Field Crops Research 210 (2017) 33–46

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Retrieving LAI, chlorophyll and nitrogen contents in sugar beet crops from multi-angular optical remote sensing: Comparison of vegetation indices and PROSAIL inversion for field phenotyping

Sylvain Jay[a,b,*], Fabienne Maupas[c], Ryad Bendoula[a], Nathalie Gorretta[a]

[a] Irstea, UMR ITAP, 361 rue J.F. Breton, 34196 Montpellier, France
[b] Aix Marseille Univ, CNRS, Centrale Marseille, Institut Fresnel, F-13013 Marseille, France
[c] Institut Technique de la Betterave, 45 rue de Naples, 75008 Paris, France

ARTICLE INFO

Keywords:
Chlorophyll and nitrogen contents
Field phenotyping
Leaf area index
Multi-angular optical remote sensing
Sugar beet

ABSTRACT

Remote sensing has gained much attention for agronomic applications such as crop management or yield estimation. Crop phenotyping under field conditions has recently become another important application that requires specific needs: the considered remote-sensing method must be (1) as accurate as possible so that slight differences in phenotype can be detected and related to genotype, and (2) robust so that thousands of cultivars potentially quite different in terms of plant architecture can be characterized with a similar accuracy over different years and soil and weather conditions. In this study, the potential of nadir and off-nadir ground-based spectro-radiometric measurements to remotely sense five plant traits relevant for field phenotyping, namely, the leaf area index (LAI), leaf chlorophyll and nitrogen contents, and canopy chlorophyll and nitrogen contents, was evaluated over fourteen sugar beet (*Beta vulgaris* L.) cultivars, two years and three study sites. Among the diversity of existing remote-sensing methods, two popular approaches based on various selected Vegetation Indices (VI) and PROSAIL inversion were compared, especially in the perspective of using them for phenotyping applications.

Overall, both approaches are promising to remotely estimate LAI and canopy chlorophyll content (RMSE $\leq$ 10%). In addition, VIs show a great potential to retrieve canopy nitrogen content (RMSE = 10%). On the other hand, the estimation of leaf-level quantities is less accurate, the best accuracy being obtained for leaf chlorophyll content estimation based on VIs (RMSE = 17%). As expected when observing the relationship between leaf chlorophyll and nitrogen contents, poor correlations are found between VIs and mass-based or area-based leaf nitrogen content. Importantly, the estimation accuracy is strongly dependent on sun-sensor geometry, the structural and biochemical plant traits being generally better estimated based on nadir and off-nadir observations, respectively. Ultimately, a preliminary comparison tends to indicate that, providing that enough samples are included in the calibration set, (1) VIs provide slightly more accurate performances than PROSAIL inversion, (2) VIs and PROSAIL inversion do not show significant differences in robustness across the different cultivars and years. Even if more data are still necessary to draw definitive conclusions, the results obtained with VIs are promising in the perspective of high-throughput phenotyping using UAV-embedded multispectral cameras, with which only a few wavebands are available.

1. Introduction

Over the last few years, sugar beet (*Beta vulgaris* L.) has received much attention for either sugar or biofuel productions. It is a credible alternative to sugarcane and therefore, increasing the crop yield by creating new cultivars, e.g., requiring less nitrogen fertilization, or having a better light use efficiency, is currently investigated. However, cultivar selection requires a deep understanding of how the plant genetic makeup (genotype) relates to the observable plant traits (phenotypes), and how the genes express themselves in a given environment (Furbank and Tester, 2011). Significant advances in genomics and gene technology have been done in the past decades, thus making in-field high-throughput phenotyping one of the major bottlenecks in plant breeding (Comar et al., 2012; Furbank and Tester, 2011; Montes et al., 2007). As phenotypes must be characterized over time, non-destructive techniques have to be developed. In this context, using optical remote

* Corresponding author at: Irstea, UMR ITAP, 361 rue J.F. Breton, 34196 Montpellier, France.
E-mail address: sylvain.jay@fresnel.fr (S. Jay).

http://dx.doi.org/10.1016/j.fcr.2017.05.005
Received 3 January 2017; Received in revised form 28 March 2017; Accepted 7 May 2017
0378-4290/

sensing has proven to be powerful to accurately estimate plant traits describing the canopy structure, e.g., plant height, green fraction, leaf area index (LAI), and the leaf biochemistry, e.g., chlorophyll and nitrogen contents (Comar et al., 2012; Jay et al., 2015; Thorp et al., 2015). An accurate retrieval of such structural and biochemical parameters is critical for plant phenotyping. For example, chlorophyll content was recently suggested to be positively correlated to sugar beet yield, as an increase in chlorophyll content may result in a higher photosynthetic assimilation and a greater production of biomass (Loel et al., 2014). Also, as nitrogen is one of the most important limiting key nutrients, it is essential to better understand how genotypes differ in the use of nitrogen sources so as to optimize nitrogen fertilization. Indeed, besides being harmful to the environment, an excessive fertilization leads to an overproduction of leaves, which does not increase significantly radiation interception. Furthermore, sugar accumulation is inversely related to nitrogen uptake (Werker et al., 1999). On the other hand, nitrogen deficiency affects leaf expansion (Milford et al., 1985), thus decreasing photosynthetic assimilation and crop yield. Therefore, a compromise has to be reached. To our knowledge, the potential of optical remote sensing for field phenotyping of sugar beet plant traits has not been explored yet, and is investigated in this study.

Multi-angular optical observations offer a great potential to achieve the required accuracy for the remote sensing of structural and biochemical crop properties for field phenotyping. Indeed, the incoming radiation in the optical domain strongly interacts with vegetation through absorption and scattering processes both at the leaf scale (Jacquemoud and Baret, 1990) and the canopy scale (Verhoef, 1984), the reflected radiation thus containing valuable information about the scene of interest. Furthermore, the use of several viewing configurations (independently or jointly) can potentially improve the retrieval accuracy when compared to using a single nadir observation (Dorigo, 2012; Duan et al., 2014; Hilker et al., 2011; Song et al., 2016; Yang et al., 2011) since the sun-sensor geometry may strongly affect the canopy reflectance sensitivity to the targeted parameter(s) (Jacquemoud et al., 2009). In fact, the anisotropy of canopy reflectance closely relates to the physical properties and geometrical arrangement of vegetation elements (Widlowski et al., 2004). Multi-angular measurements thus provide complementary sources of information to characterize the structure and biochemistry of crop canopies in a more robust and accurate way, especially if these canopies have a complex 3D structure and intermediate density (Dorigo, 2012). As a result, exploring the anisotropy of the reflectance of row-structured sugar beet canopies seems promising to obtain a high estimation accuracy as required for cultivar selection and other agronomic applications, e.g., crop management or yield prediction.

Numerous methods have been developed to extract canopy properties from (mono- or multi-angular) remotely sensed spectral data (Baret and Buis, 2008; Dorigo et al., 2007; Verrelst et al., 2015). Statistical approaches based on vegetation indices (VIs) are very popular due to their simplicity, robustness and accuracy in retrieving targeted variables. These VIs have been designed in such a way that features of interest are enhanced while undesired effects are minimized. The high spectral resolution provided by current sensors allows computing narrow-band VIs that can detect subtle changes in reflectance, e.g., the red-edge position that relates to both the LAI and leaf chlorophyll content (Cho and Skidmore, 2006; Clevers and Kooistra, 2012; Guyot and Baret, 1988). These VIs can be used to estimate either structural properties such as LAI (Darvishzadeh et al., 2011; Haboudane et al., 2004) and green fraction (Comar et al., 2012), or biochemical properties such as leaf chlorophyll content (Zarco-Tejada et al., 2004) and leaf water content (Colombo et al., 2008). However, interactions between biochemical and structural canopy parameters (e.g., LAI and leaf chlorophyll content) may add some uncertainties in the retrieval, the measured signal not only depending on the leaf biochemistry but also on the amount of leaves within the sensor field of view (Baret et al., 2007; Colombo et al., 2008). Alternatively, canopy integrated biochemical parameters (obtained by multiplying the leaf biochemical content by the LAI) can generally be estimated more accurately (Clevers and Kooistra, 2012; Colombo et al., 2008; Darvishzadeh et al., 2011; Jacquemoud et al., 1995), while still representing physically-sound quantities (Baret et al., 2007). Interestingly, the correlation between chlorophyll and nitrogen contents makes it possible to use chlorophyll VIs for quantifying the nitrogen status of crops (Clevers and Gitelson, 2013; Clevers and Kooistra, 2012; Schlemmer et al., 2013). However, differences occur between different crops: while Xu et al. (2014), He et al. (2016a,b) have reported strong correlations between VIs and leaf nitrogen content in winter wheat and barley, poor correlations were obtained by Li et al. (2016) in litchi orchards. This suggests that further studies are necessary to evaluate the potential of VI-based remote sensing to retrieve nitrogen content in sugar beet cultivars.

The use of such statistically-based methods may, however, be not fully optimal for phenotyping applications, since the latter necessitates robust remote-sensing methods that can adapt to potentially strongly different plant architectures and characterize thousands of cultivars with a similar accuracy (the huge amount of tested cultivars obviating the possibility of including all of them in the calibration data set). Alternatively, inverting radiative transfer models may appear as a more robust approach to characterize different sugar beet canopies. These physically-based models simulate light propagation within the canopy as a function of leaf and soil properties, canopy structure and sun-sensor geometry. Whenever possible, model inversion allows for the retrieval of targeted variables based on iterative optimization, look-up tables, statistically-based methods or machine learning algorithms (Baret and Buis, 2008), and provides a valuable physical understanding of interactions occurring between light and vegetation. PROSAIL (Baret et al., 1992; Jacquemoud et al., 2009) is one of the most widely used models, especially because it offers a good compromise between realism and simplicity (Verger et al., 2014) and because it is freely available to the community. PROSAIL simulates the canopy reflectance by combining the PROSPECT (Leaf Optical Properties Spectra) model of leaf optical properties (Jacquemoud and Baret, 1990) and the SAIL (Scattering by Arbitrarily Inclined Leaves) canopy reflectance model (Verhoef, 1984, 1985). Importantly, SAIL has been designed for homogeneous canopies, so it is theoretically not well suited for modeling discontinuous crop rows. A number of studies have, however, shown that reasonable estimations of leaf and canopy chlorophyll contents and LAI could be achieved for such vegetation arrangements (Dorigo, 2012; Duan et al., 2014; Jacquemoud et al., 1995).

In this study, we compare two popular remote-sensing approaches, i.e., VIs and PROSAIL inversion, based on their abilities to remotely sense the LAI as well as the leaf and canopy chlorophyll contents in sugar beet crops under field conditions. In addition, the potential of VIs for retrieving leaf and canopy nitrogen contents is investigated. Special attention is paid to the potential of the above two approaches in providing accurate and robust performances, as necessary for phenotyping applications. The considered spectral measurements are ground-based, which allows higher spatial and temporal resolutions as compared with satellite or aircraft measurements. A high revisit frequency is particularly attractive for agronomic and phenotyping applications because crop characterization may be required over a short critical period (Inoue et al., 2012).

2. Materials and methods

2.1. Field experiments

Field experiments were conducted in France during the 2015 and 2016 growing seasons. Three study sites with different soil properties were considered (Fig. 1). The "La Selve" (49°35′N, 4°01′E, denoted site 1) and "Barenton" (49°37′N, 3°39′E, denoted site 3) sites were characterized by different loamy soils, whereas the "Vaucogne" site (48°31′N, 4°21′E, denoted site 2) was characterized by a chalky soil.