

# Simulations of seasonal and inter-annual variability of gross primary productivity at Takayama with BEPS ecosystem model

Kaz Higuchi<sup>a,\*</sup>, Alexander Shashkov<sup>a</sup>, Douglas Chan<sup>a</sup>, N. Saigusa<sup>b</sup>,  
S. Murayama<sup>b</sup>, S. Yamamoto<sup>b</sup>, H. Kondo<sup>b</sup>, J. Chen<sup>c</sup>, J. Liu<sup>c</sup>, B. Chen<sup>c</sup>

<sup>a</sup> Meteorological Service of Canada, 4905 Dufferin Street, Toronto, Ont., Canada M3H 5T4

<sup>b</sup> National Institute of Advanced Industrial Science and Technology, 16-1 Onogawa, Tsukuba 305-8569, Japan

<sup>c</sup> Department of Geography, University of Toronto, 100 St. George Street, Toronto, Ont., Canada M5S 3G3

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## Abstract

In this study we use a modified version of the ecosystem model Boreal Ecosystem Productivity Simulator (BEPS) to simulate gross primary productivity (GPP) derived from measured CO<sub>2</sub> flux at the Takayama site, which is characterized by a broadleaf deciduous secondary forest. The period of simulation is from 1998 to 2002. The performance of the model is assessed in its ability to reproduce seasonal and inter-annual variations in the derived GPP. Given appropriate vegetation parameters and meteorological conditions for the site, we find that the model can simulate seasonal changes and inter-annual variability of GPP that are in close agreement with those derived from the eddy covariance CO<sub>2</sub> flux measurements. Estimated annual GPPs (in gC m<sup>-2</sup>) are 1171 (1998), 1024 (1999), 1274 (2000), 1200 (2001), and 1243 (2002). (Positive GPP is defined as ecosystem assimilation of CO<sub>2</sub>.) Although the inter-annual variability of the seasonal cycle and its upward trend are simulated relatively well, the model tends to overestimate GPP, particularly from 2000 to 2002 when the measured leaf area index (LAI) during the growing season was relatively high. Furthermore, due to certain missing phenological mechanisms in the model, it tends to overestimate photosynthetic absorption during the latter half of the growing season. Also, the model does not resolve the understory of dense evergreen dwarf bamboo at the site, thus failing to catch the start of photosynthetic activity by the understory before the leaf emergence of the woody component takes place in the spring. Results indicate that the observed inter-annual variability in GPP at the Takayama site has been influenced mostly by changes in LAI.

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## 1. Introduction

There is some evidence to indicate an increased metabolic activity in the Northern Hemisphere land

biosphere. For example, changes in the seasonal amplitude of continuous in situ measurements of atmospheric CO<sub>2</sub> over the last 20–30 years have been observed at background monitoring stations Alert, Pt. Barrow, and Mauna Loa. These changes have been interpreted as showing a net absorption of atmospheric CO<sub>2</sub> by the Northern Hemisphere ecosystems due to increased temperature and longer growing seasons caused by an apparent earlier arrival of spring (e.g.,

\* Corresponding author. Tel.: +1 416 739 4452;  
fax: +1 416 739 5704.

*E-mail address:* [kaz.higuchi@ec.gc.ca](mailto:kaz.higuchi@ec.gc.ca) (K. Higuchi).

Keeling et al., 1996). Others have used the satellite-derived Normalized Difference Vegetation Index (NDVI) to show increased “greening” of the Northern Hemisphere biosphere (Zimov et al., 1999; Myneni et al., 1997). Inverse calculations using atmospheric transport models constrained by the observed atmospheric CO<sub>2</sub> also appear to indicate a net land biospheric CO<sub>2</sub> sink in the northern midlatitudes during the first half of the 1990s (e.g., Gurney et al., 2002). These results are significant in showing the possible responses of plant behavior under a changing environment.

Process-based ecosystem models of various complexity and structure have been developed over the years in order to gain some insight into the processes that might be responsible for the evidence of changing atmosphere–biosphere carbon exchange (e.g., Sellers et al., 1986; Running and Coughlan, 1988; Aber and Federer, 1992; Potter et al., 1993; Liu et al., 1997). However, these models need to be validated if they are to be useful. One method many investigators have used is to compare model results with CO<sub>2</sub> flux measurements (and/or with gross primary productivity (GPP) derived by subtracting empirically determined ecosystem respiration from measured flux values) obtained at land sites with different ecosystem types. It is through such comparisons that we can improve the models and gain better scientific understanding of the processes of carbon movement at the ecosystem scale.

It is of interest, therefore, to validate ecosystem models at various sites around the world. In this study, we employ Boreal Ecosystem Productivity Simulator (BEPS) developed originally by Liu et al. (1997), to simulate some of the salient features of the GPP derived by adding daily values of ecosystem respiration to the observed net CO<sub>2</sub> flux measurements made at Takayama in central part of Japan (Yamamoto et al., 1999; Saigusa et al., 2002). We will designate this GPP as GPP-EC, where EC denotes eddy covariance. Although BEPS was originally constructed to calculate net primary productivity (NPP) for boreal ecosystems (with emphasis on boreal forests), it has been applied with some success in producing a spatial distribution of NPP over East Asia (Matsushita and Tamura, 2002). As part of an effort to globalize BEPS, we test the robustness of the model to estimate GPP-EC at the Takayama site without introducing any new processes into the model. The BEPS model is modified with input vegetative parameter values that reflect the temperate broadleaf deciduous forest characteristics of the Takayama site. The ability of BEPS to simulate GPP at Takayama is assessed, and the differences and similarities between the model result (denoted hereafter

as GPP-MO) and GPP-EC are interpreted within the context of the ecosystem mechanisms represented in BEPS. Variability of GPP on seasonal and inter-annual bases will be elucidated in terms of changes that take place in these mechanisms. The period of model simulation is from 1998 to 2002, for which we have GPP-EC derived mainly by using the eddy covariance CO<sub>2</sub> flux measurements (see Saigusa et al., 2005). For the first half of 1998, derived GPP was obtained from measurements using the aerodynamic method (Yamamoto et al., 1999).

## 2. Site description

The Takayama flux site was established in 1993, and is located about 15 km east of the city of Takayama (36°08′N, 137°25′E, elevation 1420 m) in the central part of Honshu, the main island of Japan. The site is mountainous, and its vegetation is characterized by a broadleaf deciduous secondary forest that is about 50 years old and is dominated by oak (*Quercus crispula* Blume) and birch (*Betula ermanii* Cham.; *Betula platyphylla* Sukatchev var. *japonica* Hara). The canopy height is about 15–20 m. The forest floor is covered by understory of dense evergreen dwarf bamboo (*Sasa senanensis* (Fr. Et Sav.) Rehder). A more detailed description of the site can be found in Yamamoto et al. (1999), Murayama et al. (2003), and Muraoka and Koizumi (2006).

## 3. Model description

The basic description of BEPS for estimating NPP, and its validation for boreal ecosystems in Canada are given in Liu et al. (1997, 1999) and Chen et al. (1999). The formulation of BEPS is based on the Forest BioGeochemical Cycles (Forest-BGC) model originally developed by Running and Coughlan (1988). In BEPS, several improvements were made over the Forest-BGC model. These included separating the canopy into sunlit and shaded components in calculating photosynthesis. Also, the use of leaf area index (LAI) obtained from remote sensing data has improved the calculated estimate of NPP. In BEPS, NPP is calculated as the difference between gross primary productivity (GPP) and autotrophic respiration ( $R_a$ ):

$$\text{NPP} = \text{GPP} - R_a. \quad (1)$$

The autotrophic respiration includes leaf, stem, and root respirations.

The most important input variables and parameters for the BEPS model are LAI, meteorological variables

Table 1  
BEPS model input parameters and their values, used for simulation of gross primary productivity (GPP) at the Takayama site

Description	Values for Black Spruce (Chen et al., 1999)	Value or frequency for Takayama	References for Takayama modeling experiment
<b>Input variables</b>			
Leaf area index ( $\text{m}^2 \text{m}^{-2}$ )	Satellite-derived for 1994	Daily	
Air temperature ( $^{\circ}\text{C}$ )	Hourly	Hourly	
Relative humidity (%)	Hourly	Hourly	
Solar radiation ( $\text{W m}^{-2}$ )	Calculated hourly	Hourly	
<b>Input parameters</b>			
Clamping factor	<b>0.5</b>	<b>0.8</b>	Leblanc and Chen (2001)
Maximum stomatal conductance ( $\text{mol m}^{-2} \text{s}^{-1}$ )	<b>0.06</b>	<b>0.39</b>	Muraoka and Koizumi (2006)
Leaf nitrogen content (%)	1.2	1.2	Kimball et al. (1997)
Maximum leaf nitrogen content (%)	1.5	1.5	Bonan (1995)
Maximum carboxylation rate at $25^{\circ}\text{C}$ ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ )	<b>33</b>	<b>48</b>	Muraoka and Koizumi (2006)
Optimal temperature ( $^{\circ}\text{C}$ )	25	25	Kimball et al. (1997)
Maximum temperature range ( $^{\circ}\text{C}$ )	40	40	Kimball et al. (1997)
Vapor pressure deficit at stomatal opening (kPa)	0.2	0.2	Dang et al. (1997)
Vapor pressure deficit at stomatal closure (kPa)	2	2	Dang et al. (1997)

Changed input parameters are indicated in bold.

(air temperature, solar radiation, precipitation, and specific humidity), and soil and vegetation properties. A list of the main input variables and parameters and their values for the Takayama site is given in Table 1. LAI values for model input are measured at the site; the LAI at the site measures the degree of leaf out on trees, but not the bamboo understory. The time step of the model is 1 h.

#### 4. Results and discussion

The BEPS model is run for the years 1998–2002. Since the focus of the present study is to assess the ability of BEPS to simulate GPP-EC at Takayama on seasonal and inter-annual time scales, our database for analysis is composed of monthly mean values.

##### 4.1. Mean seasonal comparison between measured and modeled NEP

Fig. 1a shows a 5-year averaged seasonal cycle of GPP-EC and GPP-MO, highlighting time periods during which the model's GPP deviates noticeably from GPP-EC. (Positive values of GPP indicate  $\text{CO}_2$  assimilation by plants.) In the spring (particularly in April), the photosynthetic activity of the evergreen understory at the Takayama site starts before the leaf emergence of the deciduous trees takes place, and without any noticeable change in LAI (Fig. 1b). Since BEPS does not represent the lower understory layer, the model fails to simulate the initial start of GPP by the understory during the earliest part of the growing

season. Therefore, in the spring, GPP-MO is lower than GPP-EC. The ecosystem respiration, calculated by using the Q10 relationship derived empirically by Saigusa et al. (2002) for Takayama, shows the familiar variation in carbon emission in response to seasonal temperature change (Fig. 1c).

The 5-year mean GPP-EC reaches its maximum value in July and starts to decrease thereafter. However, decrease in LAI does not typically start until after August (see Fig. 1b), producing an offset of approximately 1 month between the gradual cessation of observed photosynthetic absorption of  $\text{CO}_2$  and LAI. A significant decrease in GPP-MO and GPP-EC does not take place until September, 1 month before a sharp drop in LAI occurs in October.

In the fall, leaves start to die naturally and photosynthetic absorption of  $\text{CO}_2$  gradually decreases due to leaf senescence before a significant decrease in LAI is observed. This phenological process is not represented in BEPS. When the leaves die, they do not fall off the branches immediately, although they influence the architectural structure of the canopy and cause LAI to decrease yet remain positive. The model continues to calculate photosynthesis as long as there is positive LAI, even though the leaves stop photosynthesizing.

The overestimation of GPP by the model during the summer season could be also due to the way GPP is calculated in the model. One factor we are examining in detail is the way stomatal conductance is modeled as a function of air temperature. It should be noted here that the measured LAI is indicative of leaf out over a very

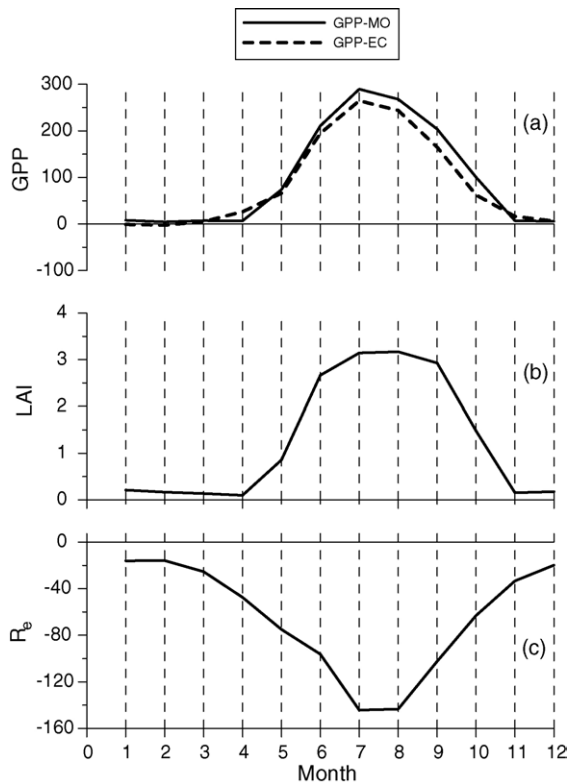


Fig. 1. Five-year (1998–2002) mean monthly values showing average seasonal cycles of (a) GPP-MO (solid line) and GPP-EC (dashed line) ( $\text{gC m}^{-2} \text{ month}^{-1}$ ), (b) measured LAI ( $\text{m}^2 \text{ m}^{-2}$ ), and (c) calculated ecosystem respiration  $R_e$  ( $\text{gC m}^{-2} \text{ month}^{-1}$ ). Both GPP and  $R_e$  are monthly cumulative, but LAI is monthly averaged.

small area around the flux tower. However, GPP-EC has a footprint area on the order of  $0.5 \text{ km}^2$ . Therefore, GPP-MO has a smaller footprint than GPP-EC. This difference in space scale could also account for some of the differences between modeled GPP and flux-derived GPP.

#### 4.2. Inter-annual variation of GPP simulated by BEPS

Fig. 2 shows seasonal time series of GPP-EC and GPP-MO from 1998 to 2002, along with monthly values of measured LAI, solar radiation (RAD), and air temperature ( $T_{\text{air}}$ ). Fig. 3 shows seasonal time series of dGPP, dLAI, dRAD, and  $dT_{\text{air}}$ , where  $d(x)$  denotes deviation of variable  $x$  from its 5-year (1998–2002) mean seasonal cycle. The latter three variables are input data to the model. Qualitative inspection of the comparison between GPP-MO and GPP-EC shows that the seasonal variation of GPP-EC and its general trend over the 5-year period are reproduced relatively well by the model. Except for the years 2000–2002, BEPS

estimates of GPP are also in relative agreement with the GPP-EC values. Correlation statistics between monthly GPP-MO and GPP-EC values for each year range from  $r = 0.98$  to  $0.99$  ( $p > 0.95$ ). It should be noted here that since the seasonal cycle (and the diurnal cycle) of plant photosynthesis is driven mainly by the physical environmental conditions, the correlation is expected to be high. However, it is more difficult to model the day-to-day variability during the growing season, with correlation dropping down to less than 0.6 on monthly time scale.

For 1998, the model calculates an annual GPP-MO =  $1171 \text{ gC m}^{-2}$  (compared to GPP-EC =  $1089 \text{ gC m}^{-2}$ ). Compared to other years, GPP starts earlier than usual in the spring. The early photosynthetic activity in 1998 results from an early increase in the LAI value; this is caused by an earlier than usual leaf emergence in the upper level woody canopy induced by above normal spring temperature (Fig. 2). In 1998, LAI is above the 5-year normal during May and June, but becomes below normal during the latter half of the growing season. In the model, this causes a corresponding below normal GPP in the latter half of the growing season.

For 1999, the model calculates an annual GPP-MO =  $1024 \text{ gC m}^{-2}$  (compared to GPP-EC =  $943 \text{ gC m}^{-2}$ ). The model overestimate of GPP for this year is about  $81 \text{ gC m}^{-2}$ , similar to that in 1998. The noticeable drop in the annual GPP from the value of the previous year however results from a comparatively low LAI during the growing season. It is interesting to note that solar radiation and air temperature show little deviations from their 5-year mean values during the growing season. Soil water content (not shown) also shows average seasonal cycle in 1999. (We will eliminate soil water content from any further discussion since the Takayama site did not experience any water stress during the 1998–2002 period.) Since BEPS uses LAI to calculate GPP, the decrease in LAI during the 1999 growing season cannot be explained by the model that does not contain phenological processes of leaf out and leaf death. It also suggests caution in attempting to parameterize LAI as a function of climatic variables, such as radiation and air temperature.

GPP-MO values for 2000, 2001, and 2002 are 1274 (GPP-EC = 1071), 1200 (GPP-EC = 1038), and 1243 (GPP-EC = 1100), respectively (units are all in  $\text{gC m}^{-2}$ .) After the below-normal LAI (and GPP) in 1999, GPP-EC increases by nearly  $130 \text{ gC m}^{-2}$ , while GPP-MO increases by about  $250 \text{ gC m}^{-2}$ , giving a model overestimate of over  $200 \text{ gC m}^{-2}$ . In the 5-year simulation, the year 2000 gives the largest difference

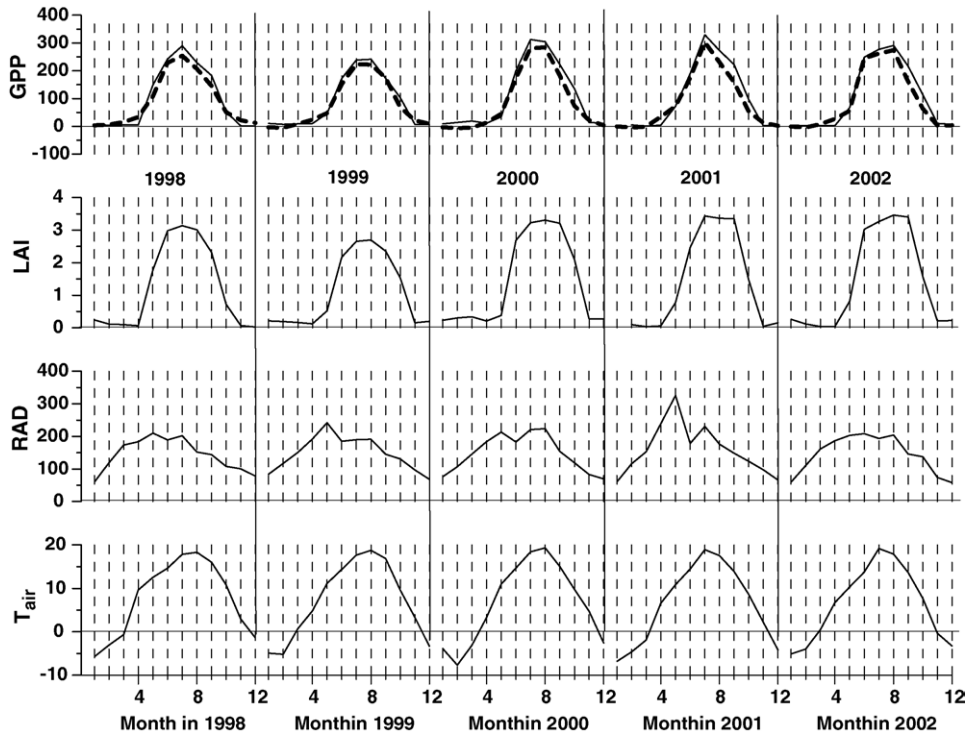


Fig. 2. Time series of monthly values of GPP-MO (solid line) and GPP-EC (dashed line) ( $\text{gC m}^{-2} \text{ month}^{-1}$ ). Also shown are LAI ( $\text{m}^2 \text{ m}^{-2}$ ), solar radiation RAD ( $\text{W m}^{-2}$ ), and air temperature  $T_{\text{air}}$  ( $^{\circ}\text{C}$ ). LAI, Rad, and  $T_{\text{air}}$  are monthly averaged.

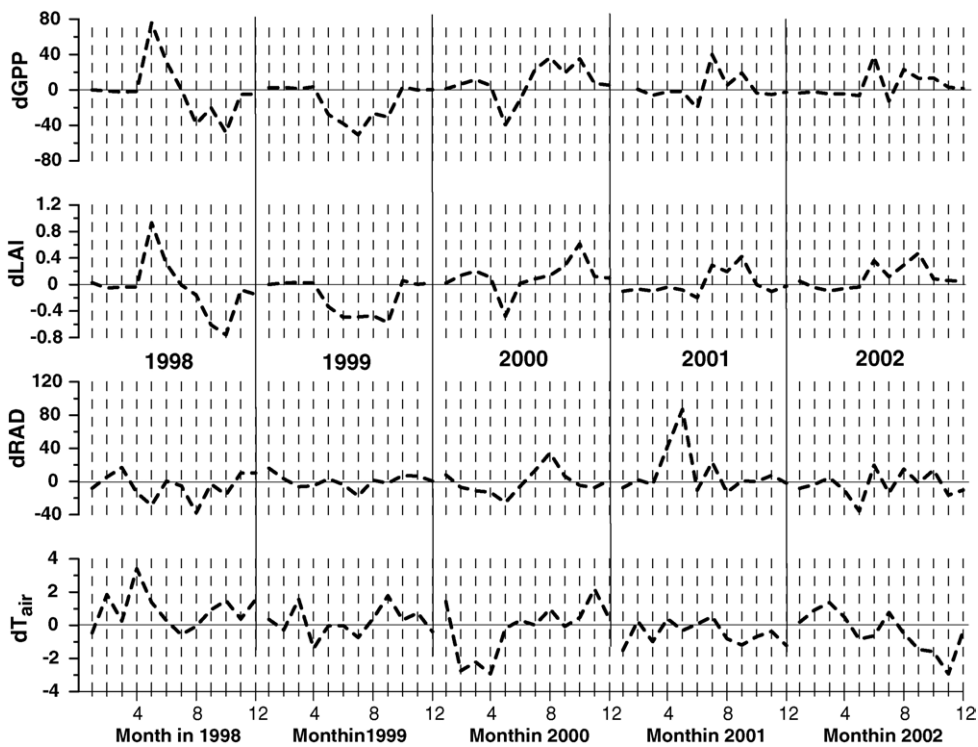


Fig. 3. Time series of deviations of GPP-MO (dGPP), LAI (dLAI), RAD (dRAD), and  $T_{\text{air}}$  ( $dT_{\text{air}}$ ) from their respective 5-year (1998–2002) mean seasonal cycles. Units are same as those in Fig. 2.

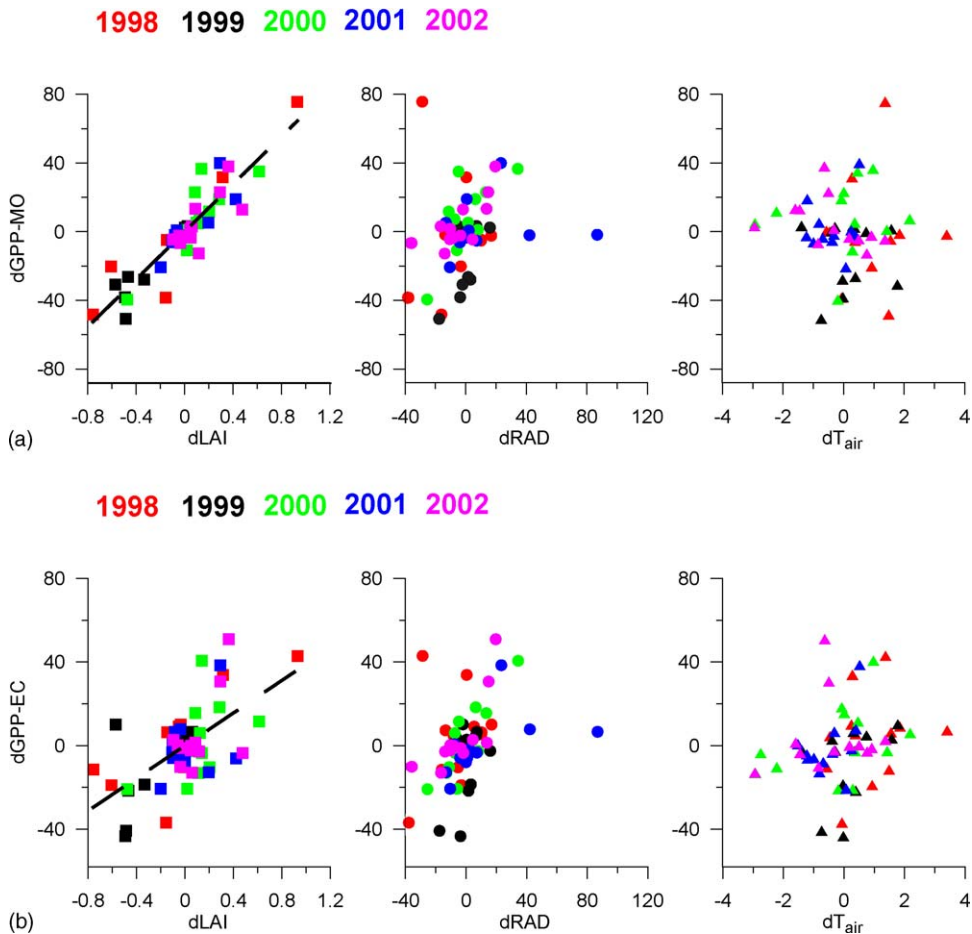


Fig. 4. Scatter diagrams showing the relationships of (a) dGPP-MO with dLAI, dRAD, and  $dT_{\text{air}}$ , and of (b) dGPP-EC with dLAI, dRAD, and  $dT_{\text{air}}$ . Dashed lines represent linear regressions. Data points for each year are shown by different colors. Units are same as in Fig. 3.

between GPP-EC and GPP-MO. For the years 2001 and 2002, the model overestimates GPP by about 14%. The seasonal evolution of GPP simulated by the model during the last 3 years is quite different from the one in 1998. In 1998, above normal GPP takes place in the spring followed by below normal GPP during the latter part of the growing season, whereas the seasonal evolution of GPP during the 2000–2002 period appears to be characterized by an opposite phase, with below normal to normal photosynthesis in the spring time, followed by above normal photosynthesis for the rest of the growing season.

Although the 2000–2002 period shows similar GPP seasonal cycle each year, there are interesting differences caused by the influences of LAI, solar radiation, and air temperature on GPP. The growing season of 2000 is characterized with below average solar radiation in May and June. The LAI usually starts to increase after April, but in 2000 it does not start until June; and in May

LAI is actually below normal. These conditions produce a decrease in GPP during the first half of the growing season. However, above average solar radiation causes an enhancement in GPP in July and August. A slower than average decline in LAI during the fall adds to the GPP enhancement.

Above average LAI values are observed in 2001 and 2002 during the growing season. These are reflected in the GPP-MO values being above average. In both years, the model overestimates the assimilation of  $\text{CO}_2$  by the forest during the months of August to October. An increase in solar radiation and LAI in the month of June in 2002 causes a brief enhancement of ecosystem  $\text{CO}_2$  uptake and contributes to the slightly larger GPP estimate for 2002 than for 2001.

In addition to the model's sensitivity to LAI, as noted above, the model shows some sensitivity to solar radiation as well during 2001 and 2002. We note, for example, that a noticeable decrease in dGPP during the

growing season in July of 2002 is caused by a corresponding decrease in dRAD during the same month (Fig. 3). There are times, however when impact of a noticeable change in dRAD does not translate into an increased dGPP due to low dLAI values. For example, during April and May of 2001, a significant increase in solar radiation is noted. Yet, its impact on GPP is minimized because of low LAI. As we will show below, BEPS is strongly dependent on LAI so that the overall performance of the model to simulate GPP depends critically on the accuracy of the LAI parameter. As indicated by the deviations of GPP and LAI from their respective 5-year mean seasonal cycles in Fig. 3, it can be seen that changes in dGPP is driven mostly by changes in dLAI; however, the relationship between changes in dGPP and dLAI does not appear to be one to one.

Fig. 4a shows the relationships of dGPP-MO with dLAI, dRAD, and  $dT_{\text{air}}$ . The regression relationship of dGPP-MO with dLAI is statistically significant ( $r = 0.9$ ,  $p > 0.95$ ), but such a relationship with radiation and air temperature is not evident. The dependence of GPP-MO on LAI is clearly demonstrated for variations on seasonal and inter-annual time scales. It is to be noted that there is an apparent but statistically non-significant relationship between dGPP-MO and dRAD. Results similar to Fig. 4a but using dGPP-EC (Fig. 4b) indicate that the model GPP sensitivity to LAI is consistent with the observation, although the correlation coefficient drops to 0.6 ( $p > 0.95$ ). At least for the Takayama site (cool temperate deciduous forest), accurate measurements of LAI throughout the growing season are a necessary requirement for reasonable estimates of GPP by BEPS.

## 5. Conclusions

In this study, we have assessed the performance of an ecosystem model BEPS in its ability to reproduce seasonal and inter-annual variability in gross primary productivity derived from flux measurements from 1998 to 2002 at a cool deciduous forest site at Takayama in central Japan. Even though the model, driven by meteorology (air temperature, solar radiation, precipitation, and specific humidity) and LAI, was originally developed to simulate NPP in boreal forest ecosystems (Liu et al., 1997), it is able to reproduce, with appropriate vegetation properties for the Takayama site, seasonal evolution and inter-annual variability of GPP that are in close agreement with that derived from flux measurements. Estimated annual GPP (in  $\text{gC m}^{-2}$ ) by the model are 1171 (1998), 1024 (1999), 1274

(2000), 1200 (2001), and 1243 (2002). Except for the year 2000, these estimated values are in satisfactory agreement with the GPP obtained from the  $\text{CO}_2$  flux measurements at the site by Saigusa et al. (2006). Intra-seasonal and inter-annual variability in GPP at Takayama has been influenced mostly by variations in LAI on similar time scales.

There are however some noticeable differences between GPP-MO and GPP-EC seasonal cycle at certain time periods of the year. In April, the evergreen understory at the Takayama site begins its photosynthetic absorption of  $\text{CO}_2$  before the leaf emergence of the deciduous trees takes place. Since BEPS does not include the lower understory layer, its photosynthetic activity (i.e., GPP) does not start until about a month later. This results in an underestimate of net transfer of  $\text{CO}_2$  from the atmosphere to the biosphere in the early spring. During the fall season, the model overestimates GPP due primarily to its sensitivity to LAI. This has contributed to the consistent overestimation of the annual GPP by the model, as compared to GPP-EC.

It is also interesting to note that since LAI measurements have much smaller footprints compared to eddy covariance flux measurements (and thus GPP-EC), it is quite possible that this difference may account for a part of the differences between the modeled and flux-derived GPP. Another factor that contributes to the difference is the uncertainty associated with GPP-EC. The daily values of GPP-EC are derived from the measured  $\text{CO}_2$  flux by adding daily ecosystem respiration estimated from nighttime flux measurements. Uncertainties originate from the flux measurements themselves and the assumption related to the usage of nighttime flux for the daytime ecosystem respiration.

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