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The dynamic simulation of rice growth parameters under cadmium stress with the assimilation of multi-period spectral indices and crop model

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ABSTRACT

Obtaining precise information regarding the levels of heavy metal stress in crops is vital for food security, agricultural production, and ecological protection. In this study, we realized the dynamic simulation of rice growth parameters in three experiment fields that were exposed to varying levels of soil Cd (cadmium) concentration, intending to monitor the stress-induced changes of growth parameters on time scale. To simulate the growth parameters Leaf Area Index (LAI), Weight of Storage Organs (WSO) and Total Above Ground Production (TAGP) more accurately, we imbedded a Cd stress factor f_{Cd} into the initial World Food Study (WOFOST) model. Then, as the spectral sensing technology is a potentially promising method to monitor crop stress conditions, an optimized methodology of assimilating multi-period spectral indices into the coupled WOFOST + PROSPECT + SAIL model was adopted to obtain the optimum value of stress factor; next, the dynamic simulation of growth parameters was adjusted. Particularly, based on the specific sensibility to contamination levels at different growth stages, TCARI (Transformed Chlorophyll Absorption in Reflectance Index), REP (Red Edge Position) and RH (Reflectance Height) were selected as the multi-period spectral indices, serving as the compared targets of the cost function in the process of assimilation. The growth parameters simulated by the modified WOFOST model preferably reflected the variations of rice growth status on a time scale with R^2 over 94% at all of the three levels. This study indicates that the optimized methodology of assimilating multi-period spectral indices into the crop model is applicable for simulating growth parameters under Cd stress, which provides a reference for dynamically monitoring heavy metal contamination in farmland environments.

1. Introduction

Food security is an important issue that affects national security and people's livelihood. In some fast-growing industrial cities of China, one of the major environmental problems is the heavy metal contamination of farmlands (Khan et al., 2007; Muchuweti et al., 2006; Nabulo et al., 2010; Rodriguez et al., 2007; Tandi et al., 2004). According to the related statistics, approximately 2.786×10^5 ha of farmland in China is severely affected by Cd (cadmium) contamination. Moreover, Cd tends to be more toxic to plants and easily enters the human diet through the food chain (Dorina and Michael, 2005; Xiao et al., 2009).

Heavy metal contamination in farmlands is concealed, permanent and irreversible. Compared with the traditional ground-based detection, the spectral sensing technology is a promising method that provides a new alternative to achieve rapid, non-destructive and real-time monitoring of the stress-induced inhibitions on crop growth parameters (Dunagan et al., 2007; Osborne et al., 2002). However, most of the previous studies adopted empirical or semi-empirical models that were established based on the relationship between sensitive spectral characteristics and the heavy metal concentrations (or crop growth parameters) (Clevers et al., 2004; Haboudane et al., 2004; Kooistra et al., 2004; Ren et al., 2008; Rosso et al., 2005; Schuerger et al., 2003). These relationships were generally built based on the statistical analysis of data consisting of leaf-level spectral reflectance from the plants that were exposed to varying levels of heavy metal stress. The lack of robustness and portability makes the statistical methods less persuasive from the viewpoint of the crop growth mechanism. The interpretation of the spectral data for monitoring purposes put more emphasis on

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the decision or classification problem, which seeks to determine if the physiological responses to stress can be detected in reflectance at the leaf level. The impacts of environmental factors and crop parameters on growth status have not been considered. In addition, the pure way of spectral analyses focus on the stress-induced variations at one or more discontinuous stages of crop growth, whereas the degrees of crop contamination are different at different growth stages, even under the same contamination condition (Wang, 1996). Hence, the multi-period spectral indices should be selected as the time-series stress indicators of contaminated crops, intending to reflect the difference in vegetation canopy reflectance at different crop growth stages.

Compared with the statistical analysis on spectral characteristics, the crop growth model WOFOST (World Food Study), which uses relevant environment and crop parameters, has the advantages of mechanism and time-scale simulation. The model can dynamically describe the fundamental processes of crop growth, such as photosynthesis, respiration, transpiration and biomass partitioning (Ma et al., 2013). Moreover, the assimilation of multi-period spectral indices into WOFOST model can not only improve the simulation precision of growth parameters, but also obtain input parameters in real time (Macdonald and Hall, 1980; Ren et al., 2011; Wu et al., 2012; Zhao et al., 2013). In this study, we realized the dynamic simulation of rice growth parameters Leaf Area Index (LAI), Weight of Storage Organs (WSO) and Total Above Ground Production (TAGP) in three experiment fields in order to monitor the Cd stress-induced changes of rice in the entire growing season. As the initial WOFOST model does not use any stress factor to describe the impacts of heavy metals on normal crop growth, we imbedded a Cd stress factor f_{Cd} into the WOFOST model (Wu et al., 2013). Furthermore, the PROSPECT + SAIL canopy radiative transfer model was coupled to the WOFOST model, and then the multi-period spectral indices Transformed Chlorophyll Absorption in Reflectance Index (TCARI), Red Edge Position (REP) and Reflectance Height (RH) were assimilated into the coupled model to obtain the optimum value of factor f_{Cd}; next, the dynamic simulation of rice growth parameters was adjusted. Overall, the methodology in this study is established based on the crop growth mechanism and spectral information, providing a new reference for dynamically simulating crop growth parameters under heavy metal stress.

2. Study area and materials

2.1. Field experiment design

The study area was located in the city of Changchun, which lies in the main grain producing area of Jilin Province, China. The Changchun region (124°18′E–127°05′E, 43°05′N–45°15′N), which covers 20,604 km^2, belongs to an area that grows single precocity rice in Northeast China Plain. The main type of rice grown in this area is Jilin japonica, whereas the main type of soil is black soil, with a pH of 7.0–7.3 and 2–4% of sufficient organic matter. However, as one of the heavy industry bases in China, several industries have existed in this area for decades, such as the China First Automobile Works. Thus, the problem of Cd contamination in rice fields has resulted from the rapid development of industry and lack of environmental protection. The planted rice is supplied with abundant fertilizers and irrigation water to avoid the unwanted stress caused by other environmental factors. Three rice fields with different contamination levels were selected as experimental fields (Fig. 1), they were categorized as Safe Level, Level I and Level II based on the respective soil Cd concentrations (Table 1). According to local rice management experience, the levels of soil Cd contamination were consistent within the same rice field. In addition, the fields were similar with regard to climate, historical land use and soil series.

2.2. Data preparation

2.2.1. Spectral sensing data

Spectral sensing data were acquired in 2009 at twelve acquisition dates: May 20 (the time is expressed as the day of the year, DOY; May 20 is thus called DOY 140), June 20 (DOY 171), June 25 (DOY 176), July 8 (DOY 189), July 19 (DOY 200), July 29 (DOY 210), August 4 (DOY 216), August 12 (DOY 224), August 30 (DOY 242), September 4 (DOY 247), September 10 (DOY 253) and September 16 (DOY 259). These above-listed dates covered the entire growing season in the study area. The rice canopy and soil reflectance measurements were conducted during cloudless or nearly cloudless conditions between 10:00 hours and 14:00 hours using an ASD FieldSpec Pro spectrometer (Analytical Spectral Devices, Boulder, CO, USA). This spectrometer was fitted with fiber optics having a 10° field of view (FOV), and was operated in the 350–2500 nm spectral regions with a sampling interval of 2 nm. Reflectance spectra were measured through calibration using a standardized white Spectralon reference panel. A panel radiance measurement was taken before and after the crop measurement with 2 scans each time. The measurements were performed from a height of 1.0 m above the rice canopy. Rice spectral measurements were taken at 40 sample sites over each experimental field at every acquisition date. Then the forty values were averaged and reported as the measured value of the corresponding field.

2.2.2. Field measurements

Field measurements were conducted to obtain the important agronomic and biological parameters of rice during the entire growing season in the study area, particularly the conditions under Cd pollution stress. The measurements primarily included LAI, WSO and TAGP, which indicated the rice growth status. In total, 40 sets of sample data were measured at every acquisition date, with the average of the 40 sets calculated as the observed values of the sample plot.

2.2.3. Climate, soil and crop data

The WOFOST crop growth model was used in this study, which has inputs of climate, soil and crop parameters (Boogaard et al., 1998). Climate parameters principally included solar radiation, air temperature (T), wind speed, vapor pressure and precipitation. The daily air temperature data from the Changchun weather station in 2009 were adopted to determine the air temperatures at the experimental fields. Soil and crop samples were taken almost synchronously with canopy spectral measurements, which were preserved separately in sample bags and transported to the laboratory for analyses. In particular, the Cd concentrations in the ground soil and in the crop samples were determined using flame atomic absorption spectrometry (AAS) following nitric–perchloric acid (2:1) digestion (Lu, 2000).

The varieties of rice that were grown in the three fields were all Jilin japonica, which generally has the same hereditary properties. Thus, the crop parameters (such as specific leaf area, net photosynthetic rate and dry matter distribution coefficient) in the model were adjusted to be constant throughout the measurements and were constant in the literature review (Boogaard et al., 1998; Wu et al., 2009) (Table 2). In addition, the sowing date, the amount of irrigation and the amount of fertilization were also collected as management information.