Field Crops Research 164 (2014) 178–188

Contents lists available at ScienceDirect

Field Crops Research

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

Predicting grain yield and protein content in wheat by fusing multi-sensor and multi-temporal remote-sensing images

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ARTICLE INFO

Article history:
Received 24 December 2013
Received in revised form 5 May 2014
Accepted 5 May 2014
Available online 20 May 2014

Keywords:
Wheat
Grain yield
Protein content
Multi-sensor RS
Multi-temporal RS
RS data fusion

ABSTRACT

Non-destructive and quick assessment of grain yield and protein content is needed in modern wheat production. This study was undertaken to determine the optimal spectral index and the best time for predicting grain yield and grain protein content in wheat by fusing multi-sensor and multi-temporal remote-sensing images. Four field experiments were carried out at different locations, cultivars and nitrogen rates in two growing seasons of winter wheat (*Triticum aestivum* L.). During the experiment periods, data were obtained on time series RS images fused with high temporal and spatial resolutions, along with grain yields and protein contents at maturity. The results showed that the normalized difference vegetation index (NDVI) estimated by fusion exhibits high consistency with the SPOT-5 NDVI, which confirmed the usefulness of related algorithm. The periods around initial gain filling and anthesis stages were identified as the best periods for estimating wheat grain yield and protein content, respectively. The use of ratio vegetation index (RVI) (Nir, Red) at the initial filling stage obtained enhanced accuracy in wheat yield prediction, while the index $R_{Nir}/(R_{Red}+R_{Green})$ during anthesis predicted grain protein content more accurately than that at other growth stages. In addition, the accumulated spectral index $\sum$RVI (Nir, Red) and $\sum(R_{Nir}/(R_{Red}+R_{Green}))$ from jointing to initial filling stage gave higher prediction accuracy for grain yield and protein content, respectively, than the spectral index at a single period. These results help provide a technical approach to the prediction of grain yield and grain protein content in wheat with remote sensing at a large scale.

1. Introduction

Grain production is one of the most important issues related to national welfare and people's livelihood. Non-destructive, real-time and accurate prediction of crop yield over large area is critical for the formulation of national food policy, price control, and foreign grain trade (Jiang et al., 1999). Grain quality has received extensive interest from the government, enterprises, and consumers because of its increasing demand in recent years. The remote sensing (RS) has been proven effective in predicting grain yield and protein content in cereal crops (Tucker et al., 1980; Benedetti and Rossini, 1993; Inoue et al., 1998; Doraiswamy et al., 2003), and will be widely used in agricultural production with improving spatial, temporal and spectral resolution at declining cost.

Tucker et al. (1980) and Wiegand et al. (1991) used ground-based spectral radiometers to identify the relationship between the normalized difference vegetation index (NDVI) and crop yield. Final grain yields were found to be highly correlated with NDVI (Tucker et al., 1980; Wiegand et al., 1991). Das et al. (1993) used greenness and transformed vegetation indices to predict wheat yield at 85–110 days before harvest in India (Das et al., 1993). These early studies led to crop yield estimation in several countries using satellite imagery. The NDVI from the National Oceanic and Atmospheric Administration–Advanced Very High Resolution Radiometer (NOAA–AVHRR) with spatial resolution of 1000 m was found to exhibit a strong relationship with wheat yield in Italy (Benedetti and Rossini, 1993), Spain (Vicente-Serrano et al., 2006), and the United States (Labus et al., 2002). Studies have been conducted to relate the NDVI data derived from the new Moderate Resolution Imaging Spectroradiometer (MODIS) with spatial resolution of 500 m and crop grain yield (Doraiswamy et al., 2004; Ren et al., 2008; Mkhabela et al., 2011; Zhao et al., 2012). However, low spatial resolution radiometric measurements are the results of a mixture of signals that represent multiple components of the agricultural landscape, especially in China where farm size is small.

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http://dx.doi.org/10.1016/j.fcr.2014.05.001
0378-4290/

Further studies proved that as compared with low-temporal resolution measurements, high-spatial resolution sensors can more accurately forecast crop yield. Hamar et al. (1996) established a linear regression model to estimate corn and wheat yield at a regional scale, which was based on vegetation spectral indices computed using Landsat MSS data (Hamar et al., 1996). Yang et al. (2006) indicated that QuickBird imagery can provide useful data for mapping within-field growth and yield variability in grain sorghum (Yang et al., 2006). Yang et al. (2009) acquired Satellites Pour l'Observation de la Terre (SPOT) 5 satellite imagery around the peak growth of the crop to estimate grain yield (Yang et al., 2009). MODIS-NDVI data, with a 250 m spatial resolution and 10-day temporal resolution, was used to estimate the winter wheat yield in Jining, Shandong Province. The use of high-spatial resolution sensor data in estimating grain yield shows application potential, yet the low temporal frequency and frequent cloud cover in most cropping regions limit the number of observations during the growth period of farm crops. Meanwhile, the temporal frequency of the most low spatial resolution sensors allows more frequent monitoring of crop growth and development.

Numerous studies have focused on fusing a high spatial resolution panchromatic image and a coarse spatial resolution multispectral image from one or more instruments to generate a time series of high spatial resolution multispectral imagery. Busetto et al. (2008) obtained time series NDVI data at an accurate Thematic Mapper (TM) scale by fusing TM data, and multi-temporal MODIS-NDVI data by using the spectral unmixing model (Busetto et al., 2008). Meng et al. (2013) developed the Spatial and Temporal Adaptive Vegetation index Fusion Model to combine the MODIS NDVI temporal information and the HJ-1 CCD NDVI spatial difference information to generate a NDVI dataset with high spatial and temporal resolutions. Gao et al. (2006) presented a new spatial and temporal adaptive reflectance fusion model (STARFM) algorithm to blend Landsat and the MODIS surface reflectance. They concluded that by combining the MODIS daily 500-m surface reflectance with the 16-day repeat cycle Landsat Enhanced Thematic Mapper Plus (ETM+) 30 m surface reflectance could produce a synthetic "daily" surface reflectance product at the ETM+ spatial resolution (Gao et al., 2006). Most of these studies focused on reflectance and albedo, and the studies involving vegetation index did not utilize the gradualness and periodicity in vegetation's temporal variation. Studies are rarely reported on combination of multi-sensor images to generate a time series of high spatial resolution multispectral imagery for estimating grain yield and protein content in field production of cereal crops, including wheat.

The current study integrates SPOT-5 and HJ-CCD data obtained from four wheat field experiments in different years and eco-sites involving different nitrogen rates to generate the time series SPOT-5 spatial resolution image. On the basis of high spatial and temporal resolution fused remote sensing data, this study aims firstly to develop an algorithm for fusing vegetation indices with different spatial and temporal resolution, then to analyze the quantitative relationship between the remote sensing data and

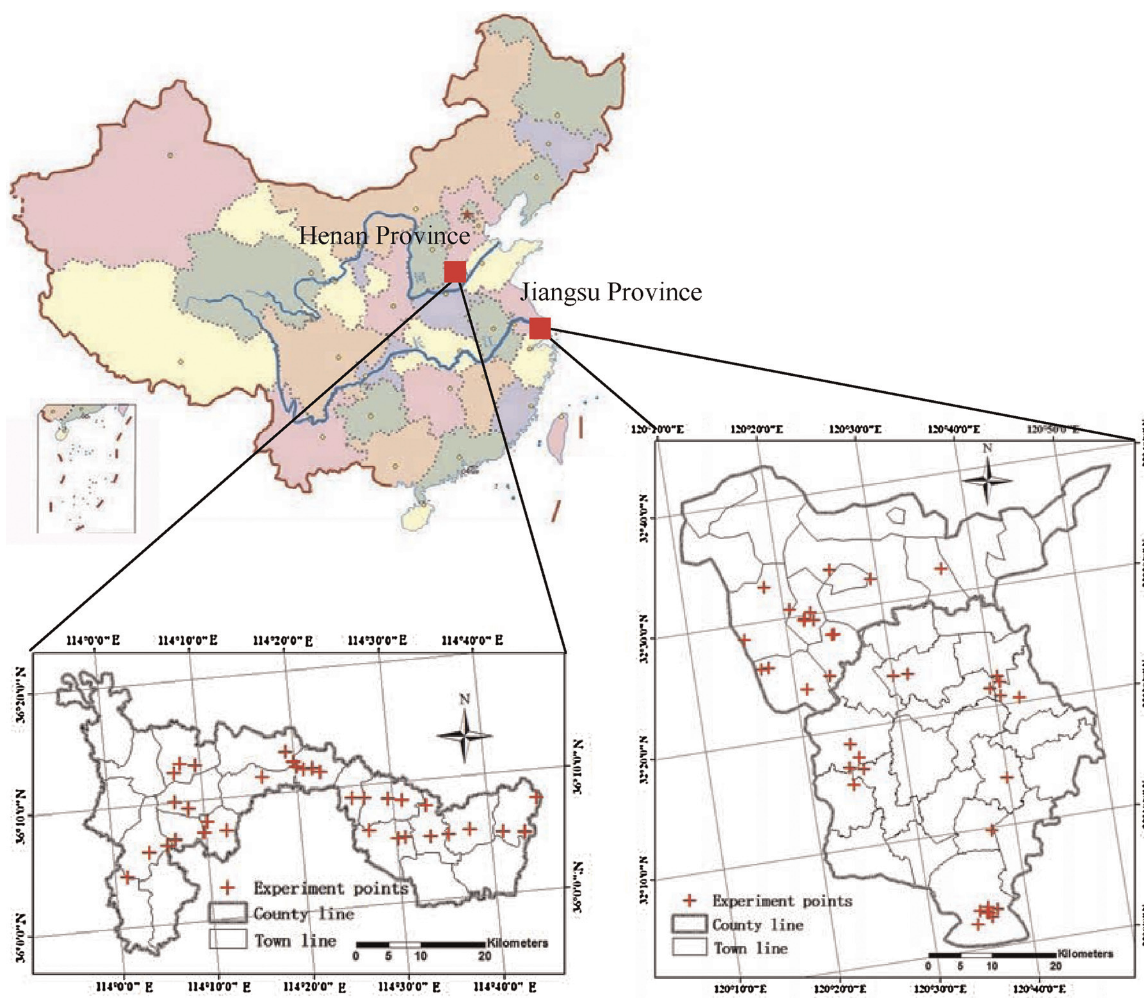

Fig. 1. Location of the study regions and distributions of the experiment points.