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Improving crop yield estimation by assimilating LAI and inputting satellite-based surface incoming solar radiation into SWAP model

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ABSTRACT

Precise crop yield forecast at regional scales would increase global food security, especially in strategic crops such as wheat and barley. Soil Water Atmosphere Plant (SWAP) is an agro-hydrological model based on a crop growth detailed module that could properly estimate crop yield using satellite observations as input data. In this study, in order to reduce crop yield estimation errors in wheat and barley, MODIS-based leaf area index (LAI) was assimilated using a sequential update algorithm into SWAP, and GLDAS/Noah-derived surface incoming solar radiation (SISR) was used as an alternative to measured SISR. The assimilation of remotely sensed LAI and using SISR as input was examined in nine different cases. Results showed that soil adjusted vegetation index (SAVI) was the best VI for LAI estimation with coefficient of determination (R^2) of 0.72 and root mean square error (RMSE) of 0.87 $m^2 m^{-2}$. Also noise equivalent variations indicated an appropriate sensitivity of SAVI along the entire range of LAI variability. GLDAS/Noah-derived SISR showed good agreement with measured SISR; therefore LAI and SISR were jointly used in the model. Simulation results showed that the lowest percent absolute error (PAE) for aboveground dry biomass and grain yield was obtained in case 7 (the assimilation of the peak LAI in addition to ten days after and before the peak LAI is reached) with 1.59% and case 5 (the daily assimilation of LAI until twenty days after the peak LAI is reached) with 6.06%, respectively. Crop yield estimates were improved by 26.25 and 14.4% compared with no LAI assimilation case. Overall, LAI assimilation into SWAP associated with the most efficient cases in this study would result in an accurate crop yield forecast in wheat and barley.

1. Introduction

Wheat and barley are two strategic crops in Iran. Accurate knowledge of crop yield before harvest is one of the essential factors in making the right decisions regarding the national food security. Agro-hydrological models forecast crop yield based on crop growth simulation; therefore crop production process may be managed and planned more effectively (Farshi et al., 1987). These models perform very well at field scales, but input data and boundary conditions uncertainties increase with the increase in scale (Huang et al., 2013). Simulation processes in crop growth models are based only on mathematical equations, and they do not consider all real-world crop and environmental conditions which vary with both time and location. Data assimilation of satellite observations would exert these conditions on crop growth models and subsequently improve their accuracy (Dorigo et al., 2007). Field data acquisition for use in distributed models is not always possible in large scales and can only be done using remote sensing. Previous studies showed that assimilating satellite observations into distributed agro-hydrological models would certainly reduce the output errors (Vazifedoust et al., 2009; Badiyeneshin et al., 2015). Some of the most widely used agro-hydrological models are WOFOST (Diepen et al., 1989), CERES (Godwin and Jones, 1991), WTGROWS (Aggarwal et al., 1994), SVAT (Mo and Liu, 2001), SWAP (Kroes and Van Dam, 2003), and Aquacrop (Raes et al., 2009). Remotely sensed data such as soil moisture (Van Loon and Troch, 2002; Ines et al., 2013), leaf area index, LAI (Dente et al., 2008; Badiyeneshin et al., 2015), and evapotranspiration, ET (Kamble and Irmak, 2008; Vazifedoust et al., 2009) were successfully assimilated into agro-hydrological models. Aside from the type of the data assimilated into the models, investigating different assimilation schemes to achieve the optimum number of days and time of assimilating data into the models is essential for operational and efficient crop yield forecasting.

The SWAP model simulates crop growth and calculates crop yield using a detailed growth module. This module is based on WOFOST model. The accuracy of SWAP simulations is highly sensitive to the accuracy of input data. Therefore, in case of accurate input data, crop

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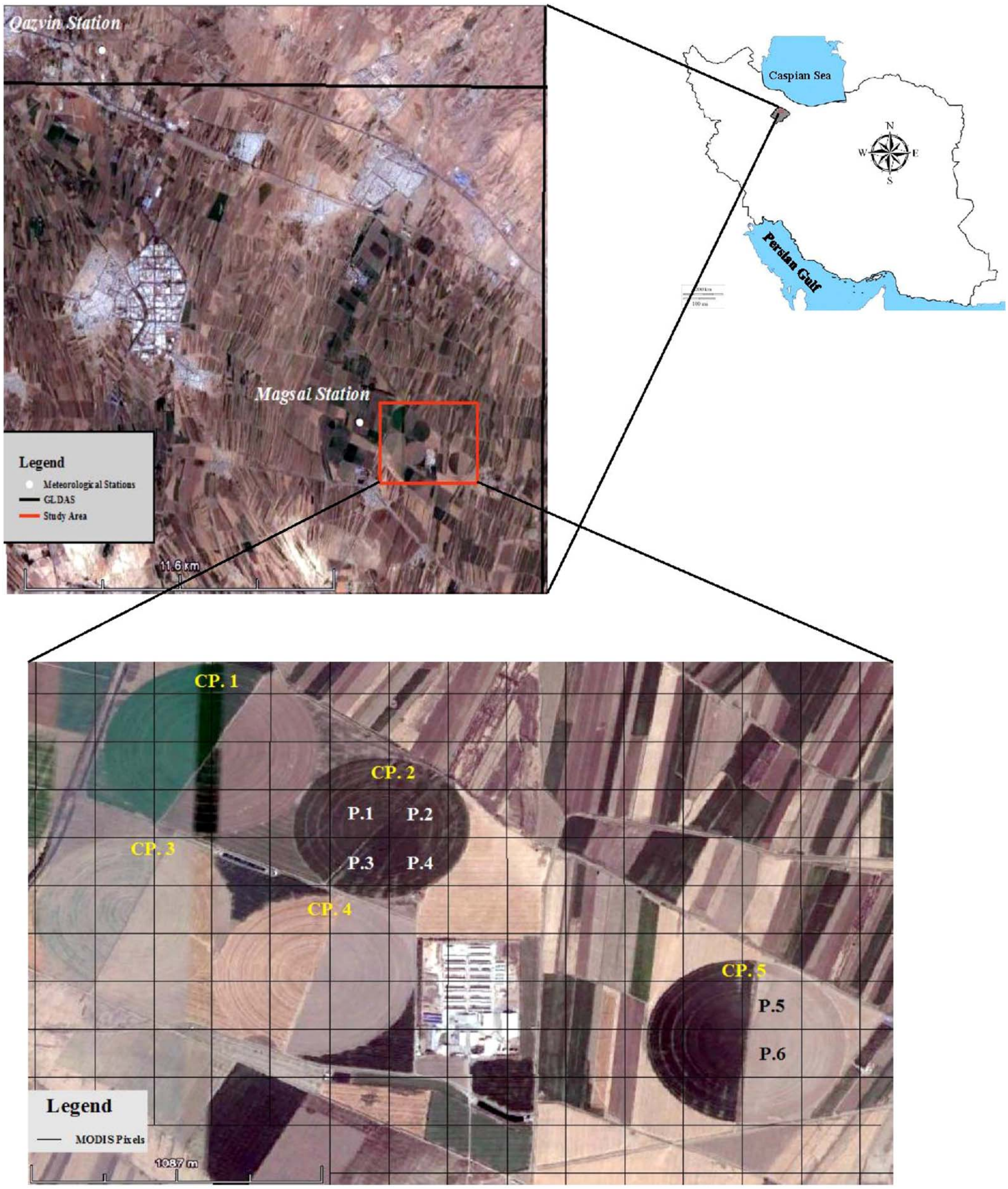

Fig. 1. Footprint of the satellite products superimposed over the study area.

yield would be estimated more reliably (Noory et al., 2011). Input data of the SWAP model is divided into four sections including crop, soil, meteorology, and upper and lower boundary conditions. Salinity and water stress are implemented in the SWAP model, but crop yield is simulated under optimum conditions of diseases, pests and soil compaction (Kroes and Van Dam, 2003). Thus, vegetation health and environmental conditions should be imposed by assimilating crop parameters such as LAI on crop yield simulation process of the model. LAI also implies the magnitude of absorbed radiation and represents the photosynthesis surface area of a plant. Accordingly, assimilating LAI into the model would significantly reduce crop yield simulation errors. Vazifedoust et al. (2009) used the Kalman Filter (EnKF) data assimilation technique in order to improve wheat yield estimation by using satellite-based LAI and relative evapotranspiration (ET_{rel}) from the ratio of SEBAL-derived actual evapotranspiration (ET_a) and Penman-Monteith potential evapotranspiration (ET_p) in the SWAP model for the Borkhar plain, center of Iran. Hao et al. (2010) in the Hebei province in China, made use of MODIS LAI product in SWAP in order to ameliorate crop yield simulation errors. Ma et al. (2013) in china, assimilated HJ-1 CCD NDVI into WOFOST with the EnKF and winter wheat yield estimation was significantly improved. Badiyeneshin et al. (2015) assimilated the LAI derived from spectral vegetation indices (VIs) calculated using MODIS imagery into the SWAP model to improve crop yield estimation. Huang et al. (2015, 2016) took TM and MODIS sensors imagery into account in order to extract satellite-based LAI and assimilated the resulted LAI into the WOFOST model for reducing the percentage error of wheat yield estimation on a regional scale. Xie et al. (2017) also improved winter wheat yield estimation by assimilating both LAI and vegetation temperature condition index into CERES-Wheat model using Landsat imagery.

There are several approaches that may be used for estimating satellite-based LAI. Creating a regression equation based on the relationship between VIs and LAI is one of the simplest and yet most accurate methods for estimating LAI. Gitelson et al. (2003), Viña et al. (2011), and Nguy-Robertson et al. (2015) used visible and near infrared (NIR) portions of the electromagnetic spectrum of several satellite sensors including MODIS, Landsat TM/ETM+, MERIS, Sentinel-2 MSI/OLCI, and Venus in order to find regression equations based on the LAI-VI relationship for different crops in different regions of the world.

On the other hand, an accurate set of meteorological data is also