VALIDATION OF A CROP YIELD AND CO2 FIXATION MODEL OVER ASIA BY CARBON PARTITIONING IN GRAIN PLANTS

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ABSTRACT:
The authors have developed and validated a photosynthetic-sterility model for grain production monitoring under the background of climate change and Asian economic growth in developing countries. This paper presents an application of the model to evaluate carbon-fixation rates in yields of paddy rice, winter wheat, and maize in Asia. The validation of the model is based on carbon partition-ing in grain plants. The carbon hydrate in grains has the same chemical formula as that of cellulose in grain vegetation. The parti-tioning of carbon in plants can validate fixation amounts of computed carbon using a satellite-based photosynthesis model. The model estimates the photosynthesis fixation of rice reasonably in Japan and China. Results were validated through examination of carbon in grains, but the model tends to underestimate results for winter wheat and maize. This study also provides daily distribu-tions of the PSN, which is the CO2 fixation in Asian areas combined with a land-cover distribution classified from MODIS data, NDVI from SPOT VEGETATION, and meteorological re-analysis data by European Centre for Medium-Range Forecasts (ECMWF). The mean CO2 and carbon fixation rates in paddy areas were 25.92 (t CO2/ha) and 5.28 (t C/ha) in Japan, respectively. Comparisons between the model’s values and MODIS seasonal PSNs show similar trends. The writers are preparing to compare computed photosynthesis rates with observed AsiaFlux data for the validation of this model at field sites of paddy, grassland and for-ests in Japan and Asian countries. The model is based on routine meteorological and remotely sensed data, enabling operational monitoring of crop yields.

1. INTRODUCTION

This study has developed and validated a photosynthetic-sterility model for grain production monitoring under the background of climate change and Asian economic growth in developing countries. This paper presents an application of the model to evaluate carbon-fixation rates in yields of paddy rice, winter wheat, and maize in Asia. The validation of the model is based on carbon partition-ing in grain plants. The carbon hydrate in grains has the same chemical formula as that of cellulose in grain vegetation. The parti-tioning of carbon in plants can validate fixation amounts of computed carbon using a satellite-based photosynthesis model. The model estimates the photosynthesis fixation of rice reasonably in Japan and China. Results were validated through examination of carbon in grains, but the model tends to underestimate results for winter wheat and maize. This study also provides daily distribu-tions of the PSN, which is the CO2 fixation in Asian areas combined with the land-cover distribution. Two validation methods for operational monitoring are a comparison between the computed seasonal PSN of this model with that of MODIS PSN and the other is to compare carbon harvested in grains with fixed grain carbon, which is computed by our model, by partitioning fixed CO2 into rice, straw and root portions of plant biomass.

2. METHOD FOR MONITORING CROP PRODUCTION AND VALIDATION

The author defined the photosynthesis rate (PSN) using Eq. (1a) shown below, with a Michaelis-Menten type of radiation re-sponse function $f_{\text{rad}, \text{mm}}$ that is proper for wheat and maize, and another type of radiation response function $f_{\text{rad}, \text{pc}}$ proposed by Prioul-Chartier (1977), which properly fits the curve of the pho-tosynthesis rate for paddy rice.

$$PSN = f_{\text{rad}, \text{mm}}(T_v) \cdot \beta \cdot eLAI$$  \hspace{1cm} (1a)

$$f_{\text{rad}, \text{mm}} = \frac{\alpha_{\text{mm}} \cdot PAR}{\alpha_{\text{mm}} + PAR}$$  \hspace{1cm} (1b)

$$f_{\text{rad}, \text{pc}} = \frac{1}{2\pi} \left\{ \alpha_{\text{pc}} \cdot PAR + PSN_{\text{max}} \right\}$$  \hspace{1cm} (1c)

In those equations, PSN is the photosynthesis rate ($gCO_2/m^2/day$), PAR is the photo-synthetically active radiation
(MJ/m²), $\beta_s$ is the stomatal opening and amm and bmm are Michaelis-Menten constants, $T_c$ is the canopy temperature (°C), eLAI is the effective leaf area index, $a_{pc}$ is the Prioul-Chartier constant, $PSN_{\text{max}}$ is the maximum PSN, and $m$ is the curve convexity constant.

The unit of the photosynthesis model is the carbon dioxide fixation rate (gCO₂/m²/DAY), which fits the objectives for carbon circulation on the earth in this era of climate change. The temperature response function of the photosynthesis rate $f_{\text{Syn}}$ is such that the rate PSN falls at low air temperatures. The function $f_{\text{Syn}}$ shows an S-shaped curve defined by Eq. (2), and is well known as the Sigmoidal-Logistic type function:

$$f_{\text{Syn}}(T_c) = \left[ 1 + \exp \left( \frac{1}{k_{\text{mir}}(T_c - T_{\text{w}})} \right) \right]^{-1},$$

where $T_{\text{w}}$ is the temperature parameter at half of the maximum photosynthesis rate, and $k_{\text{mir}}$ is the gradient of the relation between the function $f_{\text{Syn}}(T_c)$ and the air temperature. The temperature response functions for low-temperature sterility and high-temperature injury are defined by the following equation, referring to the curves obtained by Vong and Murata (1997):

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

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

where, $k_{\text{Lster}}$ is the low temperature sterility constant, $T_{\text{Lster}}$ the low sterility limit temperature, $k_{\text{Hster}}$ is the high temperature injury constant, $T_{\text{Hster}}$ is the high injury limit temperature (°C), and $T_c$ is the plant leaf temperature (°C). Finally, the response function of the compounded temperature sterility effects due to both low following low and high temperatures in grain production is expressed by the following equation:

$$f_{\text{Ster}}(T_c) = \left[ 1 - \exp \left( k_{\text{Lster}}(T_{\text{Lster}} - T_c) \right) \right] \cdot \left[ 1 - \exp \left( k_{\text{Hster}}(T_c - T_{\text{Hster}}) \right) \right].$$

It is necessary to normalize the effective LAI, because the eLAI varies with the vegetation cover ratio, which differs between individual monitoring sites. The NDVI also varies with the vegetation cover ratio. To discriminate between growth and the proportion of crop planted 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:

$$NDVI_{\text{U,i}} = \frac{NDVI_i}{NDVI_{\text{H,100}}},$$

where, $NDVI_{\text{H,100}}$ is the Unit NDVI on the i-th day, $NDVI_i$ is the NDVI on the i-th day. $NDVI_{\text{H,100}}$ is the NDVI at ripening day based on the average annual yield.

The present paper normalizes the photosynthesis rate for CPI$_U$:

$$PSN_{\text{U}} = \frac{PSN_{\text{U}}}{tPSN_{\text{U}}_{\text{H,100}}},$$

where PSN$_{\text{U}}$ is the normalized photosynthesis rate and, $tPSN_{\text{U}}_{\text{H}}$ is the annually-averaged integrated photosynthesis rate (gCO₂/m²) from sowing to the end of the harvesting stage, defined as the tPSN value in a year of average crop production. To transform the CPI index into a mechanism-based type of grain production index, the unit photosynthesis rate (PSN$_{\text{U}}$) in Eq. (5) must be multiplied by the temperature sterility function $F_{\text{Ster}}$. Integration of the photosynthesis rate over the interval from sowing $t_s$ to harvest $t_h$ defines the unit crop production index (CPI$_U$) as taking the following form:

$$CPI_{\text{U}} = F_{\text{Ster}}(T_c) \cdot \int_{t_s}^{t_h} PSN_{\text{U}} \cdot dt$$

$$F_{\text{Ster}} = \int_{t_s}^{t_h} f_{\text{Ster}}(T_c) \cdot dt$$

The CPI$_U$ Eq. (7) involves the leading term expressed via Eq. (8), which is of time-integrated shape so as to account for the effect of temperature on flowering, pollination, and ripening. During crop plant stage 1, of growth:

$$CPI_{\text{U}} = \int_{t_s}^{t_h} PSN_{\text{U}} \cdot dt$$

$$F_{\text{Ster}} = \int_{t_s}^{t_h} f_{\text{Ster}}(T_c) \cdot dt$$

At the crop plant stage 3 of harvesting:

$$CPI_{\text{U}} = F_{\text{Ster}}(T_c) \cdot \int_{t_s}^{t_h} PSN_{\text{U}} \cdot dt$$

$$F_{\text{Ster}} = \int_{t_s}^{t_h} f_{\text{Ster}}(T_c) \cdot dt$$

The model estimates daily crop situation index (CSI$_E$) and crop yield index (CYI$_E$) by defining these indices by equations (11a) and (11b) using the curve of the relation between CSI and CPI in addition to the minimum CSI$_{\text{Hmin}}$ and CYI$_{\text{Hmin}}$ for base values of the lowest condition.

1) On the case of bad harvest:

When $CFP_{\text{CPI}_E}$, crop situation index CSI$_E$ is expressed by:

$$CSI_{E} = 100 - (100 - CSI_{\text{Hmin}}) \left[ \frac{(Y - Y_0)}{(Y_0 - Y_m)} \right]^2 \frac{(t_s - t_f)}{(t_f - t_s)}$$

where, notation $Y_m$ is the minimum CPI$_{\text{Hmin}}$ at the monitoring site, $Y_0$ is the average CPI$_{\text{H}}$, $Y$ is the calculated CPI$_E$ when time $t_{\text{S/heating}}$, $t_{\text{h}}$, and $t_{\text{f}}$ are $t_{\text{S/heating}}$, $t_{\text{h}}$.

Simultaneously, when $CFP_{\text{CYI}_E}$, crop yield index CYI$_E$ is expressed by:

$$CYI_{E} = Y_{\text{ave}} - (Y_{\text{ave}} - Y_m) \left[ \frac{Y - Y_0}{Y_0 - Y_m} \right]^2 \frac{(t_s - t_f)}{(t_f - t_s)}.$$
3. DATA USED FOR MODELING AND VALIDATION

Crop production index for rice requires daily solar radiation and air temperature data, since these vary widely from day to day. The ground air temperature data at test counties are supplied by the Japanese Meteorological Agency from Automated Meteorological Data Acquisition System (AMeDAS) points. The Japanese Ministry of Agriculture, Forestry, and Fisheries provides grain statistical information, which includes crop situation index CSI for the paddy rice at ten counties for modeling and monitoring those paddy provinces. This CSI index is the ratio of crop production in the year in question to the mean annual production for the ten most recent years. Calendars of crop seeding and harvest were provided at our request by the statistics information offices for the district agricultural administrative bureaus of the same Ministry. Figure 1 shows the distribution of vegetation index NDVI in Southeast Asia including Japan derived by spot vegetation.

The NDVI is used as an index of the vegetation biomass for the crop production indices of CPI and CYI. The irradiance data are supplied from European Centre for Medium-Range Forecasts (ECMWF) and are used in computing the CPI and CYI over Asian countries other than Japan.

4. RESULTS OF THE CROP PRODUCTION INDICES AND VALIDATION

Figure 2 shows a distribution of photosynthesis rate (CO₂ fixation) in grain fields during most severe drought conditions in the North China plain. The PSN has incorporated the main factors related to photosynthesis rate, and is applicable to significant climate changes and abnormal weather conditions because of its basis in photosynthesis. Comparisons between the model’s values and MODIS seasonal PSNs show similar trends as shown in Figure 3. The writers classified the crop fields of MODIS land-use distribution into those of four cultivation modes: rice, winter wheat, spring wheat, and other crops, using a decision-tree method with two factors: vegetation phenology and water surface detection of Land Surface Water Index (LSWI) (2005, 2006). Figure 4 depicts relations between estimated Crop Yield Index CYI and Julian day for early monitoring of rice production at the example of Furukawa site in Japan. The CYI is useful for monitoring the seasonal variation of rice yield at early stages of rice.

Table 1 shows a validation of the present photosynthesis model.
Figure 3. Comparison of Computed PSN by the Present Model with that of MODIS PSN

Figure 4. Relation Between Estimated Crop Yield Index CYI and Julian day. for Early Monitoring of Rice Production at the Example of Furukawa site in Japan

Table 1: Validation of the Present Photosynthesis Model by a Carbon Weight Included in Grains
by carbon weights included in rice biomass of cellulose \((\text{C}_6\text{H}_{10}\text{O}_5)_n\) and starch. Results of the comparison show good agreement with prior data: differences between carbon contents in grain and carbon fixation estimated by the model are -3.7%, +15.7%, and +15.8%, respectively, in Japanese northern regions of Iwamizawa, Ohogata, and Furukawa. In China, the estimation error of -1.4% is small for rice at Nanjing. However, the comparison error is considerable on cases of winter wheat and maize. Authors recognize the necessity of validation sites in other countries for these grains as the case of paddy rice sites in Japan. Table 2 includes a severe case of bad harvest in 2003 to evaluate the sterility effects on carbon fixation ratio for paddy rice by correcting the estimation error with Crop Situation Index (CSI). The results imply that the present method overestimates a little on photosynthesis rate resulting in large carbon fixation and also has considerably over effects of sterility resulting in small carbon fixation. The parameterization of Michaelis-Menten constant of radiation response function and the temperature response functions for low-temperature sterility should be improved in next steps. As for the mean CO2 and carbon fixation rates in paddy areas for carbon circulation and global warming, those values were 25.92 (t CO2/ha) and 5.28 (t/ha) in Japan, respectively. The authors consider error factors relating to the results mentioned above as follows:

1. NDVI maximum value composite (MVC) of NDVI is sometimes covered by cloud effects.
2. Yield values vary considerably in a prefecture despite almost the same weather condition.
3. Resolution scale 1 km² of our model is different from that around 500 km² of average yield. The average NDVI in same area is desirable for the validation by the comparison with carbon partitioning in grain plants in actual fields.
4. Harvest index vary widely depending on species, soil fertility and early harvesting for good taste.
5. Yield data are not reliable due to statistical difficulties in large developing countries.
6. Yield definition could be different, that is dry weight, grain only, especially on the case of maize.

Authors consider applying the present model to other test sites in Australia for wheat and maize sites in central U.S.A., so that they can adjust model parameters to fit the yield data. Carbon flux data by AsiaFlux observation network selected in Table 3 will be useful for validation of this model. However, the observed tower-data include CO2 absorption and emission from carbon soil storage. The AsiaFlux data must be revised to extract CO2 fixed by the photosynthesis phenomena using ver-tical flux distribution of ecosystem data. Simultaneously, forest afforestation and reforestation projects can provide data to validate the photosynthesis rate in forests. The authors intend to support certification procedures for clean development mechanism (CDM) projects (Table 4) using the present photosynthesis model.

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Table 4. Japanese CDM experiments for afforestation and reforestation.
CONCLUSION

Authors’ research system supplies evaluation of carbon fixation by vegetation and photosynthesis-based operational monitoring of grain yields from early stages of crop growth to the harvest period in Asia. The authors described photosynthesis and sterility model, which incorporate data related to solar radiation, air temperature, and NDVI by assimilating meteorological and environmental satellite data. The system is also applicable to important fields of monitoring desertification in Asia and CDM afforestation & reforestation. The partitioning of fixed CO₂ into rice, straw and root portions of plant biomass weight was computed and the photosynthesis model was evaluated by carbon weights included in provincial rice productions. The proposed method overestimates a little on photosynthesis rate and also has considerably over effects proportional rice productions. The proposed method overestimates a photosynthesis model was evaluated by carbon weights included in portions of plant biomass weight was computed and the temperature response functions for low-temperature sterility should be improved for operating system. As for the mean CO₂ and carbon fixation rates in paddy areas, those values were 25.92 (t/ha) and 5.28 (t/ha) in Japan, respectively. The method is based on routinely collected observation and prediction data, allowing operational monitoring of crop production at arbitrarily chosen sites.

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