# TOWARDS THE IMPROVEMENT ON SATELLITE BASED MODELING OF GROSS PRIMARY PRODUCTION AT TEMPERATE HUMID FOREST

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**ABSTRACT:**

Gross Primary Production (GPP), one of the key ecosystem processes between the forest ecosystem and atmosphere, is more likely to be changed because of the global change issues. Eddy covariance method is considered as a useful technique to understand $CO_2$ flux between the forest and atmosphere. However, because of limited foot print inherited to this method, satellite based modeling is required for the global assessment of GPP. Nevertheless, because of uncertainties associated with satellite based models, verification with ground based measurements is necessary. Two satellite based models, namely MODIS - GPP and VPM - GPP were taken for verification. The verification showed that neither MODIS - GPP model nor VPM - GPP model could better predict GPP at Takayama forest. While studying the relationship between GPP and eleven potential parameters by regression analysis, only two parameters namely air temperature and absorbed PAR by chlorophyll were able to explain the seasonal dynamics of observed GPP. Soil water content and water vapor pressure deficit were considered as stress factors in VPM - GPP and MODIS - GPP model respectively. Because of humid temperate forest with plenty of rainfall, water stress was not inhibiting photosynthesis in Takayama forest. Therefore, a new model was developed by selecting only those parameters which could explain variation of GPP. Prediction by new model was better matched with the seasonal dynamics of observed GPP. As a result, this study concluded that the improvement in satellite based modeling of GPP through site-specific study is necessary to upscale tower flux data into regional and global level.

## 1. INTRODUCTION

The better understanding of the $CO_2$ exchange between the forest ecosystem and atmosphere provides important information for climate change research. Net Ecosystem Exchange (NEE) of $CO_2$ between the forest ecosystem and atmosphere is determined by Gross Primary Production (GPP) and Ecosystem Respiration (ER). Atmospheric $CO_2$ is assimilated by the vegetation during photosynthesis, which is called GPP. However, $CO_2$ is released not only by the autotrophic respiration by the vegetation, but also by the heterotrophic respiration by the soil, which is called ER.

Gross Primary Production (GPP), one of the key ecosystem processes between the forest ecosystem and atmosphere, is more likely to be changed because of the global change issues. However, the assessment of global GPP and determining the role of forest ecosystems in the global carbon cycle is particularly a difficult problem because of the high degree of spatial heterogeneity in the sinks and sources, and temporal dynamics of forest ecosystems across complex landscapes and regions. Eddy covariance method is considered as a useful technique to understand $CO_2$ flux between the forest and atmosphere. However, because of limited foot print inherited to this method, satellite based modeling is required for the global assessment of GPP.

Approaches to scale up and extrapolate the site specific measurements of GPP and ER from eddy covariance tower sites are to use process based models driven by climate data and to use satellite based remote sensing observations. Light Use Efficiency (LUE) models are one of the mostly used methods to predict global GPP. LUE is usually estimated as a function of temperature, soil moisture and/or water vapor pressure deficit (VPD). Fraction of PAR absorbed by the vegetation canopy (fPAR) is estimated as a function of greenness-related vegetation index, the Normalized Difference Vegetation Index (NDVI) or Enhanced Vegetation Index (EVI) (Huete et al., 1997).

MODIS - GPP model (Running et al., 2000) rely heavily on the LUE approach, with inputs from MODIS LAI/ fPAR product, land cover, and biome-specific climatologic data. The general model of MODIS - GPP is given as follows (Equation 1):

$$GPP = \epsilon_0 \times fPAR \times PAR \times Ts \times VPDs \qquad (1)$$

Where, $\epsilon_0$ = Maximum LUE (0.13 - 0.27 g C/ mol PAR)
depending on biomes
Ts = Stress factor of temp. (0 to 1)
VPD = Stress factor of water vapor pressure deficit (0 to 1)
fPAR = Fraction of incident PAR absorbed by vegetation canopy (0 to 1)
PAR = Incident photosynthetically active radiation

Another LUE based model, the Vegetation Photosynthesis Model (VPM) (Xiao et al., 2004), use the Enhanced Vegetation Index (Huete et al., 1997), Land Surface Water Index (LSWI), air temperature and incident photosynthetically active radiation (PAR). The general equation of this model is given by (Equation 2):

$$GPP = \epsilon_0 \times EVI \times PAR \times Ts \times \frac{1+LSWI}{1+LSWI\,max} \qquad (2)$$

Where, $\epsilon_0$ = Maximum LUE (0.52 g C/mol PAR) for temperate broadleaf forest
EVI = Enhanced Vegetation Index (0 to 1)
PAR= Incident photosynthetically active radiation (mol/m2/day)
Ts = Stress factor of temperature (0 to 1)
LSWI = Land Surface Water Index (0 to 1)

Although these LUE models have been used to estimate global or regional patterns of GPP, the LUE values on which they are based need to be calibrated rigorously because they greatly impact the accuracy of the model. Therefore, because of uncertainties associated with these satellite based models, verification with ground based flux measurement is necessary.

## 2. METHODS AND MEASUREMENTS

### 2.1 Study site

The study site was about 15 km east of Takayama city, Gifu prefecture, in the central part of Japan (36° 08'N, 137° 25''E; elevation 1420 m). The site is a mountainous, and a tower of 27 m in height is located on a ridge. Vegetation is an approximately 50-years old secondary broadleaf deciduous forest, primarily dominated by oak (*Quercus crispula*) and birch (*Betula ermanii; Betula platyphylla var. japonica*). The canopy height is about 15–20 m. Trees has leaf area index of 3.5 $m^2/m^2$. The sub canopy is dominated by maple (*Acer rufinerve; Acer distylum*) and shrubs (*Hydrangea paniculata; Viburnum furcatu*). The understory is dominated by a dense evergreen dwarf bamboo (*Sasa senanensis*). The fetch length of this deciduous forest varies from 500 m to 1 km with wind direction.

Takayama forest is a cool - temperate deciduous broadleaf forest, which is a typical forest ecosystem in Japan. This forest was selected under this study to show how the satellite based models of GPP works in humid temperate forest in Asian environment.

### 2.2 Instrumentation

Two instruments namely the ultrasonic anemometer thermometer and infrared gas analyzer were used to measure the flux above the forest canopy (Fc). The lateral flux (Fs) was measured using infrared gas analyzer combined with inlet tube which were placed at 1.3 m, 2.0 m, 5.8 m, 8.8 m, 18.0 m, and 25 m above the ground level. The three-dimensional ultrasonic anemometer thermometer was used to measure the vertical wind velocity ten times per second. The Photosynthetically Active Radiation (PAR) having wavelength between 400 nm to 700 nm was measured by using the quantum sensor in terms of Photosynthetic Photon Flux Density (PPFD). Three components of PAR namely incident PAR, reflected PAR, and transmitted PAR were measured. Above the canopy at 20 m above the ground level, both the incident PAR and reflected PAR was measured. Below the canopy level, at 2 m above the ground level, the transmitted PAR was measured. Air temperature and relative humidity were measured at 10 m, 18 m, and 25 m above the ground level. Soil temperature was measured at 1 cm, 10 cm, 20 cm, and 50 cm below the ground level using platinum resistance thermometer. Similarly, soil water content was measured at 20 cm and 40 cm below the ground level. Other climatic variables including air pressure at 1.5 m above the ground level, and wind speed at 10 m and 25 m above the ground level were measured.

### 2.3 Eddy covariance data

The covariance between the vertical wind velocity and $CO_2$ density was used to calculate Flux (Fc) for each half-hour period, which was later summed to get flux (Fc) for whole day. The lateral flux (Fs) was calculated for each hour period by integrating the change in $CO_2$ density with respect to height (25 m). The absorbed PAR by canopy was calculated by subtracting reflected PAR and transmitted PAR from the total amount of incident PAR. Incident PAR having less than 10 µmol/m²/s was used to represent night period. The gaps in these independent variables were filled by averaging the data of the adjacent hours, days, and years of exactly the same time. However, the gaps in the flux (Fc) were not filled anymore.

### 2.4 Estimation of Gross Primary Production (GPP)

The combination of Flux (Fc) and Flux (Fs) gives the NEE, which was separated into day period and night period. Both day period and night period NEE having less than 0.2 m/s friction velocity was rejected. Night time ER having less than 0.2 m/s friction velocity was gap filled using the temperature response function of night NEE. Then, day ER was calculated by using the same temperature response function of night period NEE. As a result, GPP was obtained by subtracting day period ER from the day period NEE. Using the temperature response function of day period GPP, the gaps in GPP were filled.
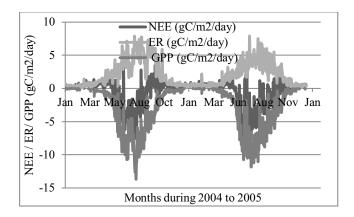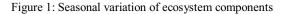
### 2.5 Satellite data

Eight days composite product of surface reflectance data (MCD43A4) recorded by MODerate Resolution Imaging Spectro Radiometer (MODIS) was obtained for the period of January 1, 2004 to December 31, 2005 from the Oak Ridge National Laboratory, Distributed Active Archive Center (ORNL, DAAC). This product was MODIS / Terra + Aqua Nadir BRDF - Adjusted Reflectance (NBAR), and had 500 m spatial resolution. The atmospheric and cloud correction was already applied by the ORNL, DAAC. Similarly, eight days composite product of GPP data was obtained from the ORNL, DAAC. Four spectral bands namely blue (450-520 nm), red (630-690 nm), near infrared (841–875 nm), and shortwave infrared (1628–1652 nm) were used to calculate different indices. Based on the geo-location information (latitude and longitude) of the flux tower site, surface reflectance data were obtained for 4 $km^2$ area (4 by 4 pixels each having 500 by 500 m) locating the tower (36° 08' 46.2'' N and 137° 25' 23.2''E) at the middle of pixels. Similarly, the GPP product, which had 1 km spatial resolution, was obtained for 4 $km^2$ (2 by 2 pixels) area. Finally, arithmetic mean from each pixel was calculated to represent Takayama forest for further calculations. Then the standard vegetation indices; namely Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), and Land Surface Water Index (LSWI) were calculated.

### 3. RESULTS AND DISCUSSIONS

### 3.1 Seasonal dynamics of ecosystem components

Three ecosystem components, namely GPP, ER, and NEE were estimated. They showed a distinct seasonal variation (Figure 1). GPP values were near zero in winter season (December, January, and February) because the deciduous leaves dominated canopy was bare and there was also low air temperature and frozen soil, which inhibited photosynthetic activities. GPP began to increase in late March and reached its peak in late June to early July. Then, GPP started to decline rapidly after its peak.



Figure 1: Seasonal variation of ecosystem components

### 3.2 Verification of MODIS-GPP model

The predicted GPP by MODIS team was compared with the observed GPP for the period of 2004 to 2005. MODIS-GPP estimation was 15.5 tC/ha/year. However, observation from eddy covariance method was 9.5 tC/ha/year. This shows that MODIS-GPP model over estimated GPP by 6 tC/ha/year. There were also differences in the seasonal dynamics between the observed GPP and predicted GPP (Figure 2).
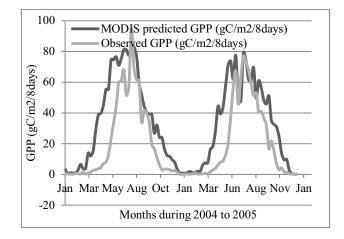


Figure 2: Verification of GPP model provided by MODIS team

### 3.3 Verification of VPM - GPP model

The predicted GPP by the VPM model was 7.0 tC/ha/year. This model underestimated the GPP by 2.5 tC/ha/year. However, the prediction by this VPM model was better than the prediction by MODIS-GPP model (Figure 3).
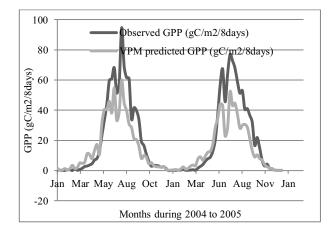


Figure 3: Verification of VPM – GPP model

### 3.4 Derivation of new model

There was discrepancy between predicted GPP from the satellite based model and observed GPP from the tower flux data. Neither

MODIS-GPP nor VPM-GPP model could better predict GPP at Takayama forest. Therefore, regression analysis was done to find out the good parameters of GPP. The regression coefficients between the observed GPP and its potential parameters have been summarized in Table 1.

Table 1: Regression analysis between the potential parameters of GPP and the observed GPP

| S.N. | Potential parameters of GPP | R2 with observed GPP |
|---|---|---|
| 1 | Incident photosynthetically active radiation (IPAR) | R2 = 0.15 |
| 2 | Air temperature (T) | R2 = 0.81 |
| 3 | Soil temperature (ST) | R2 = 0.77 |
| 4 | Water vapor pressure deficit (VPD) | R2 = 0.09 |
| 5 | Soil water content (SWC) | R2 = 0.35 |
| 6 | Land surface water index (LSWI) | R2 = 0.0009 |
| 7 | Day length (DL) | R2 = 0.41 |
| 8 | Enhanced vegetation index (EVI) | R2 = 0.85 |
| 9 | Absorbed PAR by canopy (APAR) | R2 = 0.58 |
| 10 | Absorbed PAR by chlorophyll contents (APARchl) | R2 = 0.87 |
| 11 | Atmospheric $CO_2$ concentration ($CO_2$) | R2 = 0.26 |

While considering 11 parameters, only two parameters namely; air temperature (T), and absorbed PAR by chlorophyll contents (APARchl) could well explain the variation of GPP. So, a new model (Equation 3) was developed considering only those parameters which showed a good relationship with GPP, i.e., air temperature (T) and absorbed PAR by chlorophyll (APARchl).

$$GPP = \epsilon_0 * APARchl * Ts \qquad (3)$$

Where, $\epsilon_0$ = Maximum light use efficiency observed at Takayama forest (5.6 gC/ mol APARchl)
APARchl = Absorbed PAR by chlorophyll
ATs = Stress by air temperature (fraction of 1.0)

Unlike MODIS-GPP and VPM-GPP model, water as a stress in terms of water vapor pressure deficit (VPD) or land surface water index (LSWI) was not considered in a new model. In this new model, the PAR absorbed by chlorophyll (APARchl) is assumed as absorbed PAR by canopy (APAR) multiplied by Enhanced Vegetation Index (EVI) (Equation 4).

$$APARchl = APAR * EVI \qquad (4)$$

**3.5 Verification of new model at Takayama forest**

The observed GPP was compared with the predicted GPP by new model. The model predicted GPP was 10 tC/ha/year. This model well predicted GPP as compared to other models. In addition, this model could better predict the seasonal dynamics of GPP. (Figure 4).
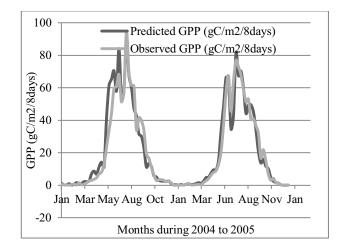


Figure 4: Verification of new model

## 4. CONCLUSION

At Takayama forest, neither soil water content nor vapor pressure deficit could explain the variation of GPP. These parameters were considered as stress factors in satellite based models. Because of humid temperate forest with plenty of rainfall, water stress was not inhibiting photosynthesis in Takayama forest. Moreover, because of the forest located at hills and valleys, water vapor pressure deficit could not explain the variation in GPP. Therefore, current satellite based models could not well predict GPP at this humid temperate forest. Therefore, a new model was developed by selecting only those parameters which showed a strong coefficient of determination with observed GPP. Prediction by this new model was better matched with the seasonal dynamics of observed GPP. As a result, this study concluded that the improvement in satellite based modeling of GPP through site-specific study is necessary to upscale flux tower data into regional and global level.

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