Improvements of rice and wheat production models by carbon partitioning with multi-satellite imageries and meteorological reanalysis data

Daijiro Kaneko\textsuperscript{a*}, Peng Yang\textsuperscript{b}, N. B. Chang\textsuperscript{c}, Toshiro Kumakura\textsuperscript{d}

\textsuperscript{a} Remote Sensing Environmental Monitor, Inc., 4-5-5, Kamariya-nishi, Kanazawaku, Yokohama, Kanagawa, JAPAN 236-0046 kand.rsem@gmail.com

\textsuperscript{b} Key Laboraty of Resources Remote Sensing & Digital Agriculture, Ministry of Agriculture, 12, Zhongguancun South Street, Haidian District, Beijing 10081, P. R. CHINA yangpeng@mail.caas.net.cn

\textsuperscript{c} Department of Civil, Environmental and Construction Engineering, University of Central Florida, 4000 Central Florida Blvd. Orlando, Florida, USA 32816-2450 nchang@mail.ucf.edu

\textsuperscript{d} Department of Civil and Environmental Engineering, Nagaoka University of Technology, 1603-1, Kamitomioka, Nagaoka, Niigata, JAPAN 940-2188 kumakura@nagaokaut.ac.jp

Abstract – The sustainable crop production is intimately linked with food security as the world population growth remains stable. The recent concern about food scarcity motivates the development of the present system entitled “Remote Sensing Environmental Monitor (RSEM)” leading to the enhancement of the capability for crop yield monitoring. The system includes a photosynthetic sterility crop yield model based on precise land use and cover (LULC) classification of crop field in two eastern Asian countries. The model estimates the photosynthetic fixation of carbon dioxide (CO\textsubscript{2}) that is geared toward estimating the rice production in Japan and China with a reasonable accuracy. This study provides daily estimates of the photosynthesis rate (PSN), which is relevant to the CO\textsubscript{2} fixation with the aid of a precise LULC classification. The computational work was carried out based on the MODIS data, NDVI data (i.e., SPOT VEGETATION), solar radiation derived from Japanese Geostationary Meteorological Satellite (GMS), and meteorological reanalysis data. The validation of such a model is based on carbon partitioning method associated with particular crop species. The ongoing thrust of improving the RSEM-based crop yield model with the carbon partitioning method has been dedicated to winter wheat using China statistical data. It will be extended to deal with similar estimation in Australian areas for model validation in the near future.

Keywords: rice, wheat, model, photosynthesis, monitoring, carbon, partitioning, remote sensing

1. INTRODUCTION

There is anticipated imbalance between the world food supply and demand in the future due to the challenge of climate change. As a consequence, the circumstances for the stability of the cereals supply are of concern. Many ways can relieve the situation, which include the increase in food production by expansion of the farmlands, increase of crop yields by selective breeding, improvements of production incentive by increasing the agriculture income via deregulation, the proper international trade between nations, and the information sharing of cereals production for a better management. However, there exist difficulties when spatial and temporal information of crop production cannot be generated in time. This study stands up for the possible improvements of information sharing by developing an early warning system to monitoring the cereals production at a timely manner using remote sensing.

Such a system of “Environmental Monitoring using Remote Sensing (EMuRS)” has been under development mainly for Asian paddy-rice so far. It may be extended to cover all three kinds of cereals including paddy-rice, winter wheat, and corn by using a similar approach. In the last few years, China switched the crop management policy by importing soy bean instead of the expansion of production lines for self-support. Demand of these three kinds of cereals was therefore altered in the market with the inclusion of the new consideration of soy bean. The proposed EMuRS system named “Remote Sensing Environmental Monitor (RSEM)” in Figure 1 has been employed to meet multiple purposes including the crop monitoring, desertification assessment, carbon fixation via vegetation photosynthesis, and the promotion for Clean Development Mechanism (CDM) afforestation/reforestation certifications. The RSEM system is particularly designed so that the photosynthesis models of cereals and vegetations can be applied to handle multiple estimation efforts of paddy-rice, winter wheat, maize, grassland, and forest. The validation processes of the photosynthesis model were completed by using the carbon partitioning method associated with the paddy-rice production. This paper describes the improvements of the wheat model based on the RSEM system. The efforts of estimating winter wheat is different with that of paddy-rice because there are fewer statistical data of wheat yield such that we have to count on the development of a satellite-based wheat yield model in Japan. The current study thus reexamines the suitability of such a photosynthesis model for wheat yield estimation at Shijiazhuang in Hebei province, Northern China. The method entitled Carbon Partitioning for Model Validation (CPMV) used in the case of paddy-rice is still effective for the case of winter wheat given that considerable errors need to be minimized so far. Shijiazhuang is an ideal site of representative winter wheat production zone which is well irrigated. The wheat yield data for validation should be reliable for the carbon partition method despite the obvious errors in the former studies of winter wheat yield analysis. In addition, the separation of crop field of the winter wheat is relatively easy as compared to that of paddy-rice.

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corn, soy bean, and spring wheat based on crops phenology with the aid of the normalized vegetation index (NDVI). In regard to the photosynthesis model of the cereals production, there are two approaches. One is the distribution study to examine the plant distribution with respect to the photosynthesis rate (PSN) by using both crop yield models and satellite imageries. The other is computation of cereal production based on discontinued spots by on-site models with locally precise area at the farm scale using high resolution satellite data. Some well-known crop yield estimates of maize and soybean were established by combining the SAIL model and MODIS in a county of Illinois, USA (Doraiswamy et al., 2005). Besides, field practices were carried out by calculating water and carbon fluxes using BIOME-BGC model in a North China Plain (Wang, et al., 2005), by predicting a county-level crop yield model for a U.S. cropland and Geographic Information System (GIS) (Wu et al., 2007), by global-scale future change in sown areas using the EPIC model approaches. One is the distribution study to examine the plant the photosynthesis model of the cereals production, there are two

\[ f_{\text{Syn}}(T_c) = \frac{1}{1 + \exp \left( \frac{T_c - T_{\text{th}}}{k_{\text{syn}}} \right)} \]  

(2)

where \( T_{\text{th}} \) is the temperature parameter at half of the maximum photosynthesis rate; and \( k_{\text{syn}} \) is the gradient of the relation between the function \( f_{\text{Syn}}(T_c) \) and the air temperature.

The temperature response functions that distinguish the low-temperature sterility and high-temperature injury conditions are defined by the following equations, referring to the curves obtained by Yong and Murata (1997).

\[ f_{\text{Lster}}(T_c) = 1 - \exp \left[ k_{\text{Lster}} (T_c - T_{\text{Lster}}) \right] \]  

(3a)

\[ f_{\text{Hster}}(T_c) = 1 - \exp \left[ k_{\text{Hster}} (T_c - T_{\text{Hster}}) \right] \]  

(3b)

where \( k_{\text{Lster}} \) is the low temperature sterility constant (dimensionless); \( T_{\text{Lster}} \), the low sterility limit temperature (ºC); \( k_{\text{Hster}} \) is the high temperature injury constant; \( T_{\text{Hster}} \) is the high injury limit temperature (ºC); and \( T_c \) is the plant leaf temperature (ºC).

Finally, the response function of the integrated temperature sterility effects due to both low and high temperature impacts on grain production is expressed as follows:

\[ f_{\text{Ster}}(T_c) = a_{\text{ster}} \cdot \exp \left[ b_{\text{ster}} (T_c - T_{\text{st}}) \right] \]  

(4)

where \( a_{\text{ster}} \), is the air temperature.

The unit of the photosynthesis model is the carbon dioxide fixation rate (gCO₂/m²/day), which is deemed as an integral part of the large scale carbon cycle on the Earth. Note that the temperature response function of the PSN, \( f_{\text{Syn}} \), falls down at low air temperatures. The function, \( f_{\text{Syn}} \), thus shows a S-shaped curve as defined by Eq. (2), and is well known as the Sigmoidal-Logistic type function.
Equations (4) and (5) (Kaneko et al., 2009, 2010):

\[ f_{\text{Ster}} (T_c) = \{1 - \exp[ k_{\text{Later}} (T_{\text{Later}} - T_c)]\} \cdot \{1 - \exp[ k_{\text{Later}} (T_{\text{Later}} - T_h)]\} \]  
(4)

It is necessary to normalize the effective LAI, because the eLAI varies with the vegetation cover ratio, which differs across individual monitoring sites. To discriminate between growth and the proportion of planted crop areas, the present paper defines a standardized NDVI, called the Unit NDVI, by dividing the NDVI by its value corresponding to the average yield over the current season. To transform the unit crop production index (CPI) into a mechanism-based type of grain production index, the unit photosynthesis rate is produced by normalization that must be multiplied by the temperature sterility function \( F_{\text{Ster}} \). Integration of the photosynthesis rate over the interval from sowing time point, \( t_s \), to harvesting time point, \( t_h \), defines the unit crop production index \( \text{CPI}_U \).

\[
\text{CPI}_U = F_{\text{Ster}} \left( T_c \right) \cdot \int_{t_s}^{t_h} \text{PSN}_U \cdot dt
\]  
(5)

\[
F_{\text{Ster}} = \int_{t_s}^{t_h} f_{\text{Ster}} \left( T_c \right) \cdot dt
\]  
(6)

3. DATA COLLECTION AND MODELING ANALYSIS

The air temperature data at test sites are collected by the Automated Meteorological Data Acquisition System (AMeDAS) through the Japanese Meteorological Agency. The atmospheric reanalysis data were collected from the European Centre for Medium-Range Weather Forecasts (ECMWF), the National Centers for Environmental Prediction (NCEP) for air temperature, radiation, and evapotranspiration (ET) for stomatal opening ratio. The Japanese Ministry of Agriculture, Forestry, and Fisheries provides grain statistical information, which includes crop situation index (CSI) for the paddy rice at ten sites in support of modeling and monitoring practices. This CSI is the ratio of crop production in a year of problem to the mean annual production for the most recent ten years. Julian days of crop seeding and harvesting were provided from the districts of Agricultural Administrative Bureau of the Japanese Ministry of Agriculture, Forestry, and Fisheries. Figure 2 shows the distribution of the NDVI in Southeast Asia including Japan derived by SPOT VEGETATION to aid in the present analysis.

4. RESULTS OF THE CROP PRODUCTION INDICES

Figure 3 shows the distribution of PSN in terms of CO₂ sequestration on crop fields during the most severe drought conditions in the Northern China Plain. With the MODIS LULC data, classification of the crop fields was made possible for those four crops including rice, winter wheat, spring wheat, and other crops, by using a decision-tree method with two factors: vegetation phenology and water surface detection based on the Land Surface Water Index (LSWI). The efforts of LULC classification associated with seasonal variations of PSN and CPI can be found out in greater detail in the literature (Kaneko et al. 2007 and 2010). Table 1 shows a validation of the present photosynthesis rice model by carbon weights present in rice biomass of cellulose (C₆H₁₀O₄)n and starch. Validation using the carbon partitioning method confirms a good agreement between the computed amounts of carbon fixation in rice and winter wheat grains and those Table 2. Validation of the improved photosynthesis model by carbon weights included in paddy grains.
sequestrated in harvested yields in Japan and China. The average differences between carbon contents in harvested rice and calibrated carbon fixation estimated by the model are -2.7%, 5.3%, and 5.1% at validation sites of Iwamizawa, Ohogata, and Ohosaki (Furukawa) in 2001 in Japan (Table 2).

According to the measurements of the FLUXNET observation tower for paddy-rice at Mase, Tsukuba by Saito (2005), the maximum photosynthetic rate, PSN$_{\text{max}}$, was 39 (gCO$_2$/m$^2$/day). In addition, Net PSN$_{\text{max}}$ of 36.53 (gCO$_2$/m$^2$/day) was measured by the chamber experiment with half openness (Sakai, 2001). Net PSN$_{\text{max}}$ in daytime was 43.62 (gCO$_2$/m$^2$/day) from the modeling outputs. Reduction of night respiration rate of 7.64 (gCO$_2$/m$^2$/day) was associated with the PSN$_{\text{max}}$ was 39 (gCO$_2$/m$^2$/day) that is similar to the computed PSN$_{\text{max}}$. Comparisons between the computed PSN$_{\text{max}}$ and the measured counterparts in a chamber and FLUXNET confirm a fairly good agreement, which supports the validity of the model using the carbon partitioning method. In the case of winter wheat, the estimation error in Table 3 was highly improved to 0.6 % and -3.4% in 2003 at Shijiazhuang. However, more yield data are needed for validation of winter wheat model. We are preparing two typical sites of Kataning near Perth in Western Australia and Laventon in Victoria states for more studies in the future.

5. CONCLUSIONS

Modern grain production estimation is related to food security that is linked with energy and water supply, global warming, and biological diversity. The present study improves photosynthesis model for paddy-rice and winter wheat by assimilating multisatellite imageries and meteorological reanalysis data in our RSEM system. These models applied to paddy rice and winter wheat in Asia confirms the integrity of the carbon partitioning method applied in both Japan and China. The average differences between carbon contents in harvested rice and calibrated carbon fixation estimated by the model are -2.7%, 5.3%, and 5.1% at validation sites of Iwamizawa, Ohogata, and Ohosaki in 2001 in Japan. In the case of winter wheat, the estimation error was highly improved too. However, more crop yield data are needed for validation of winter wheat model in the future.

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