Terrestrial Ecosystem Dynamics

Crop production monitoring by a photosynthesis-based index using meteorological data and NDVI

Daijiro Kaneko[1]

1 Department of Civil Engineering, Matsue National College of Technology
E-mail address: kand@ce.matsue-ct.ac.jp

Abstract

This paper first explain the necessity for monitoring crop production in China and India in the present age of increasing water-resource restrictions. Conventional early watching based on the growth index GDD deriving from the effective air temperature gave inaccurate estimates, as shown by data for the Crop Situation index in three specific years. It is necessary to construct and time-integrate a photosynthesis-based crop production index incorporating the effect of solar radiation in order to express the mechanism of photosynthesis. The monitoring system should include a surveillance model that takes into consideration the daily weather conditions. The author proposes a photosynthesis-based crop production index (CPI) that accounts for solar radiation, air temperature, vegetation biomass, and stomatal opening, and uses satellite and world weather data. Special emphasis should placed on rice production because of the demand for abundant irrigation in paddy fields and the fact that most rice is grown for local use, so that falls in production have greater consequences in purchasing countries.

***Key Words**: monitoring, crop production index, Remote Sensing, photosynthesis, World Weather Data, water stress*

1. Introduction

Given the atmospheric phenomenon of global warming, shortage of fresh water resources is now an capacity to support life. Unusual reductions in the discharge in the lower reaches of irrigation rivers are being observed, and a continuing fall in the groundwater level as a result of water usage. Such well-known organizations as the World Bank, the Worldwatch Institute (Sandra Postel, 1999) and World Water Council (2003) have warned about the present unsustainable use of water resources for irrigation in China, India, and the U.S., which have significant influence on the total quantity of grain production. These problems originate from the rapid increase in global population, currently 6 billion, which underlies many of the present global environment issues. Water shortages due to increasing demand by cities restricts grain production, and makes predictive crop surveillance important in order to estimate future supply and demand in Asia.

This work aims to develop a predictive method of monitoring the grain quantity in production that would be useful in the present era of increasing world population that needs both food and water. Knowledge of an impending bad harvest in China or India would assist in the planning of both Japanese internal affairs and foreign policy, reducing the economic and social strains caused by the consequent leap in grain prices and improving the security of the food supply; Japan produces only about 40% of its own grain. The author believes that a specific organization should be established to monitor grain production in the context of the social circumstances and security of the food supply in areas of Asia.

2. Relevance and background of the proposal for crop monitoring in view of limitations on water resources

2.1. Present status and issues in world trade and crop production in China and India

Fig. 1 shows the amount of grain production in China and India. Trends in the grain yield of these countries have wide significance because of their huge population and consumption. Chinese rice production should be 189.8 million tons in 2000 (FAO, 2003); rice is the staple that supports the gigantic Chinese population,

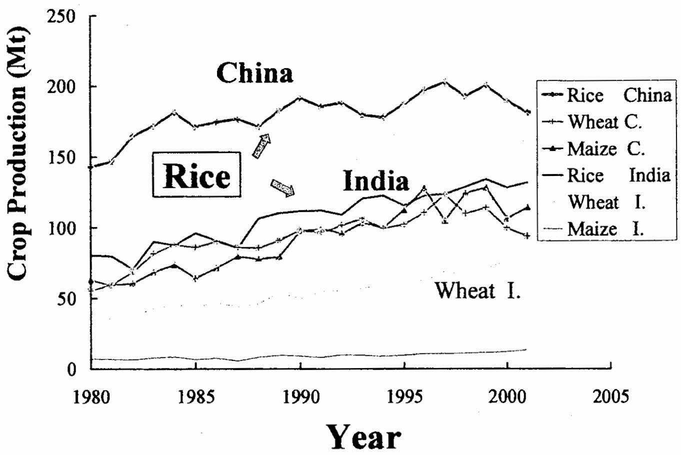

Fig. 1. Comparison of annual trend of crop production of rice and wheat in China and India, emphasizing the amounts of rice.

providing twice the quantity of food as wheat or corn. Rice in India has twice the production of wheat, and its rice harvest is increasing rapidly, from 80.3 million tons in 1980 to 131.9 Mt in 2001 as a result of population increase. Rice production in China increased gradually from 142.8 Mt in 1980 to 202.7 Mt in 1998, but has since fallen a little with the loss of paddy areas to industrialization (Otsubo, 1999). Clearly rice is an excellent grain food, which supports the population in China and India. In view of the need for urgent imports to countries that would suffer a poor harvest, the present authors pay close attention to supply capability and the trade price of rice. Fig. 2 shows exports of rice from Thailand, which is the largest rice exporting country in the world, along with the amount of wheat and corn exported from the U.S., which is the largest crop exporting country in the world market. The amount of rice exported from Thailand in 2000, 6.14 Mt, is small compared with the corn export of 47.97 Mt and the wheat export of 27.83 Mt in the same year. It is well known that people who cultivate paddy areas aim to support themselves and their nation, in contrast to wheat and corn, much of which is grown for export. Problems with the rice crop could therefore have a catastrophic effect on countries that import rice and other crops.

Figs. 1 and 2 show this fact, that although there is a large production of paddy rice, most is grown for self-support. Only 5% or less of the total world rice production is exported/imported, compared to 25% for wheat. A poor harvest of paddy rice therefore causes a major disturbance in the world grain market. Moreover, although the yield of paddy rice per unit area is higher than that of wheat, and it is able to support large populations, rice demands about 3-4 times as much water per unit weight as wheat. To maintain security of their grain supply, it is therefore important for countries to be aware of the grain situation in their neighbors. This involves the development of methods for finding in advance whether a neighboring harvest will be inadequate, and the provision of policies ahead of any resulting crisis so as to minimize its impact.

2.3. Water Resources and issues of crisis management

1) Population increase and water demands

Increasing restrictions on freshwater resources is causing concern over supply and demand of grain with the rapid increase of world population; irrigation in Asian agriculture involves the greatest use of water-resources. The writer focuses on paddy rice rather than other staples such as wheat, corn and beans because paddy rice demands so much water and so many people are dependent on rice as their staple food.

2) Recent trends in climate change

A fall in annual precipitation in Japan has become clear in recent years, with a reduction of about 80mm in the 100 years to 2000. Global warming makes both heavy rain and drought more likely, increasing fluctuations in the pattern of precipitation.

A few early warning systems exist that are promoted by the Food and Agriculture Organization (FAO, 2003) of the United Nations, and an early watch system by DEWA of Earthwatch , and by USGS. However, these are not based on quantitative monitoring and modeling as described in this paper, but are forecasts based on agricultural weather conditions, involving mainly the seasonal temperature and precipitation.

2.5. Annual climate change and the Japanese situation in grain supply and demand

1) Bad harvest and the mechanism of annual climate change

Annual climate changes which cause a poor harvest may involve fluctuations in the latitude of the monsoon rain band, or in the date at which the rainy season begins. Crop production has a statistical character due to annual meteorological variation, and a notably poor harvest used to occur roughly every ten years. More recently, grain production tends to give good harvests worldwide, so that the price has fallen continuously for several years. The present market in crops is based on continuing good meteorological conditions.

2) Issues in crop supply and demand in Japan

In the 2002 fiscal year, Japan produced 28% of the grain it needed based on weight, 40% based on calories, and 60% based on weight of staple food. This is the lowest value among the advanced nations and raises concerns about the security of the food supply in Japan.

3. Method for monitoring crop production

3.1. Conventional methods for monitoring crop production

Much work on the monitoring of grain production has been published by the crop fraternity in the Agronomy Journal, or in the fields of equipment metrology for agricultural measurement (Idso 1979, Aase 1981, Jackson et al. 1981). However, most of this work is from the U.S., which produces the largest

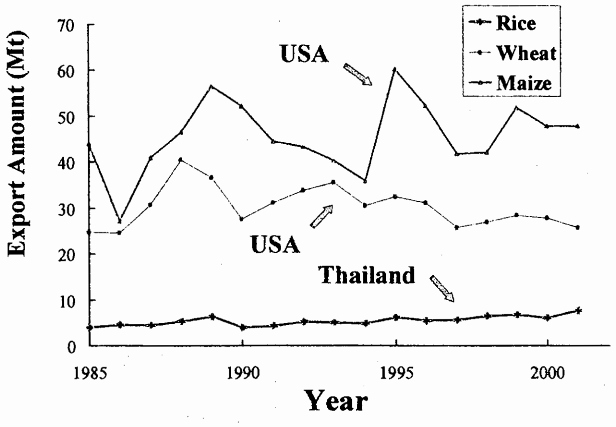

Fig. 2. Small export amounts of rice compared to wheat and maize in main exporting countries.

export crop in the world, and concerns wheat and corn rather than rice (Idso 1979, Diaz 1983). Papers on the monitoring of crop production in China or India over nationwide areas come only from the Chinese study group of Gao et al. (1998). Moreover, crop surveillance in India uses the presumptive methods of correlating crop production and satellite data (Murthy 1996, Manjunath 2002).

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 (Idso 1979, Bollero 1996).

$$GDD = \frac{T_{max} - T_{min}}{2} - T_b \tag{1}$$

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 (Aase 1981, Groten 1992, Quarmby 1993, Hayes 1996), concerning the vegetation biomass, is related to the crop production or modeled functions of the vegetation index NDVI and the photosynthetically active radiation PAR to estimate the grain quantity that will be produced (Rasmussen, 1992).

In these parameters, global solar radiation and stomatal opening are variables which change every day and are hard to account for in the amount of vegetation biomass represented by the NDVI. In crop studies to date, air temperature has been used instead of global solar radiation, and another water stress factor – transpiration control – is often also taken into consideration. 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. Rasmussen (1992) defined the integrated NDVI (iNDVI) and related it to the grain quantity in production.

$$Yield = a \cdot \int_{t1}^{t2} NDVI(t)dt + b \tag{4}$$

where, a and b are regression coefficients, and t1 and t2 are the day number of seeding and harvesting. Furthermore, Rasmussen (1998) gave the net primary production NPP using satellite data according to the following formula:

$$NPP = \varepsilon \int_0^t (aNDVI + b) \cdot PAR \cdot dt \tag{5}$$

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.

3.2. *New photosynthesis type of crop production index*

1)Concept of modeling

The final purpose of this work is to carry out early surveillance of the crop quantity in production in China and India in the present era of water-resource restriction by using the photosynthesis type of crop production index mentioned above. Apart from insect damage, the following factors are the main causes of reduced crop production: insufficient solar radiation, water stress due to rain shortage (including reduced irrigation); and insufficient fertilizer. Observation of solar radiation is not easy, and reduced solar radiation lowers the air temperature, so that many researchers have used the air temperature instead of solar radiation (Idso 1979, Williams 1989, Bollero 1996). In another words,

Distribution of Observation Sites for World Weather

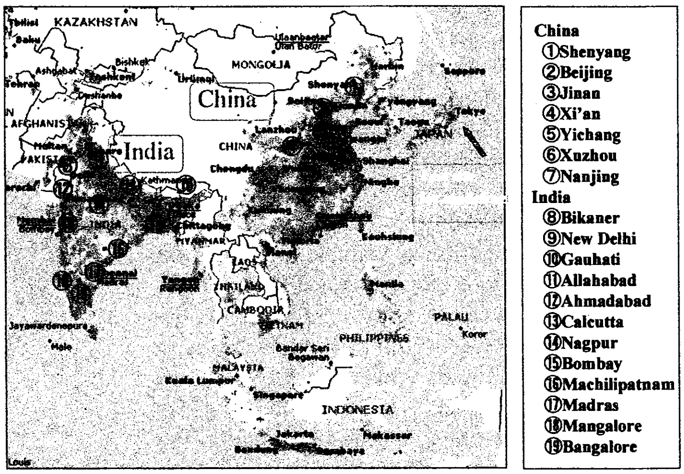

Fig. 3. Distribution of monitoring sites in China and India at World Weather points, including test sites for modeling and validation of crop production indices.

it is necessary to account for the effects of transpiration from stomata as well as solar radiation. The author believes that the crop quantity in production depends fundamentally on the integrated value of the photosynthesis rate, which depends on stomatal opening as well as solar radiation and vegetation biomass. In addition, there are the plant-physiological factors of low temperature sterility and high temperature injury during flowering and filling out of crops, which must be taken into account as well as the photosynthesis rate in the grain production index.

In view of global warming, many researches have reported the effect of the CO_2 concentration on grain production through the photosynthesis rate, from field and laboratory experiments (Moya 1998, Seneweera et al. 2002). However, since the density of CO_2 in the atmosphere is stable enough to guarantee the carbon supply for crop production, the effect of the CO_2 concentration is not taken into consideration in the grain production index. Moreover, the effect of fertilizer can be reflected in the vegetation index NDVI showing the crop vegetation biomass. Similarly, damages by blight and harmful insects are disregarded since they appear in the NDVI. The present model therefore expresses the photosynthesis rate using the solar radiation, temperature dependence on photosynthesis, water stress, vegetation biomass, and low-temperature sterility and high temperature injury effects on flowering and filling.

2) Monitoring method using photosynthesis type of crop production index

The photosynthesis rate depends on the factors considered above including solar radiation, stomatal opening, and vegetation biomass. Therefore, while modeling of crop production expresses plant growth by the vegetation index that indicates the density of crop vegetation, it is also necessary to model stomatal opening according to soil moisture and weather conditions, as in the SiB (Sellers, 1989) model in meteorology. Although soil moisture has been closely studied for many years, accurate estimates are difficult because the earth surface is confused by vegetation.

Water stress in crop studies focuses on the amount of precipitation; quantitatively, a crop water stress index can be defined by $CWSI=1-E_{ac}/E_p$. Several researchers examined the relation between water stress and the grain quantity in production using this method (Jackson et al. 1981, Diaz et al. 1983, Abdul-Jabbar 1985). However, it is not easy to model the actual evapotranspiration in defining water stress on the regional scale. The present research seeks to develop a photosynthesis-type of monitoring method by measuring the water stress so as to improve the formula (5) presented by Rasmussen. The final form of the photosynthesis rate is defined in formula (6), which takes into consideration the solar radiation, air temperature, stomatal opening, and vegetation biomass (Kaneko 2003).

$$PSN = \frac{a \cdot APAR}{b + APAR} \cdot f_{ster}(T_c) \cdot \beta_s \cdot eLAI \tag{6}$$

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

The integrated photosynthesis type of crop production index CPI is defined by the following formula concerning the period from seeding ts to harvest th.

$$CPI = \int_{t_s}^{t_h} PSN \cdot dt \tag{7}$$

Many researchers have presented crop simulation models that involve growth of crops and incorporate remote sensing data from previous years (Wiegand et al. 1986, Maas 1988, Williams et al. 1989, Perez et al. 2002). However, it is desirable to express the mechanism of growth and filling more simply than in these models, which are complex and contain many empirical constants (Monteith 1996, Sinclair and Seligman 1996). By measuring growth of crop vegetation using remote sensing instead of simulation, the present paper estimates the photosynthesis rate by treating the growth of crop as a known variable. Estimation of the total quantity of crop produced is then easy, and the result is accurate since it is based on the actual observed value of the vegetation biomass deduced from satellite data even for foreign areas where data is not available. Above, modeling has proceeded as far as the incorporating factors into the crop production index CPI such as solar radiation, air temperature, and vegetation biomass. The proposed method improves the accuracy of estimates of crop yield over methods based on the

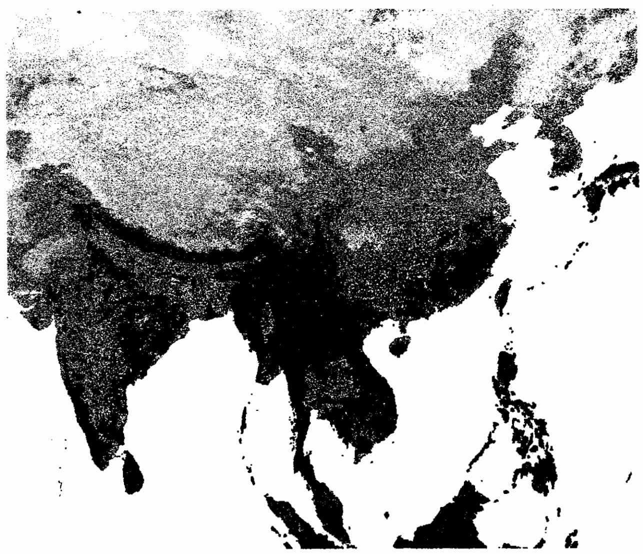

Fig.4. Distribution of the normalized difference vegetation index NDVI in Asia for use in crop production indices such as integrated NDVI and the CPI as defined in the present paper.

cumulative effective temperature GDD, and the integrated NDVI. This is because the writer estimates the photosynthesis rate from meteorological factors, and then integrate it.

4. Data used in the modeling

4.1. World Weather data and its characteristics

Fig. 6 depicts the distribution of observation points of world weather data, showing the population density distribution in China and India, which is important for grain transportation and consumption. Names surrounded by frames are the monitoring sites where weather data are applied to consider the grain production index CPI in this research. World weather data for the crop production index is selected for the following reason. Estimation of the photosynthesis rate needs daily data of solar radiation and air temperature, so that the meteorological data must be routine daily weather data as taken throughout the world. The world weather data is most suitable for the index CPI because daily regular data are currently observed as weather reports in real time. As study target points the author takes 7 points in China and 13 points in India. The CPI index requires cloud coverage to give the solar radiation at these points, and also the cloud coverage and solar radiation to verify the estimated solar radiation from the cloud amount (Kaneko 2002).

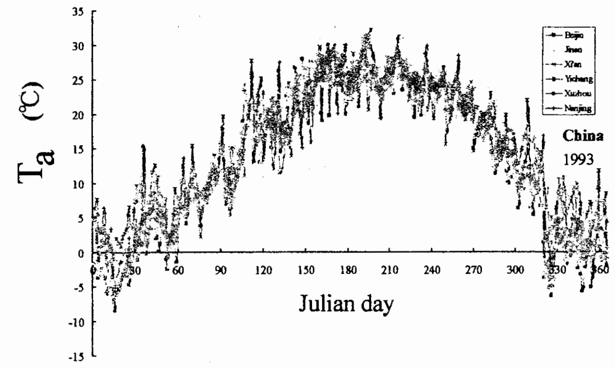

Fig. 5. Seasonal variations of air temperature at 7 monitoring points of world weather sites in China for modeling the effects of temperature in the crop production index CPI.

4.2. NDVI derived from satellite

Fig. 7 shows the distribution of the vegetation index NDVI in Asia using a data set derived from NOAA AVHRR by Tateishi (2001). The crop production index CPI requires the vegetation index NDVI at the positions of the world weather sites for which data are available as daily weather reports. The monitoring sites for CPI are 8 observation sites in China and 12 in India, along with validation points at meteorological observatories or AMeDAS sites in Japan. The vegetation index NDVI is extracted at pixel numbers calculated from the longitude and latitude of the weather observatories.

4.3. Crop statistics

The background analysis of the grain quantity of production in China and India was based on data from the Food and Agriculture Organization FAO of the United Nations. Japanese domestic data for the grain trade and the total grain tonnage produced are based on the agricultural statistics information database of the Ministry of Agriculture, Forestry, and Fisheries. Crop statistics from the FAO were used in constructing the figures for annual changes in grain tonnage in Fig.1, and the amount of grain trade in the major countries in Fig. 2.

5. Results by growing index and Crop production index

The crop production index CPI and several indices are scrutinized with the Crop Situation index for paddy rice at the large complex of paddy fields around Kuki in the mid-region of the Tone river in Kanto plain, Japan. The main results so far are as follows.

5.1. Growing index GDD

Fig.9 shows variations in the cumulative effective air temperature at monitoring sites in China. These curves are applied to practical use via the well known index of growth index GDD at seven paddy rice and spring wheat sites in China. The cumulative effective temperature as a growth index GDD is required in the form of a photosynthesis type of crop production index for the modeling of growth. Fig. 8 shows seasonal changes of the

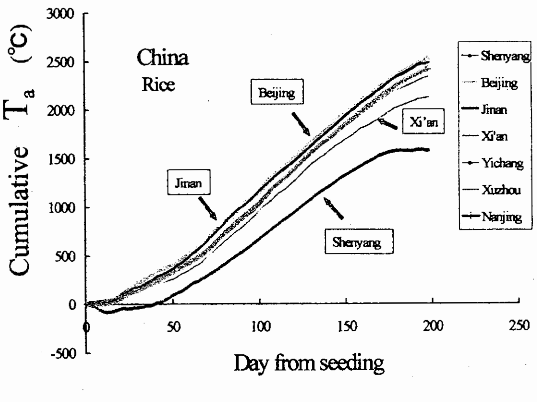

Fig.6. Variation of cumulative effective air temperature at monitoring sites in China. These curves are applied to practical use

effective temperature accumulated during each period of planting as the growing degree days index GDD for paddy rice and spring wheat at the monitoring points of the world weather points shown in Fig. 6. To examine the value of the growing index GDD as a grain production index, Fig. 10 shows the relation between the GDD and the Crop Situation index for paddy rice at Kuki, which is a verification site in Japan. The growth index GDD was able to represent the poor harvest, having low Crop Situation index 74 of paddy rice, following damage by exceptionally cold weather in 1993, but GDD could not represent the bad harvest of Crop Situation index 98 in 1998 that was due to insufficient solar radiation even though the temperature was adequate. Moreover, the GDD must distinguish between the small good harvest of Crop Situation index 102 in 1997 and the Crop Situation index 98 in 1998. Although the GDD is a growth index, it is not a direct index of grain production. In the field of agriculture, there is also a method of predicting the total grain tonnage using the shape of the growth curve of the seasonal NDVI. However, the growth curve of NDVI is not a grain production index, but a growth index, as is the integrated vegetation index iNDVI.

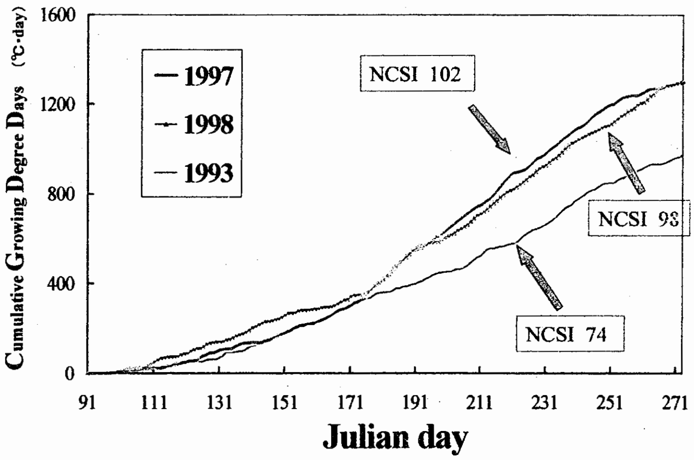

Fig.7. Seasonal curves of cumulative GDD and relation to the crop situation index NCSI of rice at Kuki site in Japan.

5.2. *Integrated NDVI (iNDVI)*

Satellite data is effective in foreign areas where it is difficult to obtain weather data. Fig. 11 shows the integrated NDVI mentioned above around the monitoring points in China. If there is neither water stress nor low temperature sterility around the time of flowering, the crop quantity of production should be high in crop areas where the integrated vegetation index iNDVI is large. Therefore the large values of the integrated vegetation index at Jinan or Yichan in Fig. 11 suggest a good harvest in those areas. This iNDVI is the integrated value of the vegetation biomass, which is incorporated also in the photosynthesis type of crop production index CPI. The iNDVI is a vegetation growing index, which measures the crop plant density. It was designed as a monitoring tool for the total grain tonnage. However, the iNDVI is really a growth index; it cannot, for example, express the effect of a lack of sunshine, or effects of low-temperature sterility during flowering and filling. Even if stomata close and photosynthesis is limited by shortage of soil moisture, leaves remain vivid green so that the reduced photosynthesis is not captured by the vegetation indexes NDVI and iNDVI. This is why Rasmussen (1992, 1998) proposed the improvement in formula (5) to take into account photosynthetically active radiation. However, the model still does not allow for low temperature sterility or water stress.

5.3. *Photosynthesis type of crop production index CPI*

Fig. 12 shows the photosynthesis-based crop production index CPI taking into consideration the vegetation index NDVI as vegetation biomass as well as solar radiation and effective air temperature GDD. The values of the Crop Situation index at Kuki site in Saitama prefecture are included in the figure. The CPI index clearly shows the poor harvest due to low temperatures in 1993, and that due to lack of sunshine in 1998,and captures also the quantitative difference between the good harvest in 1997 and these poor harvests. The discernment ability is much greater than the growing indices GDD and iNDVI. The photosynthesis-based crop production index CPI turns out to be a good index for monitoring.

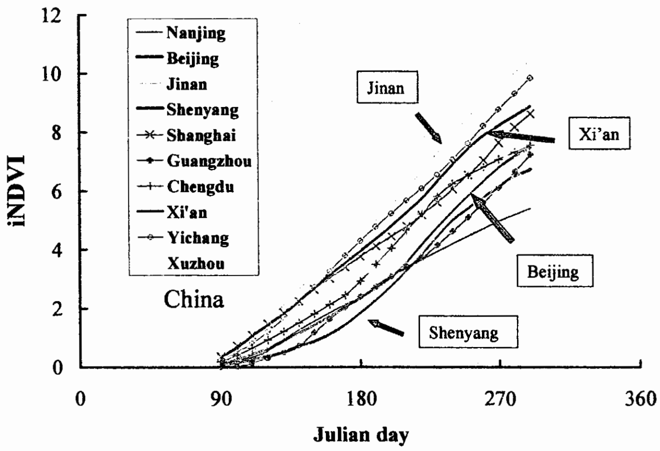

Fig. 8. Integrated NDVI (iNDVI) of paddy fields in China as a growth index for crop production.

One of the authors (Kaneko, 2003b) is also proposing a CPI that accounts for sterility below air temperatures of 18.5 centigrade and injury above 40 degrees (Matsui et al. 1997, 1997b).

6. Conclusions

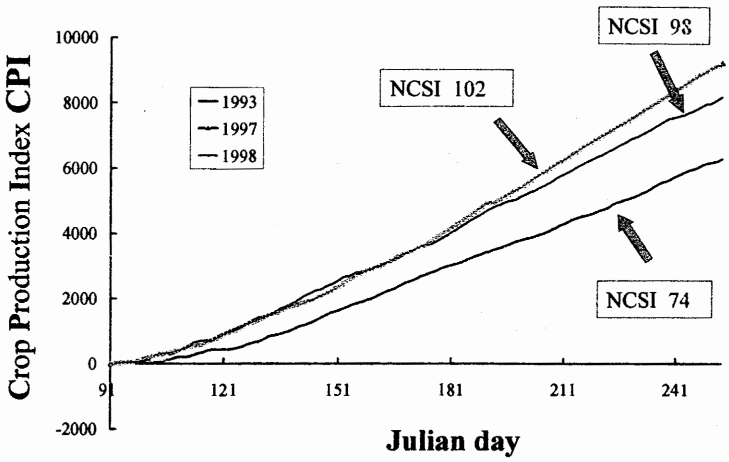

Fig. 9. Daily variation of crop production index CPI at the Kuki site in Japan with values of the crop situation index.

This paper have proposed a daily surveillance system for monitoring crop production in China and India that uses an improved photosynthesis-based crop production index, necessary to take into account water stress of crops. Monitoring of the crop quantity in production in these countries has the social background of the increasing Asian population, and the purpose is to give advance warning of poor crop production in the present era of water-resource restrictions. The proposed method for surveillance of the grain quantity in production in both countries has the following features.

It is important to monitor crop production in China and India in the present and coming era of water-resource restrictions. The background to the proposal involves social issues in Japan and its neighbors. The monitoring system includes the surveillance model, which takes into consideration daily changes in weather conditions. The model proposes to use world weather data in the monitoring model, specifically daily weather data for China and India. Without simulating the growth of crops, remotely sensed data can give the vegetation biomass of the crops in both countries using satellite data. Conventional predictive monitoring based on the growing index GDD derived from the effective air temperature was inaccurate, as shown by the Crop Situation Index in 3 years. It is necessary to construct a photosynthesis-based crop production index incorporating the effect of solar radiation so as in to express the mechanism of photosynthesis. The vegetation index NDVI from satellite should be taken into the crop production index CPI for the vegetation biomass, as proposed by Rasmussen. The author proposes a photosynthesis-based crop production index CPI taking into consideration such factors as solar radiation, air temperature, vegetation biomass, and stomatal opening using satellite data and world weather data. The present CPI index proved more accurate than the conventional cumulative GDD and the integrated NDVI as a crop production index for early monitoring of paddy rice.

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