Verification of Net Primary Production Estimation Method in the Mongolian Plateau Using Landsat ETM+ Data

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ABSTRACT We plan to estimate global net primary production (NPP) of vegetation using the Advanced Earth Observing Satellite-Ⅱ (ADEOS-II) Global Imager (GLI) multi-spectral data. We derive an NPP estimation algorithm from ground measurement data on temperate plants in Japan. By the algorithm, we estimate NPP using a vegetation index based on pattern decomposition (VIPD) for the Mongolian Plateau. The VIPD is derived from Landsat ETM+ multi-spectral data, and the resulting NPP estimation is compared with ground data measured in a semi-arid area of Mongolia. The NPP estimation derived from satellite remote sensing data agrees with the ground measurement data within the error range of 15% when all above-ground vegetation NPP is calculated for different vegetation classifications.

KEYWORDS NPP; reflectance; photosynthesis; canopy structure

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Introduction

The release of greenhouse gases such as carbon dioxide may cause global warming. On Earth, only photosynthesis by vegetation can naturally absorb carbon dioxide. Net primary production (NPP) represents the net new carbon stored as biomass in the stems, leaves, or roots of vegetation. The stored carbon is an important part of the carbon cycle. By studying carbon dioxide absorption by vegetation, we can better understand the mechanisms of global warming.

Satellite sensors allow for NPP global estimates and the NPP monitoring anywhere in the world. To use multi-spectral satellite sensor data effectively, we developed a new vegetation index VIPD by the pattern decomposition method and examined the relationship between VIPD and NPP. We are currently developing an algorithm to estimate global NPP using multi-spectral satellite sensor data such as ADEOS-II GLI data. The algorithm is based on temperate plant leaf and canopy measurements taken in Japan.

For global NPP mapping, there is a need to validate the NPP estimation for a wide range of vegetation densities. We selected a Mongolian site to validate estimation in conditions of low vegetation density. The vast, flat Mongolian Plateau makes an ideal site for verifying the NPP estimation from satellite sensor data. Moreover, the site has also been used by the ADEOS-Ⅱ/AMPEX-AMSR/AMSR-E project to verify soil moisture estimates. For that project, ground measurements of vegetation biomass and NPP were associated with the ground measurements of soil moisture.

In this study, we used multi-spectral Landsat ETM+ data to estimate the NPP. We then compared the estimation result with ground measurement data from the Mongolian Plateau.

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1 Study area and NPP ground measurement

1.1 Study area

The size of the study area (Fig. 1) is 60 km × 60 km, which lies in the northeast of Mandalgovi and 235 km south-southwest to Mongolia’s capital, Ulaanbaatar.

![Fig. 1 Study area, Mandalgovi Mongolia](image)

We took NPP measurements from April to October 2001. Areas ALM3 and ALM4 consist mainly of short grass, area CRG features shrubbery, and area C2 has intermingled short grass and shrubbery.

1.2 NPP ground measurement

To coordinate with satellite sensor data, NPP was measured at four uniform areas. We measured the latitude and longitude at the NPP ground observation points using World Geodetic System 1984 (WGS84) GPS equipment (GARMIN-III GPSplus, GARMIN), as detailed in Table 1. As the study area is used for pasturage, livestock or other animals may eat the vegetation, we erected a fence around the plot in which we measured the gross production of vegetation. Once every month, we cut the plant biomass at ground level in the enclosed area more than two repetition and measured the above-ground plant growth. The collected plants were oven dried (at 130°C for two hours) to measure the dry weight. The following Eq. (1) was used for converting the organic dry matter weight into a carbon dioxide value:

\[
C_6H_{12}O_6 \rightarrow 6CO_2 = 30 : 44
\]  

We measured NPP from April to October 2001 and from June to August 2002. Table 1 shows the NPP ground measurement data for June 2001. We compared the June 2001 ground measurement data with the June 2001 Landsat ETM+ data.

We assumed the ratio of aboveground plant growth to the underground to be approximately 2:1, as in Eq. (2). For different types of vegetation, the estimation error for underground growth approaches ±15% of the entire plant value (including aboveground and underground growth).

\[
\frac{NPP_{\text{aboveground}}}{NPP_{\text{underground}}} = 2 : (1 \pm 0.45)
\]

Table 1 summarizes the measured NPP results which were used to verify the NPP estimation derived from satellite data. Verification methods are described below.

2 Method: estimating NPP from satellite data

2.1 Pattern decomposition method and VIPD

The pattern decomposition method is used to

| name of Point | NPP ground measurement data [kgCO2/(m² * month)] |
|---------------|-----------------------------------------------|
|               | Aboveground part | Whole plant |
| ALM3          | 0.039            | 0.059±0.009 |
| CRG           | 0.018            | 0.027±0.004 |
| C2            | 0.020            | 0.030±0.005 |
| ALM4          | 0.018            | 0.027±0.004 |
analyze multi-spectral reflectance data. Any pixel \( A_i \) of satellite spectral reflectance data can be decomposed into three basic patterns: water, vegetation and soil. The following Eq. (3) demonstrates the conversion process:

\[
A_i \rightarrow C_w P_w + C_v P_v + C_s P_s
\]  

(3)

where \( i \) corresponds to the wavelength bands; \( C_w, C_v \) and \( C_s \) are the decomposition coefficients of water, vegetation and soil, respectively; \( P_w, P_v \) and \( P_s \) are the basic patterns of water, vegetation and soil, respectively, given as:

Water pattern = \( (P_{w1}, P_{w2}, \ldots, P_{wn}) \)

Vegetation pattern = \( (P_{v1}, P_{v2}, \ldots, P_{vn}) \)

Soil pattern = \( (P_{s1}, P_{s2}, \ldots, P_{sn}) \)

(4)

where \( n \) is the number of wavelength bands from visible to short-wave infrared. For Landsat ETM+ data, \( n \) equals to six (bands 1-5 and band 7).

The sum of the standard pattern for each band is 1 for normalization, as shown in Eq. (5). The decomposition coefficients \( C_w, C_v \) and \( C_s \) can be found by using least square techniques.

\[
\sum_{i=1}^{n} P_i = 1 \quad (l = w, v, s)
\]  

(5)

This study uses the VIPD determined by Eq. (6).

\[
\text{VIPD} = \frac{C_v - C_s - \sum_{i=1}^{n} A_i C_w + S_v}{S_v + S_s}
\]  

(6)

where \( S_v \) and \( S_s \) are the sum of the reflectance of all bands for standard vegetation and soil, respectively, for all typical samples.

When vegetation is alive, VIPD will approach a value, one; when vegetation dies, VIPD will be zero. VIPD should also be approximately zero for water and soil. In general, \( S_v \) and \( S_s \) are constants, which express the reflective intensity of 100% of the vegetation and 100% of the soil, respectively. To investigate VIPD in detail, the reflective intensity of the vegetation and the soil contained in the pixel should be known. For this study, \( S_v \) was 1.61. This area in Mongolia has relatively little vegetation biomass. The background soil, however, has a strong reflective intensity, which is different for each pixel. To improve the accuracy of estimation, we calculated \( S_s \) for a pure soil pixel by using Landsat ETM+ data from a non-vegetated period in early spring. These calculations yielded an \( S_s \) of 1.4.

### 2.2 General formula for NPP

Subtracting vegetative respiration \( R_v \) from gross primary production (GPP) results in NPP:

\[
\text{NPP} = \text{GPP} - \text{R}_v
\]  

(7)

Since we measured NPP in the Mongolian Plateau every month, we also estimated a monthly NPP \( [\text{kgCO}_2/(m^2 \cdot \text{month})] \). And GPP \( [\text{kgCO}_2/(m^2 \cdot \text{month})] \) can be expressed as

\[
\text{GPP} = \int_0^{\text{month}} P(\text{PAR}(t)) \, dt
\]  

(8)

where \( t \) is time, \( \text{PAR}(t) [\text{W/m}^2] \) is the photosynthetically active radiation, and \( P(\text{PAR}(t)) [\text{mgCO}_2/(m^2 \cdot \text{month})] \) is the gross photosynthesis as a function of \( \text{PAR}(t) [\text{W/m}^2] \).

The study site had a simple grassy vegetation structure. Thus, vegetative respiration \( R_v [\text{kgCO}_2/(m^2 \cdot \text{month})] \) could be well approximated from monthly average air temperature \( T \) \( [\text{C}] \) and \( R_v [\text{mgCO}_2/(m^2 \cdot \text{s})] \) is the value of the photosynthesis when PAR is infinite; \( b \) can be plotted as a curve, and when \( b \) becomes large, an increase in PAR will rapidly lead to photosynthetic saturation.

For any single leaf or canopy, photosynthesis is a function of PAR and VIPD as expressed approximately by the following Eq. (11):

\[
P(\text{PAR}(t), \text{VIPD}(t)) = \frac{\text{VIPD}(t)}{\text{VIPD}_{\text{std}}} \times P_{\text{std}}(\text{PAR}(t))
\]  

(11)

where \( P_{\text{std}}(\text{PAR}(t)) \) is the photosynthetic curve of
a standard sample and VIPD is the VIPD of a standard sample. For \( P_{\text{std}}(\text{PAR}(t)) \) and VIPD, the value of many single leaves are averaged. Table 2 lists the \( P_{\text{std}}(\text{PAR}(t)) \) and the VIPD.

Table 2 Values of VIPD and \( P_{\text{std}}(\text{PAR}(t)) \)

| VIPD | \( P_{\text{std}}(\text{PAR}(t)) \) |
|------|----------------------------------|
| 0.56 | \( n_{\text{std}} = 0.53 \text{[mgCO}_2\text{/(m}^2\cdot\text{s}]}, h = 0.027 \text{[m}^2/\text{W}] \) |

3 Semi-arid area single leaf photosynthesis

The NPP estimation algorithm used for this study is based on ground measurement data from temperate plants in Japan. Here, we examine Eq. (11) for single-leaf plants in a semi-arid area, the Mongolian Plateau.

Using a FieldSpec FR spectroradiometer (Analytical Spectral Devices, Inc.), we measured many leaves one by one and determined an average reflectance value from nine single leaves from Caragana shrubs found in the Mongolian Plateau in 2001 and 2002. Fig. 2 lists the findings.

We also calculated the reflectance of the Landsat ETM+ spectral bands as shown in Fig. 3. Using the reflectance, we calculated the VIPD of a single leaf (Table 3).

Table 3 Average reflectance of nine leaves and VIPD for the Mongolian Plateau

| Landsat ETM+ bands | Reflectance | Vegetation index VIPD |
|---------------------|-------------|-----------------------|
| Band1               | 0.077       | 0.49                  |
| Band2               | 0.116       |                       |
| Band3               | 0.071       |                       |
| Band4               | 0.445       |                       |
| Band5               | 0.290       |                       |
| Band6               | 0.145       |                       |

Using a CO\(_2\) Analyzer LCA-4 (Analytical Development Co. Ltd.), we also measured light-response photosynthetic curves for many single leaves. Fig. 4 shows the average Caragana leaf photosynthesis measured before noon and in the afternoon. The vertical and horizontal error bars show the standard deviation of measured PAR and photosynthesis, which are ±23 [W/m\(^2\)] and ±0.07 [mgCO\(_2\)/{(m\(^2\)·s)}], respectively. The photosynthetic curve \( P(\text{PAR}(t)) \) for a single leaf in the Mongolian Plateau was calculated by using Eq. (11). The value agrees with the ground measurement data within allowable measurement error.
4 NPP estimation using Landsat ETM+ data

We estimated the NPP of the study area in Mongolian Plateau using Landsat ETM+ data from June 12, 2001. The satellite data collection date corresponded with the dates of our NPP ground measurements.

4.1 Landsat ETM+ data and registration

Fig. 1 shows Landsat ETM+ path 131, row 028, 30 m spatial resolution data acquired on June 12, 2001. To align the NPP measurement points with the satellite data, we measured latitude and longitude at recognizable points (such as the airport) and selected ground control points (GCP) on the satellite image. A GPS-I plus (GARMIN) and a LandMaster GPS camera (Konia) with WGS84 were used to determine the ground coordinates.

The study site in Mongolia lacked buildings and paved roads, making GCP determination difficult. We thus used the nearby town and an intersection on the way to town as GCPs. Once the GCPs were determined, affine conversion was performed, with registration difference less than 10 m in all directions.

4.2 PAR and air temperature in June 2001

We measured global solar irradiance at the Mongolian Plateau site in 2001. Fig. 5 shows the PAR calculated from measured global solar irradiance.

Monthly average PAR was calculated by using the average of 13 sunlight hours (from 7:30 to 20:30). The resulting PAR of 230 W/m², representing June 1-30, 2001, included rainy, cloudy, and clear days.

To estimate vegetative respiration ($R_v$), we used monthly average air temperature expressed in Eq. (9). Fig. 6 shows the air temperature measured at the study site from September 2000 to July 2001.

In June 2001, the average monthly air temperature was 20°C.

4.3 Results and discussion

To understand VIPD characteristics in the Mongolian Plateau, on June 12, 2001 we calculated the VIPD from the sample area using Landsat ETM+ data. The VIPD values of water, soil, and four NPP ground measurement areas (ALM3, CRG, C2 and ALM4) were -0.101, -0.079, 0.065, 0.048, 0.048 and 0.049, respectively.

The Mongolian Plateau’s sparse vegetation can also be measured using satellite sensor data to obtain a VIPD, but it is very low.

Table 4 shows the NPP estimated by Eq. (11) for the four study areas. Sites ALM3, CRG, C2 and ALM4 have estimated NPP of 0.052 ± 0.014, 0.038 ± 0.010, 0.038 ± 0.010 and 0.038 ± 0.010 [kgCO₂/(m² * month)], respectively. Propagation of error revealed an approximately ±26% error of estimation in the estimated NPP. This error figure included the error in calculating PAR from global solar irradiance and the error in estimating GPP.
from average PAR during sunlit hours.

Table 4 NPP estimation at the four study areas in June 2001

|                | ALM3 | CRG   | C2    | ALM4  |
|----------------|------|-------|-------|-------|
| [kgCO₂ / (m² • month)] | 0.052±0.014 | 0.038±0.010 | 0.038±0.010 | 0.038±0.010 |

Next, we compared NPP values derived from satellite data and ground measurements at the four study sites. Table 1 shows the ground-measured NPP that we compared with the estimated NPP shown in Table 4. Fig. 7 shows the results of this comparison.

The NPP estimated from June 2001 Landsat ETM+ data matched the NPP measured in June 2001 at Mongolian Plateau the study sites within an acceptable range of error.

5 Conclusions

We measured aboveground NPP at the Mongolian Plateau study sites to verify the NPP estimation algorithm developed from data on temperate vegetation in Japan. We also collected the weather data on Mongolian Plateau required for NPP estimation, including global solar irradiance, PAR and air temperature. Of these data, daily averaged PAR during sunlit hours was effective for NPP estimation.

We estimated the NPP of an area in Mongolia with low vegetation density by using Landsat ETM+ data. The average estimated NPP was 0.056±0.015 kgCO₂ / (m² • month) in our 60 km×60 km study area. The NPP estimated by using satellite data agreed with ground measurement data from the four Mongolian study sites within a ground measurement error of 15%.

This research shows that the NPP estimation algorithm we developed could be applied to semi-arid areas such as Mongolia. In the future, we plan to use the algorithm to estimate global NPP from satellite data.

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