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Mapping water-logging damage on winter wheat at parcel level using high spatial resolution satellite data

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A R T I C L E I N F O

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A B S T R A C T

Damage to agricultural crops due to water-logging is becoming more frequent in this era of global climate change. In this study, we investigated the effect of water-logging on winter wheat growth (LAI and aboveground biomass) and yield at a parcel scale using high spatial resolution satellite data. For this purpose, a dynamic mapping of winter wheat LAI and biomass during growth under water-logging conditions was implemented. In addition, yield mapping and yield loss estimation were also carried out to arrive at the potential impacts of water-logging on both winter wheat growth and grain yield. Two varieties of winter wheat were investigated (Yang Mai 14 and Yang Mai 18) at tillering, jointing to booting and flowering. Field conditions were representative of water-logging treatment (contrast check (CK), waterlogging (WL) and flooding (FL)). A total of eight high spatial resolution optical satellite images, including WorldView-2, WorldView-3, Pleiades-1A, SPOT-6, GeoEye-1 and SPOT-7 were obtained at time points concurrent with eight temporal field observations. Seven widely used vegetation indices (VIs) were utilized as independent variables for LAI, biomass and yield estimation. Optimal estimation models were selected according to coefficient of determination (R^2), correlation coefficient (R) and root mean square error (RMSE) for subsequent mapping of LAI, biomass and yield. Results show that the power model, having EVI as the independent variable, had the highest accuracy for biomass estimation (R^2 of 0.78 and RMSE of 0.076 kg/m^2) while the exponential model with NDVI is the optimal model for LAI estimation (with 0.74 in R^2 and 0.64 in RMSE). GNDVI is the optimal VI for yield mapping, with 0.563 in R_{cv} (cross validated R) and 843.76 kg/hm^2 in $RMSE_{cv}$ (cross validated RMSE). As for the assessment of water-logging damage on winter wheat growth, FL showed a more serious impact than that of WL, based on results of the dynamic mapping of biomass and LAI at the same development stages. Water-logging from jointing to booting showed a more serious damage impact with respect to biomass and yield than that at the tillering and flowering stages. Our results have demonstrated the potential of multi-source and high spatial resolution remotely-sensed optical data for quantifying the impact of water-logging on winter wheat growth and grain yield at parcel scales, a research direction that has rarely been reported in agricultural remote sensing literature. This study thus provides a fundamental basis and the possibility for crop yield loss evaluation, water-logging monitoring, and for the design of mitigation strategies that would benefit even small-holder and subsistence farmers.

1. Introduction

Water-logging is becoming a more obvious constraint on food production due to the frequent occurrence of extremely high rainfall events (Wollenweber et al., 2003). Water-logging has been reported around the world, such as in Egypt and Saudi Arabia (El Bastawesy et al., 2013), Farafra Oasis in the Western Desert of Egypt (El Bastawesy et al., 2012), Jilin Province in China (Gu et al., 2011), Bihar State in India (Chowdary et al., 2008) and in the Indo Gangetic Plain in India (Pandey et al., 2010).

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Under water-logged conditions, soils are saturated with water and the diffusion of gases in water is so slow that O_2 content rapidly decreases (Jackson and Colmer, 2005). With water-logging stress, a severe oxygen deficit happens in the root zone, which will result in energy shortage and accumulations of toxins (Perata et al., 2011). Generally speaking, low-lying areas with more precipitation and poor drainage are most vulnerable to water-logging. Response to water-logging of winter wheat is influenced by three elements, including sensibility of species (Cannell et al., 1984), development stages (Belford, 1981; Setter and Waters, 2003), and duration of water-logging (Collaku and Harrison, 2002; Malik et al., 2002).

Many studies on water-logging are focused on its effects at specific stages, such as initial vegetative stage (Malik et al., 2002), grain filling stage (Li et al., 2011a) etc. In the current study therefore, the effects of water-logging on multiple crop growth stages (tillering, jointing, booting and flowering) are considered using high resolution satellite remote sensing data. Estimation of leaf area index (LAI), aboveground biomass (hereafter referred to as biomass) and yield of winter wheat are made with respect to water-logged and non-water-logged fields, and from which the damage of water-logging on winter wheat growth is mapped and grain yield loss is assessed.

In general, there are two ways to get timely information on crop biophysical parameters, which include direct and indirect methods. Direct methods for obtaining LAI involves leaf area determination and leaf collection (Zheng and Moskal, 2009). Indirect methods of obtaining LAI and biomass include ground-based, air-borne and space-borne remote sensing. In most cases however, as they are capable of providing data over large areas, indirect methods based on air-borne and space-borne remote sensing data need to be validated against a representative sample obtained from direct methods.

Traditional in-situ investigations involving destructive sampling of LAI and biomass, ascribed to direct methods, are time-consuming and labour intensive. Compared with direct methods, indirect methods involving remote sensing technologies have become widely used and cost-effective alternatives in obtaining timely and comprehensive information of plants (Kross et al., 2015; Liu et al., 2012; Yang et al., 2015; Zheng et al., 2013, Heenkenda et al., 2015, Kovacs et al., 2013, Castillo et al., 2017, Maimaitijiang et al., 2017). Images with coarse spatial resolution such as the Moderate Resolution Imaging Spectro-radiometer (MODIS) and the Advanced Very High Resolution Radiometer (AVHRR) have been widely used for crop yield estimation (Battude et al., 2016; Huang et al., 2013), monitoring vegetation conditions (Han et al., 2017; Li et al., 2011b; Tian et al., 2016, Tsalyuk et al., 2017), measurement of LAI and biomass (Ortiz et al., 2011, Li et al., 2015) and monitoring freezing disasters (Feng et al., 2009). Over the years, increasing attention has been paid to satellite datasets with moderate/medium spatial resolution (including microwave data) for acquiring more accurate crop information at regional and local scales (Jin et al., 2017). For example, in Ahmadian et al. (2016), soil line (SL) parameters (i.e., slope and intercept) were extracted with three methods using Landsat-8 OLI data, from which several soil line-related vegetation indices were built for biomass estimation of winter wheat, barley and canola. Besides, Tan et al. (2011) developed a remote sensing model for monitoring winter wheat biomass, SPAD values and LAI using Landsat thematic mapper (Landsat TM) datasets, and found that NDVI achieved the highest accuracy for biomass estimation. The relationship between vegetation indices obtained from the sun-synchronous satellites for environment and disaster monitoring and forecasting of China (HJ-1A/B) and rice growth parameters has been discussed and the authors found that cumulative vegetation indices could be utilized in the estimation of rice biomass (Wang et al., 2016). Several studies have been conducted on the application of coarse and moderate spatial resolution satellite data for biophysical parameters estimation. However, little attention has been paid to LAI, biomass and yield mapping under water-logging conditions in winter wheat fields and at parcel scales using high spatial resolution satellite data.

Mapping water-logging damage on crop growth and yield is still a daunting task due to the nature of its predictors, such as precipitation, ground water level, topography, soil type, crop type, and crop development stages. Additionally, remote sensing of water-logging damage on crops in smallholder agriculture production systems especially in the eastern plain of China is very challenging, due to irregular and fragmented agricultural fields that are also interspersed by water bodies and road networks. With the continuous development of remote sensing technologies, high spatial resolution commercial satellite data have opened new doors for the mapping and quantification of water-logging effects on winter wheat growth and yield. High spatial resolution satellite data have been proven effective in monitoring the variability of crop biophysical parameters (Battude et al., 2016; Gunlu et al., 2017; Kross et al., 2015; Marshall and Thenkabail, 2015; Zhu et al., 2017, Zhao et al., 2007) at parcel scales. Moreover, only the high spatial resolution data could reveal the variations of field crops at parcel scales. In view of the growing awareness of precision agriculture, high spatial resolution data offer the most reliable geospatial information source, as they can provide greater details of field and crop conditions at parcel scales. Information obtained from high spatial resolution data can be used in planning a wide range of precision agriculture initiatives, such as in scheduling irrigation, crop pest and disease control, fertilizer application, yield prediction, and yield loss assessment. Subsistence smallholder and large-scale commercialization farmers can benefit in this regard, while providing the much needed information for scientific research and food security policies. It is against this background that high spatial resolution satellite data are employed in this study.

One of the two most utilized methods for estimating crop biophysical parameters with remote sensing datasets is empirical modelling, in which biophysical parameters are set as dependent variables and vegetation indices as independent variables. The other uses a radiative transfer (RT) model that is based on the mechanism of radiation transfer in canopy. The radiative transfer model, simplifying complex surface systems in a manner of fixing some parameters, could be faced with too much input parameters and the ill-posed problem. Compared with the radiative transfer model, the empirical model is simple and straightforward, although its limitation is also obvious in that the empirical model in a specific region may not be appropriate for application to another region. Considering the comparative advantages of the above described methods, we have selected in this study, the empirical model for the estimation of winter wheat LAI, biomass and yield at parcel scales.

In this study, only very high spatial resolution satellite remote sensing data have been employed, and from which seven vegetation indices (VIs) were calculated and applied. In an attempt to monitor and quantitatively assess the impact of water-logging stress on winter wheat growth, we first mapped the dynamic change of winter wheat LAI and biomass using the empirical model at a parcel (smallholder) scale. Then, crop yield maps were obtained using multivariate statistical models, and from which, grain yield reduction rate as an impact of water-logging was also evaluated. Based on the LAI, biomass and grain yield estimates, analyses were made with respect to the response of winter wheat to water-logging conditions at different development stages.

2. Materials and methods

2.1. Experimental design and field data collection

The study area (approximately 1.62 hm^2) is located in the eastern part of Deqing County, Zhejiang Province, southeast China. In this area, wheat is one of the major crops cultivated in winter. This test site has an annual average temperature of 17.3 °C, and an average annual rainfall of about 1379 mm. In this study, water-logging conditions are classified into two categories. The first category is denoted as waterlogging (WL), which represents areas where the water level is at soil surface level,