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Remotely sensed green area index for winter wheat crop monitoring: 10-Year assessment at regional scale over a fragmented landscape

Grégory Duveiller[a,b,*], Frédéric Baret[c], Pierre Defourny[b]

[a] European Commission Joint Research Centre, Via Fermi 2749, Ispra (VA), Italy
[b] Earth and Life Institute, Université Catholique de Louvain, 2/16 Croix du Sud, B-1348 Louvain-la-Neuve, Belgium
[c] Environnement Méditerranéen et Modélisation des Agro-Hydrosystèmes (EMMAH), INRA-UMR 1114, Domaine Saint-Paul, Site Agroparc, 84914 Avignon, France

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ABSTRACT

Despite remarkable technological advances in earth observation systems and radiative transfer modelling, enabling the retrieval of canopy biophysical variables from satellite imagery, the use of remote sensing for operational crop monitoring at a regional or global scale has remained more qualitative than quantitative. One of the main reasons lies in the fact the imagery that can be used operationally and economically over large areas with high temporal frequency have coarse spatial resolution. However, recent research has demonstrated that coherent crop specific biophysical variables such as green area index (GAI) can be retrieved from medium spatial resolution imagery such as MODIS even when the size of the fields is close to the size of the pixels (close to 250 m). Leveraging on these results, the present paper attempts to go beyond by retrieving GAI from a more fragmented landscape, over a much larger geographical area and covering a 10-year period. Results demonstrate the possibility to monitor the dynamic processes of growth and senescence of winter wheat and grasp the inter-annual seasonal variability of growing conditions encountered over a decade. Furthermore, the satellite-derived GAI is not only consistent with ground measurements at regional scale (RMSE = 0.65 m^2/m^2, RRMSE = 25.7%), but even shows encouraging results at field level (RMSE = 0.82 m^2/m^2, RRMSE = 37.6%, when pixel/field spatial adequacy is high). By showing the possibility of monitoring crop specific growth quantitatively over a complicated landscape, the major step necessary before implementing such approach in operational situation remains identifying early in the season where the target crop is.

1. Introduction

Monitoring agricultural production at national, regional and global scale is at the core of modern economic, geostrategic and humanitarian concerns. Recent years have witnessed an increased demand for timely, accurate and comprehensive information on global crop production. As outlined by Justice and Becker-Reshef (2007), such information can help to anticipate production shortages and surpluses, thereby calming down speculation and reducing short-term price instability. Timely information about potential and observed harvest can hasten early identification of problem areas and help to organize and optimize food supplies and/or market support. Recording persistent shortfalls can stimulate policies to prioritize efforts towards ameliorating vulnerable agricultural systems. Monitoring agricultural systems with a longer temporal record can help to identify changes in production and evaluate the resilience of agricultural systems and their sustainability for the farmers, particularly against the threat of increasingly variable climatic conditions.

Forecasting crop yields generally relies on understanding how crops are responding to the growing conditions which they are subjected to during the current year. Meteorology plays a key role since the main drivers determining crop yield are solar radiation, temperature and precipitations. Lobell and Field (2007) showed how a significant part of the global year-to-year variation of yield in the recent past (since 1981) can be related to simple measures of growing season temperatures and precipitation. Statistical relationships between weather and yield can indeed provide simple forecasting tools based on a small amount of explanatory variables. However, the processes of crop growth and development that ultimately result in yield are not only dependent on weather, but on a complex dynamic and non-linear interaction between weather, genetics, soil, management practices and diseases. Building up on decades of research and experimental trials, processed-based models such as CERES (Ritchie and Otter, 1985), WOFOST (van Diepen et al., 1989), STICS (Brisson et al., 1998) and CropSyst (Stöckle et al., 2003), have been developed to emulate crop growth and development

* Corresponding author at: European Commission Joint Research Centre, Via Fermi 2749, Ispra (VA), Italy. Tel.: +39 033278 9161; fax: +39 033278 3033.
E-mail address: gregory.duveiller@jrc.ec.europa.eu (G. Duveiller).

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with success at local scale. But applying such models over large geographic extents is compromised by their important requirements in input data (e.g. soil condition, management practices, etc.) and the difficulty to calibrate their large number of parameters. Despite these problems and the resulting uncertainty on the simulations, these models can be used operationally as indicators of crop status which can be statistically related to past yields. This strategy is used in the MARS Crop Yield Forecasting System (MCYFS) of the European Commission's Joint Research Centre which relies on a combination of meteorological and remote sensing observations, agro-meteorological modelling and statistical analysis tools to provide timely forecast on crop status and yields over Europe (Micale and Genovese, 2004; Lazar and Genovese, 2004; Royer and Genovese, 2004; Genovese and Bettio, 2004).

Satellite remote sensing provides a complementary source of information for crop monitoring. The spectral properties of green canopies, with absorption of red and blue light by chlorophyll and the high scattering of near-infrared (NIR) wavelengths, are directly linked to photosynthesis, stomatal resistance and evapotranspiration, thereby facilitating the retrieval of information regarding crop status from the electromagnetic signal measured by satellite remote sensing instruments (Tucker and Sellers, 1986). The LACIE experiment (MacDonald and Hall, 1980) and the AgRISTARS program (Boatwright and Whitehead, 1986) pioneered in the use of this technology for estimating crop production in the early days of remote sensing. A pragmatic way of resuming the information available in the various spectral bands provided by the satellite is to combine them algebraically into spectral vegetation indices, such as the Normalized Difference Vegetation Index or NDVI (Rouse et al., 1973), designed to be sensitive to vegetation status while minimizing the effect of perturbing factors (such as the sun zenithal angle or the effect of the atmosphere). Indices based on red and NIR reflectance such as the NDVI have been shown to be a measure of chlorophyll abundance and energy absorption (Myneni et al., 1995). Vegetation indices are convenient but have many limitations. The advent of canopy radiative transfer modelling, with canopy models such as SAIL (Verhoef, 1984) coupled to leaf models such as PROSPECT (Jacquemoud and Baret, 1990), opened the way to retrieve quantitatively canopy biophysical variables from remote sensing observations using a physical basis. Examples of such biophysical variables include the fraction of Absorbed Photosynthetically Active Radiation (fAPAR) or the Leaf Area Index (LAI), defined as half the total developed area of green leaves per unit of ground horizontal area (Chen and Black, 1992). In fact, for crops such as cereals in which all main aerial plant organs (leaves, stems, ears) are green and photosynthetically active during a significant fraction of the growth cycle, it is more appropriate to use the term of green area index (GAI), instead of LAI, to refer to the biophysical variable retrieved from remote sensing since the radiance measured by the instrument is made of electromagnetic radiation reflected from all plant organs while the retrieved variables are mainly sensitive to the green elements (Duveiller et al., 2011b). Since LAI (or GAI) is a state variable in many process-based models, this biophysical variable can used to couple remote sensing and crop growth modelling using data assimilation techniques (see Dorigo et al. (2007) for a review). Currently, most studies that have successfully coupled crop growth with remote sensing have used high spatial resolution data to retrieve biophysical variables (Bouman, 1992; Clevers et al., 1994; Prévot et al., 2003; Verhoef and Bach, 2003; Boegh et al., 2004; Launay and Guerif, 2005; Hadria et al., 2010). However, these apply only to a limited number of fields at local scale. Some studies have attempted to address the regional scale using coarser spatial resolution to derive biophysical variables, but to do so they have focused either on agricultural landscapes which are relatively homogeneous (Bastiaanssen and Ali, 2003; Mo et al., 2005; Doraiswamy et al., 2005; Patel et al., 2006; Fang et al., 2008) or over a limited geographical area (Dente et al., 2008; Vazifedoust et al., 2009).

Despite remarkable technological advances in earth observation systems and major theoretical breakthroughs in radiative transfer modelling, crop growth modelling and data assimilation, the use of remote sensing for crop monitoring at a regional or global scale has not evolved significantly since the early days of LACIE and AgRISTARS. Perhaps one of the main reasons lies in the fact the imagery that can be used operationally and economically over large areas with high temporal frequency have a spatial resolution that is too coarse and which hardly matches the technical requirements (Duveiller and Defourny, 2010). However, Duveiller et al. (2011a) derived a coherent crop specific signal from 250 m MODIS daily imagery, retrieved using a physically based approach, that can describe the regional crop specific dynamics. This was done by controlling the degree at which the observation footprints of the coarse pixels fall within the crop-specific mask delineating the target.

This paper attempts to go beyond by testing the approach proposed by Duveiller et al. (2011a) to retrieve green area index (GAI) on a different landscape, over a larger area and over several years. The result is validated with ground measurements at field and regional level. The capacity to grasp the inter-annual seasonal variability of crop growth conditions is also assessed. Its value as a crop specific indicator of growing conditions is demonstrated by comparing it to indicators produced in the MCYFS operational system.

2. Materials and methods

2.1. Study site

This study aims to have a regional scope. The study site consists of the Walloon administrative region in Belgium (see Fig. 1). The choice of this site was largely driven by the fact that the regional government of the Walloon region builds every year a vector database, known as the SIGEC (*Système Intégré de Gestion et de Contrôle*) database, indicating what crop has been sown on every field on that year. This database was available for every year within the period 2000–2009 and it is used in this study to create a yearly crop mask of the studied crop: winter wheat (*Triticum aestivum* L.). Some numbers might be useful to provide an indication of the extent of the studied wheat area: for the year 2007 the study zone contains a total of 35,566 winter wheat fields, which have a cumulated area of about 129,000 ha and whose field sizes range from 0.02 to 52.96 ha with a mean area of 3.62 ha. These figures slightly underestimate the area of contiguous winter wheat cover which can be larger when the same crop is sown on adjacent fields. Since the scale of interest is the region (and not the field) this notion of continuous winter wheat cover is the main surface of interest in this study. This assumes that local spatial variations in management practices such as sowing dates and choice of varieties, can be neglected. Within this administrative region, two main agro-ecological regions exist over which winter wheat is one of the dominant crops: the *Région Limoneuse* and the *Condroz* (see Fig. 1). These agro-ecological regions are characterized by different landscape structure, soil types, agricultural management and (to a certain extent) climatic conditions.

2.2. Ground GAI measurements

A ground GAI dataset has been generated from measurements collected during the growing seasons of 2007 and 2009 in the framework of the GLOBAM project supported by the Belgian Scientific Policy. The spatial location of the visited fields is displayed in Fig. 1. For both field campaigns, the measurement protocol is slightly different and they do not cover the same agro-ecological