# Comparison of monitoring applicability between Crop Production Index and conventional methods using satellites

Daijiro KANEKO[1],

[1]Department of Civil Engineering, Matsue National College of Technology, 14-4, Nishiikuma-chou, Matsue, 690-8518 Japan, Professor, Phone & Fax: +81-852-36-5266,E-mail: kand@ce.matsue-ct.ac.jp

## ABSTRACT

This paper compares the applicability of the Crop Production Index CPI with conventional methods, taking into account the acquisition of the necessary data by remote sensing. The author has developed the CPI index as a remote sensing method for monitoring grain production in the early stages of crop growth in Japan and Asia. A photosynthesis based crop production index CPI takes into consideration the solar radiation, the effective air temperature, and NDVI as a factor representing vegetation biomass. The CPI index incorporates temperature influences such as the effect of temperature on photosynthesis by grain plant leaves, low-temperature effects of sterility, cool summer damage due to delayed growth, and high-temperature injury. These latter factors are significant at around the heading period of crops. The CPI index for rice was validated at ten monitoring sites in the central and northern half of Japan. This paper proves the ability of the CPI to predict poor crop production using rice yield statistics, contrasting it against conventional methods such as the cumulative Growing degree day GDD, integrated NDVI, and photosynthesis rate.

**Keywords:** monitoring, crop production, rice, photosynthesis, NDVI

## 1. INTRODUCTION

This research aims to monitor grain production by developing a photosynthesized type of crop production index, which displays functional dependence on solar radiation, temperature effects, stomatal opening, and vegetation biomass. It is important to oversee the quantity of grain in production in Japan and Asia at an early stage in the present era of increasing Asian population and water-resources restrictions. Continuous predictive monitoring of crop production in East Asia would allow orderly management of food security issues including Japan, which is one of the world's major grain importers. Conventional methods have generally been based on the cumulative value of the effective air temperature (growing degree day, GDD) by Idso [1)], Bollero et al. [2)]. or integrated NDVI proposed by Rasmussen[3)]. However, none of these methods correctly expresses the grain production by estimating the time-integrated photosynthesis rate. Many researchers have presented conventional papers on crop simulation, including Williams et al.[4)]. Priya et al.[5)] and Perez et al.[6)], and remote sensing data have been incorporated in the models by Maas [7)] and Wiegand [8)]. However, those models simulate the growth process of crops, making them highly complicated, as Monteith [9)], and Sinclair and Seligman [10)] have pointed out. Several methods use seasonal changes of the normalized difference vegetation index NDVI derived from satellite observation. The method in this paper takes the amount of growth and biomass as known, using remotely sensed data NDVI, and estimates the instantaneous photosynthesis velocity easily and accurately. The photosynthesis-based crop production index CPI proposed in this paper can predict the rice yield under conditions of low temperature sterility, sunshine shortage, and high temperature injury. This paper validates the CPI index at ten monitoring sites in Japan and verifies its particular ability to predict poor grain production, in contrast to conventional indices.

## 2. METHOD OF CROP PRODUCTION INDEX CPI

2.1 Conventional methods

Many conventional crop studies have correlated the grain quantity in production with the growth index of Growing Degree Day GDD, or with water stress indices such as stress degree day[1),2).]

$$GDD = \frac{T_{\max} + T_{\min}}{2} - T_b \quad (1)$$

where, $T_{max}$ is the maximum daily air temperature, $T_{min}$ is the minimum daily air temperature, and $T_b$ is a threshold temperature for the crop, below which physical activity is inhibited and equal to 10 ℃.

In conventional research using remote sensing, the vegetation index NDVI [11),12),13),14)], concerning the vegetation biomass, is related to the crop production. Rasmussen[3)] defined the integrated NDVI (iNDVI) and related it to the grain yield.

$$Yield = a \cdot \int_{t1}^{t2} NDVI(t)dt + b \quad (2)$$

where, a and b are regression coefficients, and t1 and t2 are the day number of seeding and harvesting.

In grain production forecasting using the latest remote sensing, daily values of the photosynthetically active radiation PAR and the vegetation biomass (NDVI) are taken into the model. Frthermore, Rasmussen (1998) gave the net primary production NPP using satellite data according to the following formula:

$$NPP = \varepsilon \int_0^t (aNDVI + b) \cdot PAR \cdot dt \quad (3)$$

where ε is the efficiency coefficient,, t is the time, and PAR is the photosynthetically active radiation.

This NPP is a photosynthesis-type model. However, this formula does not allow for such important factors as temperature influences on photosynthesis, temperature sterility and stomatal opening of crops. The present research improves modeling based on the photosynthesis type of crop production index so as to incorporate the effects of global solar radiation, temperature, stomatal opening, and vegetation biomass. Although the areas of crop study and remote sensing have generated much research, especially on the production of wheat and corn, it is all restricted to consideration of the water stress or formulas based on vegetation indices. To give a more accurate value of the grain quantity in production, the crop production index should take the form of the photosynthesis velocity so as to express the growth of crop vegetation and filling of grain, both of which relate directly to the quantity produced.

2.2 Proposed method

Rasmussen [15)] proposed a net primary production (NPP) model by taking into account the daily photosynthetically active radiation PAR and the amount of vegetation biomass (NDVI), so as to estimate the NPP from satellite data. The equation of NPP is of photosynthetic type, but sterility due to low- and high-temperature injury and stomatal opening due to shortage of water resources or inadequate irrigation are not accounted for. It is reasonable to suppose that crop production can be estimated based on a daily photosynthesis rate. Generally, temperature has two effects on the quantity of grain production: its normal influence on the rate of photosynthesis, and the effect of extremes of temperature on sterility during the stages of heading, flowering, and filling. To model these two effects, three response functions, to photosynthesis, low-temperature sterility and high-temperature injury are employed in the period before and after heading.

This research expands the form of NPP by Rasmussen to consider air temperature and stomatal opening, as well as the solar radiation and the amount of vegetation biomass already considered. The photosynthesis velocity is defined by equation (1) as follows[16), 17), 18),19),20)]:

$$PSN = \frac{a \cdot APAR}{b + APAR} \cdot f_{Syn}(T_c) \cdot \beta_s \cdot eLAI \tag{4}$$

where $PSN$ is the photosynthesis rate, $APAR$ is the absorbed photosynthetically active radiation, $\beta_s$ is the stomatal opening, $a$ and $b$ are Michaelis-Menten constants, $T_c$ is the canopy temperature, $eLAI$ is the effective leaf area index, and $f_{ster}$ is the sterility response function for the air temperature.

The authors' former paper[16)] presents sensitivity analysis curves for the Michaelis-Menten-type response function versus solar radiation and the temperature response of the photosynthesis rate as well known as the Sigmoidal-Logistic type function :

$$f_{Syn}(T_c) = \left[ \frac{1}{1 + \exp\{k_{syn}(T_c - T_{hv})\}} \right] \tag{5}$$

where $T_{hv}$ is the temperature parameter at half of the maximum photosynthesis rate, and $k_{syn}$ is the slope parameter. 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 [21)]:

$$F_{Lster}(T_c) = 1 - \exp[k_{Lster}(T_{Lster} - T_c)], \tag{6a}$$

$$F_{Hster}(T_c) = 1 - \exp[k_{Hster}(T_c - T_{Hster})] \tag{6b}$$

where, $k_{Lster}$ is the low temperature sterility constant, $T_{Lster}$ is the low sterility limit temperature, $k_{Hster}$ is the high temperature injury constant, $T_{Hster}$ is the high injury limit temperature, and $T_c$ is the plant leaf temperature.

Finally, the response function of the compounded temperature sterility effects due to both low and high temperatures in grain production is expressed by the following equation:

$$F_{Ster}(T_c) = \{1 - \exp[k_{Lster}(T_{Lster} - T_c)]\} \cdot \{1 - \exp[k_{Hster}(T_c - T_{Hster})]\} \tag{6c}$$

Next, integration of the photosynthesis rate over an interval from seeding $t_s$ to the time t of crop plant stage defines the photosynthesis-based crop production index CPI for rice having the following forms:

During crop plant stage 1, of growth:

$$CPI_U = \int_{t_s}^{t} PSN_U \cdot dt \tag{7}$$

During crop plant stage 2, of booting, heading, flowering to ripening:

$$CPI_U = F_{Ster}(T_c) \cdot \int_{t_s}^{t} PSN_U \cdot dt \tag{7a}$$

$$F_{Ster} = \int_{t_f}^{t} f_{Ster}(T_c) \cdot dt \tag{7b}$$

At the crop plant stage 3 of harvesting:

$$CPI_U = F_{Ster}(T_c) \cdot \int_{t_s}^{t_r} PSN_U \cdot dt \tag{7c}$$

$$F_{Ster} = \int_{t_f}^{tr} f_{Ster}(T_c) \cdot dt \quad (7d)$$

It is necessary to normalize the NDVI so as to remove the effect of planting area (plant coverage ratio) on the photosynthesis rate at different paddy sites. Even if the crop yield in a year was the norm, the NDVI is liable to differ each year. The plant coverage ratio per data pixel of remote sensing is dependent on the individual sites. We therefore define the standardized NDVI, called the NDVI Unit, by dividing by the annual average yield as follows:

$$NDVI_{U,i} = \frac{NDVI_i}{iNDVI_{H100}} \quad (8)$$

The photosynthesis rate is similarly normalized to give the 'PSN Unit' upon dividing by the normal photosynthesis rate averaged annually, as follows:

$$PSN_U = \frac{\int_{t_s}^{t} PSN \cdot dt}{iPSN_{100}} \quad (9)$$

The EPIC (Erosion-Productivity Impact Calculator) uses the same idea to normalize the effect of accumulation of Growing Degree Day, by defining the Heat Unit Index.

The quantity of grain production in the growth stages of heading and filling is influenced by a crop physiological mechanism called low-temperature sterility, and by high temperature injury, in addition to cumulative photosynthesis up to heading. To transform the CPI index into the appropriate photosynthesis type of grain production index, the photosynthesis rate *PSN* of equation (1) must be multiplied by the temperature sterility function $F_{str}$ of equation (3c) involving the heading term to be expressed via equation (5b and 6b), which is of time-integrated form to account for the effect of temperature on flowering, pollination, and ripening.

## 3. DATA USED IN THE MODELING

The present research uses domestic meteorological data to verify the CPI index. The ground air temperature data, which are supplied by the Japanese Meteorological Agency from the Automated Meteorological Data Acquisition System (AMeDAS) point at ten sites, distributed in the Japanese agricultural plains, have large acreages suitable for satellite monitoring of the paddy fields.

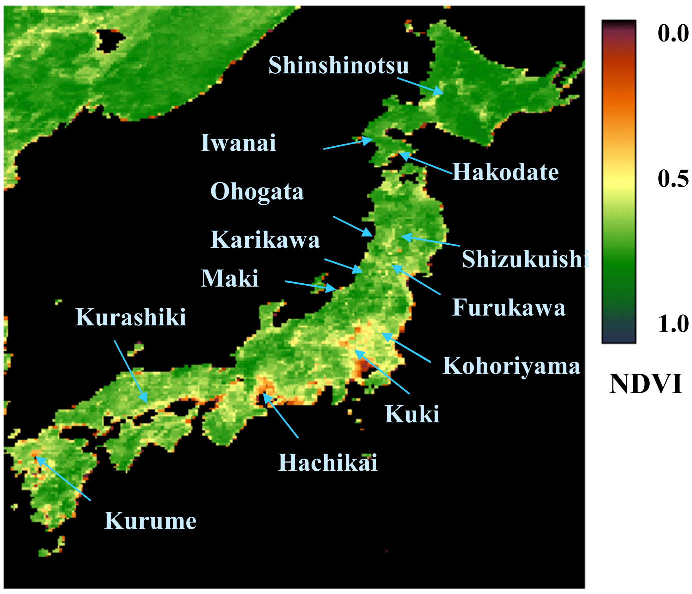


Figure 1: Distribution of NDVI and monitoringu sites in Japan for varidation of Crop Production Index CPI.

The Japanese Ministry of Agriculture, Forestry, and Fisheries provides grain statistical information, which includes crop situation index for the paddy rice at ten sites for monitoring and validation district. This crop situation index is the ratio of crop production in the year in question to the mean annual production for the ten most recent years. The Society of Agricultural Meteorology in Japan has published a special report, which summarizes the relation between the meteorological conditions and the poor harvest in 1993. The satellite NDVI data used in the CPI index is the 4-minute mesh set of vegetation index data derived from NOAA Advance Very High Resolution Radiometer (AVHRR) by Tateishi[22].

## 4. COMPARISON of the CPI and CONVENTIONAL METHODS

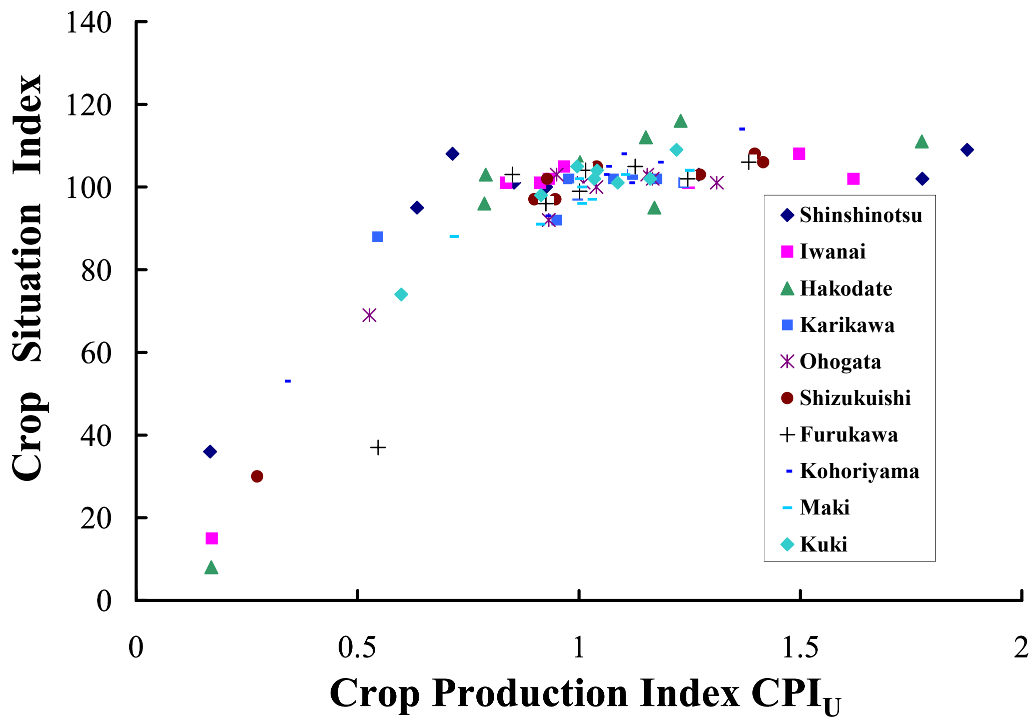


Figure 2: Relation between the crop production index $CPI_U$ and Crop situation index at ten monitoring points.

Figure 2 shows the relation between crop situation index CSI and the $CPI_U$, to verify applicability to rice yields at 10 sites in Japan. The photosynthesis rate of the $CPI_U$ index decreases as a result of the inadequate solar radiation or accumulation of air temperature. The CPI Unit becomes a little less than 1, implying poor production compared to the normal harvest averaged annually. The $CPI_U$ can predict a trend of poor production, expressed by the crop situation index decreasing linearly to below 100. The many values of the CPI index close to 1 imply the usual behavior of the photosynthesis rate governing rice yields in most years. However, abnormal weather with low temperature and much cloud, which happens about every 10 years, causes low temperature sterility and late ripening of rice. The $CPI_U$ then rapidly falls to zero, since the limiting problem is not photosynthesis but inadequate flowering and late ripening. The sterility function curve, which has a steep gradient for low air temperatures, is able to capture the very bad harvest in the worst case of the crop situation index below 50 in 1993. The third mechanism is high temperature injury, expressed by equation (6b). When the air temperature is excessive, the CSI decreases slightly with further increase in air temperature as

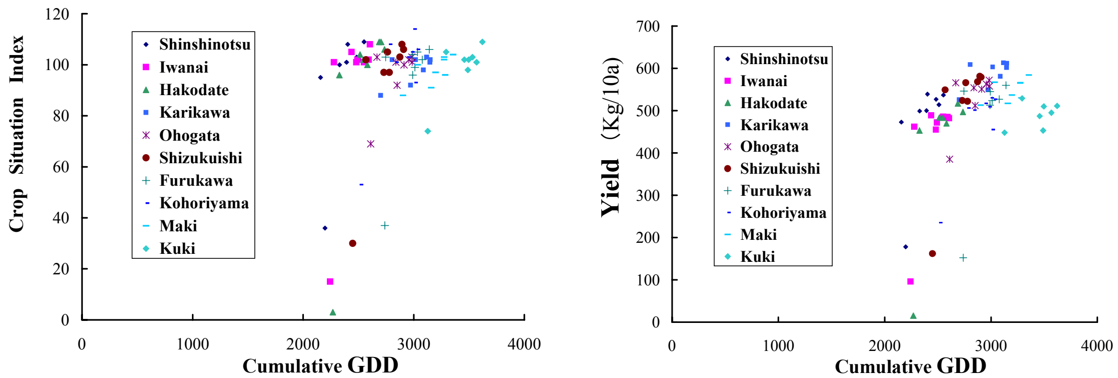


Figure 3: Comparison of monitoring applicability for Crop Production Index and conventional methods. The figures show relations between the cumulative growing degree day GDD and Crop Situation Index at ten monitoring points, and between yield and cumulative GDD.

seen on the right in Figure 2, though it is still greater than 100 in the right side range of x axis, that is greater than $CPI_U$=1 in the Figure2. According to the mechanisms included in the $CPI_U$ index, $CPI_U$ can predict rice production taking into account photosynthesis, low temperature sterility, and high temperature injury, depending on meteorological conditions.

Figure 3 shows relations between the crop situation index CSI and the cumulative growing degree day (GDD), and between the yield and cumulative GDD. The cumulative GDD has a linear relationship to the yield but shows no ability to distinguish bad production due to low temperature sterility from normal rice yields in other years. The air temperature has two effects, on growth and ripening by photosynthesis and on pollination from heading to flowering of the grain. This sterility effect on pollination is not linear in temperature, but cuts in rapidly below a threshold of about 18 degrees

Figure 4 shows relations between the crop situation index and the integrated NDVI (iNDVI), and between yield and the iNDVI. The integrated NDVI is not able to predict either the crop situation index or the yield, and in particular is unable to predict a bad harvest due to low temperature sterility. The iNDVI values depend strongly on regional characteristics such as soils, type of rice and mixcel effects, involving other plants (vegetables, trees, etc.).

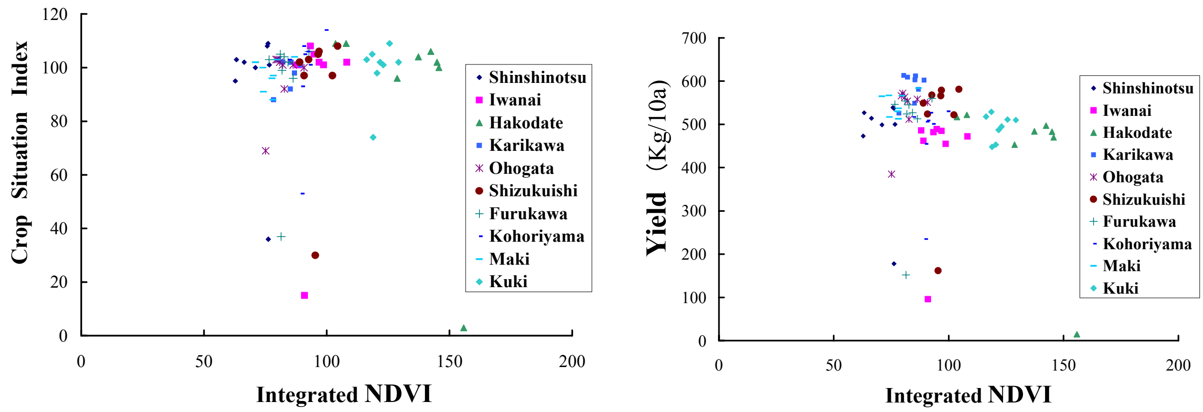


Figure4: Relations between the integrated NDVI and Crop Situation Index, and between yield and iNDVI.

Figure5: Applicability to crop production of integrated PSN based on remotely sensed data. The figures show relations between the Crop Situation Index and integrated PSN, and crop yield and iPSN.

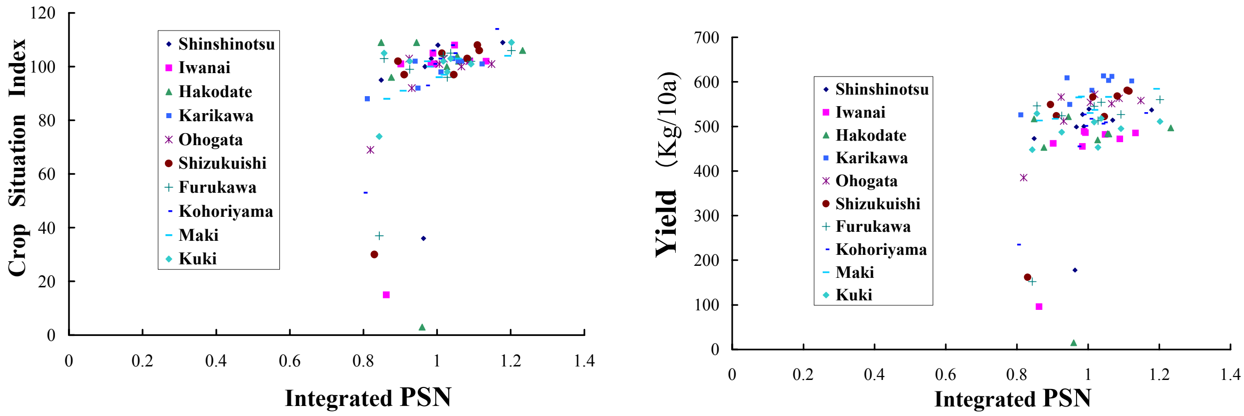


Figure5: Applicability to crop production of integrated PSN based on remotely sensed data. The figures show relations between the Crop Situation Index and integrated PSN, and crop yield and iPSN.

Figure 5 shows the performance of the integrated photosynthesis rate iPSN used as a crop yield index. The crop situation index decreases linearly with iPSN but shows no ability to predict low temperature sterility, because sterility is not dependent on photosynthesis but is related to flowering and pollination. The iPSN performs much better than the iGDD or iNDVI since it is linear with respect to crop yield; however, the iPSN values show considerable scatter arising from dependence on regional conditions.

Consequently, only $CPI_u$ is able to predict a bad harvest due to sterility effects, by making the $CPI_u$ values decrease sharply to zero based on the eigen-functional relationship between $CPI_u$ and the crop situation index CSI, as well as the yield.

## 5. CONCLUSIONS

This paper compares the applicability of the Crop Production Index CPI and conventional indices, based on remotely sensed data. The aim is to develop a remote sensing method suitable for monitoring rice production from the early stages of crop growth right up to harvesting in Japan and Asia. The present paper proposed a photosynthesis-based crop production index CPI that takes into consideration the solar radiation, the effective air temperature, and NDVI as a factor representing vegetation biomass. The CPI index incorporates the mechanism of temperature influences such as the effect of temperature on photosynthesis by grain plant leaves, low-temperature effects of sterility, cool summer damage due to delayed growth, and high-temperature injury. These latter factors are significant at around the heading period of crops. The CPI index for rice was validated at ten monitoring sites in the central and northern half of Japan using the rice crop situation index. The validation exercise clearly proves the superior ability of the present index to predict poor production using rice yield statistics in comparison to conventional methods such as cumulated growing degree day GDD, integrated NDVI, and photosynthesis rate. The method is based on routine observation data, allowing automated monitoring of crop production at arbitrary sites without any special observations.

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