# MAPPING CANOPY CHLOROPHYLL CONTENT OF POTATOES BY SENTINEL-2 AS SIMULATED WITH RAPIDEYE IMAGES

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## ABSTRACT

Sentinel-2 will be a very useful satellite for agricultural applications. Not only will it cover the VNIR/SWIR spectral region in 13 bands, it will include two important bands in the red-edge region at 705 and 740 nm. This enables accurate estimation of LAI and canopy chlorophyll content, two of the most relevant properties of agricultural crops. In this study red-edge indices derived from field radiometry measurements were tested for potato experiments in four consecutive years (2010 – 2013). For 2013, two RapidEye images were used for upscaling the results to the satellite level and for simulating chlorophyll maps at both 10 m and 20 m as will be possible with Sentinel-2 in future. In particular, the red-edge chlorophyll index ($CI_{red-edge}$) and the green chlorophyll index ($CI_{green}$) were found to be accurate and linear estimators of canopy chlorophyll content and the Sentinel-2 bands are well positioned for deriving these indices.

## 1. INTRODUCTION

Sentinel-2 is planned for launch by the European Space Agency in 2015. 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 (at 705 and 740 nm), which can be used to derive vegetation indices using red-edge bands. These are particularly suitable for estimating canopy chlorophyll content, which is a key parameter for understanding plant functioning and status. Plant stress in agriculture is often expressed as a reduction in amount of biomass or leaf area index (LAI). In addition, stress may affect the plant pigment system, influencing the photosynthetic capacity of plants. Chlorophyll content of the leaves is the main driver for this primary production.

LAI is regarded a very important canopy property since photosynthesis takes place in the green plant parts. Numerous studies have been performed for estimating LAI using vegetation indices primarily based on a NIR and a red spectral band. The strong absorption by chlorophyll in the red makes such an index least sensitive for variations in leaf chlorophyll content and most suitable for estimating LAI. On the other hand, for estimating chlorophyll content the red band is less suitable because of this strong saturation effect. In this respect, a band at the red-edge region has high potential due to the absence of the saturation effect [1]. The reflectance at the red-edge will primarily be influenced by both leaf chlorophyll content and LAI. So, remote sensing derived indices using the red-edge region will primarily provide information on the canopy chlorophyll content, being the product of LAI and leaf chlorophyll content [2]. For directly estimating leaf chlorophyll content one might focus on a green spectral band, where the saturation effect caused by chlorophyll absorption is much less than in the blue or red regions. To avoid the disturbing influence of soil brightness variations and LAI, this will most likely only work in situations of full canopy cover. This paper focuses on the potential of Sentinel-2 in estimating canopy chlorophyll content.

Previous studies using radiative transfer models showed that a few bands on the red-edge region are important for estimating canopy chlorophyll and nitrogen (N) content by means of vegetation indices. Moreover, they showed that Sentinel-2 bands are well positioned for deriving such indices [1]. For potatoes under field conditions best results in estimating canopy chlorophyll content were obtained for the $CI_{red-edge}$ and $CI_{green}$. Moreover, results using the Sentinel-2 band positions were quite similar to the optimal band positions for the $CI_{red-edge}$ [3]. This confirmed the importance of the red-edge bands on Sentinel-2.

The main objective of this paper was to upscale previously obtained field-based results and evaluate the potential of Sentinel-2 data for monitoring potato crops by using spaceborne RapidEye images as proxy for the capabilities of Sentinel-2.

## 2. MATERIAL AND METHODS

### 2.1. Potato Experimental Sites

Experimental fields with potato crops, located in the South of the Netherlands, were set up in four subsequent growing seasons (2010 – 2013). Plots of 30 by 30 m were designed with different nitrogen fertilization levels. On a weekly basis in-situ field measurements of biomass, LAI and leaf chlorophyll content were performed. In 2010, 10 plots were prepared with five levels of nitrogen (N) fertilization (0, 190, 290, 320 and 390 kg $N.ha^{-1}$) in two replicates [4]. The field used in the 2011 growing season consisted of 12 experimental plots. Each plot received four levels of initial N fertilizer (0, 161, 242 and 322 kg N.ha$^{-1}$). 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$^{-1}$) in the form of liquid organic fertilizer and organic fertilizer from stable manure. Finally, in 2013 again four levels of N fertilizer (0, 25, 45 and 70 m$^{3}$.ha$^{-1}$ of organic manure) were applied in three replicates.

LAI was collected weekly using a Plant Canopy Analyser (LAI-2000, LI-COR, Lincoln, NE). Leaf chlorophyll content 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 weekly. SPAD measurements during the growing season were converted to leaf chlorophyll content (g.m$^{-2}$) using the model suggested by [5], which is derived specifically for potatoes. The product of leaf chlorophyll content and LAI yielded the canopy chlorophyll content used in this study.

### 2.2. Field Radiometry

The study sites were measured weekly with a Cropscan Multispectral Radiometer (MSR16R). This is a 16-band radiometer measuring simultaneously reflected and incoming radiation in narrow spectral bands (Table 2). 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. RapidEye

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 6.5 m and a swath width of 77 km. Spectral specifications are given in Table 3. For this study images from 2nd and 23rd August, 2013, were available. Digital numbers have been converted to top-of-canopy reflectances by applying ATCOR. RapidEye has a red-edge band centred at 710 nm, which is very close to band B5 of Sentinel-2. This band was used for calculating the $CI_{red\text{-}edge}$, MCARI/OSAVI, TCARI/OSAVI and NDRE2 indices. For the MCARI/OSAVI and TCARI/OSAVI no specific red-edge version could be calculated, but band 3 and 4 in addition to band 2 and 5 were used. In addition, $CI_{green}$ was calculated. RapidEye does not have sufficient bands to calculate the REP and MTCI.

*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 |

*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 |

*Table 3. Specifications of the RapidEye spectral bands.*

| Band | Centre wavelength (nm) | Band width (nm) |
|---|---|---|
| 1 | 475 | 70 |
| 2 | 555 | 70 |
| 3 | 657.5 | 55 |
| 4 | 710 | 40 |
| 5 | 805 | 90 |

### 2.4. Sentinel-2

The MSI sensor on board of the Sentinel-2 satellites will have four bands at 10 m, six bands at 20 m and three bands at 60 m spatial resolution [6]. 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 (Table 1).

### 2.5. Vegetation Indices

Several vegetation indices (VIs) have been proposed for estimating canopy chlorophyll content [4]. In particular, the red-edge region has often been used for estimating chlorophyll content. Horler et al. [7] 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 Sentinel-2, the REP can be derived by applying a simple linear model to the red-infrared slope [8]. Another type of index based on the MERIS red-edge bands is the MERIS terrestrial chlorophyll index, MTCI [9].

Wu et al. also stressed the importance of the red-edge bands [10]. They suggested to replace the red and NIR spectral bands in the MCARI/OSAVI [11] and TCARI/OSAVI [12] by bands at 705 nm and 750 nm, respectively. Indeed these adapted indices showed better linearity with canopy chlorophyll content [4]. 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 performed very well in estimating chlorophyll content. Gitelson [13, 14] 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.

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 [15, 16] is presented in literature, whereas also a version 2 using 790 nm and 720 nm [17] can be found. Sometimes, also deviating names are used in literature.

The VIs studied in this paper and their definitions using the Sentinel-2 spectral bands are provided in Table 4.

*Table 4. Vegetation indices evaluated in this study (Wavelengths refer to Sentinel-2 bands).*

| Index | Formulation | Reference |
|---|---|---|
| $CI_{red\ edge}$ | $(R_{783}/R_{705}) - 1$ | [13, 14] |
| $CI_{green}$ | $(R_{783}/R_{560}) - 1$ | [13, 14] |
| REP | $705 + 35\frac{(R_{665}+R_{783})/2 - R_{705}}{R_{740} - R_{705}}$ | [8] |
| MTCI | $(R_{740} - R_{705})/(R_{705} - R_{665})$ | [9] |
| MCARI/OSAVI[705,750] | $\frac{[(R_{740} - R_{705}) - 0.2(R_{740} - R_{560})](R_{740}/R_{705})}{(1+0.16)\,(R_{740} - R_{705})/(R_{740} + R_{705} + 0.16)}$ | [10] |
| TCARI/OSAVI[705,750] | $\frac{3[(R_{740} - R_{705}) - 0.2(R_{740} - R_{560})(R_{740}/R_{705})]}{(1+0.16)\,(R_{740} - R_{705})/(R_{740} + R_{705} + 0.16)}$ | [10] |
| NDRE1 | $(R_{740} - R_{705})/(R_{740} + R_{705})$ | [15, 16] |
| NDRE2 | $(R_{783} - R_{705})/(R_{783} + R_{705})$ | [17] |

$R_\lambda$ refers to the reflectance factor at wavelength $\lambda$ nm.

## 3. RESULTS

### 3.1. Performance of VIs based on Cropscan data

For the potato experiments in respectively the 2010, 2011, 2012 and 2013 growing seasons, first the Cropscan radiometer has been used for simulating the Sentinel-2 spectral bands. After calculating all mentioned indices (Table 4) using the simulated Sentinel-2 bands for the four 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 Table 5.

For the potato experiments the $CI_{red\text{-}edge}$ and $CI_{green}$, based on the Sentinel-2 band positions using the Cropscan data, had a similar performance. The other indices also performed well for most years (Table 5), but overall $CI_{red\text{-}edge}$ and $CI_{green}$ had the highest $R^2$ values. 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 year 2013 is shown in Fig. 1. Results for the other three years have also been reported before [3]. Fig. 2 shows the results of the relationship between $CI_{red\text{-}edge}$ and canopy chlorophyll content for all four years combined. Both $CI_{red\text{-}edge}$ and $CI_{green}$ yielded an $R^2$ of 0.77 when combining all four years. Different years show slightly deviating relationships, which can be explained by use of a different cultivar, different field and particularly different growing conditions in the consecutive years. Overall results were consistent.

*Table 5. Overview of $R^2$ values of the linear relationships between indices based on Sentinel-2 spectral bands and canopy chlorophyll content using the Cropscan data for potato experiments.*

| Index | 2010 | 2011 | 2012 | 2013 |
|---|---|---|---|---|
| $CI_{red\text{-}edge}$ | 0.88 | 0.88 | 0.74 | 0.77 |
| $CI_{green}$ | 0.87 | 0.88 | 0.75 | 0.77 |
| REP | 0.84 | 0.81 | 0.17 | 0.49 |
| MTCI | 0.84 | 0.73 | 0.73 | 0.79 |
| MCARI/OSAVI[705,750] | 0.82 | 0.81 | 0.62 | 0.72 |
| TCARI/OSAVI[705,750] | 0.88 | 0.85 | 0.69 | 0.78 |
| NDRE1 | 0.75 | 0.76 | 0.64 | 0.53 |
| NDRE2 | 0.78 | 0.79 | 0.68 | 0.59 |

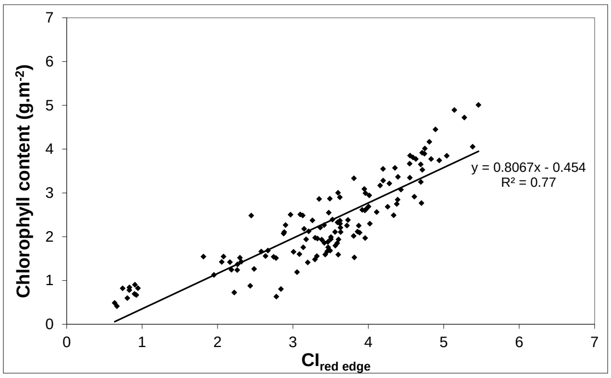


*Figure 1. Relationship between $CI_{red\text{-}edge}$, based on the Sentinel-2 spectral bands, and chlorophyll content for the potato experimental data of 2013.*

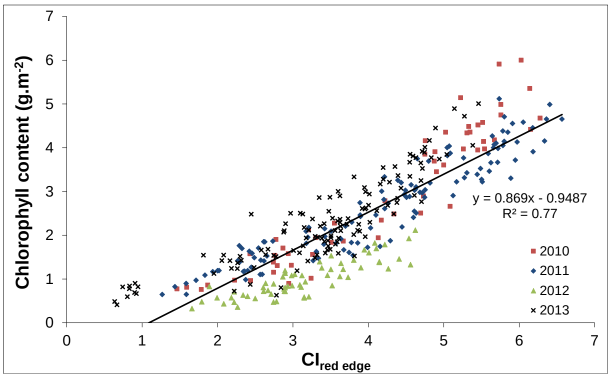


*Figure 2. Relationship between $CI_{red\text{-}edge}$, based on the Sentinel-2 spectral bands, and chlorophyll content for the four potato experiments.*

*Table 6. Overview of $R^2$ values of the linear relationships between indices based on RapidEye spectral bands and chlorophyll content.*

| Index | 02-08-13 | 23-08-13 | Combined |
|---|---|---|---|
| $CI_{red\text{-}edge}$ | 0.61 | 0.64 | 0.79 |
| $CI_{green}$ | 0.50 | 0.58 | 0.61 |
| MCARI/OSAVI | 0.01 | 0.44 | 0.06 |
| TCARI/OSAVI | 0.43 | 0.47 | 0.41 |
| NDRE2 | 0.60 | 0.63 | 0.78 |

### 3.2. Results for RapidEye Data

Table 6 shows results for the red-edge indices that could be calculated for the RapidEye bands. Results are presented for the two dates, 2nd and 23rd August, 2013, separately and for the two dates combined. As stated before, RapidEye has insufficient bands to calculate the REP and MTCI. For the MCARI/OSAVI and TCARI/OSAVI only the original versions with just one red-edge band could be calculated for RapidEye. Best results were obtained for the $CI_{red\text{-}edge}$ and the NDRE2.

The $CI_{green}$ provided slightly worse results. The MCARI/OSAVI and TCARI/OSAVI clearly were worse in estimating canopy chlorophyll content. This confirms earlier results with respect to the original versions of these two indices [4]. The results for the $CI_{red\text{-}edge}$ for both RapidEye images combined are presented in Fig. 3, whereas those for the $CI_{green}$ are illustrated in Fig. 4. The latter are shown in view of the upcoming discussion, whereas those for the NDRE2 are not shown.

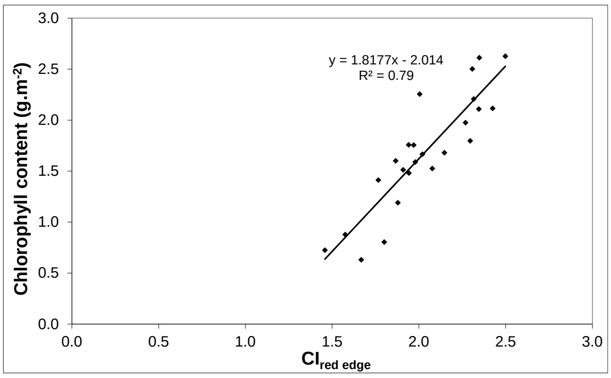


*Figure 3. Relationship between $CI_{red\text{-}edge}$ and chlorophyll content for the 2013 potato experiment. RapidEye calibrated reflectance for August 2nd and 23rd, 2013, combined.*

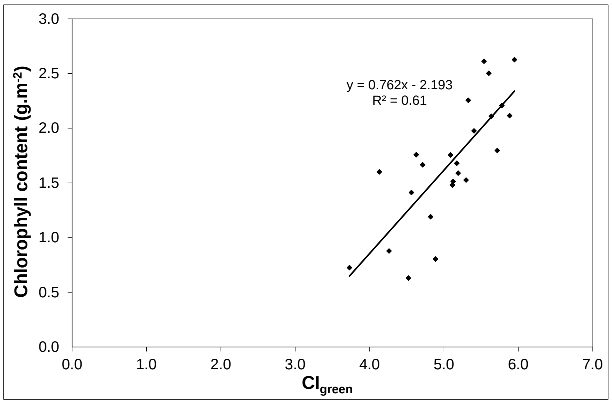


*Figure 4. Relationship between $CI_{green}$ and chlorophyll content for the 2013 potato experiment. RapidEye calibrated reflectance for August 2nd and 23rd, 2013, combined.*

## 4. DISCUSSION

Results in this paper show that the Sentinel-2 spectral bands are well positioned for calculating red-edge indices. These indices are very suitable for estimating canopy chlorophyll content of, e.g., potato crops. This is in line with earlier results for other canopy types [1, 4]. The best red-edge index was found to be the so-called $CI_{red\text{-}edge}$, using the ratio of Sentinel-2 band B7 and B5 (Table 1). In addition, good performance was also found for the so-called $CI_{green}$, using the ratio of Sentinel-2 band B7 and B3. Replacing band B7 by B8 in the latter index yielded similar good results as was tested for the Cropscan radiometer. As a result, Sentinel-2 has great potential for agricultural applications. Its spectral bands are optimally situated for estimating LAI and the canopy chlorophyll content, two of the most relevant properties of agricultural crops. Moreover, the chlorophyll content is indirectly related to the nitrogen content [4], a property that is often used as an indicator of the crop status in order to decide whether additional fertilization is needed for obtaining an optimal yield.

For timing fertilization or other management actions during crop growth to plant needs, an observation frequency in the order of one week is needed. The planned constellation of two identical Sentinel-2 satellites in theory will enable this observation frequency. The actual observation frequency will be determined by the frequency of cloud cover.

Another important issue for applications in agriculture, particularly for site-specific management (precision farming) is the spatial resolution. The spatial resolution of the red-edge bands on Sentinel-2 is 20 m, which is at the upper limit of what a farmer needs in terms of spatial detail. However, for canopy chlorophyll content estimation the $CI_{green}$ performed nearly as good as red-edge type of indices. If this $CI_{green}$ is based on the B8 and B3 spectral bands of Sentinel-2 (Table 1), then the chlorophyll content can be estimated at 10 m. The same resolution can be obtained for estimating LAI using various traditional NIR and red based indices. Figure 5 illustrates canopy chlorophyll maps at 20 m and 10 m as derived from the $CI_{red\text{-}edge}$ and the $CI_{green}$, respectively, using the RapidEye data of August 2nd, 2013, as studied in this paper.

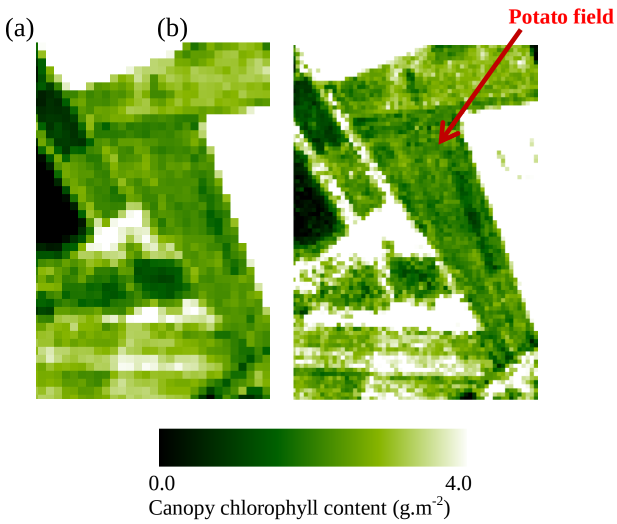


*Figure 5. Maps for Sentinel-2 canopy chlorophyll content simulated using RapidEye data of August 2nd, 2013, (a) at 20 m with the $CI_{red\text{-}edge}$, and (b) at 10 m with the $CI_{green}$.*

## 5. 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. The Sentinel-2 spectral bands have been simulated using the field radiometry data of four potato experiments, and the $CI_{red-edge}$, $CI_{green}$, REP, MTCI, MCARI/OSAVI[705,750], TCARI/OSAVI[705,750], NDRE1 and NDRE2 (cf. Table 4) were calculated. Best results in estimating canopy chlorophyll content were obtained for the $CI_{red-edge}$ and $CI_{green}$. Finally, these results were confirmed using real satellite data, in particular two RapidEye images from the 2013 growing season. Simulated chlorophyll maps illustrate the importance of $CI_{green}$ from Sentinel-2 data since this may provide results at 10 m spatial resolution.


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