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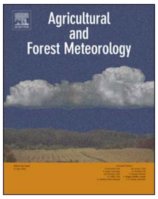

Estimates of rice lodging using indices derived from UAV visible and thermal infrared images

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ABSTRACT

Rice lodging not only causes difficulty in harvest operations, but also drastically reduces yield. Rice lodging assessment contributes greatly to rice plantation and crop field management. In this study, we collected visible and thermal infrared images with an unmanned aerial vehicle. Then, based on hybrid image analysis and field investigation, we established a comprehensive rice lodging recognition model using a particle swarm optimization and support vector machine algorithm. The results showed that color and texture features were different between lodged and non-lodged rice plants. Moreover, the temperature was distinct between lodging and non-lodging areas, with lodged rice having higher canopy temperature. The developed model based on the visible and thermal infrared images was validated using different *Indica* and *Japonica* rice cultivars. The model had a false positives rate and false negatives rate of less than 10%, and estimated lodging rate with an R^2 greater than 0.9. These results indicated that combination of visible and thermal infrared images feature significantly increased the rice lodging recognition accuracy. The developed model can be used to monitor rice lodging and estimate the lodging rate.

1. Introduction

Rice is the most widely consumed staple food worldwide. The sustained high yield of rice is of great significance to global food security. A large number of studies have shown that lodging clearly limits the yield and the quality of rice. Cultivation of lodging-resistant rice cultivars and the development of anti-lodging cultivation techniques have been of significant interest in the rice-related research (Ookawa et al., 2010; Plaza-Wüthrich et al., 2016; Setter et al., 1997). Monitoring lodging is a critical part in the research of rice lodging. The traditional methods of identifying rice lodging areas and locations rely on manual *in situ* assessments, which usually are less efficient and unable to meet the actual needs due to the vast land areas involved.

Remote sensing technology provides a feasible and reliable tool to obtain timely information on crop lodging over vast areas of land. It has been developed rapidly and applied broadly in recent years. Currently, there are three major technologies for assessment of lodging: crop spectral analysis of satellite images, radar system-based optical remote sensing, and unmanned aerial vehicles (UAVs) imagery-based remote sensing (Li et al., 2014a,b). Different overall spectral reflectance of lodging and non-lodging areas is attributed to different spectral features of the stalk and leaf, respectively. These spectral features have been utilized to estimate the lodging grade (Liu et al., 2005). This satellite remote sensing covers large land areas; however, its value for lodging assessment is limited by the spatial- and temporal-resolution as well as the spectral band features (Li et al., 2014a,b). Moreover, optical remote sensing technology has some intrinsic limitations. For example, spectral differences between lodging and non-lodging crops are usually weak, and such weak spectral features are buried in a complicated, mixed, large number of background spectral bands (Schaepman et al., 2009). In addition, the change of spectral features could be caused by many other factors, such as soil environment or other crop stresses including water or fertilizer stress. (Carter and Mccain, 1993; Miphokasap et al., 2012). Therefore, it is difficult to extract weak lodging information from other factors like water or fertilizer stress. Synthetic aperture radar (SAR) instruments provide all-weather data and are sensitive to

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the structural changes of the crop. Yang et al. (2015) reported an excellent separation of lodging wheat from normal wheat using SAR technology. However, radar system-based optical remote sensing is more applicable to large and relatively homogeneous areas. In a small patchwork field, especially when images are relatively small as compared to the spatial resolution of the scanner, and the presence of mixed pixels, the subsequent image analysis will be difficult and inaccurate (Somers et al., 2011). To monitor the lodging within a relatively small land area, UAVs offer a simple, versatile, cost-effective way of collecting images which also have high resolution (Bendig et al., 2015). Collecting red-green-blue (RGB)-imagery by UAV combined with color feature or texture features extraction can be used for lodging area assessment (Li et al., 2014a,b). In addition, aerial RGB images can be synthesized into three-dimensional (3D) canopy images (Murakami et al., 2012; Yang et al., 2017). However, when utilizing UAV technology for lodging assessment, we found that other factors, such as fertilizers, affect the color features obtained from spectral analysis. 3D structures are more accurate for lodging assessment but require a large amount of computation and take more time for image acquisition.

Thermal infrared imagery has wide applications (Dugdale et al., 2015; Kunde et al., 2004; Zhao et al., 2015) and is well suited for crop monitoring. In particular, thermal infrared imagery has been extensively studied for crop water content monitoring and drought stress monitoring (Jones et al., 2009; Sepúlveda-Reyes et al., 2016). It also found applications in crop diseases detection (Li et al., 2014a,b), crop yield and biomass estimation (Zhang et al., 2011), and sprouting status monitoring (Vadivambal et al., 2010).

Therefore, the objectives of this study were (i) to analyze changes of color, texture, temperature features under the non-lodged and lodged rice; (ii) to measure the daily change of crop temperature of non-lodged and lodged rice and identify the optimal time window, which had the maximum temperature difference between non-lodged and lodged rice crops; (iii) to estimate rice lodging using fused RGB images and thermal infrared images collected by the UAV and extract the lodging area based on the developed models, (iiii) to extract the lodging area based on the developed models. This study established a UAV imagery-based crop lodging estimation method.

2. Materials and methods

2.1. Field experiments

Field experiments were conducted in Taizhou and Yangzhou (China). Two *Japonica* cultivars and two *Indica* cultivars were used in this study. The seeds were sown on May 20, 2016 and then manually transplanted on June 16, 2016. During transplantation, the spacing between rows was 0.3 m, and the spacing between the two *Indica* rice and two *Japonica* rice cultivars was 0.16 m and 0.12 m, respectively. At the beginning of September, some rice crops became lodged, and the non-lodging crops were pushed over manually. The detailed information is provided in Table 1. Previous research on crop showed that the nitrogen application rate affected the crop temperature (Fois et al., 2009; Girma et al., 2006). For this reason, nitrogen fertilizer treatments were designed to test whether nitrogen application rate affect the proposed rice lodging recognition method.

Table 1
Information of experimental sites and treatment.

Sites	Cultivars	Nitrogen Treatment	Latitude	Longitude
Yangzhou	N9108*Japonica*)	70 kg ha^{-1}	32°25′N	119°31′E
		210 kg ha^{-1}		
	SY63*Indica*)	70 kg ha^{-1}		
		210 kg ha^{-1}		
Taizhou	W24*Japonica*)	210 kg ha^{-1}	32°51′N	120°01′E
	Y6*Indica*)	210 kg ha^{-1}		

2.2. Image acquisition and processing

A hand-held Flir® E40 thermal imager (FLIR Systems, Inc., Wilsonville, OR, USA) was used to record low altitude thermal infrared (TIF) images. The image capturing height of the hand-held thermal imager was about 1 m. The radiometric resolution is less than 0.1 °C, and the spatial resolution is less than 0.1 cm. A ZENMUSE XT thermal camera (spectral band 7.5–13.5 μm; resolution: 320 pixels; FLIR Systems, Inc.) and a DJI X5R camera (resolution: 4608 × 3456 pixels; DJI-Innovations, Inc., Shenzhen, China) were installed on a DJI Inspire 1 drone (DJI-Innovations, Inc.) to record TIF images and visual images of the rice canopy, respectively. The drone flight altitude was 60, 100, and 150 m, in which 60 m flight height was used for model establishment and validation, while 100 m and 150 m were used to investigate the effects of flight altitude on the modeling. The images were acquired on sunny days without strong wind, every 2 h between 8 a.m. to 8 p.m. The Fluke 941 illuminometer (measurement range: 20–20000 lux; resolution: 1 lux; Fluke, Inc., Everett, USA) was used to measure the light intensity in different rice communities.

The color extraction of from visual RGB images was conducted using Matlab (V2016a, MathWorks, Natick, MA, USA). TIF images were read using Flir® Tools (version 6.2, FLIR Systems, Inc.) and the temperatures were exported to Matlab for further analysis. The RGB images and TIF images were matched and fused according to literature (Jin et al., 2017a,b,c). In the fusion processing, square panels of 30 cm width were distributed in the field to be used as ground control points (GCPs) to get more accurate positioning of the images. Image segmentation was performed on the RGB and TIF hybrid images to obtain subsample images with a size of 20 × 20 pixels and actual size of 40 × 40 cm. The information of used computer is as follows: CPU, Intel Xeon 3; GPU, GALAXY GTX 1050Ti 4G; RAM: Kingston DDR3 12G. The program running time is between 900 ms and 1500 ms.

2.3. Extraction of feature values

2.3.1. Color features

According to Eqs. (1)–(3), individual red (R), green (G), and blue (B) channel characteristics were extracted from RGB images, while the ExG characteristics were extracted according to Eq. (4) (Jia et al., 2004). Chlorophyll has absorption peaks in the red (r) and blue (b) channels and a reflection peak in green (g) channel. In addition, chlorophyll is an important part of green plants. Therefore, the g value of green plant is bigger than r value and b value. For the above reasons, ExG value ($ExG = 2 \times g - r - b$) of green plant is much bigger than other objects, and the ExG value is changed with the greenness value of plants. ExG has been widely cited and used in crop growth evaluation and field monitoring.

$$\mathrm{r}= \frac{R}{R + G + B} \tag{1}$$

$$r = \frac{G}{R + G + B} \tag{2}$$

$$b = \frac{B}{R + G + B} \tag{3}$$

$$ExG = 2 \times g - r - b \tag{4}$$

2.3.2. Texture features

The rice field texture features were described using coarseness (F_{crs}), contrast (F_{con}), linelikeness (F_{lin}), and directionality (F_{dir}) according to the published literature (Tamura et al., 1978). The equations used are as follows: