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SPECIAL FEATURE: ORIGINAL ARTICLE

Lessons learned from CarboEastAsia: Carbon and water cycles in East Asian terrestrial ecosystems

Dataset of CarboEastAsia and uncertainties in the CO_2 budget evaluation caused by different data processing

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Abstract The datasets of net ecosystem CO_2 exchange (NEE) were acquired from 21 forests, 3 grasslands, and 3 croplands in the eastern part of Asia based on the eddy covariance measurements of the international joint program, CarboEastAsia. The program was conducted by three networks in Asia, ChinaFLUX, JapanFlux, and KoFlux, to quantify, synthesize, and understand the carbon budget of the eastern part of Asia. An intercomparison was conducted for NEE estimated by three gap-filling procedures adopted by ChinaFLUX, JapanFlux, and KoFlux to test the range of uncertainty in the estimation of NEE. The overall comparison indicated good agreement among the procedures in the seasonal patterns of NEE, although a bias was observed in dormant seasons depending on the different criteria of data screening. Based on the gap-filled datasets, the magnitude and seasonality of the carbon budget were compared among various biome types, phenology, and stress conditions throughout Asia. The annual values of gross primary production and ecosystem respiration were almost proportional to the annual air temperature. Forest management, including clear-cutting, plantation, and artificial drainage, was significant and obviously affected the

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annual carbon uptake within the forests. Agricultural management resulted in notable seasonal patterns in the crop sites. The dataset obtained from a variety of biome types would be an essential source of knowledge for ecosystem science as well as a valuable validation dataset for modeling and remote sensing to upscale the carbon budget estimations in Asia.

Keywords CarboEastAsia · Carbon budget · Intercomparison · Net ecosystem CO_2 exchange

Introduction

During the past decade, more than 80 observational sites have been established for long-term measurements of CO_2, water vapor, and energy fluxes based on the eddy covariance method in various terrestrial ecosystems in the eastern part of Asia (between 90 and 145°E) and registered at AsiaFlux (http://www.asiaflux.net), which is one of the regional networks in FLUXNET (Baldocchi et al. 2001; http://fluxnet.ornl.gov/). Most AsiaFlux sites are under the influence of the Asian monsoon climate, such as the early summer rainy season in East Asia, and typhoons (tropical cyclones) in the mid- and low-latitude seashore regions. Asian tropical ecosystems often include a long dry season that is related to the El Niño Southern Oscillation events. An increasing number of datasets are utilized to elucidate ecosystem–atmosphere interactions, in particular, the carbon and water cycles in the eastern part of Asia. Despite the continuous progress and new findings in estimating those cycles, critical issues, such as advection, energy imbalance, and standardized data processing, remain unresolved. In particular, standardization of the data process has not been implemented among the Asian sites due to differences in approach by the principal investigators in calculating half-hourly fluxes, controlling data quality and assurance, and filling the missing data based on their site-specific conditions. One of the obstacles to the standardization may relate to the fact that most sites in Asia are inconvenient for eddy covariance measurements because of their highly heterogeneous landscape, complex topography, particularly tall canopies in tropical forests, and humid climates with heavy rain and snow. Each investigator had to develop an individual method deemed most suitable for the site.

CarboEastAsia is the first joint program started in 2007 among three regional networks of China, Japan, and Korea (i.e., ChinaFLUX, JapanFlux, and KoFlux) to cope with climate change protocols by synthesizing measurement, theory, and modeling in quantifying and understanding carbon fluxes and storage in the eastern part of Asia. Under the program, a sufficient number of datasets were acquired from various ecosystems including forests, grasslands, and croplands located in seven countries under a wide range of climatic zones from sub-arctic to tropics from 1998 (oldest) to 2007 (newest). The synthesis activity of the CarboEastAsia resulted in a total of 27 sites with total site–years of 71, which created the largest dataset for eddy covariance measurement in Asia with a unique and valuable source of knowledge in various ecosystems in the eastern part of Asia. The objectives of this paper are to introduce the study sites and data availability, to present the magnitude and variability of carbon budget estimated by the CarboEastAsia dataset, and to show the range of uncertainties in carbon budget due to different gap-filling procedures of the three networks.

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Materials and methods

Study sites

The study sites consisted of 21 forests, 3 grasslands, and 3 croplands located in 7 countries (i.e., Russia, Mongolia, China, Korea, Japan, Thailand, and Indonesia) covering boreal forests in high latitudes (>64°N) to tropical rain forests in equatorial regions (∼2°S) and productive mid-latitude croplands (rice paddy, wheat, and corn) to less productive alpine meadows. The locations, ecosystem types, and dominant species are listed in Table S1 in the supplements.

Measurement and data processing

Towers were installed at each site with eddy covariance measurement systems consisting of three-dimensional sonic anemometer thermometers, infrared gas analyzers for CO_2 and water vapor, and a data acquisition system. Open and/or closed-path analyzers were used depending on the site (see Table S2 in the supplements for more detailed information).

A half-hourly net ecosystem CO_2 exchange (NEE) was estimated over the canopy by calculating CO_2 storage below the height of the flux measurement system. The basic data quality control (e.g., spike removal in the half-hourly and the raw data with a sampling frequency of 5 or 10 Hz) was applied. A detailed description of the flux calculation, correction, and quality control with site-specific methods is found in the references in Table S2 in the supplements. The gap-filling methods applied by ChinaFLUX, JapanFlux, and KoFlux are described in the next section. In the following analysis, positive and negative values of NEE indicate CO_2 emission and absorption, respectively.

Gap-filling and flux partitioning

ChinaFLUX

Gaps in the observed NEE were filled basically by the nonlinear regression method presented by Falge et al. (2001). Missing data in small gaps (<2 h) were linearly interpolated, and larger gaps were filled by the following nonlinear regression equations separately in the daytime and at night.

The observed values of daytime NEE ($\mathrm{NEE_{day}}$) were fitted to the Michaelis–Menten equation as a function of the photosynthetic photon flux density (PPFD) with a 10-day moving window,

$$\mathrm{NEE_{day}} = -\frac{\varphi \cdot \mathrm{PPFD} \cdot \mathrm{GPP_{SAT}}}{\varphi \cdot \mathrm{PPFD} + \mathrm{GPP_{SAT}}} + \mathrm{RE_{day}}, \qquad (1)$$

where φ is the initial slope, $\mathrm{GPP_{SAT}}$ is the value of gross primary production (GPP) at light saturation, and $\mathrm{RE_{day}}$ is the daytime ecosystem respiration (RE). The variables φ, $\mathrm{GPP_{SAT}}$, and $\mathrm{RE_{day}}$ are the regression parameters.

The nighttime NEE ($\mathrm{NEE_{night}}$) values, representing ecosystem respiration (RE) at night ($\mathrm{RE_{night}}$), were fitted to the Lloyd and Taylor equation (Lloyd and Taylor 1994) after filtering out the data in the less turbulent conditions using threshold values of friction velocity (u_*).

$$\begin{aligned}\mathrm{NEE_{night}} &= \mathrm{RE_{night}} \\ &= R_{\mathrm{ref}} \cdot \exp\left(E_0\left(\frac{1}{T_{\mathrm{ref}} - T_0} - \frac{1}{T_{\mathrm{a}} - T_0}\right)\right),\end{aligned} \qquad (2)$$

where R_{ref} and E_0 are the regression parameters. R_{ref} is the $\mathrm{RE_{night}}$ at reference temperature T_{ref} (=283.2 K), E_0 expresses the temperature sensitivity of $\mathrm{RE_{night}}$, the value of T_0 is set as a constant (=46.0 K), and T_{a} is the temperature. For most ChinaFLUX sites, the air temperature was used for T_{a}, but, for a few minor cases, the soil temperature (∼5 cm in depth) was used for T_{a} when it gave a better regression (higher R^2 values). Equation (2) worked well to estimate NEE except for the case when the soil moisture significantly affected NEE. In a sub-tropical forest site (QYZ; see Tables S1 and S2 in the supplements for details of the site) where severe droughts were observed, the soil water content was taken into account for the regression (Yu et al. 2008).

Finally, the values of GPP were estimated by GPP = −NEE + RE assuming that the dependence of the daytime RE on the environmental variables was equal to that at night. The overall procedures of data processing in China FLUX are described by Yu et al. (2006).

JapanFlux

The gap-filling method applied by JapanFlux was based on a combination of a look-up table and non-linear regression methods. The look-up table method using environmental variables, such as radiation (PPFD or solar radiation), air temperature, and the vapor pressure deficit (VPD), was applied after small gaps were filled by linear interpolation. When the look-up method failed for some reason, such as data shortage, a non-linear regression was applied. The basic procedures of this method are similar to those of ChinaFLUX, but the daytime NEE data were fitted to the non-rectangular hyperbola function (Thornley 1976) as follows:

$$\mathrm{NEE_{day}} = -\frac{\varphi \cdot \mathrm{PPFD} + \mathrm{GPP_{SAT}} - \sqrt{(\varphi \cdot \mathrm{PPFD} + \mathrm{GPP_{SAT}})^2 - 4\varphi \cdot \mathrm{PPFD} \cdot \theta \cdot \mathrm{GPP_{SAT}}}}{2 \cdot \theta} + \mathrm{RE_{day}}, \quad (3)$$

where θ is a parameter of convexity and is fixed as a constant (=0.9). The regression parameters φ, $\mathrm{GPP_{SAT}}$, and $\mathrm{RE_{day}}$ were determined daily for each site with a moving window of 15–29 days.

The $\mathrm{RE_{night}}$ was estimated by the nighttime NEE with a 39-day moving window after applying u_*-filtering. The u_*-threshold was estimated for each site as listed in Table S3 in the supplements. The $\mathrm{RE_{night}}$ values were fitted to the Lloyd and Taylor equation, which was similar to Eq. (2). The procedures of u_*-filtering, gap-filling, and flux partitioning are described in detail by Ueyama et al. (2012) as well as by Hirata et al. (2008).

KoFlux

The missing daytime NEE was estimated using a modified look-up table (Reichstein et al. 2005). The method calculates a median of NEE under similar meteorological conditions within 7 days and replaces the missing values with the median. The intervals of similar meteorological conditions were 50 W $\mathrm{m^{-2}}$ for net radiation, 2.5 °C for temperature, and 5.0 hPa for VPD. If similar meteorological conditions are unavailable within the time frame, its interval increases in increments of 7 days before and after the missing data point until it reaches 112 days. When temperature or VPD is missing but net radiation is available, net radiation is used exclusively following the same approach. To estimate nighttime flux, KoFlux used a method suggested by van Gorsel et al. (2007). This method selects the data collected in the early evening (i.e., a few hours after sunset), when the sums of NEE and storage are expected to be maximum and the advection is expected to be small (van Gorsel et al. 2007), and uses the data to derive a temperature response function (i.e., Lloyd and Taylor 1994 as in Eq. 2) to parameterize $\mathrm{RE_{night}}$ for the missing and remaining hours of the night. Since R_{ref} and E_0 are time-dependent parameters, KoFlux estimated R_{ref} over a short-term period (i.e., 28 days) and E_0 over a long-term period (i.e., 365 days). Details of the data processing are described in Hong et al. (2009) and Kwon et al. (2009).

Results and discussion

Comparison of NEE estimated using three gap-filling procedures

Figure 1a–d show the results of a comparison of seasonal patterns of NEE estimated by three gap-filling procedures. Four sites, which were widely distributed ecosystems in the eastern part of Asia, were selected to present the similarity

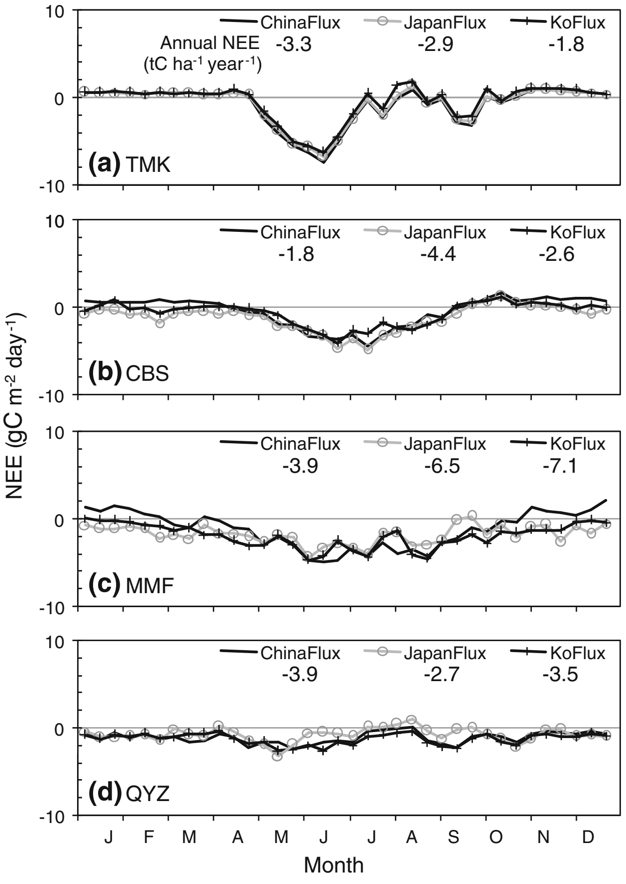

Fig. 1 Comparison of NEE estimated using three gap-filling procedures: **a** a cool-temperate larch forest site (TMK); **b** a temperate mixed forest site (CBS); **c** a temperate mixed forest site (MMF); and **d** a subtropical planted pine forest site (QYZ). A closed-path system was used for the TMK site (**a**) and an open-path system was used for the CBS (**b**), the MMF (**c**), and the QYZ (**d**) sites. The *numbers* indicate annual NEE values estimated by the three procedures

and/or difference in the patterns of NEE generated by the three gap-filling methods.

The overall seasonal patterns of NEE were similarly captured among the three procedures at various ecosystems. However, the data in TMK (Fig. 1a) showed that the difference in the annual NEE was not negligible (from the highest of −1.8 tC ha^{-1} $year^{-1}$ to the lowest of −3.3 tC ha^{-1} $year^{-1}$), although the seasonal patterns estimated by the three procedures were very similar. This result suggested that the seasonal patterns of NEE did not suffer significantly from the different gap-filling procedures but the difference in annual NEE of at least 1–2 tC ha^{-1} $year^{-1}$ was not avoidable.

The results in Fig. 1b, c are also noteworthy. In the seasonal patterns of NEE for CBS and MMF, some differences were found in which gap-filling results by JapanFlux and KoFlux underestimated NEE in the cold season in Fig. 1b, c. One cause of the systematic bias in the cold season could be due to the difference in data screening criteria; for example, the ChinaFLUX procedure rejected all the negative NEE values (i.e., CO_2 uptake) during the dormant seasons to obtain regression parameters for the NEE_{day}, whereas JapanFlux and KoFlux used all the data without disregarding the negative NEE values. As a consequence, the annual NEE values were higher (lower CO_2 uptake) by the ChinaFLUX method (−1.8 tC ha^{-1} $year^{-1}$ for CBS and −3.9 tC ha^{-1} $year^{-1}$ for MMF) than by the JapanFlux method (−4.4 and −6.5 tC ha^{-1} $year^{-1}$ for MMF) and the Koflux method (−2.6 and −7.1 tC ha^{-1} $year^{-1}$).

The issue of the different data screening criteria is related to the fact that the open-path eddy covariance systems sometimes caused unlikely downward daytime CO_2 fluxes (i.e., CO_2 uptake) over ecosystems during dormant seasons under low temperature conditions when photosynthetic activity was hardly expected. A recent study suggested that the downward daytime CO_2 fluxes still appeared during the dormant season even after applying appropriate corrections standardized in FLUXNET, but the reason has not been clarified (Ono et al. 2008). One practical criterion to avoid this problem is to reject all the downward daytime CO_2 flux during dormant seasons. However, the criterion should be applied carefully since the decision of the dormant season is quite difficult, particularly for the beginning and the end of the growing season of evergreen plants. There is also a risk when applying this criterion, namely that another bias may be induced by rejecting all negative NEE values. To test the sensitivity of the criteria, the datasets of CBS and MMF were gap-filled by the JapanFlux program under the condition that all the negative NEE were rejected when the air temperature was below 0 °C. The result indicated that the gap-filled daily NEE during cold periods when the air temperature was below 0 °C for both CBS and MMF became close to that of ChinaFLLUX. The annual NEE changed from −4.4 (negative NEE not rejected) to −2.7 (negative NEE rejected) tC ha^{-1} $year^{-1}$ for CBS and from −6.5 (negative NEE not rejected) to −2.5 (negative NEE rejected) tC ha^{-1} $year^{-1}$ for MMF. The difference in the data screening criteria corresponded to the change in the annual NEE as 1.7 (CBS)–4.0 (MMF) tC ha^{-1} $year^{-1}$, which was almost at the same level as the annual NEE values. There were some other discrepancies among the seasonal patterns of NEE during short periods in the summer in Fig. 1b–d, but the difference in the three gap-filling procedures caused no significant biases.

Annual budgets of GPP, RE, and NEE

Figure 2a–c shows the relationships between annual average air temperature and annual budgets of GPP, RE, and NEE. To minimize the influence of different gap-filling procedures, the datasets processed by the JapanFlux procedure were used for the analysis. The absolute values of annual carbon budget components include some uncertainties originated by the use of different gap-filling and data screening criteria. Caution is required when analyzing the results from sites exposed to long winters. However, one result was clear, namely that the annual values of GPP and RE were highly dependent on the annual air temperature over wide latitudinal ranges from Siberia to tropical Asia without a systematic difference among forests, grasslands, and croplands. The annual values of NEE were independent of the temperature. Positive annual values of NEE (i.e., CO_2 source) were found particularly in two disturbed forest ecosystems: one in the tropical drained peat swamp forest (PDF) (6.5 and 3.7 tC ha^{-1} $year^{-1}$ for 2002 and 2003; annual temperature of 26 and 27 °C) and the other in the young larch plantation in a cool-temperate zone (TSE) (4.5 and 1.5 tC ha^{-1} $year^{-1}$ for 2004 and 2005; annual temperature of 5 and 6 °C).

The seasonal patterns of GPP, RE, and NEE are shown in Fig. 3a, b for PDF and TSE. The PDF site was affected by the change in hydrological processes from a constructed canal, and the decomposition rate of soil organic matter had been enhanced by soil drying during the study period (Hirano et al. 2007). In the TSE site, a mature mixed forest was clear-cut, and young larch trees were planted in 2003 (Takagi et al. 2009). In addition, the annual NEE was positive in 2004 and 2005. The result suggested that disturbances by forest management (clear-cut and plantation) and artificial drainage were the main factors that bring ecosystems to an obvious carbon source.

There were many data points with large deviations from the fitted curves, particularly in GPP in the mid-temperate zone from 5 to 20 °C (Fig. 2a). An extremely high value in

GPP from the fitted curve was obtained in a planted cedar forest (TKC) (25.7 tC ha^{-1} year^{-1} for 2007; annual temperature of 10 °C) with tree ages of 40–50 years, suggesting high productivity in the growth of planted cedar. Notably low values in GPP were obtained at two agricultural fields: a rice paddy field (MSE) (10.0–11.3 tC ha^{-1} year^{-1} for 2001–2005; annual temperature of 13 and 14 °C), and a mixed cropland (HFK) (11.7 tC ha^{-1} year^{-1} for 2006; annual temperature of 15 °C). Another double-crop farming site (YCS) showed higher GPP than MSE and HFK (17.3–20.9 tC ha^{-1} year^{-1} for 2003–2005; annual temperature of 13 and 14 °C).

In a sub-tropical zone with annual air temperature of ~20 °C, notable negative deviations in GPP were observed at two sites: a sub-tropical planted pine forest (QYZ) (16.0–17.0 tC ha^{-1} year^{-1} for 2003–2004; annual temperature of 19 °C) and a sub-tropical seasonal forest (BNS) (18.9–21.4 tC ha^{-1} year^{-1} for 2003–2005; annual temperature of 21 °C). The lower values of GPP than the regression curve could be explained by the restricted photosynthetic activity during high-temperature periods (see Fig. 3g, h), affected by seasonal drought with limited precipitation (discussed in detail in Yu et al. 2008; Tan et al. 2011).

The typical seasonal patterns of the carbon budget components for five forest sites, PDF, TSE, TKC, QYZ, and BNS (Fig. 3a–c, g, and h, respectively), and three crop sites, MSE, HFK, and YCS (Fig. 3d–f, respectively), are shown. Single-crop farming was applied at MSE, and double-crop farming was applied at HFK and YCS. Even though the high monthly net CO_2 uptake was recorded in July at MSE (Fig. 3d) compared with other sites, the limited growing period length might be the cause of the low annual GPP.

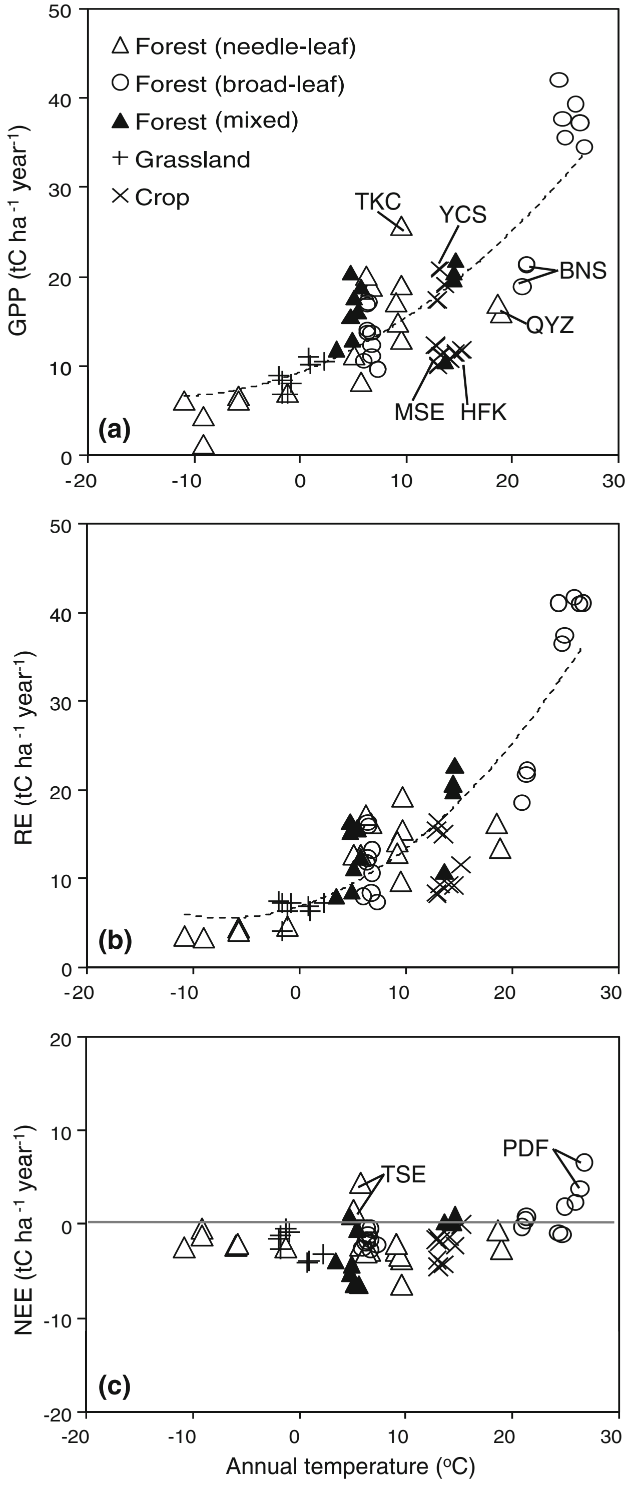

Fig. 2 Relations between annual air temperature (T) and annual GPP, RE, and NEE. *Broken lines* in (**a**, **b**) show regression curves for GPP ($GPP = 0.018T^2 + 0.437T + 9.267$; $R^2 = 0.693$) and RE ($RE = 0.027T^2 + 0.374T + 6.742$; $R^2 = 0.762$). All data, representing annual values for every year and every site including forests, grasslands, and croplands, were used for the regression

Conclusion

The data for the NEE was acquired, and the annual values of NEE, GPP, and RE were examined at 27 sites in the eastern part of Asia under an international joint program, CarboEastAsia. The gap-filling procedures adopted by ChinaFLUX, JapanFlux, and KoFlux were compared, and the seasonal patterns of NEE had good agreement, even though some discrepancies were observed. In the cold season, different data screening criteria caused a systematic bias in NEE, which was related to the management of the daytime downward CO_2 flux measured by an open-path sensor (LI-7500; LI-COR) during the apparent dormant season when photosynthetic activity was hardly expected. This result suggests that further studies are still critically necessary to clarify the cause of observational errors of the eddy covariance method,

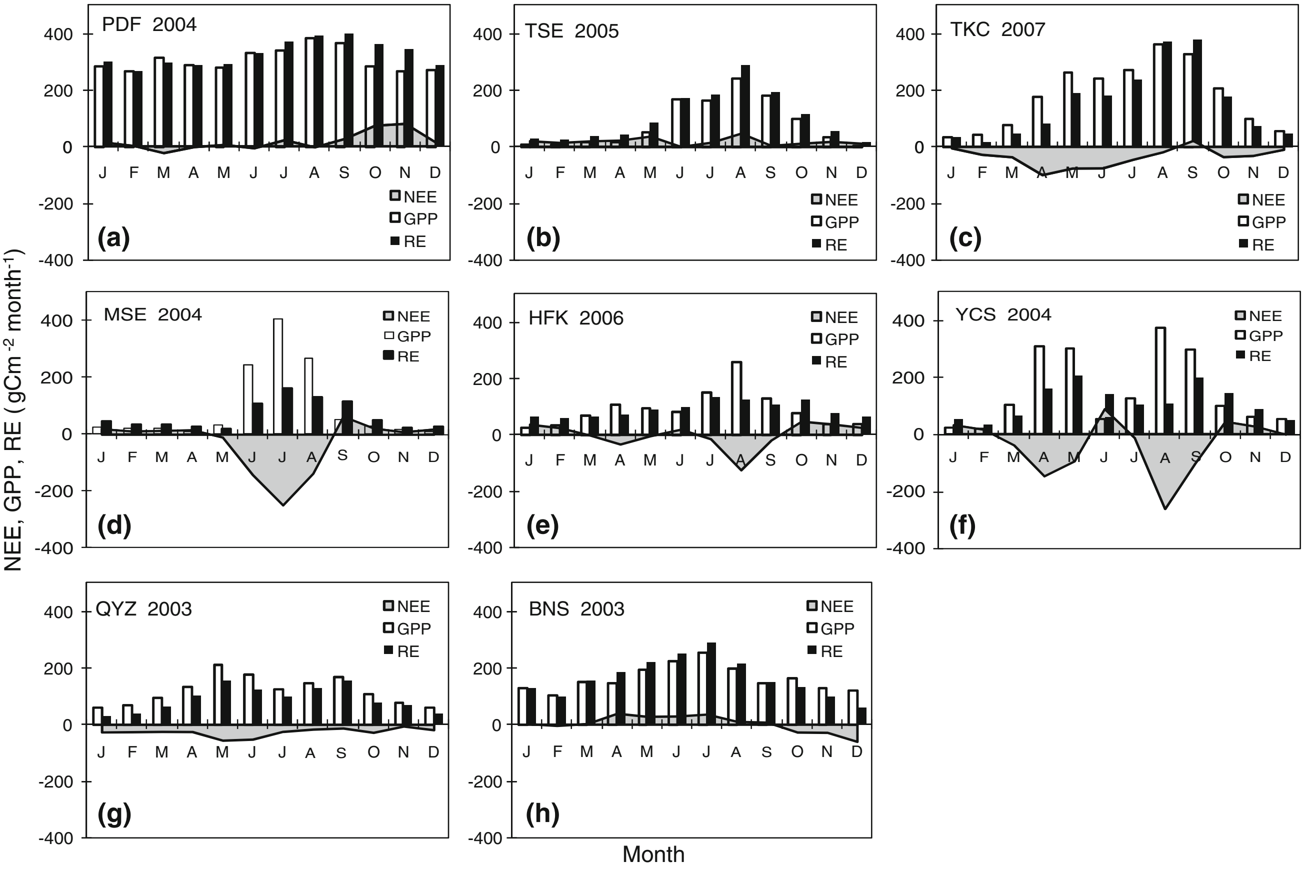

Fig. 3 Monthly values of GPP (*white bars*), RE (*black bars*), and NEE (*lines*) estimated at the study sites indicated

particularly in open-path sensors in the cold season and to improve quality-control and gap-filling algorithms. Studies are indispensable to determine whether already acquired datasets in the FLUXNET community are affected by systematic bias in the data processing criteria, as is suggested in the present study. Studies are also required to develop observation systems with fewer technological problems.

The annual values and seasonal patterns of the carbon budget components were compared among different biome types throughout the study sites. The annual GPP showed high temperature dependency over wide latitudinal ranges except for a few productive planted forest and sub-tropical forests with drought stress in mid-summer. The effects of disturbances such as forest management and artificial drainage were significant factors that obviously affected the annual carbon budgets. Different agricultural management resulted in notably different seasonal patterns in the crop sites. The CarboEastAsia dataset, obtained from a wide variety of ecosystems in the eastern part of Asia, would be an essential source of knowledge as well as a valuable validation dataset for developing advanced techniques in modeling and remote sensing to update the terrestrial carbon budget estimations in Asia.

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