International Journal of Applied Earth Observation and Geoinformation 23 (2013) 192–203

Contents lists available at SciVerse ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

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

Winter wheat yield forecasting in Ukraine based on Earth observation, meteorological data and biophysical models

Felix Kogan[a], Nataliia Kussul[b,f,*], Tatiana Adamenko[c], Sergii Skakun[b,f], Oleksii Kravchenko[b], Oleksii Kryvobok[d], Andrii Shelestov[b,e,f], Andrii Kolotii[b,f], Olga Kussul[f], Alla Lavrenyuk[f]

[a] National Oceanic and Atmospheric Administration, National Environmental Satellite Data and Information Services, 5200 Auth Rd, Camp Springs, MD 20746, USA
[b] Space Research Institute NASU-NSAU, Glushkov Ave, 40, build. 4/1, Kyiv 03680, Ukraine
[c] Ukrainian Hydrometeorological Center, Zolotovoritskaya str., 6-B, Kyiv 01034, Ukraine
[d] Ukrainian Hydrometeorological Institute, Nayku Ave, 37, Kyiv 03650, Ukraine
[e] National University of Life and Environmental Sciences of Ukraine, Heroyiv Oborony str., 15, Kyiv 03680, Ukraine
[f] National Technical University of Ukraine "Kyiv Polytechnic Institute", Peremogy Ave, 37, Kyiv 03056, Ukraine

A R T I C L E I N F O

Article history:
Received 22 July 2012
Accepted 10 January 2013

Keywords:
Remote sensing
Agriculture
Yield
Wheat
Ukraine

A B S T R A C T

Ukraine is one of the most developed agriculture countries and one of the biggest crop producers in the world. Timely and accurate crop yield forecasts for Ukraine at regional level become a key element in providing support to policy makers in food security. In this paper, feasibility and relative efficiency of using moderate resolution satellite data to winter wheat forecasting in Ukraine at oblast level is assessed. Oblast is a sub-national administrative unit that corresponds to the NUTS2 level of the Nomenclature of Territorial Units for Statistics (NUTS) of the European Union. NDVI values were derived from the MODIS sensor at the 250 m spatial resolution. For each oblast NDVI values were averaged for a cropland map (Rainfed croplands class) derived from the ESA GlobCover map, and were used as predictors in the regression models. Using a leave-one-out cross-validation procedure, the best time for making reliable yield forecasts in terms of root mean square error was identified. For most oblasts, NDVI values taken in April–May provided the minimum RMSE value when comparing to the official statistics, thus enabling forecasts 2–3 months prior to harvest. The NDVI-based approach was compared to the following approaches: empirical model based on meteorological observations (with forecasts in April–May that provide minimum RMSE value) and WOFOST crop growth simulation model implemented in the CGMS system (with forecasts in June that provide minimum RMSE value). All three approaches were run to produce winter wheat yield forecasts for independent datasets for 2010 and 2011, i.e. on data that were not used within model calibration process. The most accurate predictions for 2010 were achieved using the CGMS system with the RMSE value of 0.3 t ha^{-1} in June and 0.4 t ha^{-1} in April, while performance of three approaches for 2011 was almost the same (0.5–0.6 t ha^{-1} in April). Both NDVI-based approach and CGMS system overestimated winter wheat yield comparing to official statistics in 2010, and underestimated it in 2011. Therefore, we can conclude that performance of empirical NDVI-based regression model was similar to meteorological and CGMS models when producing winter wheat yield forecasts at oblast level in Ukraine 2–3 months prior to harvest, while providing minimum requirements to input datasets.

1. Introduction

As population on the Earth increases and climate changes likely to impact global crop production, food security becomes a topic of great importance. This problem is addressed within the Global Agricultural Monitoring System of Systems (GLAM, 2010) that aims to integrate multiple satellite datasets and in situ observations to provide services for monitoring crop production, agro-meteorological parameters, and water resources. The two main components of crop production monitoring are crop yield forecasting and crop area estimation. Therefore, providing accurate crop yield forecasts several months in advance of the harvest is crucial at global, national and region scales.

Ukraine is one of the most developed agriculture countries and one of the biggest crop producers in the world. According to the 2011 statistics provided by the U.S. Department of Agriculture

* Corresponding author at: Space Research Institute NASU-NSAU, Glushkov Ave, 40, build. 4/1, Kyiv 03680, Ukraine. Tel.: +380 44 5264174; fax: +380 44 5264124.
E-mail addresses: Felix.Kogan@noaa.gov (F. Kogan), inform@ikd.kiev.ua, kussul@mail.ru (N. Kussul), adamenko@meteo.gov.ua (T. Adamenko), kryvobok@uhmi.org.ua (O. Kryvobok), andrii.shelestov@gmail.com (A. Shelestov), olgakussul@gmail.com (O. Kussul), alla.lavrenyuk@gmail.com (A. Lavrenyuk).

0303-2434/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jag.2013.01.002

(USDA) Foreign Agricultural Service (FAS), Ukraine was the 8th largest exporter and 10th largest producer of wheat in the world. Timely and accurate crop yield forecasts for Ukraine become a key element in providing support to policy makers in food security (Gallego et al., 2012; Kussul et al., 2010, 2012; Skakun et al., 2007).

At present, the two most utilized approaches to forecast crop yield are empirical regression-based models and biophysical crop models. Empirical models connect crop yield with some selected predictors, for example, vegetation indices derived from remote sensing data, meteorological observations, and usually require little data inputs. Though these models are easy to implement they lack robustness and generalization ability. Also, empirical models are data-driven, i.e. their performance strongly depends on available datasets. Nevertheless, Becker-Reshef et al. (2010) recently proposed a generalized regression-based model for forecasting winter wheat yields that was first built and validated for Kansas, USA, and then directly applied to Ukraine without any adaptation and calibration against Ukrainian yield statistics. When running the model for Ukraine six weeks prior to harvest (in June) for years 2001–2008, the RMSE of the official versus predicted yields was 0.44 t ha^{-1} which was equivalent to a 15% error, and the of RMSE of the official versus predicted production was 1.83 millions of tons which was equivalent to a 10% error. When running the model in real-time in May of 2009, model forecast of wheat production for Ukraine was within 6.3% of the official 2009 statistics (Becker-Reshef et al., 2010).

Biophysical models simulate the growth of crops to retrieve biophysical crop parameters such as crop production, biomass, water use, etc. Such models include the World Food Studies (WOFOST) (Van Keulen and Wolf, 1986; Boogaard et al., 1998) model that is implemented within the Crop Growth Monitoring System (CGMS)[1] operationally used in Europe, the Erosion Productivity Impact Calculator (EPIC) (Williams et al., 1984), the Crop Environment Resource Synthesis (CERES) (Ritchie and Otter, 1985). The main difficulty of applying such models is that they require numerous input parameters to run the model, in particular soil type, crop type, weather data, and crop management factors (sowing date, emergence, flowering, ripening, physiological maturity, etc.). Though these models are quite generic and robust, appropriate adaptation and calibration of these models is required to account for the agricultural specifics of the given region.

Satellite data play important role in crop yield forecasting since they can provide timely, repeatable, continuous, human-independent information for large territories (Kussul et al., 2009). Satellite-derived products such as leaf area index (LAI), green area index (GAI), vegetation index (Normalized Difference Vegetation Index – NDVI, Enhanced Vegetation Index – EVI), meteorological parameters (from MeteoSat or NOAA-AVHRR satellites) can be assimilated into crop growth models to improve their performance (Maas, 1988; Clevers et al., 1994; Clevers and van Leeuwen, 1996; Heinzel et al., 2007; de Wit and van Diepen, 2008; Fang et al., 2011; Curnela et al., 2011; Roerink et al., 2012; de Wit et al., 2012). They can also be used as a predictor parameter in empirical regression-based models. In particular, NDVI, GAI and Vegetation Health Index (VHI) have been successfully applied to forecast crop yield (Salazar et al., 2007, 2008; Ren et al., 2008; Becker-Reshef et al., 2010; Mkhabela et al., 2011; Kogan et al., 2012; Kouadio et al., 2012).

As to Ukraine, previous works have mainly focused on forecasting crop yield at the scale of the country (Becker-Reshef et al., 2010; Kogan et al., 2011). Less attention has been paid to providing forecasts at the oblast level. Oblast is a sub-national administrative unit that corresponds to the NUTS2 level of the Nomenclature of Territorial Units for Statistics (NUTS) of the European Union.[2] Also, no studies have been made for Ukraine to compare performance of empirical regression-based models against bio-physical models. Therefore, the objective of the study presented in this paper is several-fold:

(i) to explore feasibility and assess relative efficiency of using satellite data for winter wheat yield forecasting for Ukraine at oblast level;
(ii) to compare three approaches to forecasting winter wheat yield in Ukraine at oblast level:
  - empirical regression-based model that uses as a predictor 16-day NDVI composites derived from Moderate Resolution Imaging Spectroradiometer (MODIS) at the 250 m resolution,
  - empirical regression-based model that uses as predictors meteorological parameters, and
  - adapted for Ukraine Crop Growth Monitoring System (CGMS) that is based on WOFOST crop growth simulation model and meteorological parameters;
(iii) to compare the outputs of three models against official statistics, and assess and analyse corresponding errors with target to fuse these outputs as a mixture of experts (Bishop, 2006; Rasmussen and Williams, 2006).

2. Study area and materials description

2.1. Study area

Ukraine is composed of 24 oblasts and the Autonomous Republic of Crimea with the area of oblasts ranging from 8097 to 33,310 km^2 (average oblast area is approximately 24,000 km^2). In general, Ukraine can be divided into the following agro-climatic zones (Fig. 1): Plane-Polissya in the north (mixed forest zone, 26% of the entire Ukrainian territory), Forest-Steppe in the centre (34%) and Steppe in the south (the most intensive cultivated area, 40%).

Wheat is one of the most important and grown crops in Ukraine. For past five years wheat accounted on average for almost 45% of production of all grains, and 48% of all crop areas. Winter wheat constitutes on average 95% of the wheat crop production while the rest 5% are accounted by spring wheat. Winter wheat is typically sown in the autumn, and harvested in July next year.

2.2. Materials description

In the study the following datasets were used:

- MOD13Q1 product at the 250 m resolution for 2000–2011.
- ESA Global Land Cover map (GlobCover) at the 300 m resolution for 2009.
- Monthly meteorological observations from 180 stations in Ukraine for 2000–2011.
- Official statistics of winter wheat yield for Ukraine at oblast level for 2000–2011.

NDVI values for Ukraine were extracted using the MOD13Q1 product generated from the MODIS instrument on board the Terra satellite. MOD13Q1 data are provided every 16 days at the 250 m resolution in the sinusoidal projection. NDVI images are composited over a 16-days interval to create a cloud-free map with minimal atmospheric and sun-surface-sensor angular effects (Huete et al., 1999). Data for the territory of Ukraine and 2000–2011 time

[1] http://mars.jrc.ec.europa.eu/mars/About-us/AGRI4CAST/Models-Software-Tools/Crop-Growth-Modelling-System-CGMS.

[2] http://epp.eurostat.ec.europa.eu/portal/page/portal/nuts_nomenclature/introduction.