Estimation of Net Primary Production in Paddy Fields of Japan using Satellite Data

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Abstract: Our goal is to estimate global Net Primary Production (NPP) using ADEOS-II/GLI data. For that reason, We have developed the estimation method of NPP using Modified Vegetation Index based on Universal Pattern Decomposition Method (MVIUPD) from the ground measurement data of various kinds of trees in temperate zone. This estimation method needs MVIUPD and some climate data. To validate this estimation method, we have applied this method to satellite data in various vegetation areas. And to estimate the accuracy of this estimation method and improve it, we compare the estimated NPP from satellite data with the NPP of the ground truth data. In previous study, it was concluded that NPP estimated from Landsat/ETM+ data agrees with the ground truth data for grass fields in Mongolia and cedar forest in Nara, Japan. However, in paddy fields, the estimated NPP from satellite data does not agree with the ground truth data from rice yield data. A case of Nara in Japan, NPP estimated from Landsat/TM and ETM+ data was about 55% of the ground truth data. In paddy fields, the estimated NPP from satellite data is underestimated. We think that the productivity of rice is higher than that of forest. In paddy fields, rice is got enough water and nutrition by people, but in forest, trees are not. We compared the estimated NPP from satellite data with the NPP of the ground truth data in some paddy field areas, and determined a factor of this algorithm. As a result, it was clear that the estimated value is about 60% of the ground truth data. Using this result, we estimated annual NPP in Japan using ADEOS-II/GLI data.
Keywords: net primary production, vegetation index, Universal Pattern Decomposition Method (UPDM), ADEOS-II/GLI.

1. Introduction

Increase of atmospheric carbon dioxide content is caused by anthropogenic carbon dioxide emissions and release of carbon dioxide into the atmosphere causes global warming. It is very important to understand of carbon cycle in the terrestrial, ocean and atmosphere. Vegetation absorbs carbon dioxide by photosynthetic activity. Annual plant growth is the difference between photosynthesis and autotrophic respiration, and is called net primary production (NPP). Global terrestrial NPP has been estimated at about 60 PgC/yr through integration of field measurements [1][2].

Remotely-sensed data can be also used to estimate NPP by vegetation. Many estimation methods have been developed and global NPP distribution map was produced using NOAA/AVHRR and Terra/MODIS data. In particular, multi-spectral data observed by MODIS are used for the estimation of the vegetation parameters such as Leaf Area Index (LAI) and fAPAR. In addition to these vegetation parameters, numerous environmental parameters such as air temperature and humidity are also used as input parameters for the physiologically based models (e.g., BIOME-BGC)[3][4][5].

We have developed the estimation method of NPP from the measurement of temperate forests for the purpose of simple calculation using satellite multi-spectral data. This estimation method needs a vegetation index MVIUPD (Modified Vegetation Index based on Universal Pattern Decomposition Method) obtained from satellite data and climate data such as solar radiation and air temperature. For the modification and validation of this algorithm, it is necessary to apply the method to satellite data and examine the applicability for vegetation of various types and climate area. In previous study, it was concluded that NPP estimated from Landsat/ETM+ data agrees with the ground truth data for grass fields in Mongolia and cedar forest in Nara, Japan [6][7]. However, in paddy fields, the estimated NPP from satellite data does not agree with the ground truth data from rice yield data. A case of Nara in Japan, NPP estimated from Landsat/TM and ETM+ data was about 55% of the ground truth data [8]. In paddy fields, the estimated NPP from satellite data is underestimated. We think that the productivity of rice is higher than that of forest. In paddy fields, rice is got enough water and nutrition by people, but in forest, trees are not. In this study, we estimate NPP in some paddy field areas using ADEOS-II/GLI data and compare the estimated NPP from satellite data with the NPP of the ground truth data.

2. ADEOS-II/GLI data

The second Advanced Earth Observing Satellite (ADEOS-II), also known as “Midori-II”, was designed to observe the earth multi-spectrally. It was launched by H-IIA Vehicle No.4 on 14 December 2002 by Japan Aerospace Exploration Agency (JAXA). Unfortunately, ADEOS-II ceased operation on 25 October 2003, but it did observations for about 7 months (from April to October 2003). The satellite had a polar, circular, sun-synchronous 800 km orbit with a 4-day repeat cycle.

ADEOS-II carried the following sensors: Advanced Microwave Scanning Radiometer (AMSR), the Global Imager (GLI), Sea Winds (SeaWinds), Polarization and Directionality of the Earth’s Reflectances (POLDER), and Improved Limb Atmospheric Spectrometer-II (ILAS-II). In this study, we used GLI data.

GLI made observations in 36 bands with both 1 km and 250 meter spatial resolution. The multi-spectral observations are comprised of 23 bands in VNIR, 6 bands in SWIR, and 7 bands in Middle and Thermal Infrared (MTIR) region.

GLI standard products over land include L1 data (radiance), L2 data (reflectance), and L3 data (vegetation index and so on). GLI standard data products include products with 1 km spatial resolution (L1A, L1B, L1BMap, L2A, L2, L2Map, L3B, L3STAMap), and 250 m spatial resolution (L1A, L1B, L1BMap). In this study, we used GLI L2A_LC (version 180) global mosaic data. L2A_LC includes L2A products to study land and cryosphere. L2A_LC data is an apparent reflectance at sensor level stored as 2 byte unsigned short integers. We calculated the earth-sun distance for each scene and considered the path radiance from Rayleigh scattering.

L2A_LC data are composite over 16 days using 1 km spatial resolution data and the L2A_LC global mosaic data are comprised of 56 areas. The area number of 15 includes Japan and we use its area data in this study. Table 1 lists available composite data used in this study.

Table 1. Available ADEOS-II/GLI 16-day composite data used in this study.

Name	16-day composite period
Apr. 07, 2003	20030407 to 20030422
Apr. 23, 2003	20030423 to 20030508
May 09, 2003	20030509 to 20030524
May 25, 2003	20030525 to 20030609
Jun. 10, 2003	20030610 to 20030625
Jun. 26, 2003	20030626 to 20030711
Jul. 12, 2003	20030712 to 20030727
Jul. 28, 2003	20030728 to 20030812
Aug. 13, 2003	20030813 to 20030828
Aug. 29, 2003	20030829 to 20030913
Sep. 14, 2003	20030914 to 20030929
Sep. 30, 2003	20030930 to 20031015
Oct. 16, 2003	20031016 to 20031031

3. Algorithm to estimate Net Primary Production using multi-spectral data

1) Vegetation index used for NPP estimation

The NPP estimation algorithm is based on a vegetation index (MVIUPD). MVIUPD is calculated from the pattern decomposition coefficient obtained by the universal pattern decomposition method (UPDM) [9]. UPDM modifies the pattern decomposition method (PDM [10][11]), allowing sensor-independent spectral analysis to derive the same coefficient values for the spectral bands on different sensors. Each pixel is represented as a linear sum of standard spectral patterns for water, vegetation, and soil. In addition, supplementary patterns are included when necessary. For example, for a detailed analysis of vegetation change, a supplementary yellow leaf spectral pattern can be added as follows:

$$A(i) \rightarrow uC_w \times P_w(i) + uC_v \times P_v(i) + uC_s \times P_s(i) + uC_4 \times P_4(i) . \tag{1}$$

Reflectance of band *i* is given as *A(i)*, and $P_w(i)$, $P_v(i)$, $P_s(i)$, and $P_4(i)$ are the standard spectral patterns for water, vegetation, soil, and the supplementary yellow leaf pattern for band *i*. The continuous of spectral pattern ($P_k(\lambda)$ ($k=w,v,s,4$)) was determined with spectral range from 350 nm to 2500 nm as follows,

$$P_k(\lambda) = \frac{\int d\lambda}{\int |R_k(\lambda)| d\lambda} \times R_k(\lambda) \qquad (k=w,v,s,4), \tag{2}$$

where $R_k(\lambda)$ represents the continuous spectral reflectance of standard patterns $P_k(\lambda)$. The $P_4(\lambda)$ is defined using the yellow leaf residual as follows,

$$P_4(\lambda) = \frac{\int d\lambda}{\int |r_4(\lambda)| d\lambda} \times r_4(\lambda) , \tag{3}$$

where $r_4(\lambda)$ is the residual value for a yellow leaf for the *i* band. The standard pattern of band *i* is $P_k(i)$, for satellite data analysis is derived from the continuous standard pattern $P_k(\lambda)$. The normalized standard spectral patterns are calculated from the ground spectral measurement data of water, vegetation, soil, and the supplement yellow leaf, respectively.

In this study, we used ADEOS-II/GLI L2A_LC wavelength bands as an example and analyzed the reflectance data of nine bands (band 5,8,13,15,19,24,26,28,29).

Eq. (4) calculates the vegetation index based on universal pattern decomposition method (UPDM) [12]:

$$MVIUPD = \frac{uC_v - uC_w - 0.2 \times uC_s - uC_4}{uC_w + uC_v + uC_s} . \tag{4}$$

Here, ($uC_w+uC_v+uC_s$) represents the sum of the total reflectance, and uC_w forces MVIUPD values to be negative over surface that lack vegetation, such as snow-covered area. The coefficient 0.2 with uC_s was determined so that the error from the relationships of MVIUPD for vegetation photosynthesis and cover ratio became the smallest. The range of MVIUPD is –0.2 at lack vegetation area to 1.3 at active vegetation area.

2) Estimation algorithm using satellite data

NPP is obtained by subtracting respiratory loss R_d from gross primary production (GPP) as follows:

$$NPP = GPP - R_d . \tag{5}$$

It was reported that the respiratory loss of leaves depends on the air temperature [13]. In this study, respiratory loss *Rd* is estimated using the following empirical relationship.

$$R_d = \frac{7.825 + 1.145T[^\circ C]}{100} \times GPP . \tag{6}$$

GPP is an accumulated photosynthesis over a term such as a year and a month. We estimate a photosynthesis using MVIUPD and photosynthetically active radiation (PAR) [14].

$$GPP = \int P(PAR(t), MVIUPD(t))dt \, . \tag{7}$$

The detail description of the photosynthesis *P (PAR(t), MVIUPD(t))* is as follows:

$$P(PAR(t), MVIUPD(t)) \cong \frac{MVIUPD(t)}{MVIUPD_{std}} \times P_{std}(PAR(t)) \, , \tag{8}$$

$$P_{std}(PAR(t)) = a \times \left(\frac{0.515 \times 0.028 \times PAR(t)}{1 + 0.028 \times PAR(t)} \right) , \tag{9}$$

$$MVIUPD_{std} = 0.77 \, ,$$

$$PAR = 0.48 \times SolarRadiation \, .$$

Here, *P (PAR(t), MVIUPD(t))* and P_{std} *(PAR(t))* are in units of [$mgCO_2/m^2/s$] and *PAR(t)* is in [W/m^2]. Thus, the photosynthesis of the vegetation can be estimated by its MVIUPD value using Eq. (8) and (9). Now in Eq. (9), the parameter a is 1 through the ground measurement of temperate trees, and we determine a new parameter for paddy fields in this study.

In order to estimate GPP, we accumulate Eq. (8) over a term. It is expected that *MVIUPD(t)* changes gradually with a time except for the sudden change such as a forest burning and crop cultivation. In contrast to that, *PAR(t)* changes with shorter time range than *MVIUPD(t)*. In addition to that, it is necessary to accumulate photosynthesis with a change of PAR because photosynthesis expressed by Eq. (9) is not linear to PAR. However, it is difficult to acquire the detail change of PAR over wide area observed by satellite data.

Thus, we developed the method to calculate an accumulated photosynthesis by using daily or monthly mean PAR. In particular, it is important to study how to calculate the mean of PAR. In particular, simple daily mean of PAR for 24 hours is calculated including the night time in which vegetation does not photosynthesize. It suggests the daily mean of PAR for 24 hours is not suitable for estimate the accumulated photosynthesis for the day.

We introduced the effective daylength for photosynthesis and determined the effective daylength based on the daylength between sunset and sunrise so that photosynthesis calculated by the mean of PAR for the effective daylength agrees with the accumulated photosynthesis. As a result, it was clear to be suitable to use the effective daylength defined as follows:

$$h = H - h' \, . \tag{10}$$

Here, *h* is effective daylength [hour] for vegetation photosynthesis and *H* is the daylength [hour] between sunrise and sunset. Sunrise and sunset are calculated from the latitude, longitude, and date. We determined *h'* as 2 hours.

Finally, we obtained the following equation to calculate the accumulated photosynthesis, namely GPP. It is assumed that MVIUPD value does not change for the day and the value is expressed by $MVIUPD_{day}$. $\overline{PAR_h}$ is mean of PAR during effective daylength (*h*) and its unit is [W/m^2].

$$dailyGPP = \int_{day} \frac{MVIUPD_{day}}{MVIUPD_{std}} \times P_{std}(PAR(t))dt \tag{11}$$

$$\cong \frac{MVIUPD_{day}}{MVIUPD_{std}} \times P_{std}(\overline{PAR_h}) \times (\Delta t \times h) \, , \tag{12}$$

$$\Delta t = 3600[s] \, .$$

This method to estimate NPP has an estimation error of 26%.

4. Study area used in this analysis

In previous study, it is clear that in paddy fields the estimated NPP using satellite data is underestimated. In this study, we apply the NPP estimation model described in previous section to satellite data in some paddy field areas of Japan. The validation site of this model is Yamagata, Akita, Niigata, and Toyama in Japan. Every area is famous for single crop area of rice. Fig. 1 shows the study area. Three area surrounded by lines are study area of paddy fields.

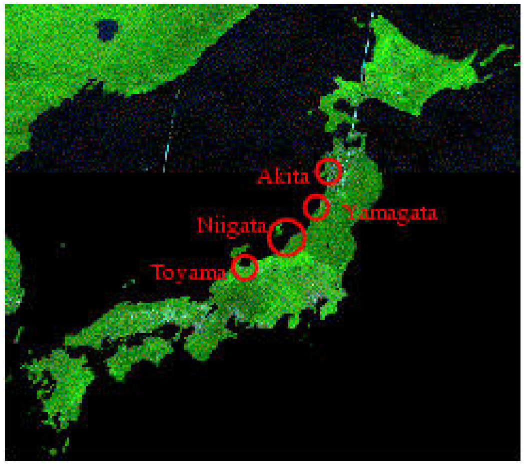

Figure 1. Study area for paddy fields in Japan.
(False-color ADEOS-II/GLI imagery, R : band29, G :band 19, B : band13)

ADEOS-II/GLI L2A_LC data are 1 km spatial resolution data, so we must find large paddy fields area in three study areas. The detailed analysis area is determined using 1/25000 map by Geographical Survey Institute [15]. As a result, we analyze 49 pixels in Yamagata, 60 pixels in Akita, 120 pixels in Niigata, and 190 pixels in Toyama.

5. Estimation of Net Primary Production in paddy fields

1) Ground truth data : rice yield

The rice yield is examined for each cities in Japan. The rice yield data means the almost dry weight of brown rice (unpolished rice) per a unit ground area. We estimate the dry weight of all rice matter using the two relationships between rice yield and the dry weight of above ground (Eq. (14)) and between the dry weight of above ground and below ground (Eq. (15)). These relationships are obtained from paddy fields in Akita Prefecture of Japan [16].

$$D_{all} = D_A + D_B, \quad (13)$$

$$D_A = 2.69 \times D_{yield}, \quad (14)$$

$$D_B = 0.07 \times D_A. \quad (15)$$

Here, D_{all} is dry weight of all rice matter. D_A is dry weight [kg] of above ground and D_B is dry weight [kg] of below ground. D_{yield} is almost dry weight [kg] of brown rice. Table 2 shows the rice yield for three cities including study area, Akita, Niigata, and Toyama. Third column is rice yield data [kg/10a] in 2003 given by The Ministry of Agriculture, Forestry and Fisheries of Japan ([17]) and fourth column is dry weight of all rice matter calculated from the above empirical equations. This calculated result includes an error of 5%.

Table 2. Rice yield and dry weight of all rice matter in three study areas.

study area	city name	rice yield D_{yield} [kg/10a]	dry weight of all rice matter D_{all} [g/m^2]
Yamagata	Sakata city	604	1738
Akita	Ogata village	543	1563

Niigata	Niigata city	546	1572
Toyama	Toyama city	502	1445

2) Estimation of NPP in paddy fields

Seasonal changes of vegetation indices NDVI and MVIUPD were examined using thirteen ADEOS-II/GLI data indicated in Table 1. Fig. 2 shows the seasonal changes of NDVI and MVIUPD for paddy fields in Akita. Both indices begin to increase from the beginning of May and decrease to the middle of October. The largest value is got beginning of August. In another study areas, Niigata and Toyama, we could see the same seasonal changes in both indices. In these study areas, rice is generally planted in the middle of May and cultivated in the end of September. From seasonal change of indices, we can guess these periods.

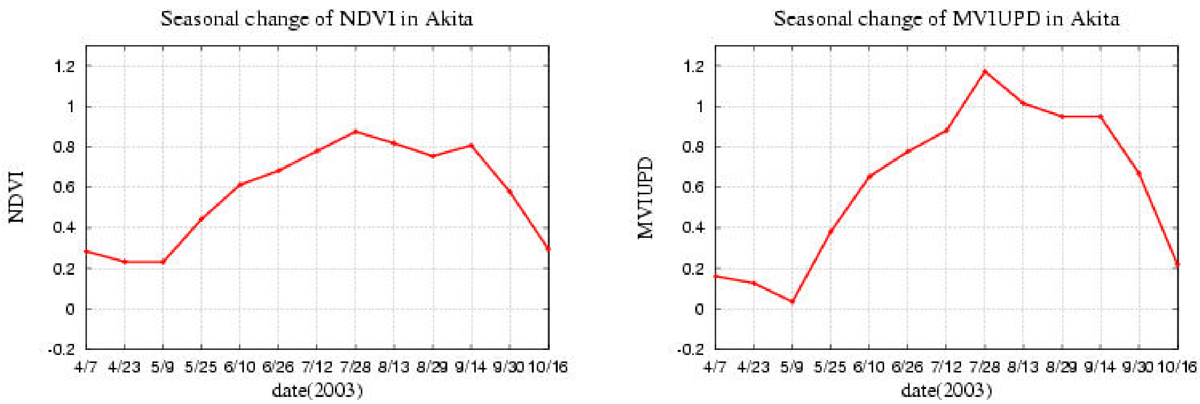

Figure 2. Seasonal change of NDVI and MVIUPD for paddy fields in Akita.

In this study, the NPP for paddy fields was estimated using MVIUPD from May 9 to Oct. 16, 2003. However, analyzed pixels include various land cover pixels, so we must select pixels covering only paddy fields. From seasonal changes of MVIUPD, the difference between the maximum MVIUPD and the minimum MVIUPD was used to determine whether the pixel covers paddy fields. If the difference is larger than 0.8, we estimated NPP in its pixel.

$$\max MVIUPD - \min MVIUPD > 0.8 . \qquad (16)$$

In all pixels that we analyzed, the maximum MVIUPD was the value of Jul. 28 and the minimum MVIUPD was the value of May 9.

Fig. 3 shows the seasonal change of MVIUPD in Niigata. In Niigata, for some pixel, MVIUPD of Jul. 12 was extremely small. Pixels that MVIUPD of Jul. 12 is smaller than MVIUPD of Jun. 26 were excepted from the NPP estimation.

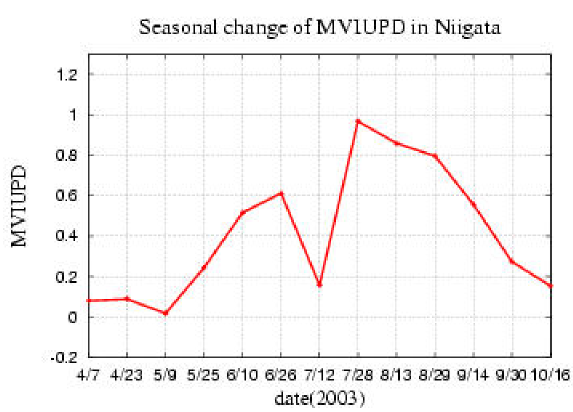

Figure 3. Seasonal change of MVIUPD for paddy fields in Niigata (MVIUPD of Jul. 12 is extremely small.).

When we couldn't calculate MVIUPD from satellite data because of cloud pixel, we got MVIUPD to interpolate linearly.

In addition to the change of MVIUPD, we used PAR and air temperature data for the NPP estimation. Table 3 shows solar radiation and air temperature data measured at the nearest observatory from each study areas ([18]) and daylength between sunrise and sunset. These values are average for 16 days, which is the same as ADEOS-II/GLI L2A_LC data shown in Table 1. In Akita, solar radiation was no data until Jun. 3, so we used the data of Morioka in its term. Morioka and Akita are almost same latitude.

Table 3. Climate data and daylength for each study area.

ADEOS-II/GLI data	Solar radiation [MJ/m^2]				Air temperature [$°C$]				Daylength H [hour]			
	Yamagata	Akita	Niigata	Toyama	Yamagata	Akita	Niigata	Toyama	Yamagata	Akita	Niigata	Toyama
May 09, 2003	21.26	18.48	20.24	19.75	16.4	15.8	16.6	17.0	14.5	14.5	14.0	14.0
May 25, 2003	22.98	23.08	21.35	20.93	19.1	18.7	19.3	20.5	14.5	15.0	14.5	14.5
Jun. 10, 2003	16.67	16.13	16.58	12.61	21.9	21.2	22.7	22.3	15.0	15.0	15.0	14.5
Jun. 26, 2003	11.02	12.91	12.79	12.59	19.8	19.8	21.2	22.2	15.0	15.0	14.5	14.5
Jul. 12, 2003	18.57	18.73	16.72	12.68	21.0	21.0	22.3	22.4	14.5	14.5	14.5	14.5
Jul. 28, 2003	15.45	13.34	16.09	16.34	24.2	23.5	25.4	25.8	14.0	14.0	14.0	14.0
Aug. 13, 2003	11.72	13.16	12.81	14.49	23.0	22.9	24.4	25.4	13.5	13.5	13.5	13.5
Aug. 29, 2003	12.11	13.00	13.09	13.86	22.9	22.2	24.3	25.2	13.0	13.0	13.0	13.0
Sep. 14, 2003	13.04	13.36	12.83	13.51	19.1	18.4	20.7	21.1	12.0	12.0	12.0	12.0
Sep. 30, 2003	12.54	12.57	12.32	13.29	15.6	14.5	16.8	16.6	11.5	11.5	11.5	11.5

Table 4 shows latitude and longitude used to calculate daylength in Table 3.

Table 4. Latitude and longitude for each study area.

	Yamagata	Akita	Niigata	Toyama
latitude	38.9° N	40.00° N	37.91° N	36.71° N
longitude	139.8° E	140.00° E	139.05° E	137.20° E

From the above climate data and MVIUPD, NPP for each 16 days was calculated by accumulating daily NPP and sum of NPP was 1077.6 [g/m^2] in Yamagata, 1171.1 in Akita, 887.9 in Niigata, and 819.1 in Toyama. The NPP obtained from rice yield data is 1738 [g/m^2] in Yamagata, 1563 in Akita, 1572 in Niigata, and 1445 in Toyama as described in Table 2. Table 5 shows the estimated NPP from satellite data and the calculated NPP from ground truth data in paddy fields including previous studies. Fourth column is the ratio of the NPP estimation. The NPP value estimated from satellite data is about 60% of ground truth data.

Table 5. The NPP value and the ratio of the NPP estimation.

Study area	The estimated NPP from satellite data [g/m^2]	The calculated NPP from ground truth data [g/m^2]	The ratio of the NPP estimation
Nara	818.3	1524	54%
Yamagata	1077.6	1738	62%
Akita	1171.1	1563	75%
Niigata	887.9	1572	56%
Toyama	819.1	1445	57%

We think that the productivity of rice is higher than that of forest. In paddy fields, rice is got enough water and nutrition by people, but in forest, trees are not. This algorithm that we used in this study to estimate NPP was established through the ground measurement of temperate trees, so the parameter obtained in Eq. (9) could not apply for paddy fields. We determined a new parameter for paddy fields and a is 1/0.6. In paddy fields, Eq. (9) becomes as follows:

$$P_{std}(PAR(t)) = \frac{1}{0.6} \times \left(\frac{0.515 \times 0.028 \times PAR(t)}{1 + 0.028 \times PAR(t)} \right). \tag{17}$$

3) Estimation of annual NPP in Japan

We estimated annual NPP in Japan, 2003 from ADEOS-II/GLI L2A_LC data using above parameter in paddy fields. Annual NPP is sum of monthly NPP and to estimate monthly NPP we need monthly MVIUPD, solar radiation, air temperature, and daylength.

MVIUPD values was calculated using ADEOS-II/GLI reflectance data from April to October. Each month from April to September has two composite scenes, so the higher MVIUPD value of two scenes was selected on each pixel as monthly MVIUPD. MVIUPD values of January, February, and March 2003, were derived through linear interpolation from October 2003 replaced as October 2002 to April 2003. In similar way, MVIUPD values of November and December 2003, were derived through linear interpolation from October 2003 to April 2004 replaced by April 2003.

The monthly mean solar radiation data in 2003 is the meteorological reanalysis data, which were developed by the National Center for Environmental Prediction and the National Center for Atmospheric Research (NCEP/NCAR).

Air temperature data at 2 m above the Earth's surface were derived from operational atmospheric model archives at the European Center for Medium-Range Weather Forecasts (ECMWF).

The daylength is the time between sunrise and sunset. Sunrise and sunset was calculated from the latitude, longitude, and date.

The monthly NPP was calculated from these data. When monthly mean air temperature exceeds 10 [$°C$], it was identified the growing period and calculated the monthly GPP [19]. If the difference between the maximum MVIUPD and the minimum MVIUPD is larger than 0.8, we consider the pixel covers paddy fields and calculated annual NPP with a new parameter determined in previous subsection (Eq. (17)). Fig. 4 shows the annual NPP in Japan, 2003 using ADEOS-II/GLI L2A_LC data.

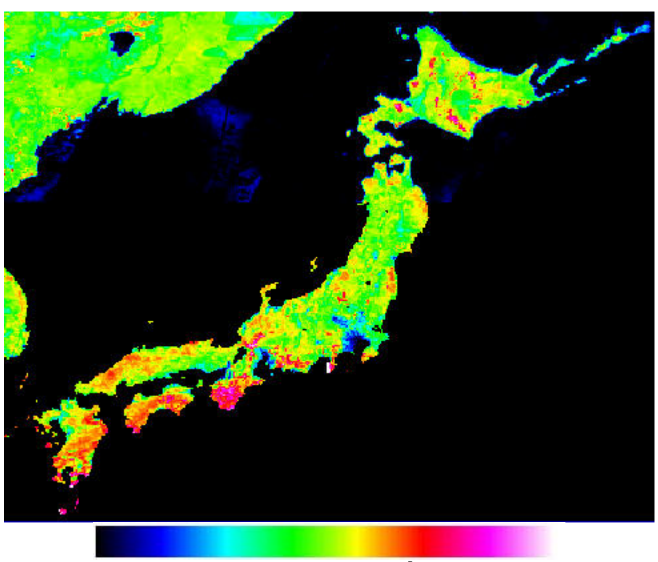

Figure 4. The annual NPP in Japan, 2003 using ADEOS-II/GLI data.

3. Conclusions

The purpose of this study is to validate the NPP estimation method in paddy fields and to determine a parameter to this algorithm. Using ADEOS-II/GLI data from April to October, we estimated NPP for paddy fields in Yamagata, Akita, Niigata, and Toyama, and compared it with the dry weight of all rice matter obtained from rice yield data. As a result, the estimated NPP is about 60% of ground truth data. Based on these results, we determined a parameter for paddy fields as 1/0.6 and estimated the annual NPP in Japan from ADEOS-II/GLI data using this parameter.

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