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

Daijiro Kaneko*[a], Peng Yang*[b] and Toshiro Kumakura*[c]

[a]Remote Sensing Environmental Monitor, Inc., 4-5-5, Kamariya-nishi, Kanazawaku, Yokohama, Kanagawa, JAPAN 236-0046;
[b]Key Laboratory of Resources Remote Sensing & Digital Agriculture (Ministry of Agriculture); Institute of Agricultural Resources & Regional Planning, Chinese Academy of Agricultural Sciences, 12, Zhongguancun South Street, Haidian District, Beijing, P.R. CHINA 100081;
[c]Department of Civil and Environmental Engineering, Nagaoka University of Technology, 1603-1, Kamitomioka, Nagaoka, Niigata, JAPAN 940-2188

KEYWORDS: Photosynthesis Rate, Yield Monitoring, CO_2 Fixation, Modeling, Validation, Remote Sensing.

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 car-bon-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 model for estimating CO2 fixation and grain yields using a photosynthetic-sterility model, which integrates solar radiation and air temperature ef-fects on photosynthesis, along with grain-filling from heading to ripening. Monitoring crop production using remotely sensed and daily meteorological data can provide an important early warning of poor crop production to Asian countries, with their still-growing populations. Grain production monitoring would support orderly crisis management to maintain food security in Asia, which is facing climate fluctuation through this century of global warming. Prices of grain tripled compared to those of the last decade and are showing instability because of global finan-cial uncertainty. The proposed crop production index (CPIU) takes the amount of growth as known, using the normalized dif-ference vegetation index (NDVI), and estimates the instantane-ous photosynthesis rate (PSN) as well as low temperature steril-ity and high temperature injury from the heading to the ripening stage (Kaneko, Ohnishi, and Ishiyama 2003; Kaneko et.al., 2004, 2005; Kaneko, 2006, 2007, Kaneko, Kumakura and Yang, 2009) . As for related horizontal distributions, a decision-tree method classifies the distribution of crop fields in Asia using MODIS fundamental land-cover and SPOT VEGETATION data, which include the NDVI and Land Surface Water Index (LSWI). This study also provides daily distributions 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_{rad_mm} that is proper for wheat and maize, and another type of radiation response function f_{rad_pc} proposed by Prioul-Chartier (1977), which properly fits the curve of the pho-tosynthesis rate for paddy rice.

$$PSN = f_{rad} \cdot f_{Syn}(T_c) \cdot \beta_s \cdot eLAI \qquad (1a)$$

$$f_{rad\_mm} = \frac{a_{mm} \cdot PAR}{b_{mm} + PAR} \qquad (1b)$$

$$f_{rad\_PC} = \frac{1}{2m} \cdot \{a_{pc} \cdot PAR + PSN_{max}\} - \frac{1}{2m} \cdot \sqrt{(a_{pc} \cdot PAR + PSN_{max})^2 - 4m \cdot a_{pc} \cdot PSN_{max} PAR} \qquad (1c)$$

In those equations, PSN is the photosynthesis rate (gCO_2/m^2/day), PAR is the photo-synthetically active radiation

(MJ/m2), βs is the stomatal opening amm and bmm are Michaelis-Menten constants, Tc is the canopy temperature (ºC), eLAI is the effective leaf area index, apc is the Prioul-Chartier con-stant, PSNmax is the maximum PSN, and m is the curve con-vexity 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 fSyn issuch that the rate PSN falls at low air temperatures. The func-tion f_{Syn} shows an S-shaped curve defined by Eq. (2), and is well known as the Sigmoidal-Logistic type function:

$$f_{Syn}(T_c) = \left[\frac{1}{1 + \exp\{k_{syn}(T_c - T_{hv})\}} \right], \qquad (2)$$

where T_{hv} is the temperature parameter at half of the maximum photosynthesis rate, and K_{syn} is the gradient of the relation between the function $f_{Syn}(T_c)$ 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).

$$f_{Lster}(T_c) = 1 - \exp[k_{Lster}(T_{Lster} - T_c)] \qquad (3a)$$

$$f_{Hster}(T_c) = 1 - \exp[k_{Hster}(T_c - T_{Hster})], \qquad (3b)$$

where, k_{Lster}, is the low temperature sterility constant, T_{Lster} the low sterility limit temperature, k_{Hster} is the high temperature injury constant, T_{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 he following low and high temperatures in grain production is expressed by the following equation:

$$f_{Ster}(T_c) = \{1 - \exp[k_{Lster}(T_{Lster} - T_c)]\} \cdot \{1 - \exp[k_{Hster}(T_c - T_{Hster})]\} \qquad (4)$$

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:

$$NDVI_{U,i} = \frac{NDVI_i}{NDVI_{H100}}, \qquad (5)$$

where, $NDVI_{U,i}$ is the *Unit NDVI* on the i-th day, $NDVI_i$ is the *NDVI* on the i-th day, $NDVI_{H100}$ is the *NDVI* at ripening day based on the average annual yield.
The present paper normalizes the photosynthesis rate for CPI_U.

$$PSN_U = \frac{PSN}{iPSN_{100}}, \qquad (6)$$

where PSN_U is the normalized photosynthesis rate and, $iPSN_{100}$ is the annually-averaged integrated photosynthesis rate (gCO_2/m^2) from sowing to the end of the harvesting stage, defined as the *iPSN* 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_U) in Eq. (6) must be multiplied by the temperature sterility function F_{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:

$$CPI_U = F_{Ster}(T_c) \cdot \int_{t_s}^{t_h} PSN_U \cdot dt \qquad (7) \quad (2)$$

$$F_{Ster} = \int_{t_f}^{tr} f_{Ster}(T_c) \cdot dt \qquad (8)$$

The CPI_U Eq. (7) involves the heading 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:

$$CPI_U = \int_{t_s}^{t} PSN_U \cdot dt \qquad (9a)$$

$$CPI_U = F_{Ster}(T_c) \cdot \int_{t_s}^{t} PSN_U \cdot dt \qquad (9b)$$

$$F_{Ster} = \int_{t_f}^{t} f_{Ster}(T_c) \cdot dt \qquad (9c)$$

At the crop plant stage 3 of harvesting:

$$CPI_U = F_{Ster}(T_c) \cdot \int_{t_s}^{t_r} PSN_U \cdot dt \qquad (10a)$$

$$F_{Ster} = \int_{t_f}^{tr} f_{Ster}(T_c) \cdot dt \qquad (10b)$$

The model estimates daily crop situation index (CSE_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 CSE_{min} and CYI_{min} for base values of the lowest condition.
1) On the case of bad harvest:
When $CPI<CPI_0$, crop situation index CSI_E is expressed by

$$CSI_E = 100 - (100 - CSI_{min}) \left\{ \frac{(Y - Y_0)}{(Y_0 - Y_m)} \right\}^2 (t_e - t_s)/(t - t_s) \qquad (11a)$$

where, notation Y_m is the minimum CPI_{min} at the monitoring site , Y_0 is the average CPI_0, Y is the calculated CPI_U, when time $t<t_{heading}$, $t_e=t_{hd}$, and $t>t_{heading}$, $t_e=t_{hv}$
Simultaneously, when $CYI<CYI_0$, crop yield index CYI_E is expressed by

$$CYI_E = Y_{ave} - (Y_{ave} - Y_{min}) \left\{ \frac{Y - Y_0}{Y_0 - Y_m} \right\}^2 (t_e - t_s)/(t - t_s), \qquad (11b)$$

where, Y_{ave} is the mean yield , Y_{min} is the minimum yield, Y is the calculated CYI_U, when time $t<t_{hd}$, $t_e=t_{hd}$, and time $t>t_{hd}$, $t_e=t_{hv}$, Y_{ave} : mean yield per unit area, $Y_m= CPI_{min}$, $Y=CPI$,
when time $t<t_{hd}$, $t_e=t_{hd}$, and when time $t<t_{hd}$, $t_e=t_{hv}$.
2) On the case of good harvest ($Y_m>Y_0$):

$$CSI_E = 100 + (CSI_{max} - 100)\left\{\frac{Y-Y_0}{Y_m-Y_0}\right\}^{\frac{1}{2}}(t_e - t_s)/(t-t_s) \quad (11c)$$

where, $Y_m= CPI_{min}$, $Y_0=CPI_0$, $Y=CPI_U$, when time $t< t_{hd}$, $t_e=t_{hd}$, and time $t>t_{hd}$, $t_e=t_{hv}$
When $CYI>CYI_0$, crop yield index CYI_E is expressed by

$$CYI_E = Y_{ave} + (Y_{max} - Y_{ave})\left\{\frac{Y-Y_0}{Y_m-Y_0}\right\}^{\frac{1}{2}}(t_e - t_s)/(t-t_s) \quad (11d)$$

where, $Y_m= CPI_{max}$, $Y_0=CPI_0$, $Y=CPI_U$, when time $t<t_{hd}$, $t_e=t_{hd}$, and time $t>t_{hd}$, $t_e=t_{hv}$, and Y_{ave} is the mean yield per unit area.

The validation utilizes carbon weights included in provincial grain yields by comparing with the values of the photosynthesis model. References of carbon partitioning by Sasaki et al. (2005) and Harvest Index by Sinclair et al. (1998) give partitioning of fixed CO_2 into rice, straw and root portions of plant biomass weight.

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 Meteoro-logical Data Acquisition System (AMeDAS) points. The Japa-nese Ministry of Agriculture, Forestry, and Fisheries provides grain statistical information, which includes crop situation in-dex 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 statis-tics information offices for the district agricultural administra-tive bureaus of the same Ministry. Figure 1 shows the distribu-tion 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 (CO_2 fixa-tion) in grain fields during most severe drought conditions in the North China plain. The PSN has incorporated the main fac-tors related to photosynthesis rate, and is applicable to signifi-cant climate changes and abnormal weather conditions because of its basis in photosynthesis. Comparisons between the mod-el'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 esti-mated Crop Yield Index CYI and Julian day for early monitor-ing 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

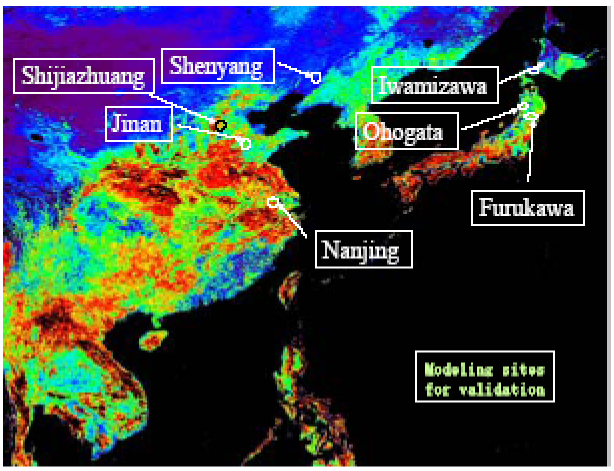

Figure 1. Validation Sites in East Asia Including Japan for Validation

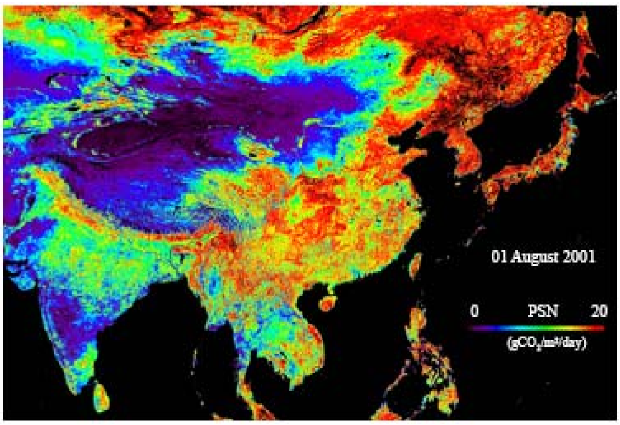

Figure 2. Distribution of Photosynthesis Rate (CO_2 Fixation) in Southeast Asia on 1 August 2001

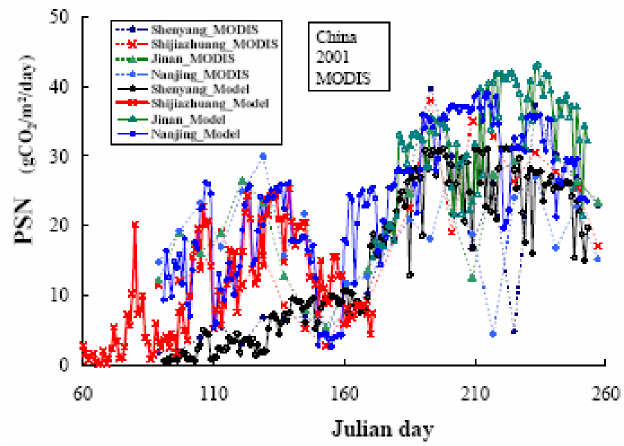

Figure 3. Comparison of Computed PSN by the Present Model with that of MODIS PSN

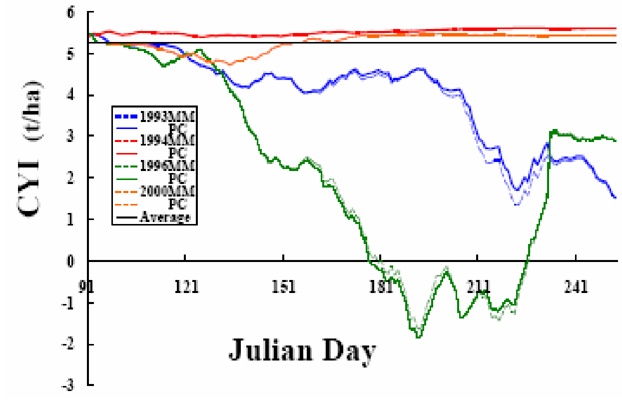

Figure 4. Relation Between Estimated Crop Yield Index CYI and Julian day. for Early Monitoring of Rice Production at the Example of Furukawa site in Japan

		Nation	Japan			China			Variable and formulae
Year / Conditions		Province	Hokkaido	Akita	Miyagi	Jiangsu	Hebei	Shandong	Province
		region	Iwamizawa	Ohogata	Furukawa	Nanjing	Shijiazhuang	Jinan	region
		grain	paddy	paddy	paddy	paddy	w. wheat	maize	grain
		Harvest Index	0.42	0.486	0.507	0.529	0.41	0.46	HI
		year	2001	2001	2001	2001	2001	2001	
		model type	PC	PC	PC	PC	MM	MM	Michaelis-Menten(MM), Priced-Charter(PC)
Evaluation from plants		grain areas (ha) $\times10^3$ (ha)	24.3	9.33	45.6	2010	2580	2505	A_{grain}
		grain Production $\times10^3$ (t)	120.0	54.30	247.2	16933	11227	15324	P_{grain}
		Yield (t/ha)	4.94	5.82	5.42	8.42	4.35	6.12	Y_T
		Dry_W_y (t/ha)	3.55	4.18	3.89	6.05	3.12	4.39	$Y_{DW}=Y_t*0.718$
		Ratio C/Carbohydrate	0.444	0.444	0.444	0.444	0.444	0.444	$R_{CCA}=72/162$
		Carbon_y (t/ha)	1.58	1.86	1.73	2.69	1.39	1.95	$Y_C=Y_{DW}*R_{CCA}$
		Carbon_fixation_Grain (Production) $\times10^3$ (t)	38.3	17.3	78.9	5403	3583	4890	$C_{FGP}=Y_{DW}*R_{CCA}*A_{grain}$
Evaluation from this model	CO_2	CO_2 fixation (Model) (gCO_2/m^2)	2986	3654	3264	4256	1592	2942	F_{My}
		CO_2 fixation (β s) (gCO_2/m^2)	—	—	—	—	1303	2314	$F_{M\beta}$
		CO_2 fixation (tCO_2/ha)	29.86	36.54	32.64	42.56	13.03	23.14	$F_{M\beta t}$
		Respiration_night (tCO_2/ha)	12.33	15.09	13.48	17.58	1.86	9.55	Paddy: $R_N=F_{M\beta t}*0.413$ Wheat: $R_N=F_{M\beta,t}*0.143$
		Carbon respiration_night (tC/ha)	3.37	4.12	3.68	4.80	0.51	2.61	R_N
		Net fixation (tCO_2/ha)	17.53	21.45	19.16	24.98	11.16	13.58	$F_{net}=F_{M\beta t}-R_N$
		Net provincial CO_2 fixation (Million t)	0.43	0.20	0.87	50.2	28.8	34.0	$F_{NPC}=F_{net}A_{grain}/10^3$
	Carbon	Ratio C/CO_2	0.273	0.273	0.273	0.273	0.273	0.273	$R_{CCO}=12/44$
		Net C fixation (t/ha)	4.78	5.85	5.22	6.81	3.04	3.70	$C_{FNet}=F_{net}*R_{CCO}$
		C_fixation_aboveGround (t/ha)	3.61	4.42	3.95	5.15	2.30	2.80	$C_{FAbG}=C_{FNet}*0.736$
		C_fixation_Grain-only (t/ha)	1.52	2.15	2.00	2.72	0.94	1.29	$C_{FGO}=C_{FAbG}*HI$
		Provincial C fixation_Grain_Model $\times10^3$ (t)	36.9	20.1	91.3	5477	2434	3226	$C_{FGM}=C_{FGO}*A_{grain}$
		Provincial C_fixation in whole grain plant $\times10^3$ (t)	116.2	54.6	238.2	13695	7854	9278	$C_{FWM}=C_{FNet}*A_{grain}$
Ratios and errors		Carbon fixation ratio in Grain (model/yield_data)	0.96	1.16	1.16	1.01	0.68	0.66	$R_{CGY}=C_{FGM}/Y_C$
		Estimation Error (%)	-3.7%	15.7%	15.8%	-1.4%	32.1%	34.0%	$(1-R_{CGY})*100$

Table 1: Validation of the Present Photosynthesis Model by a Carbon Weight Included in Grains

by carbon weights included in rice biomass of cellulose $(C_6H_{10}O_5)_n$ 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

Prefecture	Hokkaidou		Niigata		Miyagi	
County	**Iwamizawa**		**Ohogata**		**Furukawa**	
Year	**2001 Good harvest**	**2003 Bad harvest**	**2001 Good harvest**	**2003 Bad harvest**	**2001 Good harvest**	**2003 Bad harvest**
Yield (t/ha)	5.43	4.25	5.82	5.37	5.42	5.42
Net fixation (tCO_2/ha)	17.53	15.14	19.16	15.20	21.45	15.29
C_fixation_Grain-only (t/ha)	1.52	1.31	2.15	1.52	2.00	1.60
Carbon_y (t/ha)	1.58	1.24	1.86	1.71	1.73	1.16
CSI	**101**	**79**	**102**	**94**	**103**	**69**
Carbon fixation ratio in grain (model/yield data)	**0.96**	**1.06**	**1.16**	**0.89**	**1.16**	**1.37**
Carbon fixation ratio in grain corrected by sterility	no sterility	**0.83**	no sterility	**0.84**	no sterility	**0.95**
Estimation Error	**-3.7%**	**-16.6%**	**15.7%**	**-16.4%**	**15.8%**	**-5.3%**

Table 2: Correction of Carbon Estimation Errors to Evaluate the Sterility Effects on Carbon Fixation Ratio for Paddy Rice Using Crop Situation Index (CSI)

No.	Nation	Site	Province	Land cover	Position
1	**Japan**	Tomakomai	Hokkaido	Forest (Larch)	42.05° N, 142.10° E
2		Fujiyoshida	Yamanashi	Forest (Red pine)	35.45° N, 138.77° E
3		Tsukuba_Mase	Ibaragi	**Paddy**	36.05° N, 140.02° E
4	**China**	Xilinhot	Nei Monggol	Degraded Steppe	43.55° N, 116.67° E
5		Kubuqi	Ningxia	Shrab land	40.37° N, 108.53° E
6		Haibei(Kobresia)	Gansu	Alpine meadow	37.62° N 101.30° E
7		Jinzhou	Shandong	Maize	41.82° N, 121.20° E
8		**Luancheng**	Hebei	**Winter wheat & Maize**	37.88° N, 114.68° E
9		Taoyuan	Jiangxi	**Double rice**	28.92° N, 111.50° E
10	**Thailand**	Bukit	East Kalimantan	Tropical forest	0.85° S, 117.03° E
11		Kog_Ma	ChiangMai	Tropical forest	18.42° N, 99.72° E
12	**Bangladesh**	Mymensingh	Mymensingh	Paddy	24.73° N, 90.43° E

No.	Nation	Site	Province	Land cover	Position
1	**Japan**	Tomakomai	Hokkaido	Forest (Larch)	42.05° N, 142.10° E
2		Fujiyoshida	Yamanashi	Forest (Red pine)	35.45° N, 138.77° E
3		Tsukuba_Mase	Ibaragi	**Paddy**	36.05° N, 140.02° E
4	**China**	Xilinhot	Nei Monggol	Degraded Steppe	43.55° N, 116.67° E
5		Kubuqi	Ningxia	Shrab land	40.37° N, 108.53° E
6		Haibei(Kobresia)	Gansu	Alpine meadow	37.62° N 101.30° E
7		Jinzhou	Shandong	Maize	41.82° N, 121.20° E
8		**Luancheng**	Hebei	**Winter wheat & Maize**	37.88° N, 114.68° E
9		Taoyuan	Jiangxi	**Double rice**	28.92° N, 111.50° E
10	**Thailand**	Bukit	East Kalimantan	Tropical forest	0.85° S, 117.03° E
11		Kog_Ma	ChiangMai	Tropical forest	18.42° N, 99.72° E
12	**Bangladesh**	Mymensingh	Mymensingh	Paddy	24.73° N, 90.43° E

Table 3: AsiaFlux Proper Sites for Comparison with the Present model

No.	Nation	Site	Province	Land cover	Position	Area(km^2)
1	Philipine	Ajuy	Iloilo (Panay island)	Mahogany reforestation for Water Resources	11.15° N, 123.01° E	10
2	China	Huizhou	Guangdong	Eucalyptus	23.08° N, 114.40° E	330
3	Laos	Khammouan	1500km^2 in Khammouan	Eucalyptus	17.3° N, 104.8° E	500
4	Indonesia	Semarang	Kendal (Mid Jawa)	Acacia	6.97° S, 110.42° E	10
5		Sumbela	Lombok island	Environmental afforestation (Fruits, nuts, and timber)	8.44° S, 116.68° E	3.50 1.30 0.53
6		Tanjungenim (Palembang)	South Sumatera	Acacia	2.92° S, 104.75° E	1900
7	Australia	Albany	West Australia	Eucalyptus	35.02° N, 117.89° E	260
8		Perth	West Australia	Eucalyptus	31.94° S, 115.86° E	300
9	New Zealand	Pan Pac	Napier (North Island)	Eucalyptus	39.48° S, 176.92° E	300

Table 4. Japanese CDM experiments for afforestation and reforestation

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 apc 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 some-times covered by cloud effects.
2. Yield values vary considerably in a prefecture despite al-most the same weather condition.
3. Resolution scale 1 km^2 of our model is deferent from that around 500 km^2 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 fertili-ty 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 CO_2 absorption and emission from carbon soil storage. The AsiaFlux data must be revised to extract CO_2 fixed by the photosynthesis phenomena using ver-tical flux distribution of ecosystem data. Simultaneously, forest afforestation and reforestation projects can provide data to vali-date the photosynthesis rate in forests. The authors intend to support certification procedures for clean development mechan-ism (CDM) projects (Table 4) using the present photosynthesis model.

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 ste-rility 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 CO_2 into rice, straw and root portions of plant biomass weight was com-puted 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 of sterility. The parameterization of radiation response function and the temperature response functions for low-temperature sterility should be improved for operating system. As for the mean CO_2 and carbon fixation rates in paddy areas, those values were 25.92 (t CO_2/ha) and 5.28 (t/ha) in Japan, respectively. The method is based on rou-tinely collected observation and prediction data, allowing oper-ational monitoring of crop production at arbitrarily chosen sites.

ACKNOWLEDGEMENT

This study is funded by Grants-in-Aid (No. 21580319) for Scientific Research. We wish to express thanks to the Japan Society for the Promotion of Science, which belongs to Ministry of Education, Culture, Sports, Science and Technology.

REFERENCES

Kaneko, D., Ohnishi, M., and Ishiyama T., "Proposal of early monitoring method for crop production in China and India In the recent era of water resources restriction", Environmental Systems Research, Japan Society of Civil Engineers, 31, 235-244 (2003). (In Japanese with English abstract)

Kaneko, D., M. Ohnishi, and T. Ishiyama, and R. Tateishi, "Proposal of a photosynthesis type of crop yield index for monitoring crop production in China and India in the era of water resource restriction". 4th International Crop Science Congress, Brisbane, Australia, 4p, September (2004)

.
http://www.cropscience.org.au/icsc2004/poster/2/8/252_daijir.htm#TopOfPage.

Kaneko, D., Ohnishi, M., Ishiyama, T., and Tateishi, R., "Modeling of a photosynthetic crop production index for early warning using NDVI and Meteorological data", Proceedings of SPIE, Remote Sensing for Agriculture, Ecosystems, and Hydrology □ , 11th SPIE International Symposium on Remote Sensing, Proc. SPIE 5568, 1-10, Gran Canaria, Spain (2004).

Kaneko, D., Ohnishi, M., and Ishiyama, T., "Photosynthetic rice production index for early warning using Remote Sensing and meteorological data, Proceedings of SPIE", Remote Sensing for Agriculture, Ecosystems, and Hydrology□, 12th SPIE EUROPE International Symposium on Remote Sensing, Proc. SPIE 5976, 1-9, Bruges, Belgium (2005).

Kaneko, D., "Developing a photosynthetic prediction model for rice yield using remotely sensed and meteorological data ", 2nd Recent Advances in Quantitative Remote Sensing, 549-554, Valencia, Spain (2006).

Kaneko, D., "Estimation of rice situation index in Japan using remotely sensed and meteorological data", Journal of theRemote Sensing Society of Japan, 26(3), 202-212 (2006). (In Japanese with English abstract) Kaneko, D., "Evaluation of CO2 fixation in Japanese paddy fields by a photosynthesis model using satellite data, "Annual Journal of Hydraulic Engineering, Japan Society of Civil Engineers, 50, 475-480 (2006). (In Japanese with English abstract)

Kaneko, D., "Crop yield monitoring based on a photosynthetic sterility model using NDVI and daily meteorological data"□ Proceedings of 14th SPIE EUROPE International Symposium on Remote Sensing, 6742, F67420, 1-12, September (2007).

Kaneko, D., T. Kumakura, P. Yang, Data assimilation for crop yield and CO2 fixation monitoring in Asia by a photosynthetic-sterility model using satellites and meteorological data, International Journal of Global Warming, 1(3), 179-200 (2009).

Prioul, J. L, and Chartier, P., "Partitioning of transfer and carboxylation components of intracellular resistance to photosynthetic CO2 fixation: a critical analysis of the Methods used", Annals of Botany, 789-800 (1977).

Vong, N. Q., and Murata, Y., "Studies on the physiological characteristics of C3 and C4 crop species. I. The effects of air temperature on the apparent photosynthesis, dark respiration and nutrient absorption of some crops", Japanese Journal of Crop Science, 46, 45-52 (1997).

Sasaki, H., Hara, T., Ito, S., Miura, S., Hoque, M. M., Lieffering, M., Kim, H. Y., Okada, M., and Kobayashi, K., Seasonal changes in canopy photosynthesis and respiration, and partitioning of photosynthate, in rice (Oryza sativa L.I) grown under free-air CO2 enrichment, Plant and Cell Physiology, 46(10), 1704-1712 (2005).

Sinclair, T. R., 1998, Historical Changes in Harvest Index and crop nitrogen accumulation, Crop Science, 38, 638-643 (1998).

Xiao, X., Boles, S., Liu, J., Zhuang, D., Frolking, S., Li, C., Salas, W., and Moore □, B., " Mapping paddy rice agriculture in southern China using multi-temporal MODIS images", Remote Sensing of Environment, 95,480-492 (2005).

Xiao, X., Boles, S., Frolking, S., Li, C., Babu, Y., Salas, W., and Moore, B., "Mapping paddy rice agriculture in Southeast Asia using multi-temporal MODIS images", Remote Sensing of Environment, 100, 95-113 (2006).