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Interpreting spatial heterogeneity of crop yield with a process model and remote sensing

Shi Hu, Xingguo Mo*

Key Laboratory of Water Cycle and Its Related Land Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, PR China

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ABSTRACT

A process-based crop growth model (Vegetation Interface Processes (VIP) model) is used to estimate crop yield with remote sensing over the North China Plain. Spatial pattern of the key parameter—maximum catalytic capacity of Rubisco (V_{cmax}) for assimilation is retrieved from Normalized Difference of Vegetation Index (NDVI) from Terra-MODIS and statistical yield records. The regional simulation shows that the agreements between the simulated winter wheat yields and census data at county-level are quite well with R^2 being 0.41–0.50 during 2001–2005. Spatial variability of photosynthetic capacity and yield in irrigated regions depend greatly on nitrogen input. Due to the heavy soil salinity, the photosynthetic capacity and yield in coastal region is less than 50 μmol C m^{-2} s^{-1} and 3000 kg ha^{-1}, respectively, which are much lower than that in non-salinized region, 84.5 μmol C m^{-2} s^{-1} and 5700 kg ha^{-1}. The predicted yield for irrigated wheat ranges from 4000 to 7800 kg ha^{-1}, which is significantly larger than that of rainfed, 1500–3000 kg ha^{-1}. According to the path coefficient analysis, nitrogen significantly affects yield, by which water exerts noticeably indirect influences on yield. The effect of water on yield is regulated, to a certain extent, by crop photosynthetic capacity and nitrogen application. It is believed that photosynthetic parameters retrieved from remote sensing are reliable for regional production prediction with a process-based model.

1. Introduction

Due to the growing population and diminishing hectare of farmland, grain production increasing by per unit of area in the main agricultural area, such as North China Plain (NCP), is critical for the nation food security. A basic and emergent issue for production enhancement is to investigate what factors limiting the current production and how to ameliorate the situation. Even though process-based crop growth model can simulate crop yield in different environmental and management situations, it still faces great challenges to capture the spatial and temporal variability of crop yield due to the uncertainty of spatial environmental driving data (e.g., weather, soil, management, irrigation, fertilization).

Remote sensing has been widely used for retrieving this kind of environmental information in recent years, due to its high inherent spatial and temporal density. Through some forms of empirical function or physical scattering models, remote sensing data can be translated into data which are corresponding to forcing parameters or state variables in ecological modeling (Mo et al., 2005). Two kinds of data are most frequently been derived, one is the surface climatic data and the other is some vegetation-related information. The surface climatic data mainly include air temperature (Hamdi et al., 2009), humidity (Lohnert et al., 2009), precipitation and radiation (Michaelides et al., 2009; Troy and Fwood, 2009). The second kind of data includes individual environmental factors (e.g., surface temperature, soil moisture content) and vegetation growth indexes (e.g., LAI, V_{cmax}), which are usually expressed as parameters in the model and their spatial pattern are hard to obtain. With the support of remote sensing, vegetation-related information can be readily obtained and the modeling capability of process-based model is intensified. This is confirmed by Ottle and Vidal-Madjar (1994) and Gillies et al. (1997) who used the surface temperature to improve the simulation of energy balance components, Burke et al. (1998) who utilized the surface soil moisture content derived from microwave data to update the process modeling of bare soil, and Matsushita and Tamura (2002) who successfully simulated net primary productivity in East Asia with the aid of LAI retrieved from remote sensing. However, there is no report on photosynthetic capacity pattern retrieved from remote sensing data yet. Previously, the regional photosynthetic capacity is defined based on the data at some typical sites corresponding to yield levels (Mo et al., 2009), because there is no empirically or theoretically derived transfer function between V_{cmax} and remote sensing data.

* Corresponding author. Tel.: +86 10 64889307.
E-mail address: moxg@igsnrr.ac.cn (M. Xingguo).

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Several literatures have attributed spatial variation of crop yield to regional climate variables (Twine and Kucharik, 2009; Lobell et al., 2009), irrigation facility (Mo et al., 2009; Reidsma et al., 2009), soil nutrient status (Shahandeh et al., 2005; David et al., 2005) and a combination of all the above-mentioned factors. According to Kaufmann and Snell (1997), roughly 19% of the variability in corn yield in USA is due to climate variables and about 74% of the variability can be explained by soil variables (e.g., capital, labor, fertilizers, pesticides, etc.). In the North China Plain, the effect of water, nitrogen and soil alkalization on crop yield have been studied separately. It is reported that the available nitrogen is closely related to wheat yield and thousand-grain weight with partial correlation coefficients of 0.57 and 0.50, respectively (Chen et al., 2008). It is also shown that water is the limiting factor to winter wheat yield in the northern part of NCP when nitrogen is sufficient, and soil salinity is the key factor limiting crop yield in costal regions (Mo et al., 2005; Jin et al., 1999).

In this paper, we design an approach to retrieve photosynthetic capacity pattern from remote sensing data for simulation of regional crop yield. Based on the pattern of crop yield, some questions are focused: (1) what factors show significant effects on crop yield and how they impact wheat yield; (2) how to increase current production level.

2. Materials and methods

2.1. Region description

The Beijing–Tianjin–Hebei region is located at north part of the North China Plain, which covers Beijing, Tianjin and part of Hebei province and extends from latitude 36°05′N to 40°24′N and longitude 113°11′E to 119°45′E. The prevailing cropping system is a wheat–maize rotation, which represents traditional cropping system in the North China Plain and accounts for 90% of the cereal sowing area. The mean annual temperature is between 3.8 °C and 13.1 °C and varies gradually from subhumid in the southern to semi-arid in the northern part. The annual precipitation is about 500–800 mm, which distributes irregularly among seasons. About 75% of the rainfall occurs from late June to September during the maize growth stage, and only 25% occurs in wheat growing period, from October to May. Due to insufficient rainfall in wheat growing period as well as insufficient surface water for irrigation, groundwater is the major irrigation water source in the study area. The soil texture in this region is categorized as silt, sandy silt and sandy loam (Fig. 1).

2.2. Model introduction

The ecological system model used in this study is a dynamic ecosystem model (Vegetation Interface Processes (VIP) model) which simulates radiation, water, heat and CO_2 transfer processes over the crop growing seasons (Mo et al., 2004; Mo and Liu, 2001). The main biochemical processes in the model include land surface energy balance, water cycle as well as carbon cycle (Fig. 2, Mo et al., 2009).

Energy fluxes are described with a two-source scheme that discerns the canopy and soil surface separately (Shuttleworth and Wallace, 1985). Transfer of solar radiation within the crop canopy is simulated with 20 sub-layers that distinguishes the direct and diffuse components of both the visible (300–700 nm) and the near infrared (700–1300 nm) fractions (Mo and Liu, 2001).

Water cycle deals with the total above-canopy evapotransoiration and soil moisture transfer. The total above-canopy evapotransoiration which consists of soil evaporation, canopy transpiration and its intercepted water evaporation can be simulated, respectively, in the form similar to the Penman–Monteith equation (Monteith and Unsworth, 1990). The soil moisture budget is estimated using a six-layer scheme and described with Darcy's law.

Carbon cycle includes assimilation via photosynthesis, crop growth and soil organic matter decomposition schemes. The crop growth model includes photosynthetic production, the daily growth of crop dry mass is expressed as the balance of gross photosynthesis, respiration and senescence, more details can be seen in Mo et al. (2005).

The model focuses on biochemical mechanism on photosynthesis, crop dry mass formation and water consumption, because the energy transfer, water cycle and carbon cycle are interacted via evapotranspiration, stomata conductance and photosynthesis. In this paper, we mainly pay attention to the photosynthesis of C_3 (wheat) crop. Considering the highly nonlinear response of photosynthesis to incident light, photosynthetic rates for sunlit and shaded leaves are estimated separately, then summed and upscaled to the canopy using a stomatal conductance/photosynthesis relationship (Leuning et al., 1995). The detailed biochemical approaches of photosynthesis of C_3 (wheat) crop, according to Farquhar et al. (1980), Collatz et al. (1991) and Sellers et al. (1996), are employed. The net assimilation rate of CO_2 (A_n, μ mol C m^{-2} s^{-1}) is expressed as:

$$A_n = \min(A_R, A_E, A_S) - R_d \quad (1)$$

where A_R is the Rubisco limiting rate, A_E is the light-limited rate, A_S is the capacity for the export or utilization of the products of photosynthesis, R_d is the leaf respiration rate (μ mol C m^{-2} s^{-1}). The Rubisco limiting rate A_R is expressed as:

$$A_R = V_c \left[\frac{c_i - \Gamma^*}{c_i + K_c(1 + O_2/K_o)} \right] \quad (2)$$

where V_c is the maximum catalytic capacity of Rubisco (μ mol C m^{-2} s^{-1}), c_i, O_2 are intercellular concentration of CO_2 and O_2 (Pa), respectively. Γ^* is the CO_2 compensation point (Pa, $=0.5O_2/S$, S is the Rubisco specificity for CO_2 relative to O_2); K_c, K_o are Michaelis constant for CO_2 and O_2, respectively (Pa). In VIP model, V_c decline exponentially with an extinction coefficient k_v and expressed as:

$$V_c = V_{c\max} \exp(-k_v L) \quad (3)$$

where V_{cmax} is the values of V_c at top of canopy, k_v is taken as 0.6 and L is the leaf area index. For more details about A_E and A_S, please refer to Mo and Liu (2001).

A key parameter in this photosynthetic scheme is the maximum catalytic capacity of Rubisco (V_{cmax}) which is determined by the amount of activated enzyme (Rubisco) present. The value of V_{cmax} is affected by any factor which may affect the amount of activated enzyme (Rubisco) present. When there are no environmental stresses, the concentration of Rubsico in the leaf has highest level and crop maintains its maximum V_{cmax} value. During leaf senescence or under environmental stresses, Rubisco decomposes and its concentration in leaf falls, resulting in V_{cmax} value declining. Although V_{cmax} is the mean value in growing seasons in the VIP model (so we would not pay more attention to temporal variation of V_{cmax} in this study), it is still affected by the degree of environmental stresses, leading to spatial variation of V_{cmax}. The VIP model has not yet dealt with nitrogen cycle mechanically in this study. As nitrogen is a key factor to determine the photosynthetic capability and V_{cmax} value, the influence of soil nitrogen, soil water and their interactions is assumed to be accounted for by V_{cmax} values here. Thus, to some extent V_{cmax} is considered to be an empirical parameter reflecting the background of crop photosynthetic capacity in this study.