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Estimation of corn yield using multi-temporal optical and radar satellite data and artificial neural networks

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ABSTRACT

The yield forecasting of corn constitutes a key issue in agricultural management, particularly in the context of demographic pressure and climate change. This study presents two methods to estimate yields using artificial neural networks: a *diagnostic approach* based on all the satellite data acquired throughout the agricultural season, and a *real-time approach*, where estimates are updated after each image was acquired in the microwave and optical domains (Formosat-2, Spot-4/5, TerraSAR-X, and Radarsat-2) throughout the crop cycle. The results are based on the Multispectral Crop Monitoring experimental campaign conducted by the CESBIO (Centre d'Études de la BIOsphère) laboratory in 2010 over an agricultural region in southwestern France. Among the tested sensor configurations (multi-frequency, multi-polarization or multi-source data), the best yield estimation performance (using the *diagnostic approach*) is obtained with reflectance acquired in the red wavelength region, with a coefficient of determination of 0.77 and an *RMSE* of 6.6 q ha^{-1}. In the *real-time approach* the combination of red reflectance and C_{HH} backscattering coefficients provides the best compromise between the accuracy and earliness of the yield estimate (more than 3 months before the harvest), with an R^2 of 0.69 and an *RMSE* of 7.0 q ha^{-1} during the development of the central stem. The two best yield estimates are similar in most cases (for more than 80% of the monitored fields), and the differences are related to discrepancies in the crop growth cycle and/or the consequences of pests.

1. Introduction

During the last fifty years, the world production of corn has increased at a rate of approximately 13 million tons per year, exceeding 1 billion tons in 2013 (FAO, http://faostat.fao.org/). To produce this amount, the area allocated to cultivation has regularly increased (by more than 1 million hectares per year), making corn the second most abundant crop in terms of area (after wheat). In France, corn is one of the main crops cultivated from spring to autumn, particularly in the Languedoc-Roussillon-Midi-Pyrénées region, where the yields observed during the 15 past years are comparable to those observed across the country (according to the statistics of the Direction Régionale de l'Alimentation, de l'Agriculture et de la Forêt, DRAAF). Many studies have demonstrated the usefulness of satellite images for agricultural purposes, taking advantage of both extensive coverage and regular revisits to map land use (McNairn et al., 2014), to detect irrigation (Fieuzal et al., 2011), to estimate biomass (Claverie et al., 2012; Battude et al., 2016) and to survey crop health (Yang et al., 2015). Nevertheless, the early monitoring of crops remains limited, and the few studies addressing this topic are focused on crop mapping (McNairn et al., 2014; Marais Sicre et al., 2016), while estimates of yield are usually obtained once the harvest has been done or by using in situ agronomic approaches, which are limited by their spatial sampling (Kalluri et al., 2003).

Remote sensing studies addressing the monitoring of crop phenology are mainly based on images acquired in the visible and near-infrared wavelengths. These data are often used to calculate vegetation indices, such as the normalized difference vegetation index (NDVI, Rouse et al., 1974) and other vegetation indices (Haboudane et al., 2004), which are mainly linked to the leaf area index (LAI) or to the fraction of absorbed photosynthetically active radiation (Asrar et al., 1984; Baret and Guyot, 1991). The main limitations of these approaches are related to the properties of optical images (almost unusable in conditions of heavy cloud cover). In the microwave domain, studies have demonstrated the application of radar data for crop monitoring, in particular the contribution of the multi-frequency, multi-polarization and/or multi-incidence aspects (Fieuzal et al., 2013; Fieuzal and Baup, 2016; Larranaga et al., 2013; Moran et al., 2012), such as the opportunities offered by

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the polarimetric and/or interferometric indices (Baup et al., 2016; Betbeder et al., 2016b; Lopez-Sanchez et al., 2012; Yang et al., 2014). The main limitations of using backscattering coefficients are their sensitivity to soil parameters (*i.e.,* top soil moisture and roughness when vegetation is sparse) and the difficulty to constitute dense image series. Recently, multiple satellite missions (like Sentinel) have enabled the acquisition of regular Earth observations, providing quasi-synchronous optical and radar images that are useful to the understanding and comparison of the sensitivities of remote sensing signals.

Regardless of the spectral domain (*i.e.,* optical or microwave), previous studies have taken advantage of the temporal dynamics of signals to estimate yield by assimilating crop parameters (*e.g.,* LAI or crop biomass) derived from satellite images into crop models (Betbeder et al., 2016a; Fieuzal et al., 2016; Dempewolf et al., 2014; Dente et al., 2008; Duchemin et al., 2015; Kouadio et al., 2014; Rinaldi et al., 2013; Xin et al., 2013; Battude et al., 2016; Claverie et al., 2012). In these approaches, the accuracy is closely linked to the errors associated with the inversion of the intermediate assimilated parameter, in order to limit the multiplicative bias on the final variable. Other approaches based only on ground measurements enable direct monitoring of specific crop parameters and yield prediction by training statistical algorithms on the field data (Martin et al., 2012; Sharma and Franzen, 2014; Yin et al., 2011; Yin et al., 2012). The representativeness of the collected dataset often limits the application of these empirical approaches at the regional or larger scale, the range of validity being specific to the observed agricultural practices and environmental conditions. Among the wide range of statistical algorithms, artificial neural networks (ANN) offer the major advantage of improved prediction capability (with significantly better performance than multiple linear regressions, Lek et al., 1996), especially when relations are complex (as in the case of yield, which is related to variety, cultural practices, and climatic and edaphologic conditions). The prediction capabilities of ANN have been used in many fields (Lek and Guegan, 1999; Svozil et al., 1997), and their combination with the capabilities of Earth observation satellites is promising for land mapping and surface parameter retrieval (Villmann et al., 2003; Rodriguez-Fernandez et al., 2015).

The objective of this study is thus to take advantage of dense satellites series acquired in the optical and microwave domains over corn to estimate and forecast yields using a statistical method (ANN).

2. Materials

2.1. Study area

The study area is located in southwestern France near Toulouse (Fig. 1), a 420 km^2 area centered on the coordinates: 43°29′36”N, 01°14′14”E. The network of monitored fields is located in the alluvial plain near the meteorological station of Lamasquère (the distance between the fields and the meteorological station is less than 7 kilometers). The region is governed by a temperate climate, with an annual rainfall of approximately 600 mm and mean daily air temperature ranging from a few degrees in winter to 25 °C in summer. The soils are mainly dominated by silt (47%), followed by clay (29.7%) and sand (23.3%), indexed by three classes of the European Soil Map (HYPRES, European Soil Bureau working group (2016)) texture classification system (*i.e.*, Fine, Medium and Medium Fine). Agricultural activity occupies 90% of the landscape, with surfaces dedicated to crops (56.8%), forests (7.9%), urban areas (2.4%), grasslands (32.1%) and water bodies (0.8%) (Marais Sicre et al., 2014). This paper focuses on one of the main summer crops of the study area–corn–for which the sowing period is in spring and the harvest is in autumn.

During corn growth, the succession of the first phenological stages is fast (according to the BBCH scale presented by Meier (2001). Following emergence (stages 0–10), leaves appear (stages 10–20), and the central stem develops (stages 30–40), followed by the male inflorescence (50–60), which occurs at the apex of the plant. After flowering (stages 60–70), one or two ears develop in the axil of a leaf, in the middle part of the plant (stages 70–80). During the agricultural season, corn is subjected to high temperatures, and irrigation compensates for the low rainfall to enable crop development. Within the region, the water used for irrigation is delivered through three techniques: pivot, reel, or full coverage. The number of water applications varies, ranging from five to more than ten (depending on the farmer), with the amount of water ranging from 15 to 30 mm (depending on the corn phenological stage and the particularities of the fields).

2.2. In situ data

During the MCM'10 experiment (Baup et al., 2012), a dense network of 30 corn fields (representing 345 ha) was intensively monitored throughout the agricultural season (Fig. 1) to acquire the following data: climatic information, agricultural practices, phenological stages, and the biophysical variables of the vegetation and soil. Sizes and local slopes of these fields ranged from 0.5 to 39.3 ha and from 0.07 to 0.78°, respectively. Among these fields, eight were selected for quantitative measurement of the crop height, top soil moisture and surface roughness. Climatic data were collected by a standard meteorological station installed near the city of Lamasquère. Half-hourly measurements were accumulated to obtain the daily values of precipitation.

Agricultural practices (irrigation, tillage) and the main phenological stages (emergence, leaf development, stem elongation, flowering, development of fruit, senescence) were collected at each satellite overpass. Precise yield values and dates of sowing and harvesting were collected from farmers. The corn was sowed during the spring between the 8th of April and the 23rd of May and was harvested between the 5th and the 27th of October. The mean yield, approximately 110 q ha^{-1}, was similar than the 103 q ha^{-1} observed in Haute-Garonne County for irrigated corn. The yield values ranged from 80 to 126 q ha^{-1}, which was higher than the temporal variability of yields observed in Haute-Garonne County during 2000–2014 (77–113 q ha^{-1}, (DRAAF, 2016).

Soil roughness was measured using a 2-m pin profilometer immediately after sowing. Two standard statistical parameters (*i.e.,* the standard deviation of the roughness heights and the autocorrelation length, abbreviated as h_{rms} and l_c, respectively) were calculated and assumed to be constant from sowing to harvest since no tillage events were performed during this period. The mean h_{rms} and l_c were 1.2 and 4.5 cm, values characteristic of smooth surface.

The dielectric constant of the soil was measured at each satellite overpass using mobile theta probe sensors. The volumetric soil moisture of the first five centimeters was derived from the in situ calibration function presented by Baup et al. (2012) (R^2 = 0.75, RMSE = 4.1%, n = 403). For each field, the mean values of top soil moisture (TSM) were averaged from at least 15 measurements per field and ranged between 9 and 29% m^3 m^{-3} throughout the crop cycle.

2.3. Satellite data

Fig. 2 presents an overview of the satellite images acquired during the corn crop cycle. From April to October, regular high spatial resolution images (of less than 20 m) were quasi-synchronously provided by TerraSAR-X (TS-X, 9 images) and Radarsat-2 (RS-C,