

IMPROVEMENT OF TERRESTRIAL GPP ESTIMATION ALGORITHMS USING SATELLITE AND FLUX DATA

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ABSTRACT:

In our research approach, Gross Primary Production (GPP) is directly estimated from canopy reflected light. Photosynthesis is done only exposed area by solar light. We consider that reflected radiance has information of the exposed area, since photosynthesis can be directly estimated from reflected light¹⁾. Photosynthesis process in chlorophyll consists of 2 processes. The one is light reactions that can detect by vegetation index. The other is carbon reduction is controlled by stomata opening and closing which effected by weather conditions. We study the relationship between these variables and photosynthesis conditions. This research objective is to improve accuracy of terrestrial GPP estimation algorithm by using Vegetation Index (VI) and combine with Fluxes data that can reveal empirical photosynthesis rate in each site around the world. The first part of GPP estimation algorithm is to find maximum GPP (Pmax_best) of plant under most favourable conditions (No stresses) from light response curve. Next step, we will analyze with weather conditions to find Pmax for GPP estimation. Present research's results show Pmax_best highest in deciduous needle leaf forest, grassland and evergreen needle leaf forest, respectively. Our results indicated that Pmax_best and VI have a tendency. Linear relationship was found between Pmax_best and NDVI in grassland ($r^2 = 0.92$), deciduous needle leaf forest ($r^2 = 0.71$) and paddy field ($r^2 = 0.87$). These relationships can be one of representative for improving global GPP estimation algorithms in GCOM-C/SGLI project.

1. INTRODUCTION

Ecosystem process model and remote sensing is one of efficiency approach from view point of regional and global scale. Many researchers have been estimate GPP by light use efficiency (LUE) model. Light use efficiency is the key physiological parameter at canopy scale, and at the daily time step is a component of remote sensing algorithms for GPP over regional to global domains (D. Turner, 2003). In LUE models, GPP is usually estimated as a product of LUE, PAR and FPAR. FPAR is estimated using NDVI or Leaf area Index (LAI). Canopy radiative transfer models are efficiency but some models are complex and need many parameters. These kinds of model are mainly use Leaf Area Index (LAI) (D. Turner et al., 2003, F. Lagergren, et al., 2005) by finding relationship with satellite derived VI. The relationship may cause large error. Because observed reflected light by satellite is sensible to vegetation coverage than vegetation depth. In previous study (Furumi et al., 2005, Y. Xiong et al., 2005, K. Muramatsu et al., 2009) GPP estimation algorithms was developed and includes a non linear relationship between GPP and PAR, and also use VI but only one set of parameters of the nonlinear photosynthesis curve is use in the model. However, the model is capable to including various types of photosynthesis curve of each biome (vegetation types) that is the aim of this research. In this research approach, GPP is directly estimated from canopy reflected light and consideration of photosynthesis rate in each biome. Photosynthesis is done only exposed area by solar light. We consider that reflected radiance has information of the exposed area, since photosynthesis can be directly estimated from reflected light. Photosynthesis composed of 2 processes, first is light reactions is mainly controlled by light intensity and

chlorophyll contents of leaf that are reflected by Vegetation Index (VI) and second process is carbon reductions (or Calvin cycle) is controlled by stomata opening and closing which effected by environmental variables (air temperature, vapor pressure deficit ;VPD , etc.), which can vary considerably over short time periods. We study the relationship between these variables and photosynthesis conditions. Our GPP model based on Photosynthesis capacity and presence environmental variables. GPP calculation is based on the assumption that under most favorable condition of photosynthesis (Pmax_best). The chlorophyll content of a leaf reflects the photosynthesis ratio under the most favorable condition. The chlorophyll content of a leaf can be detected by VI in growing period. In less favorable conditions (such as VPD is high) photosynthesis rate will decrease. GPP estimation algorithms of Y. Xiong et al., 2005 is overestimate because of VI and standard Pmax_best were used and the study did not consider about short term changes by environmental variables in plant photosynthesis process (Pmax). Pmax can detect by meteorological flux data. The objective of current study are to examine the relationship of Pmax_best and VI over growing season at six flux tower sites in 6 kind of biome types (Grassland, Evergreen Needle leaf Forest, Deciduous Needle leaf Forest, paddy field and evergreen broad leaf forest) in various weather conditions (Temperate to tropical). The study sites will increase to other biomes in near future. Relationship of Pmax_best and environmental variables will study to assess their relative important in different biomes. Result will considered in relation to design of algorithms for satellite-based GPP calculation.

2. METEIRALS AND METHODS

2.1 Sites description

In this research 6 flux tower sites in various 6 biomes and difference climate zone from FLUXNET Canada (CA-let), Ameriflux (US-Nc3, US-Me2) and Asiaflux (JP-Tmk, JP-Mase, TH-Skr) network in each biome; follow the International Geosphere-Biosphere Programme (IGBP), were studied see Table 1.

2.2 Methodology

We analyzed satellite dataset for VI and flux data for Pmax_best calculation. Detail flow chart of methodology show in Figure 1.

2.2.1 Satellite data: we use the tower location to locate satellite pixel. Spatial image resolution consider base on flux tower's foot print. If 1 pixel data cannot use such as cloud problem we also apply 3X3 window size to find average of VI near each flux tower except for the cloudy pixel.

ADEOS-II/GLI (Global Imager) satellite: JAXA's standard product L2A, 16-day Composite (April to October 2003), totally 13 scenes were used for each study sites.

SPOT-VGT: 10 days composite (D10) VI data that have spatial resolution is 1km. in year 2003 were utilized. Data were downloaded from <http://free.vgt.vito.be/>.

MODIS (Moderate Resolution Imaging Spectro radiometer; Terra MODIS) : MOD13A2; vegetation Indices , 16 day-Composite, spatial resolution 1km. were used in Ca-Let, US-Me2, JP-Tmk and TH-Skr. MOD13Q1 vegetation Indices , 16 day-Composite, 250 m. were used in JP-Mase and Yatsugatake validation site. MOD09A1; surface reflectance band1-7, 8 day-Composite, 500m. and MCD43A4; Nadir BRDF adjusted reflectance, 16day-Composite, 500m. were used for flux towers that have footprint less than 1 km. such as US-Nc3.

NDVI: is described as the following equations (Rouse et al., 1974);

$$NDVI = \frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + \rho_{RED}} \quad (1)$$

Where ρ_{NIR} (GLI-Band13) is reflectance in near infrared region, and ρ_{RED} (GLI-Band19) is reflectance in visible red region.

MVIUPD: The modified vegetation index based on UPDM was determined as follows. (K. Muramatsu et al, 2000)

$$MVIUPD = (uCv - 0.2uCs - uC4 - uCw) / (uCw + uCv + uCs) \quad (2)$$

A linear relationship with vegetation cover and the quantity of photosynthesis was assumed (Y. Xiong, 2005)

2.2.2 Fluxdata: Data in year 2003 of every sites and year 2002 of Ca-Let site for validation had downloaded from Fluxnet net work (www.Fluxnet.ornl.gov). Ca-Let had downloaded from Fluxnet Canada. US-Nc3 and US-me2 from Ameriflux and JP-Tmk, JP-Mase and TH-Skr from Asiaflux.

Preprocess: Firstly, Fluxnet Canada , Ameriflux (Level2 data) and Asiaflux's half-hour fluxes data were calculated by average and aggregated temporally to 16-day averages to match the temporal resolution of the ADEOS-II/GLI data set. Parameters are Net primary production (NEP), Friction Velocity (u^*), Photosynthetically active radiation (PAR), Air temperature (T_a), Vapor Pressure Deficit (VPD), Precipitation (PPT), Net radiation (Rn), Soil temperature (T_s),etc. From this process we can determine growing season from which month that have NEP more than zero. Moreover VPD threshold for light response curve calculation, also determine from NEP curve that midday depression of photosynthesis occurred.

Respiration: Ecosystem respiration (Rec) is plant respiration (R_{plant}) plus soil respiration (R_{soil}). First, we selected NEP night time data ($NEP < 0$) and precipitation less than zero; because soil water have effect to respiration rate, to find exponential relationship of air temperature and NEP nighttime that is Rec as show in Eq. (3). Eq. (4) is an empirical formula expressing the relationship between the air temperature and the Rec at the site measured by the eddy covariance method under nearly neutral atmospheric stability conditions to avoid the flux underestimation on stable nights (friction velocity (u^*) < 0.2 m/s) (Saigusa et al.,2005). Figure 2 (b) shows u^* of Ca-let site. This equation is used to evaluate not only the nighttime Rec but also the daytime Rec by extrapolate to daytime by also equation (4). In JP-Tmk, soil respiration was used instead air temperature (Hirata et al, 2007).

Table 1. Description of study sites

Site name		CA-Let	Us-Nc3	US-Me2	JP-Tmk	JP-Mase	TH-Skr
Site Description	Country	Lethbridge,Canada	Nc.US.	Or.US.	Hokkaido Japan	Tsukuba Japan	Sakaerat,Thailand
	Latitude	49.709	35.971	44.452	42.737	36.054	14.492
	Longitude	-112.94	-79.093	-121.557	141.519	140.027	101.916
	BiomeType	GRA	GRA	ENF	DNF	PD	EBF
	Dominant species	Short/mixed grass prairie (C3/C4)	Tall fescue,C3/C4 grasses and forbs	Ponderosa pine	Japanese Larch	Rice	Dipterocarp
	Treeage (years)	-	1	90	45	-	-
	Elevation (m)	960	168	1253	140	13	535
	Canopy height (m.)	-	0.1-1	14	16	1.2	35
	Flux measurement height (m)	4	6	31	27	3	45
	Growing season (No of days)	May-Oct (207)	Throughout year	Throughout year	May-Oct (207)	May-Sept (144)	Throughout year
Site climatic conditions	Respiration(Rec) Eq.	Rec=0.29*exp(0.037*ta)	Rec=0.32*exp(0.035*ta)	-	Rec=0.3*exp(0.079*ts)	Rec=0.18*exp(0.067*ta)	**Rec=0.025*2.57*exp((ta-10)/10)
	Precipitaion(mm.)*	0.02	0.08	0.02	0.06	0.08	0.07
	Airtemp(°C)*	5.36	14.36	4.51	6.61	12.9	24.1
	PAR(μmol/m2/s)*	282.45	315.06	478.24	286.3	269.22	323.76
	U* threshold (m/s)	0.2	0.2	-	0.3	0.1	0.2
	VPD threshold (kPa)	2.1	2	2	2	2	2
	VPD (kPa)*	0.65	0.53	0.5	0.24	0.41	0.93
	GPP (mgCO2/m2/s)*	0.15	0.17	0.15	0.28	0.2	0.71
	Pmax_best(mgCO2/m2/s)*	0.42	0.69	0.53	1.21	0.84	1.26
	Reference	T.G.Gilmanov et al. 2005	D.S. Ellsworth,et al.2004	Beverly E.Law.1999	R. Hirata et al.2007	M. Saito et al.2005	M. Moreles et al.,2007
Growing season is the months that positive NEP							
* 2003 Annual mean ** Van't Hoff (1898) equation							
Description of Biome type DNF: deciduous Needleleaf forest; MX: mixed forest; DBF: deciduous broadleaf forest; ENF: evergreen Needleleaf forest; EBF: evergreen Broadleaf forest; PD: Paddy field							
ts=Soil temperature ta=Air temperature							

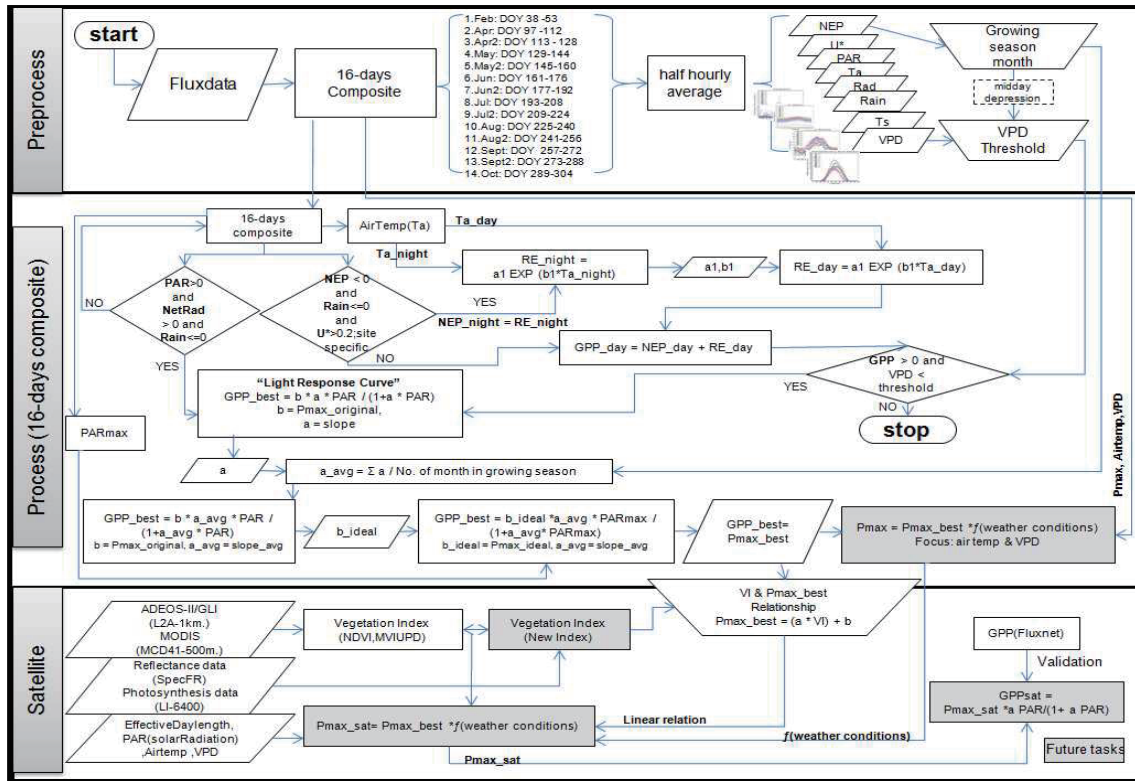


Figure 1 Methodology flow chart (detail)

$$NEE = -NEP, (NEP \text{ night} = Reco) \quad (3)$$

$$Reco = a \exp (b * T_{air}) \quad (4)$$

Light response curve: firstly, finding Pmax_best; the best condition for GPP (GPP_best), we select only favorable conditions for plant photosynthesis. The calculation was done on data that have NEP>0 and VPD < 2-2.5 kPa. (Leuning R., et al., 2005) and only used day time (PAR>0) for fitting the NEP and PAR relationship curve. Before fitting, PAR should mask out rainy day and PAR sensor error. Using Eq (5) for GPP_best calculation

$$GPP_best = NEP + Reco \quad (5)$$

After calculation GPP_best by (Eq.5) then plot light response curve. In practice, GPP is usually estimated from incident or intercepted PAR using a saturating Michaelis–Menten type model (Eq.6). The relationship between GPP_best and PAR is expected to exponential function (rectangular hyperbola) then find a and Pmax_best by using eq. (6)

$$GPP_best = Pmax_best * a PAR / (1+ a PAR) \quad (6)$$

$$Pmax = Pmax_best * f(\text{weather conditions}) \quad (7)$$

In eq. (6), a is initial slope to photosynthesis capability. Pmax calculate from Pmax_best and weather conditions as eq.(7). Then, estimate GPP by equation (8)

$$GPP = Pmax * a PAR / (1+ a PAR) \quad (8)$$

Secondly, satellite data set were use to derive VI. Third, analyze the relationship between Pmax_best and NDVI of each biome.

3. RESULTS AND DISCUSSION

3.1 Half-hourly data

Half hourly average of fluxdata in each month of CA-Let site showed in figure 2 (a) to (d). Half hourly data can show diurnal change better than monthly data such as midday depression of photosynthesis; before second peak of NEP diurnal curve that mostly occur in afternoon (in Ca-let site around 14pm. see arrow in figure 2 (a) when air temperature and VPD are high (figure c and d respectively); causes stomata closure.

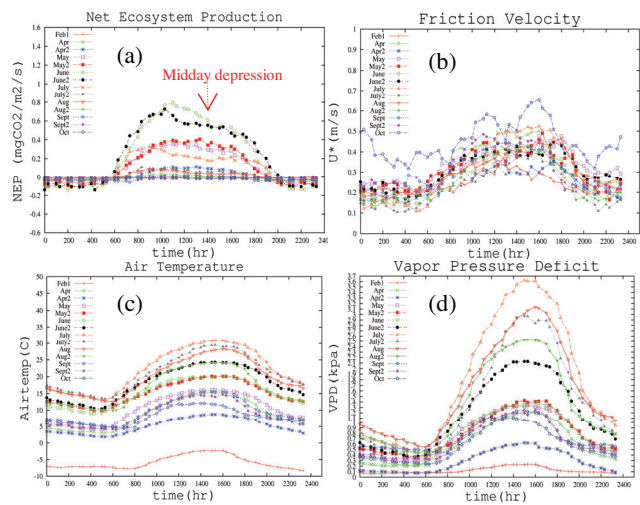


Figure 2 Diurnal variation of half-hourly each line mean each month: (a) Net primary production (NEP), (b) Friction Velocity

(u*), (c) Air temperature (Ta), (d) Vapor Pressure Deficit (VPD) of CA-Let site

All sites were analyzed but only Ca-Let site is shown here. Parameters from flux tower that we also consider for photosynthesis process are net radiation (Rn), PAR and Precipitation (PPT).

3.2 Respiration

The value of Rec had significant positive correlation with air temperature. However, the relation was rather exponential more than linear. Line show in figure 3. (a) to (e) showed the results of fitting air temperature and night time NEP by exponential equation. The highest Rec is in TH-Skr that is located in tropical zone. The lowest Rec in CA-let that is located in temperate zone. When used the relationship in TH-Skr site is not good if use same exponential equation or Van Hoff's model (this study, $Rec = 0.025 * 2.57 * \exp((ta-10)/10)$) Saigusa, 2008 suggested Rec of TH-Skr should use the Van Gorsel's filtering.

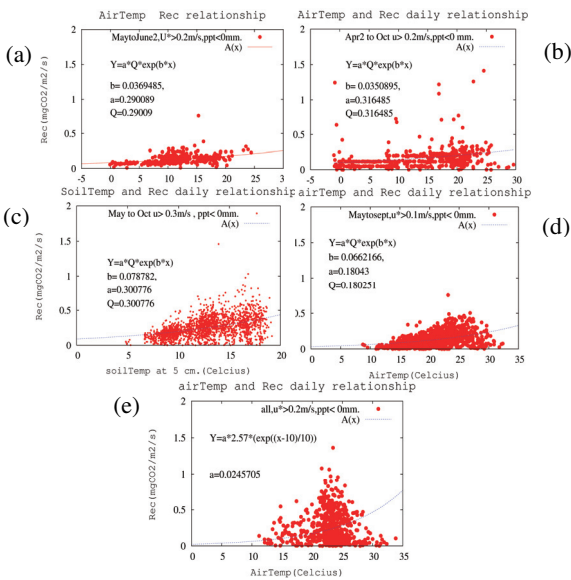


Figure 3 Ecosystem Respiration (Rec); relationship of air/soil temperature and NEP night time (NEP<0), (a) CA-Let, (b) US-Nc3, (c) JP-Tmk, (d)JP-Mase, (e)TH-Skr

3.3 Pmax_best and Vegetation Index

3.3.1 Pmax_best: Light response curve are shown in figure 4(a) to (f). The light saturated plateau is generally abrupt in shade leaves, but more gradual in sun leaves; higher Pmax_best and lower initial slope in sun leaves. (Lamberts H., et al., 2005). We average slope (in growing season months) of least square fitting curve and then fit again with this average slope then we can get Pmax_best in each months without influence of weather condition. Pmax_best monthly were plot in figure 4 (g), Pmax are highest in JP-Tmk, JP-Mase, TH-Skr, CA-Let, US-Nc3 and US -Me2, respectively. Japanese Larch forest in Tomakomai site is highest photosynthesis capacity which can be refer to Saigusa et al., 2008 that among the 11 sites, the maximum GPP was observed in a temperate larch forest.

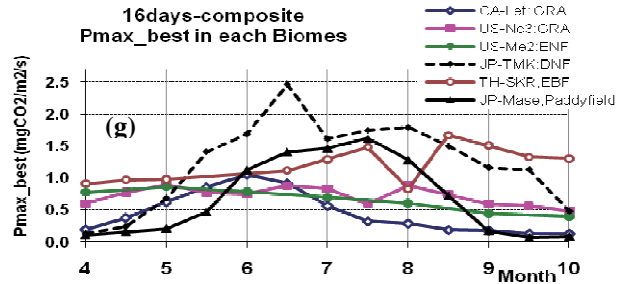
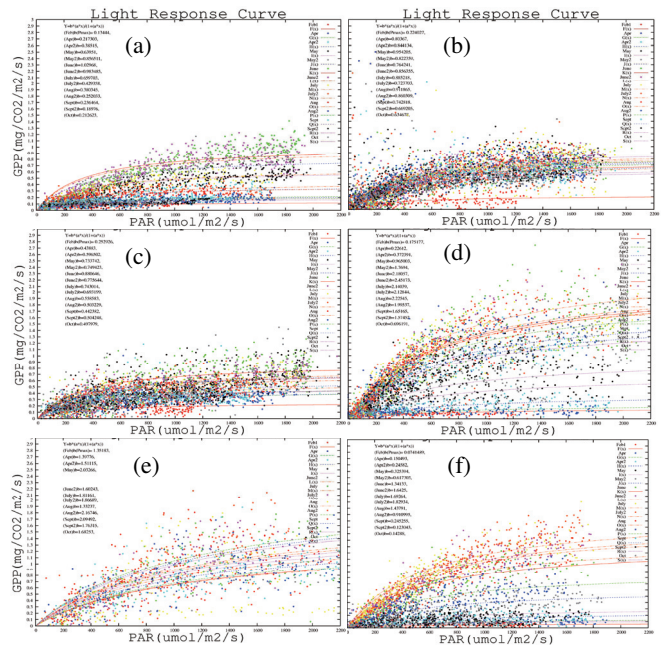


Figure 4. Light response curve in 6 biomes (a) Grassland; CA-let, (b) Grassland; US-Nc3, (c) Evergreen Needleleaf forest; US-Me2, (d) Deciduous Needleleaf forest; JP -Tmk, (e) Evergreen Broadleaf Forest; TH-Skr, (f) Paddy field; JP-Mase, Each lines mean fitting curve in each month. (g) Monthly Pmax_best (mgCO2/m2/s)

3.3.2 Vegetation Index: GLI-NDVI show seasonal change (figure 5) in CA-Let, JP-Tmk and JP-Mase. In US-NC3, NDVI was decrease in July because of annually mowing grass (fluxnet website). NDVI are mostly highest in June-July.

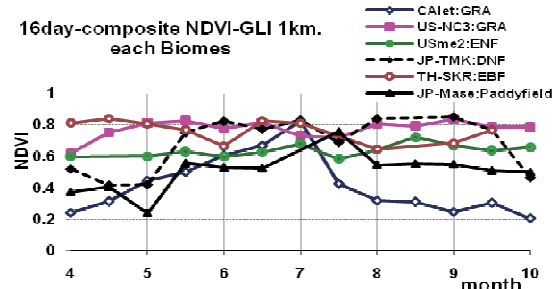


Figure 5. NDVI of each site from April to October in 2003.

3.3.3 Relationship of Pmax_best and VI: The relationship between Pmax_best and VI for flux sites of Grassland; CA-let, Grassland; US-Nc3, Deciduous Needleleaf forest; JP -Tmk, Evergreen Needleleaf forest; US-Me2, Paddy field; JP-Mase, Evergreen Broadleaf Forest; TH-Skr in Figure 6 as (a), (b), (c), (d), (e), (f), respectively. In Ca-Let and JP-Tmk, Pmax_best and VI relationship had linearly relation as show in figure 6. These

linearly relationships (or empirical model) from 6 flux sites are calibrated for GPP_best estimation across year and biomes. Further works, these models will be used to scaling up from local to regional and global scale GPP. While US-Nc3, US-Me2 and TH-Skr show the group of points. This mean that evergreen plant, perennial crops or plants throughout a year VI not so much change (can't see much difference because satellite observe chlorophyll reflectance from leaves) but these kind of biomes have difference Pmax that depend on photosynthesis condition. In these 3 sites' VI are not varies within a year so we can determine Pmax_best by a range of value for GPP algorithm. This stage we estimate Pmax_best from VI and in next step we will estimate Pmax that depend on weather conditions. Figure 6. (b) has low VI points show annually grass mowing in US-Nc3 site. Figure 6. (e) show that spatial resolution 250 m. has better relationship than 1km. and 500m. for JP-Mase site. (f) Groups of points are little sparse and in this study shows NDVI has better linear relationship with Pmax_best than MVIUPD. Nevertheless, we have to find another new VI for improvement of these relationships. The standard errors of linear regression ($y = ax \pm b$) of CA-Let is $a = \pm 0.17$, $b = \pm 0.07$, JP -Tmk is $a = \pm 0.58$, $b = \pm 0.41$ and JP-Mase is $a = \pm 0.25$, $b = \pm 0.15$.

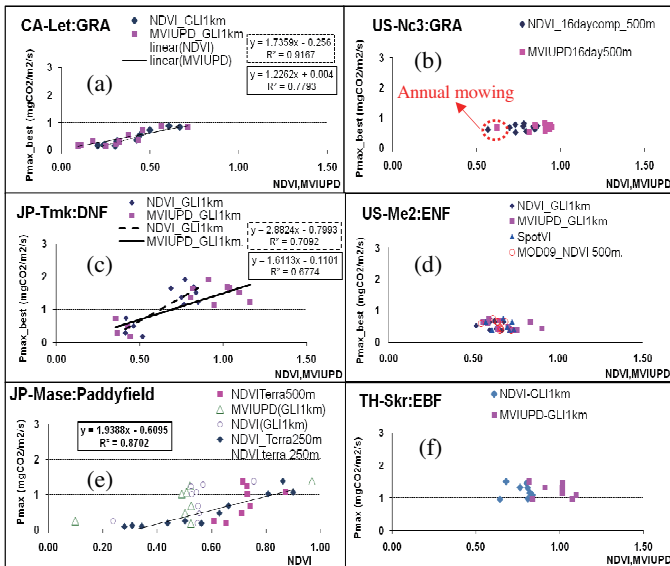


Figure 6. Relationships of Pmax_best and VI in each biome, (a) Grassland; CA-let, (b) Grassland; US-Nc3, (c) Deciduous Needleleaf forest; JP -Tmk, (d) Evergreen Needleleaf forest; US-Me2, (e) Paddy field; JP-Mase (f) Evergreen Broadleaf Forest; TH-Skr

3.4 Validation

The empirical model from CA-Let site ($Pmax_best = 1.7359(VI) - 0.256$) was used for validation by apply to CA-Let fluxdata in year 2002. And apply empirical model from JP-Tmk ($Pmax_best = 2.8824*(VI) - 0.7993$) to Yatsugatake site in 2009 (Larch forest in Yamanashi, Japan)

3.4.1 Inter annual: MOD13A2 of year 2002 (VI, 16 day composite, 1km.) was used for input VI values to CA-Let's empirical model. Figure 7 (a) show Monthly Pmax_best from empirical model estimated (dot line) with error bar of linearly fitting error propagation of standard error and flux data (solid line) with error bar of least square fitting standard error. Even though, model values in October are overestimate while in other months, our models successfully estimate Pmax_best in 2002. The graph show flux data are within standard error (SE) range of modeled Pmax_best. figure 7 (b) Show 1:1 line after plot

between Pmax_best model and flux has high relationship ($r^2=0.83$) on 1:1 line. Error bars show standard error.

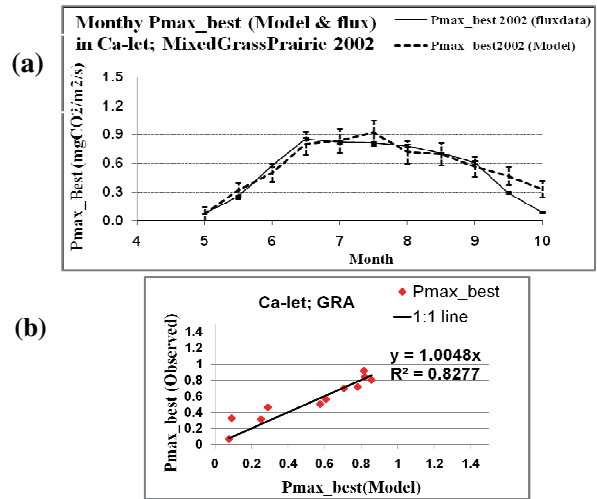


Figure 7. (A) Monthly Pmax_best from model with Standard Error bar (dot line), flux data (solid line) and error bars in 2002. (b) Relationship of Pmax_best model and flux on 1:1 line

3.4.2 Across-site: Empirical model from JP-Tmk was used to validate with Yatsugatake site. Figure 8 show monthly Pmax_best from model (solid line) and average Pmax of 2 samples in Larch forest which were measured in morning (9-10:30 am.) by LI-6400 in 30-31 July 2009 (Ikegami et al, 2010) as shown in figure 8 with red dot. NDVI from MOD13Q1 of year 2009 (VI, 16 day composite, 250m.) are input to empirical model. The Larch's canopy has higher Pmax_best (1.8 mgCO₂/m²/s) than the samples (1.6 mgCO₂/m²/s). Although, measurement Pmax_best is within standard error range of modeled Pmax_best but the standard error are still high because of empirical model of Larch forest in Tomakomai; ($Pmax_best = 2.8824*(VI) - 0.7993$) in figure 6(c) have high error. NDVI is not good enough index especially in high depth of canopy forest.

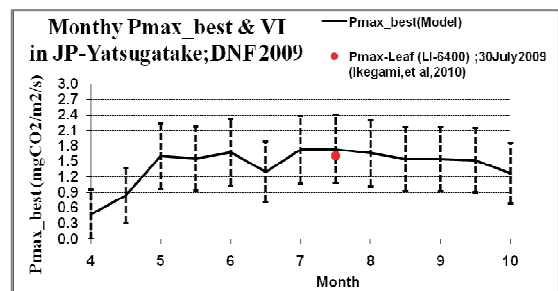


Figure 8. Yatsugatake in 2009, Monthly Pmax_best (modeled; solidline), Pmax of leaf (by LI-6400; round-dot) and standard error bars

4. CONCLUSION

In this article we presented the empirical Pmax_best model for estimation of terrestrial GPP_best in best condition of vegetation in various 6 biomes and difference climate zone. Satellite derived VI and our Pmax_best relationship that combined fluxes data in each biome can reveal plants photosynthesis capacity. Our model can apply to another year in same biome and in difference biome. Though, more validation is needed to evaluate the accuracy and reliability of the empirical model. We found GPP estimation have main effected by Rec It's better to estimate Rec more accurately. In next step,

this Pmax_best model will consider weather condition that caused variation in terrestrial GPP. And new VI that can improve these relationships across wide range of vegetation types will be examined.

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