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Towards three-dimensional modeling light capture of crop canopy considering regional variation of incident radiation

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Highlights: A GIS-based model was adopted to simulate the regional variation of incident photosynthetically active radiation (PAR) in mountainous area. The PAR capture of rice and tobacco canopies at four special eco-sites was calculated utilizing three-dimensional modeling. This provides the basis for using functional-structural models to simulate crop growth and assess plant types at different regions accurately.

Keywords: crop growth simulation, functional-structural plant modeling, GIS, PAR, regional variation

INTRODUCTION

Crop growth and yield is greatly affected by environmental conditions. For instance, mean radiation of 20-21 MJ m^{-2} d^{-1} is needed for potential growth of rice (Peng et al. 2004). Reduction of incident radiation in rainy season in tropical and subtropical regions can limit rice growth significantly, and rice yield may decrease 30% if the incident radiation drop 50% during reproductive period (Singh 2005). Rice yield in mountainous area of Yunnan, China, could be 90% higher comparing to the major rice producing areas in the middle and lower reaches of Yangtze River Plain, although they all belong to subtropical region (Li et al. 2009). Studies showed that mild air temperature is one of the main environmental factors for high yielding in Yunnan (Ying et al. 1998; Katsura et al. 2008), and high incident radiation also plays an important role for high yielding in this region. Despite of mountain shading, incident radiation in Yunnan is significantly higher than that in Yangtze River Plain because of its lower latitude and high altitude (Li et al. 2009). Incoming radiation and other environment factors can be modified substantially by terrain. In order to accurately simulate crop growth at different regions, accurate simulation of the environmental conditions by considering regional variations is required. Rice and tobacco crop rotation is commonly used in Yunnan. The objectives of this paper are: using a GIS-based model to quantify diurnal incident radiation in different regions of Yunnan; simulating light interception of rice and tobacco based on three-dimensional canopy architectural models. This study can provide a preliminary exploration for crop growth simulation and quantitative assessment of plant types under different environmental conditions.

SIMULATIONS

The digital elevation model (DEM) of Yunnan province (Fig. 1a) was divided into 90 square units with the span of 1° × 1° latitude and longitude in ArcGIS (Esri, USA). Solar elevation angle, azimuth and extraterrestrial radiation for each given moment in a day were calculated for each square unit according to its center position. The solar radiation for each raster grid (1 km × 1km) was calculated using Hybrid model (Yang and Koike 2005; Gueymard 2012). The input parameters include: the altitude, air temperature and relative humidity. Direct and diffuse radiative transmittances were calculated separately by considering the extinction of ozone thickness, precipitable water and aerosols to radiation. The surface pressure, ozone thickness, precipitable water, turbidity coefficient were all calculated by empirical functions with input parameters. Then the radiation on the earth surface was calculated via extraterrestrial radiation and direct or diffuse radiative transmittance. Conversion parameter of 1.9 was used to transfer broadband radiation (W m^{-2}) output by Hybrid model to photosynthetically active radiation (PAR, μmol m^{-2} s^{-1}, Wang et al. 2007).

The shading to each raster grid in each square unit was determined via ArcGIS Spatial Analyst tool Hillshade. The temperature lapse rate, i.e. the rate of decrease of atmosphere temperature with the increase of altitude, was calculated by linear regression of daily mean air temperature and altitude of each meteorological station in Yunnan (Fig. 1b). Daily mean air temperature error was calculated by subtracting measured values at meteorological stations from the values computed with temperature lapse rate. Inverse Distance Weighted (IDW) method in ArcGIS Spatial Analyst was used to interpolate daily mean air temperature error. The daily mean air temperature of each raster grid was calculated by temperature lapse rate and compensated with temperature error. The relative humidity of each meteorological station was directly interpolated for each raster grid with IDW method in ArcGIS. Meteorological data was downloaded from China Meteorological Data Sharing Service System (http://www.cma.gov.cn/2011qxfw/2011qsjgx/).

The architecture data of rice cultivar Y58S/9311 was adopted from Zheng et al. (2008). The architecture data of tobacco cultivar K326 was collected using FastSCAN^{TM} (Polhemus, USA) at the Zhaowei experimental site (24.35N, 102.52E, 1642 m) in 2012. Scenario analyses of diurnal PAR distributions were conducted for Lijiang (27.13N, 101.03E, 1170 m), Xundian (25.56N, 103.25E, 1883 m), Yuxi (24.35N, 102.52E, 1642 m) and Puer (23.02N, 101.28E, 1360 m). The PAR interception of crop canopy was simulated using DSHP model (Wang et al. 2006).

RESULTS AND DISCUSSION

The simulated results at 12:00 on July 6, 2011 showed that there was more direct PAR but less diffuse PAR in higher altitude regions of Yunnan province under clear sky (Fig. 1c, 1d), due to the decrease of substance contents in the atmosphere which can absorb and scatter radiation with the increase of altitude.

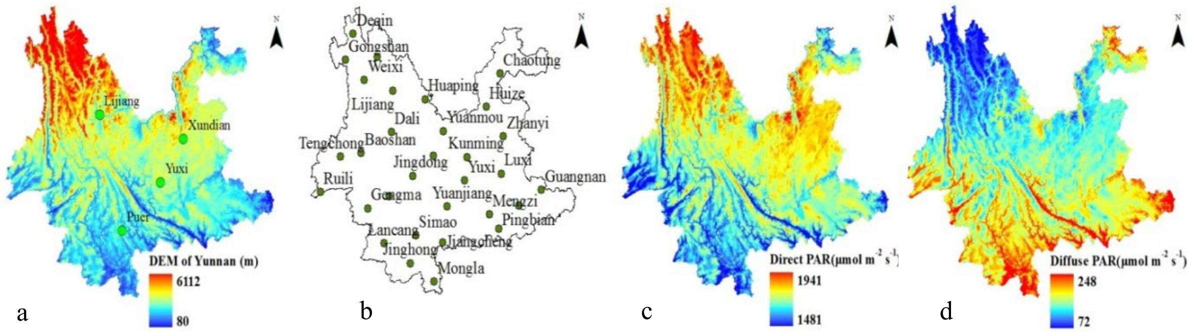

Fig. 1. The digital elevation model of Yunnan province and positions of the four specific eco-sites (a), the distribution of meteorological stations in Yunnan (b), the direct (c) and diffuse (d) PAR distribution in Yunnan at 12:00 on July 6, 2011

Diurnal courses of incident PAR were similar for the four eco-sites under clear sky. The differences of incident PAR can be identified among the four eco-sites although they were mild (Fig. 2a, 2b). The simulated diurnal courses of PAR interception of rice and tobacco canopies at the four eco-sites are showed in Fig. 2c, d. No significant differences were observed at early morning (7:00-9:00) or late afternoon (17:00-18:00) between the PAR interception of rice (Fig. 2c) and tobacco (Fig. 2d) canopy. In contrast, rice canopy intercepted more PAR than tobacco at higher solar elevation angles (10:00-16:00), as rice leaf area index (8.1) was substantially higher than that of tobacco (2.8). The decrease of PAR interception of rice canopy occurred at 13:00 (Fig. 2c) because of its steep leaf angle coincide with high solar elevation angle (ca. 85°). It was not the case for tobacco canopy because of its rather flat leaves (Fig. 2d).

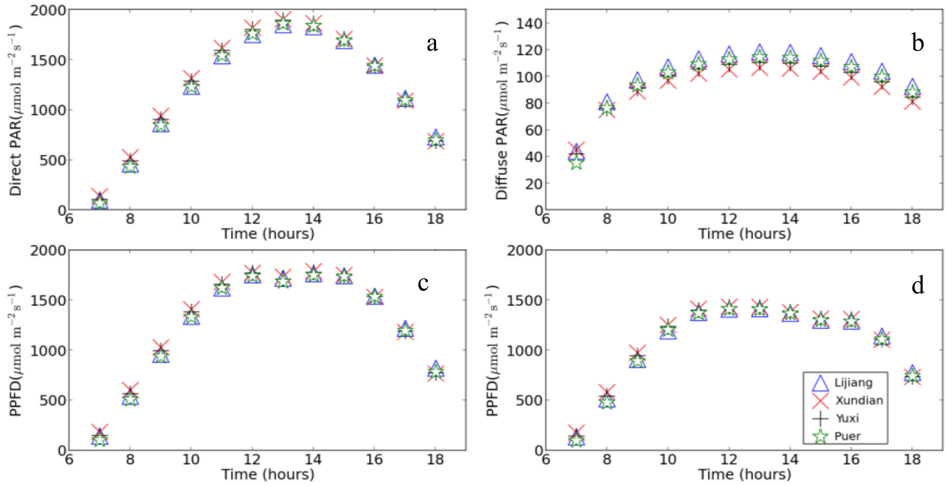

Fig. 2. The simulated diurnal courses of incident direct (a) and diffuse (b) PAR, the PAR interception of rice (c) and tobacco (d) canopies at the four specific eco-sites in Yunnan under clear sky on July 6, 2011

The visualizations of PAR distribution within rice and tobacco canopies in Yuxi at 12:00 were shown in

Fig. 3. In current study, the model test was not implemented yet because of the lack of measured data, and only scenario in clear sky condition was analyzed. As accurate simulation of incoming radiation is substantially affected by sky cloud cover in mountainous area, this will be incorporated in the future work. Currently our simulation was conducted based on the static canopy model. Dynamic model can be adopted in future to assess the effects of regional variation of incident radiation on crop growth.

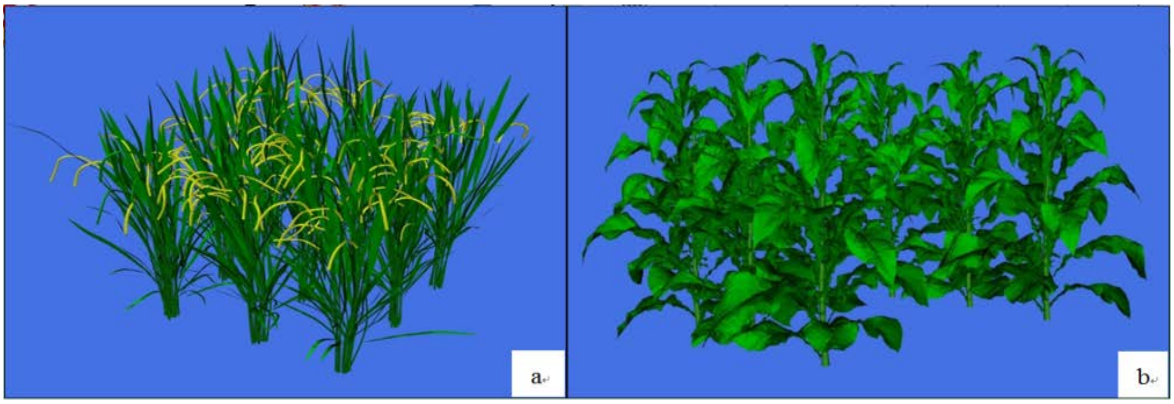

Fig. 3. Visualization of PAR distribution in rice (a) and tobacco (b) canopies in Yuxi at 12:00 on July 6, 2011

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