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Development and implementation of a multiscale biomass model using hyperspectral vegetation indices for winter wheat in the North China Plain

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ABSTRACT

Crop monitoring during the growing season is important for regional management decisions and biomass prediction. The objectives of this study were to develop, improve and validate a scale independent biomass model. Field studies were conducted in Huimin County, Shandong Province of China, during the 2006–2007 growing season of winter wheat (*Triticum aestivum L.*). The field design had a multiscale set-up with four levels which differed in their management, such as nitrogen fertilizer inputs and cultivars, to create different biomass conditions: small experimental fields (L1), large experimental fields (L2), small farm fields (L3), and large farm fields (L4). L4, planted with different winter wheat varieties, was managed according to farmers' practice while L1 through L3 represented controlled field experiments. Multitemporal spectral measurements were taken in the fields, and biomass was sampled for each spectral campaign. In addition, multitemporal Hyperion data were obtained in 2006 and 2007. L1 field data were used to develop biomass models based on the relation between the winter wheat spectra and biomass: several published vegetation indices, including NRI, REP, OSAVI, TCI, and NDVI, were investigated. A new hyperspectral vegetation index, which uses a four-band combination in the NIR and SWIR domains, named GnyLi, was developed. Following the multiscale concept, the data of higher levels (L2 through L4) were used stepwise to validate and improve the models of the lower levels, and to transfer the improved models to the next level. Lastly, the models were transferred and validated at the regional scale using Hyperion images of 2006 and 2007. The results showed that the GnyLi and NRI models, which were based on the NIR and SWIR domains, performed best with $R^2 > 0.74$. All the other indices explained less than 60% model variability. Using the Hyperion data for regionalization, GnyLi and NRI explained 81–89% of the biomass variability. These results highlighted that GnyLi and NRI can be used together with hyperspectral images for both plot and regional level biomass estimation. Nevertheless, additional studies and analyses are needed to test its replicability in other environmental conditions.

Introduction

Knowledge about crop characteristics during its growing season is very important for disease monitoring, yield prediction, and for adapting agricultural management to optimize yield and to avoid over-fertilization (Laudien et al., 2006; Miao et al., 2009; Oerke et al., 2010). Traditionally, expensive field-based destructive measuring of agronomic parameters, such as biomass, plant and soil

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nitrogen content, and Leaf Area Index (LAI) is necessary in order to accurately describe crop growth (Atzberger, 1998; Thenkabail et al., 2000). Alternatively, agronomic parameters can be monitored using non-destructive spectral reflectance observations (Kumar et al., 2003) obtained from satellite, airborne or hand-held imaging spectrometers. In-season and within-field crop development and growth can be described using crop reflectance. The prediction of crop parameters with remote and close range sensing data has become very common in the last decade (Addink et al., 2007; Oerke et al., 2010). Various airborne sensors (e.g. APEX, AVIRIS, CASI, and HyMap) and satellite sensors (e.g. CHRIS-PROBA, HJ-1/HSI, and Hyperion) are available for this purpose or will be launched in the near future (e.g. EnMAP, HyspIRI, and PRISMA).

One major advantage of hyperspectral spectrometers is their high spectral resolution (bandwidth ≤3 nm) and continuous acquisition of reflectance values between 350 nm and 2500 nm. Numerous vegetation indices (VIs), mainly situated in the red and near infrared (NIR), and sometimes in the green spectral region, were published (Clevers and Jongschaap, 2001; Todd et al., 1998). These VIs use the wavelengths around the minima and maxima of crop reflectance caused by leaf pigments and cell structure (Roberts et al., 2011). Combined with agronomic parameters, such as biomass or nitrogen concentration, crop models can be developed (Clevers and Jongschaap, 2001; Gnyp et al., 2014; Todd et al., 1998). In the simplest approach, single or multiple time-integrated VIs were used to estimate crop parameters by regression modeling (Serrano et al., 2000).

Canopy reflectance is mainly determined by LAI and other properties (e.g. leaf angle, soil optical properties). When LAI shows a close relation to biomass, a good relation between canopy reflectance and biomass can be expected (Gnyp et al., 2013; Liu et al., 2010; Serrano et al., 2000). High correlations between biomass and reflectance are shown in hyperspectral data collected by field spectrometer, airborne, and satellite sensors (Babar et al., 2006; Cho et al., 2007; Psomas et al., 2011). Narrow-band VIs have already demonstrated excellent relations with wheat biomass (Xavier et al., 2006) or Green LAI (Haboudane et al., 2004; Hinzman et al., 1986).

Thenkabail et al. (2000) introduced the Normalized Ratio Index (NRI) based on the visible (VIS) and NIR spectra without using shortwave infrared (SWIR) domain. According to van Leeuwen (2009), the NIR domain is defined from 700 nm to 1100 nm and the SWIR from 1100 nm to 2500 nm. The NRI represents the best band combination. Using 2006 EO-1 Hyperion data, Koppe et al. (2010) found that NRI calculated from the NIR and SWIR bands (centered at 874 nm and 1225 nm) performed much better than broad-band or other narrow-band VIs in regional winter wheat biomass estimation.

Although the importance of monitoring agricultural production at regional scales has been identified as a key task (Bouman, 1995; Clevers and Jongschaap, 2001), yield and biomass estimation were rarely addressed at the regional scale using multispectral and hyperspectral data due to uncertainties in prediction associated with this scale and limited data availability (Bareth, 2009; Lobell et al., 2003; Ma et al., 2008). However, this situation has changed rapidly in recent years (Lu, 2006). For example, Cho et al. (2007) estimated grass biomass in Southern Italy using HyMap data. Psomas et al. (2011) studied grassland in the Swiss Plateau. In the North China Plain, Ren et al. (2008) predicted winter wheat yield; Bao et al. (2009) monitored winter wheat biomass using MODIS data; and Koppe et al. (2012) estimated winter wheat biomass using Hyperion data. Remote sensing has proved to be an effective alternative for mapping aboveground biomass in remote areas at the regional scale (Ji et al., 2012).

For the development and implementation of a multiscale biomass model, the NRI was tested. This index was derived by Koppe et al. (2010) based on 2006 Hyperion imagery against 2007 spectral field measurements in the same study area for winter wheat biomass estimation. Several selected VIs were also compared to the NRI. Moreover, a new index, the GnyLi (named in this study by the authors Gnyp and Li who did most of the field and data analyses work), was introduced using the absorption and reflectance features in the NIR and SWIR spectral regions. The VIs were used to build the biomass models based on a newly proposed bottom-up approach. Finally, the models were tested against independent field-observed datasets. Due to the increasing availability of hyperspectral satellite data, the importance of developing validated algorithms and models for field and regional applications, especially in crop production, is apparent.

Study site and data

Study site description

The study site Huimin County (~1400 km^2) is located in the North China Plain (117.4° E, 37.3° N), at the lower stretch of the Yellow River (Huang He), approximately 100 km west of the Bo Hai Sea in the Northeastern Shandong Province (Fig. 1). This area is characterized by the warm-temperature sub-humid continental East Asian monsoon climate controlled by the thermal low-pressure area at the Tibetan Plateau. A clear seasonal change between arid, cool winter and humid, hot summer days exists. The annual average temperature is 12.5 °C and the total annual precipitation is 600 mm with a summer maximum. Yellow loamy fluvisols with the alluvial loess as subsoil substrate are typical for the area. Soil and climate allow double-cropping per year. The dominant cropping system is a summer maize and winter wheat rotation. Winter wheat is sown in October and harvested in early June of the following year. The specific study fields L1-L3 are located in Xizhangliu village and L4 in the Xili, Xujia and Donjie villages.

Multiscale set-up of the study fields

Level 1 (L1): small experimental fields

The small experimental field plots (L1) included 48 plots in total, each in a size of 4.5 m by 7.5 m. Two cultivar experiments with four replications and six nitrogen (N) fertilizer treatments were set up. The cultivars were *Kenong9204* (new cultivar) and *Lumai23* (local cultivar). Each replication consisted of six N treatments: (1) *Control* (no N input), (2) 40% of optimum N rate (*Opt*), (3) 70% of *Opt*, (4) 100% of *Opt*, (5) 130% of *Opt*, and (6) conventional N fertilization. The last one represents the local farmers' practice with a total N input of approximately 300 kg N/ha. The optimal rate was plot-specific, based on expected plant N demand and measured soil N supply for the growing periods from the sowing through harvest (Li et al., 2008).

Level 2 (L2): large experimental fields

The large experimental field plots (L2) had a plot size of 10 m by 15 m with four replicates of five differently fertilized plots. The application rate of nitrogen fertilizer like urea $(NH_2)_2CO$ was either 0, 25, 50, 75 or 100 kg N/ha before sowing the local winter wheat cultivar *Weimei8* in early October of 2006. When the phenological stage of BBCH 30 was reached, each plot was divided into two parts (7.5 m by 10 m), one with and one without N topdressing. L2 includes 20 plots before topdressing and 40 after topdressing.

Level 3 (L3): small farm fields

The L3 experiment comprised farm fields with both controlled and conventional management. For *Control* and *Opt* plots, the plot size was 150 m^2. The conventionally managed plots' size ranged from 150 m^2 to 1750 m^2. Totally, 14 small farm fields were selected