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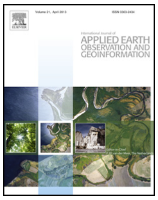

Estimating inter-annual variability in winter wheat sowing dates from satellite time series in Camargue, France

Giacinto Manfron[a,*], Sylvestre Delmotte[b], Lorenzo Busetto[a], Laure Hossard[b], Luigi Ranghetti[a], Pietro Alessandro Brivio[a], Mirco Boschetti[a]

[a] *IREA CNR, Institute for Electromagnetic Sensing of the Environment, Italian National Research Council, Via Corti 12, Milan, Italy*
[b] *INRA UMR0951 Innovation, French National Institute for Agricultural Research, 2 Place Pierre Viala, 34060 Montpellier Cedex 2, France*

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ABSTRACT

Crop simulation models are commonly used to forecast the performance of cropping systems under different hypotheses of change. Their use on a regional scale is generally constrained, however, by a lack of information on the spatial and temporal variability of environment-related input variables (e.g., soil) and agricultural practices (e.g., sowing dates) that influence crop yields. Satellite remote sensing data can shed light on such variability by providing timely information on crop dynamics and conditions over large areas. This paper proposes a method for analyzing time series of MODIS satellite data in order to estimate the inter-annual variability of winter wheat sowing dates. A rule-based method was developed to automatically identify a reliable sample of winter wheat field time series, and to infer the corresponding sowing dates. The method was designed for a case study in the Camargue region (France), where winter wheat is characterized by vernalization, as in other temperate regions. The detection criteria were chosen on the grounds of agronomic expertise and by analyzing high-confidence time-series vegetation index profiles for winter wheat. This automatic method identified the target crop on more than 56% (four-year average) of the cultivated areas, with low commission errors (11%). It also captured the seasonal variability in sowing dates with errors of ±8 and ±16 days in 46% and 66% of cases, respectively. Extending the analysis to the years 2002–2012 showed that sowing in the Camargue was usually done on or around November 1st (±4 days). Comparing inter-annual sowing date variability with the main local agro-climatic drivers showed that the type of preceding crop and the weather conditions during the summer season before the wheat sowing had a prominent role in influencing winter wheat sowing dates.

1. Introduction

The management of agricultural systems in European regions varies considerably in space and time due to differences in environmental conditions (e.g., pedo-climatic conditions), available technologies (e.g., crop varieties), agricultural policies (e.g. subsidies, environmental regulations), and market prices (Bakker et al., 2005; Dury et al., 2012; Pettorelli et al., 2005). Monitoring and understanding the diversity and dynamics of agricultural systems on a regional scale is crucial to support their evolution towards a more sustainable future (Zheng et al., 2012).

Various tools and approaches can be adopted to monitor agricultural systems and support their adaptation (Basso et al., 2013), including crop simulation models, which are commonly used to understand the current performance of cropping systems, and to predict future trends under different hypotheses of change (Soltani et al., 2016). These hypotheses may relate to: (1) the development and adoption of new crop varieties more resistant to diseases or thermal stresses, or hybrids, for instance (Bregaglio and Donatelli, 2015; Webber et al., 2016); (2) new cropping systems, such as direct seeding, intercropping, or agroforestry (Khaledian et al., 2009; Miao et al., 2016; van der Werf et al., 2007); and (3) the impact of climate change on cropping systems, and consequent adaptation strategies, such as changing the sowing dates (Holzkämper et al., 2015; Nendel et al., 2014).

When simulating the future of cropping systems, particularly on a regional scale, a key issue concerns the availability of appropriate information on crucial crop cultivation variables to be provided as input in crop models (Moulin et al., 1998; Therond et al., 2011; Yuping et al., 2008). Retrieving details on crop management is

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* Corresponding author.
E-mail address: manfron.g@irea.cnr.it (G. Manfron).

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often challenging (Clavel et al., 2011; Jiang et al., 2014) because they vary considerably within and between regions, and year by year (Therond et al., 2011; Vyas et al., 2013; Yuping et al., 2008). Among the possible sources of information, censuses conducted by governmental agencies or regional institutions provide aggregated data that may not be detailed enough for crop modelling purposes (Grassini et al., 2015). Data coming from interviews with farmers are more complete, but limited in number and related to a given year, so they are not always sufficiently representative of the spatial and temporal diversity of a region (Chen et al., 2002). The sowing date is an essential information to the accuracy of simulations obtained with crop models (Folberth et al., 2012; Van Wart et al., 2015). For most crops, the sowing date is crucial to explain crop performance variables, such as yield (Delmotte et al., 2011; Kogan et al., 2013). Sowing date variability can span several months for some plant species, depending on the inter-annual climate variability in the region and on local agricultural practices.

In this setting, analyzing long-term time series of satellite images is an efficient way to elucidate inter- and intra-annual sowing date variability (Bradley et al., 2007; Guyet and Nicolas, 2015). Earth Observation satellite data archives can be used to estimate this variable as they provide regular and synoptic information on crop characteristics (Justice et al., 2002; Kumar and Monteith, 1981; Rembold et al., 2013). In particular, time series of spectral vegetation indexes (VIs), such as the Enhanced Vegetation Index (EVI) (Huete et al., 2002), can be used to characterize vegetation dynamics and retrieve information on key phenological stages by various means, such as thresholding, curve fitting, derivatives' analysis, etc. (Curnel and Oger, 2007). This approach was first used to monitor natural ecosystems and is often termed land surface phenology (LSP) (Ganguly et al., 2010).

Many studies have focused on estimating the timing of crop phenological stages like emergence, flowering or senescence, for example (e.g. Sakamoto et al., 2005; Boschetti et al., 2009; Manfron et al., 2012; Pan et al., 2015). In agricultural applications, a further and more challenging step is to use the same approach to investigte more specific information about farming practices. For instance, agricultural flooding and the duration of rice paddy flooding were investigated by Sakamoto et al. (2007) and by Ranghetti et al. (2016), while crop management practices such as forage cutting were examined by Halabuk et al. (2015).

As claimed by (Jin et al. (2016) it is generally accepted that this is virtually impossible to detect sowing dates on the basis of remote sensing data alone as there is a period after crop sowing and before crop emergence in which the crop cannot be detected with remote sensing. Sowing dates must therefore be inferred from satellite data on the basis of crop- and region-specific assumptions. Successful applications can be found for rice sown/transplanted in flooded fields because the presence of the water prior to any vegetative growth can be detected on satellite images (Sakamoto et al., 2005; Boschetti et al., 2015b).

For other crops, previous studies often focused on identifying the so-called "green-up" date (i.e., coinciding with the earliest reliable evidence of vegetation on satellite images), from which sowing dates could be inferred using various methods. In an application for monitoring wheat in northern India, Lobell et al. (2013) assumed that green-up coincided with crop emergence and calculated sowing dates by going back a fixed time (three weeks) from this date. Green-up was established as the point where the curve fitted to the VIs reached 10% of its maximum amplitude for the year in question. A similar approach was taken by Vyas et al. (2013) in the same geographical area, exploiting daily normalized difference VI (NDVI) produced by the Indian geostationary satellite INSAT 3A CCD. Green-up was identified using a threshold method and the sowing date was set at 7 days prior to green-up. These methods proved efficient for the subtropical areas of northern India, where wheat is sown between October and November, then undergoes a rapid, monotonic increase in biomass up to the flowering phase, and the total growing period lasts from 100 to 170 days.

In temperate climates, winter wheat is sown in autumn and takes from 180 to 300 days to mature (Asseng et al., 2012). After emerging, winter wheat undergoes a tillering stage, then requires a period of cold for up to 90 days (until the end of winter), during which it remains dormant. This is followed by a rapid stem elongation and subsequent plant growth. Hence the "double hump" pattern observed in winter wheat time series by Pan et al. (2012) and by Chu et al. (2016), makes it rather difficult to use the previously mentioned solutions based on identifying green-up and then backtracking a fixed number of days to estimate the sowing date. The green-up typically detectable from coarse-resolution satellite data relates to the post-dormancy vegetative phase, and the duration of the dormancy period varies both spatially and temporally, depending on crop variety, for instance, and winter weather conditions.

Jin et al. (2016) analyzed winter wheat in Shanxi province (China), based on images with a 30 m resolution acquired every two days by the HJ-1 a/b multispectral sensor. They could identify two green-up times, one after sowing (before dormancy), and another more robust one preceding the head development phase. They were thus able to estimate winter wheat sowing dates by applying the relation proposed by Lobell et al. (2013) to the first green-up identified. This was made possible by their use of data with a very high spatial and temporal resolution. Such data are not readily available worldwide and none dating back long enough for use it in medium- to long-term analyses. The feasibility of reliably detecting the weaker green-up preceding dormancy is however not demonstrated, particularly when moderate-resolution satellite data are used.

Employing the same satellite data, Pan et al. (2015) used metrics derived from NDVI signals to map the phenological stages of winter and summer crops in China. These authors estimated only the green-up after dormancy for winter wheat, without retrieving sowing dates.

Based on this literature review, we decided to develop a specific algorithm to estimate winter wheat sowing dates in temperate climates from moderate-resolution satellite data. The study was conducted in the Camargue region (France). Durum wheat sowing conditions vary greatly in this region, influenced by environmental conditions, agricultural practices and subsidies, and sowing may take place in appropriate conditions over a time frame of about ten weeks (Mouret J.C., pers. comm., Dec. 5, 2015). No data are currently available on the local intra- and inter-annual variability of winter wheat sowing dates, but this variability needs to be analyzed, and the factors influencing the timing of this operation need to be clarified in order to improve the crop models used to characterize the present conditions and simulate future scenarios (including e.g., climate change). In this context, the aims of the present study are twofold: (1) developing an approach based on remote sensing capable of identifying a robust sample of areas where winter wheat is grown from MODIS time series with a 250 m spatial resolution, and estimating the corresponding sowing dates; (2) analyzing the inter-annual variability of winter wheat sowing dates in the Camargue over the years 2002–2012 in relation to meteorological and anthropic drivers.

2. Materials and methods

The study involved three main phases to develop, apply and validate the proposed method (Fig. 1). MODIS data were first preprocessed and representative temporal crop signatures were extracted by exploiting reference information (Sections 2.2.1 and