

DAGRICULTURAL BIOPHYSICAL PARAMETERS AND THE TASSELED CAP TRANSFORMATION FOR RAPIDEYE DATA

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ABSTRACT

Deriving information about the chlorophyll (Chl) and/or nitrogen (N) status of senescent wheat using spectral indices obtained from satellite data can be useful to predict plant water status, salvageable N, N use efficiency, grain protein content and dry-down rates. RapidEye's Tasseled Cap Feature Yellowness (YEL) corresponds to the reflectance characteristics of senescent crops, with relatively higher reflectance in the visible portion of the spectrum due to chlorophyll breakdown, and lower reflectance in the NIR range due to cell structure decomposition. The goal of this study was to evaluate the potential and accuracy of YEL, in comparison to the Plant Senescence Reflectance Index (PSRI), for estimating chlorophyll and nitrogen concentration of senescent winter and spring wheat (*Triticum aestivum* L.). Preliminary results showed that YEL had a higher potential to estimate Chl in senescent winter wheat in comparison to PSRI, while PSRI demonstrated stronger correlations to Chl in senescent spring wheat than YEL. For the estimation of N concentration, YEL yielded much stronger, statistically significant correlations and a higher accuracy than PSRI. Results indicated the capability of YEL to predict both Chl and N concentration, probably attributable to the additional information provided by the Red-edge band. YEL may be used to characterize in-field senescence status variations, potentially providing ancillary information for the assignment of precision management zones related to yield and wheat quality parameters.

Key words: Tassled Cap; RapidEye, chlorophyll, nitrogen, senescent wheat

INTRODUCTION

Senescence is the final stage of annual plant development and it is characterized by well-orchestrated degradation and remobilization processes. Leaf nitrogen (N) and other soluble constituents are mobilized from the degrading photosynthetic apparatus (Chl breakdown) to the seeds after anthesis (Hörtensteiner & Kräutler 2010; Bieker & Zentgraf 2013; Xue et al. 2007). N retained from wheat leaves, in particular from the flag leaf and the upper canopy, accounts for up to 90% of the total grain N content (Kichey et al. 2007; Wang et al. 2005). Senescence is triggered by endogenous signals, e.g. plant growth regulators and hormone levels, but also by exogenous factors, such as drought, waterlogging, high soil salinity, mineral nutrition deficiency, high or low solar radiation, and extreme temperatures (Thomas & Stoddart 1980; Smart 1994; Edwards et al. 2012). With the onset and progress of senescence, chlorophyll (Chl) is degraded much faster than carotenoids, which causes reflectance to increase in the red spectrum, while in the blue spectrum only a small increase of reflectance is observed (Knipling 1970; Penuelas et al. 1995; Wilson et al. 2014; Sanger 1971; Verdebout et al. 1994; Gitelson et al. 2002; Zur et al. 2000). With the advancement of senescence, degradation processes form metabolites (polyphenols, denatured proteins, "brown pigments"), which visually evoke a brownish color and which were reported to absorb light in the visual and red-edge/NIR region (400-800 nm) (Verdebout et al. 1994; Penuelas &

Filella 1998). The decrease of NIR reflectance during senescence is induced by the breakdown of cell structures, which decreases light scattering properties, e.g. mesophyll and intercellular space, and furthermore reduces the feedback of transmitting radiation in the subsequent canopy layers (Knipling 1970).

Information on the chlorophyll and/or nitrogen concentration of wheat during senescence can be useful to predict plant water status and dry-down rates. Mapping variations of senescence (crop drying patterns) within a field can potentially provide additional information to designate precision management zones, e.g. to highlight areas that are more or less sensitive to abiotic conditions, which could ultimately drive spatial variations in grain quality and quantity. Recent studies pointed out that site specific harvesting bears the potential to increase wheat quality and net return rates in quality incentive markets (Morari et al. 2013; Diacono et al. 2012; Meyer-Aurich et al. 2008; Wright et al. 2004; Freeman et al. 2003). In accordance with previous studies, Diacono et al. (2012) reported that climatic conditions, especially available soil water, play a major role in affecting the spatial patterns of yield as well as other quality parameters of wheat crops in rain fed agricultural systems (Buttafuoco et al. 2010; Ibrahim & Huggins 2011; Basso et al. 2007). Practically, the longer the duration and the slower the rate of senescence, the greater the probability is for higher yields (Herbek & Lee 2009). Further, remotely estimating canopy Chl and/or N at these late stages of plant growth could provide information on salvageable N, N use efficiency, N status, grain protein content, and rate of senescence, and might be useful to indicate spatial patterns related to yield or wheat quality conditions.

Merzlyak et al. (1999) developed the Plant Senescence Reflectance Index (PSRI), which was found to be responsive to changes in the carotenoid-chlorophyll ratio of senescing leaves, and therefore was proposed to be used to estimate the onset, the stage, and the relative rates and kinetics of senescence or ripening processes. Hatfield et al. (2010) found PSRI very suitable to detect differences in plant senescence across fields. Further, by comparing the change rate of the canopy from green to senescent, PSRI can be used to determine the rate of senescence in different crops.

An alternative approach to the use of indices for deriving biophysical properties of surface features from satellite imagery is the Tasseled Cap Transformation (Kauth & Thomas 1976). The Tasseled Cap Transformation assigns fixed weights to the original reflectance values of the individual spectral bands to generate transformed features, which can directly be associated with biophysical properties of surface features, e.g. the brightness or moisture variation of surface objects. Tasseled Cap Features (TCFs) were developed for several sensors, such as Landsat (Kauth & Thomas 1976; Crist & Cicone 1984; Huang et al. 2002; Baig et al. 2014), SPOT (Ivits et al. 2008), IKONOS (Horne 2003) and RapidEye (Schönert et al. 2014).

The high temporal and spatial resolution of RapidEye satellite imagery allows for the assessment of in-field variability of crop biophysical characteristics, and therefore provides valuable information for site specific management to increase the productivity and quality of crops. TCFs for RapidEye data were derived from spectral variances typically present in agricultural scenes (Schönert et al. 2014). The first TCF, Brightness, was aligned to correspond with the variance of soil brightness. The second TCF, Greenness, corresponds to the direction of the spectral variation of vital vegetation, and therefore, represents the typical reflectance characteristics of green vegetation, with relatively higher reflectance at the NIR range. Yellowness (YEL), the third TCF, shows a contrast between the Blue + Green bands, and the Red + Red Edge + NIR bands. YEL corresponds to the reflectance characteristics of senescent crops, which generally show higher reflectance at the visual spectrum due to chlorophyll breakdown, and lower reflectance at the NIR range due to cell structure decomposition.

The aim of this work was to assess the suitability and accuracy of RapidEye's TCF YEL for estimating the biophysical parameters Chl and N of wheat. To have a (relative) measure, how well YEL performs at the estimation of Chl and N, it was compared to the commonly used index PSRI.

MATERIALS AND METHODS

Study Area

The study area was in the Palouse region of Northern Idaho (46°30'N, 116°49'W) and Eastern Washington (46°47'N, 117°26'W), USA, which is characterized by many small hills. These study sites are managed as no-till and have silt loam soils developed in loess deposits with some ash. Both farms are completely rain fed with precipitation ranging from 330 to 610 mm annually (Soil Survey Staff 2014). The test fields located at the farm in Northern Idaho and Eastern Washington were named Odberg (O) and Aeschlimann (A) (Tab. 1).

Satellite Data

The RapidEye satellite system is a constellation of five identical earth observation satellites with the capacity to provide large area, multi-spectral images with frequent revisits in high resolution (6.5 m at nadir). In addition to the

Blue (B) (440-510 nm), Green (G) (520-590 nm), Red (R) (630-685 nm) and near-infrared (NIR) (760-850 nm) bands, the sensor has a Red-edge (RE) (690-730 nm) band, especially suitable for vegetation analysis (s. Eitel et al. 2007). The RapidEye level 3A standard product covers an area of 25x25 km, is radiometrically calibrated to radiance values (Anderson et al. 2013), and is ortho-rectified and resampled to 5 m spatial resolution. All level 3A images used in this study (Tab. 1) were calibrated to top of atmosphere (TOA) reflectance.

Table 1. Ground reference data of chlorophyll (SPAD) and nitrogen (N) concentration of winter (WW) and spring wheat (SW) and corresponding RapidEye imagery.

| Field | Crop | Sampling Date | No. of Samples | Min. / max. / standard deviation of | | Tile-ID | Image Date |
|-------|------|----------------------------|----------------|-------------------------------------|----------------|---------|----------------------------|
| | | | | SPAD | N | | |
| A | WW | 18 th July 2012 | 12 | 7.1/55.6/17.30 | 0.86/3.09/0.85 | 1160613 | 13 th July 2012 |
| A | WW | 31 st July 2012 | 12 | 0.5/20.8/7.60 | No data | 1160613 | 3 rd Aug. 2012 |
| O | SW | 18 th July 2012 | 12 | 23.2/52.6/9.53 | 1.96/3.79/0.56 | 1160515 | 15 th July 2012 |
| O | SW | 24 th July 2012 | 12 | 4.9/42.3/12.43 | No data | 1160515 | 4 th Aug. 2012 |

Field Data and Spectral Indices

Field data collection included measuring leaf chlorophyll meter readings at the upper canopy (SPAD) and leaf nitrogen concentration (%N) of both soft white winter and spring wheat (*Triticum aestivum* L.). SPAD measurements represent unit-less relative values, which have been proven to be positively correlated to Chl content of wheat (Reeves et al. 1993) and other crops (Zhu et al. 2012). The average of twelve SPAD (Minolta SPAD-502[®]) values from fully-expanded upper leaves were used in this analysis. %N was also averaged from twelve top of canopy leaf samples processed by dry combustion. Due to the highly heterogeneous nature of the hilly Palouse, wide differences in SPAD and %N were observed during these time periods (Tab. 1).

All field sampling points were located on the satellite images, buffered with a 10-meter-radius circle, and the corresponding mean image TOA values extracted from these areas were used to calculate YEL and PSRI values for each point. YEL (Schönert et al. 2014) and PSRI (Merzlyak et al. 1999) were calculated by

$$YEL = -0.7564 \times B - 0.3916 \times G + 0.5049 \times R + 0.14 \times RE + 0.0064 \times NIR$$

$$PSRI = \frac{R - G}{NIR}$$

where B, G, R, RE and NIR represent the values of Blue, Green, Red, Red-edge, and NIR bands respectively.

Correlation Analysis and Prediction Accuracy

The relationships of both, YEL and PSRI to Chl and N concentration in senescent wheat were investigated by correlation analysis. Then regression models were developed, combining Chl ground reference measurements from different sampling dates, taken at fields with winter wheat and spring wheat, to compare the prediction accuracy of YEL and PSRI. Equally, N field measurements were pooled and a regression model was built to compare the accuracy of YEL and PSRI as an estimator of N concentration in senescent wheat. For an estimation of the accuracy, the k-fold cross-validation (with k = 4) method was used. In k-fold cross-validation, folds are randomly assembled and taken out one by one, while each sample of the fold is estimated by the linear function of the remaining model. On the one hand, by applying the remaining model functions to unseen data (fold taken out), the prediction accuracy of the full model can be approximated, even though no independent validation set exists. On the other hand, k-fold validation allows for the inspection of the stability of the full model, since in a stable model, subsets of the model should have similar regression equations and coefficients of determination. Mean absolute error (MAE_{cv}) and root square mean error (RMSE_{cv}) returned by the cross-validation process was used to compare the prediction accuracy of YEL and PSRI.

RESULTS AND DISCUSSION

YEL and PSRI vs. Chl and N Concentrations

Generally, YEL and PSRI showed a strong negative linear relationship to Chl concentration in senescent wheat (Tab. 2). YEL yielded higher coefficients of determination (R^2) values than PSRI for the field with winter wheat (A), whereas PSRI showed higher predictive potential at the field, where spring wheat was sown (O) (Tab. 2). Correlations were significant ($p = 0.01$), except for YEL at the spring wheat field (24th July). At the winter wheat site (18th July), YEL explained approximately 16% more of the total variance compared to the PSRI, whereas, at the latest senescence stage (31st July) the estimation capacity of both indices were comparable (Tab. 2). At the spring wheat field, both indices performed poorly at the first date, although PSRI yielded a significant correlation, while YEL did not ($p = 0.01$) (Tab. 2). Even though images were acquired 11 days after the ground sampling at the spring wheat field (24th July), and changes in crop senescence during this time could have been drastic, YEL and PSRI

Table 2. Coefficient of determination of chlorophyll (SPAD) and nitrogen (N) concentration of winter (WW) and spring wheat (SW), Yellowness (YEL) vs. PSRI.

| Field | Crop | Sampling Date | Tested Index | Coefficient of Determination (R^2) for | |
|-------|------|---------------------------|--------------|--|-------|
| | | | | SPAD | N |
| A | WW | 18 th July '12 | YEL | 0.77 | 0.77 |
| | | | PSRI | 0.61 | 0.57 |
| A | WW | 31 st July '12 | YEL | 0.84 | |
| | | | PSRI | 0.83 | |
| O | SW | 18 th July '12 | YEL | 0.45* | 0.74 |
| | | | PSRI | 0.53 | 0.37* |
| O | SW | 24 th July '12 | YEL | 0.78 | |
| | | | PSRI | 0.89 | |

* not significantly correlated at level of confidence $p=0.01$

study demonstrated different optical properties than vital crops, strong statistically significant correlations at the winter and spring wheat fields of $R^2 = 0.85$ and $R^2 = 0.66$, respectively, were observed for the relation of N to Chl. This indicates that the N-Chl dependency subsists, explaining the correlation of YEL to N found. The significant correlation of YEL to N, despite the non-significant correlation to Chl concentration ($p = 0.01$) observed at the winter wheat site 18th July, may indicate that other optical properties, which might have been masked by the strong absorbing features of Chl in a vital status, contribute to the YEL-N relationship (Tab. 3).

The greater potential of YEL for the estimation of N might be associated with the inclusion of the Red-edge band, which shows a higher sensitivity to a wider range of Chl levels than the Red and Green bands used in the PSRI. Red reflectance is a poor predictor of low to high levels of Chl or N, since it saturates at low Chl levels (Gitelson & Merzlyak 1998; Gitelson et al. 1996; Eitel et al. 2011). Also, several studies suggested that the wavelength in the red-edge region is superior to the green in regards to its responsiveness to stress induced changes in Chl (e.g. Carter & Knapp 2001; Eitel et al. 2011).

showed significant correlations of $R^2 = 0.78$ and $R^2 = 0.89$, respectively (Tab. 2).

For the estimation of N concentration in senescent crops, YEL yielded significant correlations at the winter wheat (18th July) and spring wheat fields (18th July) with $R^2 = 0.77$ and $r = 0.74$, respectively, while PSRI was only significantly correlated to N concentration ($R^2 = 0.57$) at the winter wheat site (18th July) (Tab. 2). Results revealed that YEL, compared to the PSRI, provided higher R^2 values for the estimation of N concentration (Tab. 2).

Studies investigating green plant reflectance properties have shown that varying N concentration positively correlates with Chl concentration, which in turn is one of the key drivers of the reflectance properties of plants in the visible part of the spectrum (Evans 1983; Moorby & Besford 1983; Thomas & Oerther 1972; Knipling 1970).

Although the senescent crops investigated in this

Cross-validation

All correlations for the pooled data related to Chl were statistically significant ($p = 0.01$), and ranged from 0.73 to 0.87 (Tab. 3). As expected, YEL yielded a higher R^2 value and accuracy ($MAE_{cv} = 5.93$, $RMSE_{cv} = 7.15$) than PSRI ($MAE_{cv} = 6.43$, $RMSE_{cv} = 8.80$) at the pooled winter wheat model (A_p), whereas PSRI demonstrated a higher R^2 value and accuracy ($MAE_{cv} = 4.55$, $RMSE_{cv} = 6.35$) at the spring wheat model (O_p) compared to YEL ($MAE_{cv} = 5.91$, $RMSE_{cv} = 7.79$) (Tab. 3). Results indicated that PSRI is a better predictor of Chl concentration at the pooled data set where both crop types were combined (AO_p), with an MAE_{cv} of 5.53 and an $RMSE_{cv}$ of 10.84 compared to YEL ($MAE_{cv} = 7.45$, $RMSE_{cv} = 12.88$) (Tab. 3, Fig. 1).

Table 3. Coefficient of determination of pooled data and corresponding cross-validated mean absolute error (MAE_{cv}) and $RMSE_{cv}$ for predicting chlorophyll (SPAD) and nitrogen (N) concentration of senescent winter (WW) and spring wheat (SW), Yellowness (YEL) vs. PSRI.

| Field | Crop | Sampling Date | No of Samples | Tested Index | Coefficient of Determination (R^2) for | | MAE_{cv} | $RMSE_{cv}$ |
|--------|------|---------------------------|---------------|--------------|--|------|------------|-------------|
| | | | | | SPAD | N | | |
| A_p | WW | 18 th July '12 | 24 | YEL | 0.83 | | 5.93 | 7.15 |
| | | 31 st July '12 | | PSRI | 0.73 | | 6.43 | 8.80 |
| O_p | SW | 18 th July '12 | 24 | YEL | 0.81 | | 5.91 | 7.79 |
| | | 24 th July '12 | | PSRI | 0.87 | | 4.55 | 6.35 |
| AO_p | SW | all | 48 | YEL | 0.74 | | 7.45 | 12.88 |
| | WW | | | PSRI | 0.80 | | 5.53 | 10.84 |
| AO_p | SW | 18 th July '12 | 24 | YEL | | 0.80 | 0.32 | 0.38 |
| | WW | 18 th July '12 | | PSRI | | 0.63 | 0.42 | 0.51 |

The MAE_{cv} and $RMSE_{cv}$ for the N prediction is in the unit of leaf nitrogen concentration (%N), while the error metrics for SPAD are unit-less.

concentration (corresponding with an earlier state of senescence) leveled off. The rate of Chl degradation and the corresponding gradual spectral change, and/or other factors, such as water content, might have caused the non-linearity.

For the estimation of leaf nitrogen concentration (%N), YEL yielded a higher R^2 value and accuracy ($MAE_{cv} = 0.32$ %N, $RMSE_{cv} = 0.38$ %N) than PSRI ($MAE_{cv} = 0.42$ %N, $RMSE_{cv} = 0.51$ %N) (Tab. 3, Fig. 2).

Even though Chl and N concentration of senescent crops were efficiently predicted by the pooled linear regression models of YEL and PSRI, further analysis indicated that the underlying correlation between spectral reflectance and biophysical properties were better described by a quadratic function. It was observed that all lines of best fit approaching relatively high levels of Chl/N

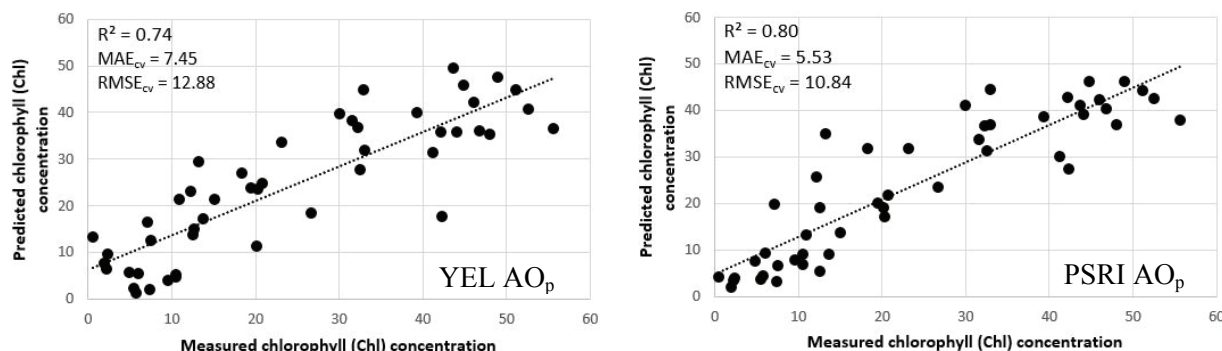


Figure 1. Cross-validated predicted chlorophyll (Chl) concentration vs. measured Chl concentration of YEL and PSRI: pooled Chl measurements of winter and spring wheat (AO_p). Cross-validated MAE_{cv} and $RMSE_{cv}$ for the prediction of Chl are unit-less.

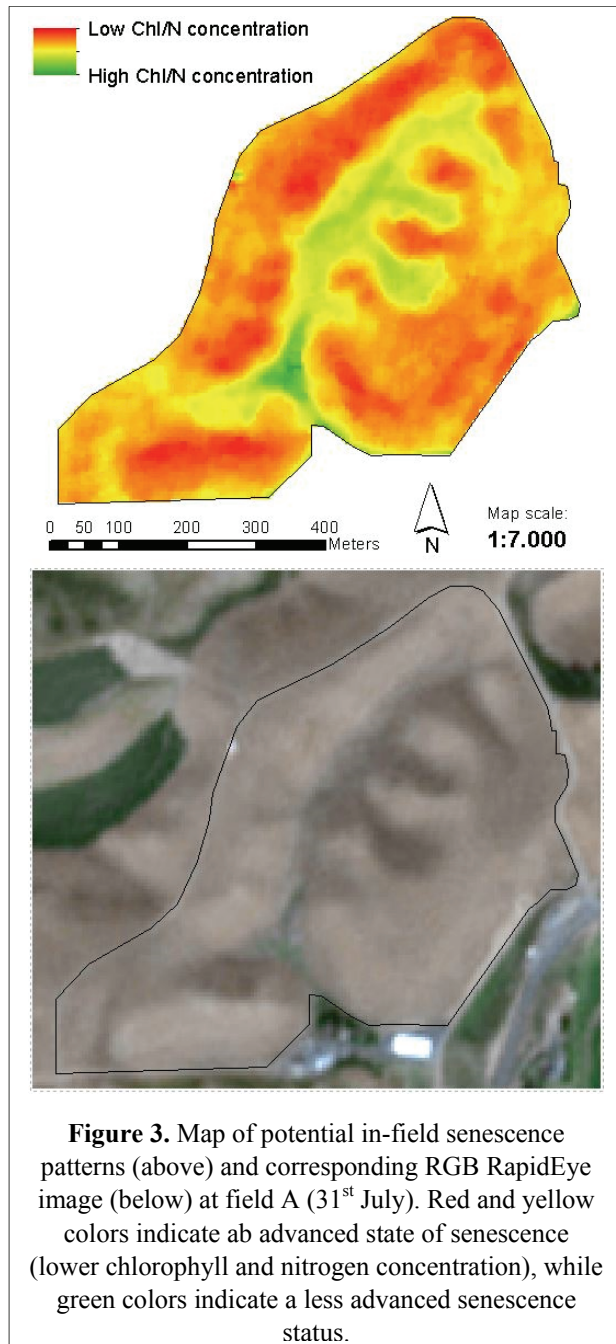
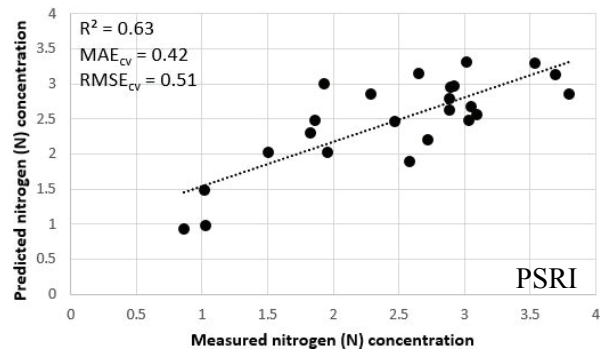
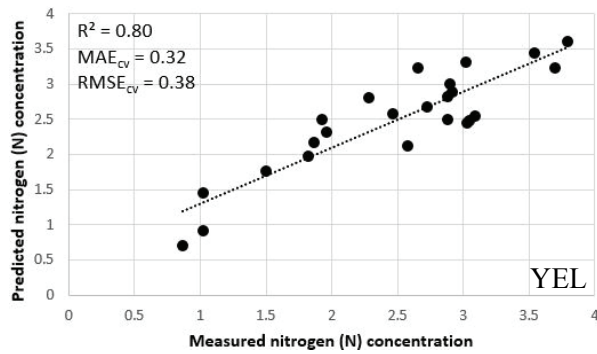


Figure 2. Cross-validated predicted nitrogen (N) concentration vs. measured N concentration of YEL and PSRI. For analysis, N measurements of winter and spring wheat were pooled. Cross-validated MAE_{cv} and $RMSE_{cv}$ for the prediction of N is in the unit of leaf nitrogen concentration (%N).

As mentioned in the introduction, determining Chl and/or N post anthesis could be useful to estimate the in-field senescence variations of crops (crop drying patterns), which might be indicative of yield and crop quality conditions. Spatial variations of senescence within fields can potentially be mapped and used as additional information for the delineation of harvesting zones. Figure 3 illustrates an example of a map of YEL values at the field, where winter wheat was sown (31st July), potentially depicting senescence patterns within this field. In the map, areas coded with red and yellow colors are relatively low in Chl and N, and therefore, most likely to be in a more advanced senescence state compared to areas marked by green colors (relatively high Chl and N concentration). For comparison, the corresponding RGB image is displayed below the map.

CONCLUSION

Results of this preliminary study demonstrated that RapidEye's Tasseled Cap Feature YEL offers great potential for the prediction of senescent crop biophysical parameters. YEL and PSRI showed strong linear relationships to the Chl concentration in senescent wheat. However, the prediction power and accuracy of YEL was greater for winter wheat, while for spring wheat, PSRI provided better results. PSRI was a better estimator of Chl at the pooled data set, where winter and spring wheat was combined. For the prediction of N in senescent crops, YEL outperformed PSRI, showing statistically significant, strong correlations, while PSRI provided only moderate or non-significant relationships. Results indicated that the correlation of YEL and PSRI to Chl and N might be non-linear, suggesting that quadratic functions can yield higher prediction

accuracies. Altogether, results indicated that YEL seems to provide similar, if not better estimations of Chl and N in senescent wheat.

Results demonstrated the capability of YEL to predict both Chl and N concentration, which can probably be attributed to the additional information provided by the Red-edge band. This makes RapidEye a useful tool for understanding and mapping the variability of Chl or N concentrations, and senescence patterns within individual fields. In conjunction with soil fertility and yield maps, senescence patterns might aid in the assignment of precision harvesting zones related to yield and wheat quality parameters.

Further studies on the relationship between YEL and Chl and N concentration are needed to corroborate these results, and make them extensive to other crop types or cultivars. Furthermore, research should be focused on in-field senescence pattern variations, microclimatic conditions, and their impact on the amount of yield and yield quality parameters.

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