Computers and Electronics in Agriculture 151 (2018) 41–49

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

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

Original papers

Wheat and maize yield forecasting for the Tisza river catchment using MODIS NDVI time series and reported crop statistics

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ARTICLE INFO

Keywords:
Yield forecast
Wheat
Maize
MODIS
NDVI

ABSTRACT

Stakeholders, policy makers, government planners and agricultural market participants in Central Eastern Europe require accurate and timely information about wheat and maize yield and production. The study site, the lowlands (altitude below 200 m) of the Tisza river catchment is by far the most important wheat and corn producing region in the Carpathian basin, and even in Central Eastern Europe. The conventional sampling of on-field data and data processing for crop forecasting requires significant amounts of time before official reports can be released. Several studies have shown that wheat and maize yield can be effectively forecast using satellite remote sensing. In this study, a freely available MODIS NDVI satellite data based wheat and maize yield forecasting methodology was developed and evaluated for estimating yield losses effected by drought.

Wheat and maize yield was derived by regressing reported yield values against time series of 15 different peak-season MODIS-derived NDVI. The lowest RMSE values at the river basin level for both wheat and maize yield forecast versus reported yield were found when using at least six or more years of training data. Wheat forecast for the 2000 to 2015 growing seasons were within 0.819% and 19.08% of final reported yield values. Maize forecast at county level for the 2000 to 2015 growing seasons were within 0.299% and 17.14% of final reported yield values. The Nash–Sutcliffe efficiency index (E_1) is positive with E_1 = 0.322 in the case of wheat forecast, and with E_1 = 0.401 in the case of maize forecast, which means the developed and evaluated forecasting method performs acceptable forecast efficiency. Nevertheless the occurrence of extreme drought or extreme precipitation can alter the forecasting efficiency resulting over or underestimation. Overall statement, which based on MODIS NDVI, possible yield losses can easily be forecasted 6–8 weeks before harvesting and applying simple threshold levels, yield losses can be mapped simply.

1. Introduction

National and international agricultural agencies, insurance agencies, and international agricultural boards commodities and governmental agencies are interested in crop yields and acreage under crop production since global trading prices of agricultural commodities depend largely on their seasonal production levels. International humanitarian agencies rely on early and reliable information on crop production to organize emergency response and food aid interventions (Rembold et al., 2013). In crop production drought is one of the most complex natural hazards because of its slow onset and impact on yield which can be monitored with remote sensing (Zambrano et al., 2016).

Remote sensing techniques are widely used in agriculture and agronomy Atzberger (2013). The agricultural application of satellite remote sensing (RS) technology requires a quantitative processing of satellite RS data with high accuracy and reliability. The reason for this first of all agricultural vegetation develops from sowing to harvest as a function of meteorological driving variables (e.g., temperature, sunlight, and precipitation). The production depends secondly on the physical landscape (e.g., soil type), as well as climatic driving variables and agricultural management practices. All variables are highly variable in space and time. Moreover, as productivity can change within short time periods, due to unfavourable growing conditions such as drought, agricultural monitoring systems need to be timely.

As changes in crop vigour, density, health and productivity affect canopy optical properties, crop development and growth have been monitored by the use of satellite images since the early days of remote sensing; Already in the early 80s, it was shown by Tucker and coworkers that green vegetation can be monitored through its spectral reflectance properties (Tucker, 1979; Tucker et al., 1980) and 79% of the variation in total wheat dry-matter accumulation can be explained by integrating normalized difference vegetation index (NDVI) over the

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https://doi.org/10.1016/j.compag.2018.05.035
Received 14 March 2018; Received in revised form 25 May 2018; Accepted 29 May 2018

growing season (Tucker et al., 1981). Satellite observations can play a role in providing information about crop type, crop conditions and crop yield from the field level to extended geographic areas like countries or continents.

The success of the remote sensing based biomass monitoring stems from its close relation to the canopy Leaf Area Index (LAI) and fAPAR (fraction of Absorbed Photosynthetically Active Radiation) (Prince, 1991; Baret and Guyot, 1991). Due to its almost linear relation with fAPAR, NDVI can be readily used as an indirect measure of primary productivity. The aforementioned relationship between vegetation indices and biomass/fAPAR enables the early estimation of crop yield, since yield of many crops is mainly determined by the photosynthetic activity of agricultural plants in certain periods prior to harvest (Benedetti and Rossini, 1993; Baret et al., 1989). In Rembold et al. (2013), a comprehensive overview is provided regarding biomass and yield mapping approaches. Most of the experiments and research concentrated on obtaining quantitative relation between satellite (or airborne) RS data and crop yields and used two main types of the possible general strategies (Ferencz et al., 2004). The incorporates satellite RS data into (existing or advanced) agrometeorological or plant-physiological, crop growth models (see e.g. Badhwar and Henderson, 1981; Brakke and Kanemasu, 1981; Asrar et al., 1984; Wiegand and Richardson, 1990; Maas, 1992; Delécolle et al., 1992; Reynolds et al., 2000; Senay et al., 2000; Patel et al., 2001; Richter et al., 2011; Vuolo et al., 2013). The second type of general strategy is based on direct mathematical relationships between satellite RS data and crop yields. Some direct yield methods use meteorological and agronomical data in operation also; and in a few cases some models use only satellite RS data, with ground-truth reference (crop yield) data necessary only in the calibration phase (e.g. Idso et al., 1977; Aase and Siddoway, 1981; Gallo and Daughtry, 1981; Tucker et al., 1981; Hatfield, 1983; Steven et al., 1983; Rudorff and Barista, 1991; Hamar et al., 1996; Maselli et al., 2000; Del Frate and Wang, 2001; Shao et al., 2001; Balint and Mutua, 2011; Dempewolf et al., 2014). These models assume basically that the vigour of the crop canopy, observed in the spectral RS data, is directly related to the yield of the given crop.

The objective of this study is to develop and test remote sensing based technology for early season wheat and maize yield forecasting in the lowlands of the Tisza river catchment, Central Eastern Europe with using regression-based modelling combining (Moderate Resolution Imaging Spectroradiometer) MODIS time series data and annual reported crop statistics. The concept was based on our earlier experiences and results (Tamás et al., 2015). The aim is to provide first RS based approximations of wheat and maize yield before the final results using the conventional system become available to help improve timely decision-making. In the validation process, we are not only evaluating the absolute deviations of MODIS normalized difference vegetation index NDVI-derived wheat and maize yield data from reported values, but also the significant difference is being assessed between the predicted and observed yield values within different yield ranges. Thus beside overall forecasting accuracy, those yield range can be identified in which the forecasting model performs the best or extremities (drought or too much precipitation) have significant effect on yield forecasting.

2. Materials and methods

2.1. Study site

The study site is the part of an international catchment, the lowlands (altitude below 200 m) of the Tisza river catchment is by far the most important wheat and corn producing region in the Carpathian basin, and even in Central Eastern Europe (Fig. 1). As an example, based on the annual reports of the Hungarian central statistical offices, approximately of 55% of the arable lands are covered by wheat and maize. The region suffering from water management problems floods, surplus water and drought phenomena occur regularly. Surplus water and drought often occur in the same year or even in the same vegetation period. For crop production, light or radiation, temperature and water relationships (soil moisture) are the three cardinal climatic factors affecting vegetative development and flowering of crop species. Plain sites of Tisza catchment have a substantial global radiation. The average energy input by radiation onto the surface is 4430 MJ/m^2/year, which is a vast resource for plant production. This relatively high radiation is due to the long photoperiod, which comprises 2050 h/year. In Hungary, the average annual daily temperature is 10–11 °C, and for the growing season it is 17.5 °C.

The most variable climate element in the plain site is the precipitation. The average annual precipitation is around 600 mm, but differences between years and the seasonal distribution are extreme. For example, (based on the data of the National Weather Service) looking at figures from Debrecen, middle of the lowland, the minimum and maximum annual precipitations between years 1901 and 2010 were 321 mm and 953 mm, respectively. It is seen that July rainfall may be close to zero or up to 150 mm. This provides an unpredictable water supply for the vegetation and makes crop and fruit production vulnerable. This vulnerability is also explained by the difference between annual precipitation and annual evapotranspiration. It is well known that in mid-season the potential evapotranspiration is high and the precipitation does not meet it, and so there is shortage of soil moisture for crops, furthermore the high clay content can be also a huge problem concerning readily available water content of soils. Climate change models predict that Tisza river basin will experience more serious drought events, and on the other hand more extreme precipitation events in the future. According to statistical data, droughts occur every second or third year during summer, especially in July and August. Therefore maize is more affected by the drought than wheat, since wheat has been already harvested in the first quarter of July, but maize has its flowering period just in the middle of the most drought risk affected period.

2.2. Crop statistical data

The final official reported yield values were published by the Hungarian Central Statistical Office for the corresponding Nomenclature of Territorial Units for Statistics (NUT) 3 regions and by Statistical Office of the European Union (EUROSTAT) for Romanian, Slovakian, Serbian NUT 2 regions and collected from 2000 to 2015.

Remarkable yield amounts were detected in 2001, 2004, 2005, 2008 and 2014 ($>$ 7 t/ha for maize $>$ 4 t/ha for winter wheat); and average in 2006 and 2011 (~6.7 t/ha for maize ~4 t/ha for winter wheat). On the other hand, due to drought phenomena, severe wheat and maize yield losses were detected in 2000, 2002, 2003, 2007, and 2012 (−3 t/ha loss for maize −1 to 1.5 t/ha loss for wheat) (Fig. 2).

These data are strongly related to the SPI and meteorological data, except for year 2010, when an extreme amount of precipitation (900–1300 mm/year) was observed on the plain sites of the Tisza river basin, and, due to the surplus drainage water cover on the fields for a long period and plant diseases, the quantity of the yields remained average (Tamás et al., 2015).

2.3. MODIS NDVI data

In the case of low resolution satellite images, because of their large swath width, low resolution systems have a much better synoptic view and temporal revisit frequency compared to high resolution sensors (Rembold et al., 2013). On the other hand the spatial resolution seriously complicates the accuracy of yield detection, the interpretation (and validation) of the signal, as well as the reliability of the derived information products. Labus et al. (2002) calculated NDVI from an Advanced Very High Resolution Radiometer (AVHRR) time series for the U.S. state of Montana and found strong correlations between wheat yield and integrated NDVI, as well as late-season NDVI parameters.