Colaizzi, P.D., Haberland, J., Kostrzewski, M., Waller, P., Choi, C., Riley, E., Thompson, T., Lascano, R.J., Li, H. & Moran, M.S. (2000). Coincident detection of crop water stress, nitrogen status and canopy density using ground-based multispectral data. In Proc. of the Fifth Int. Conference on Precision Agriculture, Bloomington, MN, USA.

[14] Drusch, M., Del Bello, U., Carlier, S., Colin, O., Fernandez, V., Gascon, F., Hoersch, B., Isola, C., Laberinti, P., Martimort, P., Meygret, A., Spoto, F., Sy, O., Marchese, F. & Bargellini, P. (2012). Sentinel-2: ESA's Optical High-Resolution Mission for GMES Operational Services. *Remote Sensing of Environment* **120**, 25-36.

[15] Jacquemoud, S. & Baret, F. (1990). Prospect - a model of leaf optical properties spectra. *Remote Sensing of Environment* **34**(2), 75-91.

[16] Verhoef, W. (1984). Light scattering by leaf layers with application to canopy reflectance modeling: the SAIL model. *Remote Sensing of Environment* **16**(2), 125-141.

[17] Jacquemoud, S., Verhoef, W., Baret, F., Bacour, C., Zarco-Tejada, P.J., Asner, G.P., François, C. & Ustin, S.L. (2009). PROSPECT + SAIL models: A review of use for vegetation characterization. *Remote Sensing of Environment* **113**(SUPPL. 1), S56-S66.

[18] Kuusk, A. (1991). The angular-distribution of reflectance and vegetation indexes in barley and clover canopies. *Remote Sensing of*

Environment **37**(2), 143-151.

[19] Feret, J.B., François, C., Asner, G.P., Gitelson, A.A., Martin, R.E., Bidel, L.P.R., Ustin, S.L., le Maire, G. & Jacquemoud, S. (2008). PROSPECT-4 and 5: Advances in the leaf optical properties model separating photosynthetic pigments. *Remote Sensing of Environment* **112**(6), 3030-3043.

[20] Uddling, J., Gelang-Alfredsson, J., Piikki, K. & Pleijel, H. (2007). Evaluating the relationship between leaf chlorophyll concentration and SPAD-502 chlorophyll meter readings. *Photosynthesis Research* **91**(1), 37-46.

[21] Gitelson, A.A., Viña, A., Ciganda, V., Rundquist, D.C. & Arkebauer, T.J. (2005). Remote estimation of canopy chlorophyll content in crops. *Geophysical Research Letters* **32, L08403** (doi: 10.1029/2005GL022688).