# A cross-biome comparison for net ecosystem productivity using satellite images and climate data

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**Abstract:** Micrometeorological and mass flux measurements at eddy covariance flux towers can be used to estimate net ecosystem productivity (NEP) of $CO_2$ between the atmosphere and terrestrial ecosystem. The network of flux tower sites that includes a wide range of biomes offers the opportunity to investigate the relationship of site-specific climate data and the biophysical performance of vegetation indices. Satellite remote sensing provides consistent and systematic observations of vegetation and ecosystems, and plays an important role to scale-up $CO_2$ fluxes from flux tower sites to regional and global scales. In this study, we combined analyses of satellite images from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Terra satellite with climate data from flux tower sites. Flux tower sites include a tropical rain forest site (Bukit Soeharto, Indonesia), a tropical seasonal deciduous forest site (Mae Klong, Thailand), a tropical seasonal evergreen forest site (Sakaerat, Thailand), and a cool-temperate deciduous forest site (Takayama, Japan), and these four sites are part of the AsiaFlux network. Micrometeorological flux measurements were conducted from 2001 to 2003. Availability of $CO_2$ flux data made it possible to assess satellite-based models that estimate the seasonal dynamics of NEP of forest. Our result supported inclusion of parameters for cloudiness and the phenological status of the vegetation, as well as use of biome-specific parameterization.
**Keywords:** Eddy covariance technique, Forest ecosystem, Net ecosystem productivity, Process-based model, Solar radiation.

## 1. Introduction

One approach to extrapolate site-specific measurements is to use process-based models, driven by a multi-layer database of climate and vegetation types. Process-based models simulate the dependency on productivity on a number of interacting processes, such as photosynthesis and respiration, and have the potential to more accurately describe how ecosystem processes will respond and interact in future climate conditions. Several studies revealed key differences in the functional properties of dominant vegetation types (Baldocchi *et al*. 2000[1], Nemani *et al*. 2003[2]). Another study showed that, in latitude-wise and biome-wise sensitivity analyses using the Sim-CYCLE model (Ito *et al*. 2002[3]), parameters of strength were in the order; cloud cover (the ground level radiation), air temperature and precipitation (Yasuoka *et al*. 2005[4]). To understand the relative magnitude of these various factors, it will be important to monitor critical components of the carbon cycle at regional and global scales.

Solar radiation is required by most models that simulate plant growth, because the growth is primarily based on photosynthetic processes, which involve the utilization of radiation and its conversion to chemical energy. Therefore, detailed measurements of light environment provide the basis for examining forest productivity. However, incident radiation transmitted through the forest canopy fluctuates both daily and seasonally, especially in a deciduous forest. A single microsite within a forest canopy receives both direct and diffuse radiation. As diffuse radiation has a rather uniform directional distribution, the differences in incident radiation are caused mainly by direct radiation such as sunflecks. Sunfleck frequency is determined by the position of the solar track, the location within gaps, gap size, canopy height and leaf phenology. Furthermore, solar altitude and weather events also alter light condition. In recent years, various techniques for the light measurement and estimation have been developed. However, the high variability of radiation makes light simulation a computationally expensive task. Because light simulation models may suffer from a potential loss of precision, modeled estimates require validation with ground-based measurements. In recent years, $CO_2$ flux data from the tower sites are useful for parameterization and validation of model estimates. Continuous $CO_2$ flux measurements between forests and the atmosphere at flux tower sites has allowed for a more detailed examination of the photosynthetically active period (leaf phenology) and the seasonal dynamics of net ecosystem productivity (NEP). Model simulated NEP was compared with daily NEP estimates from the flux tower at four forest sites.

The objectives of this study are: (i) to characterize radiation data by examining its diurnal and seasonal changes using satellite images and climate data, (ii) to develop a light simulation model to estimate the seasonal dynamics of NEP, and

(iii) to validate the model approach by comparing the estimate of NEP with that by the eddy covariance technique of four forest ecosystems.

## 2. Materials and methods

### 1) Study sites

Flux tower sites include a cool-temperate deciduous forest site at Takayama, Japan (36°08’25’’N, 137°25’35’’E, 1420 m a.s.l.), a tropical rain forest site at Bukit Soeharto, Indonesia (0°51’41’’S, 117°02’41’’E, 20 m a.s.l.), a tropical seasonal deciduous forest site at Mae Klong, Thailand (4°34’34’’N, 98°50’37’’E, 160 m a.s.l.), and a tropical seasonal evergreen forest site at Sakaerat, Thailand (14°29’36’’N, 101°55’19’’E, 535 m a.s.l.). These four sites are part of the AsiaFlux network.

### 2) Light environment

*2.1 Radiation at the top of the Earth’s atmosphere*

The seasonal distribution of radiation is determined by the rotation of the Earth about its own axis and by its elliptical orbit about the Sun. Solar radiation at the top of the Earth’s atmosphere therefore depends on time of day, time of year, and latitude, which may be described by the angle between the direction of the Sun and the vertical for a point on the Earth’s surface.

*2.2 Radiation at the canopy surface*

Solar radiation passing through the atmosphere is attenuated by scattering and absorption by various atmospheric constituents, such as aerosols, individual molecules, water droplets and clouds. As a result of attenuation, solar radiation reaching the canopy surface consists of two components: direct radiation and diffuse radiation. The sum of these two components is referred to as global solar radiation. An empirical approach pioneered by Ångströn (1924)[5] is used to estimate solar radiation at the canopy surface, and is given by:

$$S_t = S_0\left[a_n + b_n\left(\frac{n}{N}\right)\right] \qquad (1)$$

where $S_t$ and $S_0$ are global radiation received at the Earth’s surface and at the top of the Earth’s atmosphere, respectively. $N$ is daylength, and $n$ is number of the hours of sunshine duration in the day.

Another relatively simple method of estimating daily global radiation by relating the daily temperature range to global radiation was proposed by Hargreaves *et al*. (1985)[6]:

$$S_t = S_0\left[a_t + b_t\left(T_{13:30} - T_{10:30}\right)\right] \qquad (2)$$

where $T_{13:30}$ and $T_{10:30}$ are temperature at 13:30 and 10:30, respectively. These data can be obtained by using thermal band of satellite images from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Terra and Aqua satellites.

*2.3 Radiation within the canopy*

The crown properties such as tree height, species composition and the foliage distribution cause a complicated non-stationary pattern of direct, diffuse and scattered radiation. To characterize spatially and temporally heterogeneous radiation within the canopy, an instantaneous fraction of photosynthetically active radiation (fPAR) under diffuse light condition is known as an useful index (Sakai *et al.* 2005[7]). The instantaneous fPAR under diffuse light condition is a reliable estimator of the intensity and duration of PAR on a completely clear day. A complete description of the sampling scheme and field measurement protocols is summarized by Sakai *et al.* (2005)[7].

By attenuation of solar radiation in the canopy, leaf area index (LAI) was calculated by the equation:

$$LAI = -\frac{1}{k_l}\ln\left(\frac{I_b}{I_t}\right) \qquad (3)$$

where $k_l$ is light extinction coefficient. We assumed the valu of $k_l$ as 0.83 in four forest ecosystems. $I_t$ and $I_b$ are radiation at top and bottom of the canopy, respectively.

### 3) Photosynthesis and respiration rates

Generally canopy photosynthesis depends on various environmental factors, such as air temperature, water vapor partial pressure and $CO_2$ concentration. However, we consider here only significance of light condition, and other factors were assumed to be constant over the canopy depth even through vertical gradients of these factors exist in most plant canopies. The relationship between radiation and photosynthetic rate was approximated using the following equation:

$$A_g = \frac{\alpha I + GA_{max} - \sqrt{(\alpha I + GA_{max})^2 - 4\theta\alpha I GA_{max}}}{2\theta} \quad (4)$$

where $A_g$ is gross photosynthetic rate, $\alpha$ is the initial slope of the light-response curve, $I$ is incident radiation, $GA_{max}$ is the light-saturated rate of gross photosynthesis and $\theta$ is the convexity of the light-response curve. A constant $\theta$ of 0.80 was given to all leaves.

Respiration increases with temperature, because temperature increases the rate of the enzymatic reactions in respiration. Therefore, the ecosystem respiration rate was calculated as a function of temperature:

$$R_e = k_r Q_{10}^{\frac{Ta}{10}} \quad (5)$$

where $Q_{10}$ is the relative increase of the respiratory flux for a 10 K increase in temperature $T_a$. $Q_{10}$ was 2.57 in all four forest ecosystems.

**4) Eddy covariance technique**

In the recent years, $CO_2$ flux between the forest and atmosphere is measured continuously at the flux tower site. Micrometeorological flux measurements were conducted from 2001 to 2003. The data were used for comparison of the estimates of NEP. Details of the instrumentation, flux corrections and calculations have been described (Saigusa *et al*. 2002[8]).

## 3. Results and discussion

**1) Characterization of solar radiation**

The amount of solar radiation changed with time of day and season. Figure 1 shows the variations in total daily solar radiation at the top of the Earth's atmosphere at four flux sites. Solar radiation at the top of the Earth's atmosphere differed at four flux sites. Takayama site has large seasonal changes in total daily solar radiation at the top of the Earth's atmosphere due to the upper latitude. Other three sites had only slight changes in total daily solar radiation at the top of the Earth's atmosphere through the season due to low latitudes. During summer (June, July and August), the total daily solar radiation values at Takayama site were much higher than those at other sites.

The frequent and rapid change was caused by cloud conditions throughout the whole day. Relative sunshine duration (cloud cover) could be calculated from the global solar radiation. Figure 2 shows variations of solar radiation with sunshine duration. Relative sunshine durations at Takayama, Mae Klong and Sakaerat were 34.9%, 71.9% and 71.2%, respectively. In Takayama site located in the mountainous area, cloud cover contributed large part of day. Figure 3 shows variation of solar radiation with temperature. Prediction of solar radiation at the canopy surface was better with the method using sunshine duration. However, to scale up from ecosystem processes to large regions, remote sensing date is available. Although terrestrial ecosystem model is an essential component in an integrated model for global change, there is a shortage of data necessary because processes in ecosystem occur over a wide range of spatial and temporal scales.

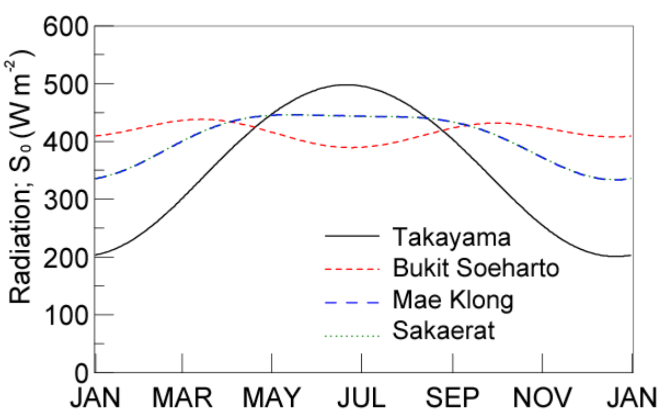


**Figure 1. Seasonal variation of daily global radiation of the top of the atmosphere.**

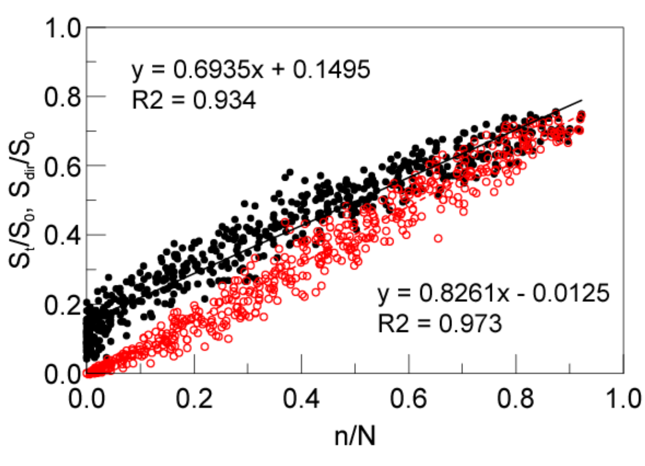


**Figure 2. Variations of solar radiation with sunshine duration. Closed circles show global radiation at the top of the Earth's atmosphere relative to radiation at the top of the Earth's atmosphere; $S_t/S_0$. Open circles show the direct radiation at the top of the Earth's atmosphere relative to radiation at the top of the Earth's atmosphere; $S_{dir}/S_0$.**

The scaling-up scheme for the meteorological input parameters is elaborated. Therefore, global understanding is an impossible task to achieve without extensive and intensive use of remotely sensed data.

To characterize heterogeneity of the light environment within the canopy, the diurnal courses of radiation at different canopy heights were examined. The relationship between instantaneous fPAR and relative daily total radiation was examined to establish the validity of fPAR as an index of microsite light availability within the forest canopy (Fig. 4). To characterize spatially and temporally heterogeneous light environment within the forest canopy, an instantaneous fPAR under diffuse light condition was an useful index.

Detailed characterization of solar radiation, i.e., the spatio-temporal variation of solar radiation resulting from the cloud cover and plant phenology, is important for accurate modeling of forest ecosystem process, and may allow us a less labor- and time-consuming alternative without the need for a heavy parameterization. Since the estimation of canopy photosynthesis is dependent on the proportions of diffuse versus direct light, our detailed classification of light intensity would minimize errors in the estimation of leaf photosynthesis.

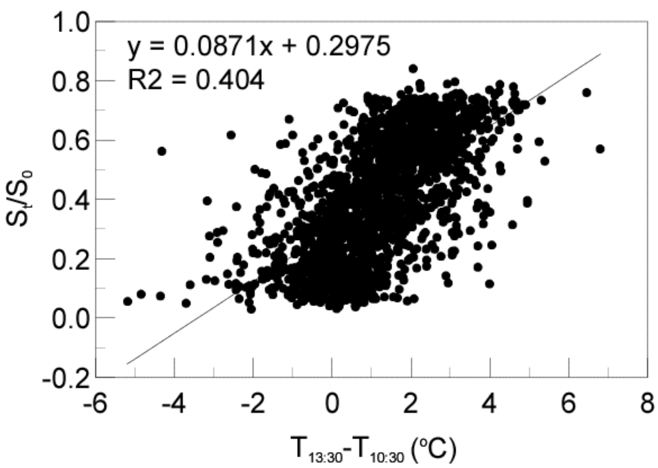


**Figure 3. Variation of solar radiation with temperature.**

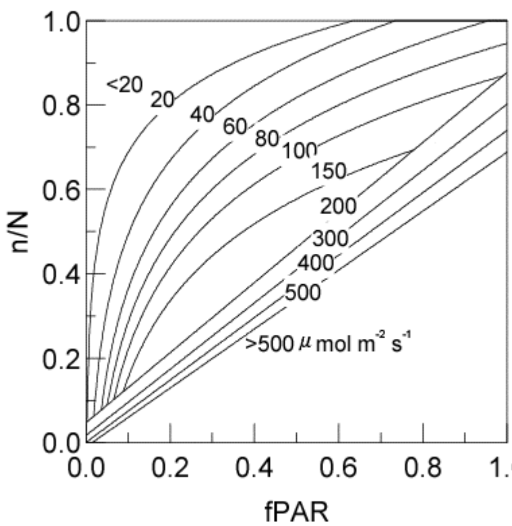


**Figure 4. Relationship between fPAR and the intensity and duration of PAR. The values in the figure indicate PAR intensity.**

**2) The comparison for net ecosystem productivity at four forest ecosystem**

Figure 5 shows the seasonal dynamics of modeled NEP and measured NEP in 2003. The annual NEP measured flux tower was 234, 251 and 608 gC $m^{-2}$ $yr^{-1}$ in 2003 at Takayama, Mae Klong and Sakaerat, respectively. On the other hand, the annual NEP estimated by the process-based model was 304, -307 and 793 gC $m^{-2}$ $yr^{-1}$ in 2003 at Takayama, Bukit Soeharto, Mae Klong and Sakaerat, respectively. Comparisons of flux tower data with modeled data showed generally good agreement at Takayama site. This result suggests that accurate simulation of process of cool-temperate deciduous forest depended largely on reliable estimates of solar radiation and air temperature. On the other hand, data of Mae Klong and Sakaerat sites had a high bias, although the comparison between Mae Klong and Sakaerat sites showed that the seasonal dynamics of modeled NEP at Sakaerat site mimic better than those of modeled NEP at Mae Klong in terms of phase and amplitude. The productivities of tropical rain forests were clearly very sensitive to climate perturbations. It is well-known that precipitation is a dominant control on plant photosynthesis and ecosystem respiration in tropical rain forest. More field and laboratory studies across leaf, canopy and landscape levels are needed to better understand in the plant-growing season. With further validation and development, the process-based model will have the potential to be applied at large spatial scales to estimate NEP of forests, which would improve our understanding of the carbon cycle of the terrestrial biosphere.

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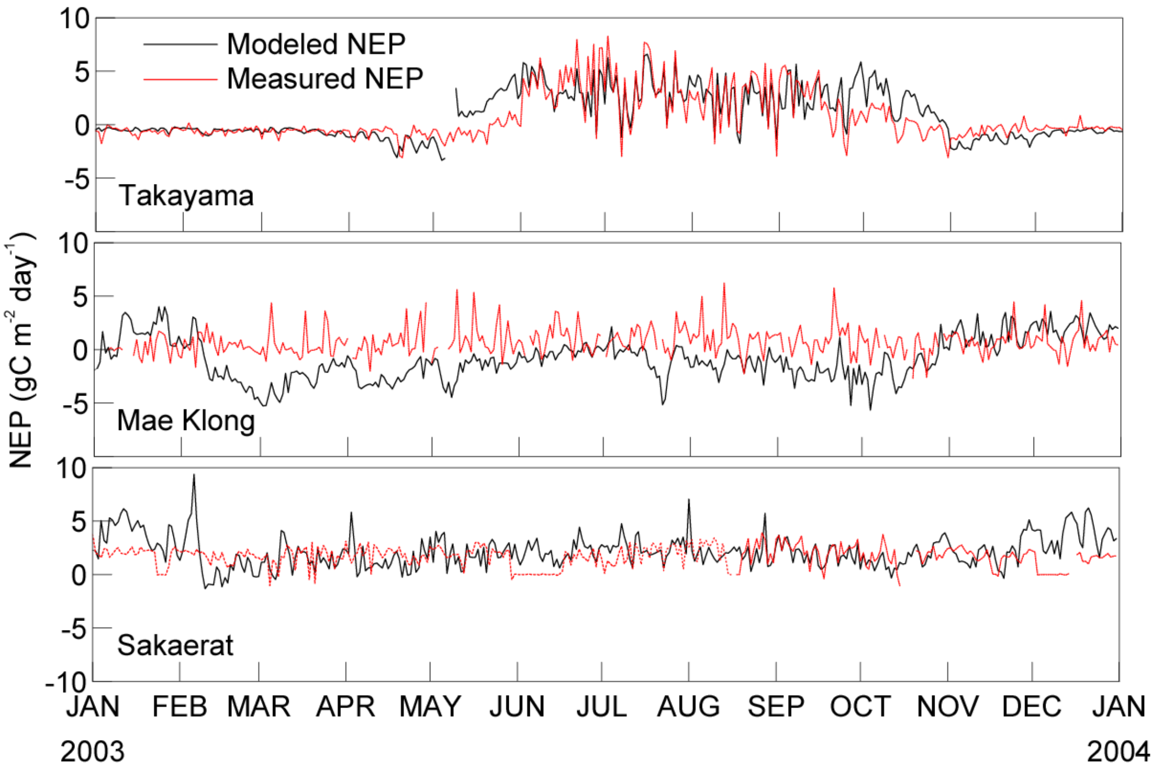


**Figure 5. Seasonal variations of daily net ecosystem productivities at Takayama, Mae Klong and Sakaerat sites in 2003.**

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