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Carbon budget of tropical forests in Southeast Asia and the effects of deforestation: an approach using a process-based model and field measurements

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Abstract

More reliable estimates of carbon (C) stock within forest ecosystems and C emission induced by deforestation are urgently needed to mitigate the effects of emissions on climate change. A process-based terrestrial biogeochemical model (VISIT) was applied to tropical primary forests of two types (a seasonal dry forest in Thailand and a rainforest in Malaysia) and one agro-forest (an oil palm plantation in Malaysia) to estimate the C budget of tropical ecosystems, including the impacts of land-use conversion, in Southeast Asia. Observations and VISIT model simulations indicated that the primary forests had high photosynthetic uptake: gross primary production was estimated at 31.5–35.5 $\mathrm{t\,C\,ha^{-1}\,yr^{-1}}$. In the VISIT model simulation, the rainforest had a higher total C stock (plant biomass and soil organic matter, 301.5 $\mathrm{t\,C\,ha^{-1}}$) than that in the seasonal dry forest (266.5 $\mathrm{t\,C\,ha^{-1}}$) in 2008. The VISIT model appropriately captured the impacts of disturbances such as deforestation and land-use conversions on the C budget. Results of sensitivity analysis implied that the ratio of remaining residual debris was a key parameter determining the soil C budget after deforestation events. The C stock of the oil palm plantation was about 46% of the rainforest's C at 30 yr following initiation of the plantation, when the ratio of remaining residual debris was assumed to be about 33%. These results show that adequate forest management is important for reducing C emission from soil and C budget of each ecosystem must be evaluated over a long term using both the model simulations and observations.

1 Introduction

More detailed estimations of carbon (C) stocks within forest ecosystems and C emissions induced by deforestation are important environmental research goals. According to various estimates, C emission from land-use change accounts for about 12% (van der Werf et al., 2009) or 20% (IPCC, 2007) of the total anthropogenic emissions worldwide. Several studies have evaluated the amount of C emission due to deforestation around the world using various models (Cramer et al., 2004; Huang et al., 2008; Kato et al., 2009; McGuire et al., 2001; Ramankutty et al., 2007; Shevliakova et al., 2009). To evaluate the annual C emission from land-use change caused by anthropogenic deforestation, several models considered the different decay rates of harvested forest products, based on the method by Houghton et al. (1983). Cramer et al. (2004) reported that C emission due to land-use change had a great uncertainty in Southeast Asia: 1.08 Gt yr^{-1} according to Houghton (1999) and 0.30–0.49 Gt yr^{-1} according to Cramer et al. (2004). Model simulations suggested that, despite uncertainties in the deforestation area, a large amount of C would be released through deforestation in the future (Cramer et al., 2004). Kato et al. (2009) estimated that 44.4 Gt C had been emitted globally over the prior 100 yr, and the global C emission induced by land-use change was estimated as 0.5 Gt C yr^{-1} in the 1980s. At the regional scale, many model simulations of the impacts of deforestation have specifically examined Amazonian forests (e.g., Malhi et al., 2008), whereas fewer studies have investigated the impacts of land-use change on the C stocks of ecosystems in Southeast Asia.

According to the global forest resource assessment conducted in 2010 (FAO 2010), tropical forests excluding rubber plantations, accounted for 19.3 million ha. Since 1990, the area of tropical forests in Malaysia had decreased by 1.2 million ha. Those deforested areas have been converted mostly into farmlands or agro-forests. The area of oil palm plantations in Malaysia increased especially rapidly, from 2.0 million ha in 1990 to 4.2 million ha in 2007 (FAO, 2010). Consequently, Malaysia has become one of the major palm oil producing countries, producing more than 40% of the world's supply (Fitzherbert et al., 2008).

A more detailed understanding of the impacts of deforestation on the net C budget of ecosystems in Southeast Asia is needed for C management and mitigation of climate change. In the present study, we adopted a process-based terrestrial biogeochemical model, Vegetation Integrative SImulator for Trace gases (VISIT), to estimate the C budget of primary tropical forest ecosystems and the impacts of land-use conversion, while considering both instantaneous emissions from rapid C pools and gradual decomposition of slow pools, such as coarse woody debris. The change in vegetation structure (e.g., biomass and canopy leaf amount), plant ecophysiological properties (e.g., photosynthetic capacity and respiration) and soil biogeochemical properties (e.g., soil texture) are important factors to consider for a more detailed assessment in model simulation. Furthermore, in the case of cropland, we must consider C exports through crop harvests when evaluating the net ecosystem C budget (e.g., Chapin et al., 2006; Poulter et al., 2010) is properly evaluated. The objectives of the present study were to: (1) clarify the similarities and differences between a wet and dry forest to evaluate the potential applicability of the VISIT model, (2) compare the model simulations of tropical ecosystems with field data and modify the VISIT model accordingly, and (3) evaluate the C budget before and after land-use conversion in Malaysia using the VISIT model. Based on our findings, we discuss the potential applicability of the VISIT model and some problems related to its application in Southeast Asia.

2 Materials and methods

2.1 Site description

The present study was conducted in two primary forests, a rainforest (RF) in Malaysia and a dry evergreen forest (DEF) in Thailand, and an oil palm plantation (OPP) in Malaysia (Fig. 1). The RF was in the Pasoh Forest Reserve (2°5′ N, 102°18′ E) and the OPP was adjacent to the reserve. The annual mean air temperature in the Pasoh area was 27.1 °C (1992–1994; Bekku et al., 2003) and the monthly mean maximum and minimum air temperatures were 32.5 °C and 22.5 °C in the Pasoh area, respectively (1991–1997; Manokaran et al., 2004). The annual precipitation ranged from 1450 to 2341 mm (1995–2000; Malaysian Meteorological Services). The RF is a tropical evergreen forest dominated by Dipterocarpaceae, with total aboveground biomass of 403 t dry matter ha^{-1} in 1998 (Hoshizaki et al., 2004). At the OPP, oil palms (*Elaeis guineensis*) were planted first around 1976 and clear-cut in October 2001; palm seedlings were replanted in 2002 for the second rotation. Based on the Malaysian and FAO soil classification systems, the soil texture at 5-cm depth was heavy clay in the RF and sandy clay loam in the OPP (Adachi et al., 2005), respectively. Soil C contents at 5 cm depth in RF and OPP were 2.92% and 1.55%, respectively (Adachi et al., 2006).

The DEF was located at the Sakaerat Environmental Research Station (14°30′ N, 101°55′ E). The annual mean temperature was 24.1 °C and the monthly mean maximum and minimum air temperatures in DEF were 28.1 °C and 21.0 °C, respectively (2001–2003; from the AsiaFlux Database). The annual precipitation was 1733 mm in 2003 (Ishida et al., 2006). Trees of the Dipterocarpaceae, Moraceae and Meliaceae are dominant (Yamashita et al., 2010). The total aboveground biomass was 452.6 t dry matter ha^{-1} in 1993 (Kanzaki et al., 2008). The soil in the DEF was classified as a Typic Paleudult, and the soil C content was 2.48% at 5 cm depth (Yamashita et al., 2010).

2.2 Model overview

A process-based terrestrial biogeochemical model (VISIT) was developed based on a simple C cycle model (Sim-CYCLE; Ito and Oikawa 2002; Kato et al., 2009), in which the atmosphere-ecosystem exchange and internal dynamics of C are simulated at a daily time step. The model enables us to evaluate atmosphere-ecosystem exchange of greenhouse gases (CO_2, CH_4 and N_2O) and to simulate long-term dynamics, including the impacts of disturbance (Ito et al., 2005).

We conducted a spin-up calculation for 2000 yr to create an appropriate initial state of ecosystem C pools and budgets using the climate data for 1948–2008, repeatedly at each site. In this model, the ecosystem structure of the C stock is represented by four sectors: tall canopy trees, understory plants, dead biomass and mineral soil. The ecosystem budget of CO_2, that is, the net ecosystem production (NEP), is obtained as the difference between photosynthetic uptake (gross primary production, GPP) and respiratory emissions from plants and microbes. The CO_2 efflux from the soil surface, the soil respiration (SR), is obtained as the sum of plant root respiration and microbial

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heterotrophic respiration. These biogeochemical C flows are calculated, based on models of the ecophysiological responses of the vegetation to environmental parameters.

Moisture conditions such as soil water content, which determine the effect of water stress on plant production and soil decomposition, are simulated in a hydrological subscheme. In the submodel, soil moisture content is calculated from the water-budget equation using data of precipitation data (input), and estimated evapotranspiration and runoff discharge are estimated in another submodel (Ito and Oikawa, 2002). The VISIT model was originally developed for a cool-temperate deciduous broad-leaved forest (Inatomi et al., 2010).

In the present study, we also modified the VISIT model by adding land-use conversion processes. To evaluate the effect of land-use conversion from a primary forest to an oil palm plantation, we incorporated three processes in the model: (1) removal of the existing aboveground forest biomass; (2) production of woody and root debris; and (3) planting of oil palm seedlings. When a clear-cut occurs at a certain stand age in the simulation, it was assumed that all canopy trees are cut and exported, except for a part of the stems, leaves, and roots that are left behind as residual woody debris. VISIT model is able to individually define the ratio of remaining stems, leaves and roots as residual debris. McGuire et al. (2001) reported various conversion ratios for the amount of C stored in the products obtained from tropical ecosystems that is released to atmosphere: 33% of total biomass C remained in the soil as residual woody debris, 40% and 27% of total biomass C was returned to the atmosphere within the 1st and 10th year, respectively. In the present study, residual debris was added to soil C and the decomposition ratio of this debris was assumed to be the same as the litter decomposition rate. C export from crop harvest was changed according to the ratio of remaining residual debris, and harvested C was separated into 1 yr and 10 yr carbon pools at a ratio of 40:27. Therefore, about 60% of harvested C was decayed within 1 yr. C flux from soil in 1 yr and total C flux in 10 yr in Table 5 were in addition to the annual C flux from soil to harvested C, respectively. Representative ecophysiological

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parameters of the primary forests (DEF and RF) and the OPP are presented in Table 1. Although the VISIT model does not simulate the stem density explicitly, the difference between the forest and oil palm canopies might be captured reasonably well as the differences in photosynthetic capacities and allocation coefficients. After planting, oil palm seedlings are managed as they grow. When the trees are 5 yr old, 5% of the leaves are pruned every year, and they are harvested from 10 yr of age, accounting for a carbon loss of 3.3 t C ha^{-1} yr^{-1}.

2.3 Soil parameters used in the model

The soil characteristics of DEF, RF and OPP were represented by four soil parameters (bulk density, pH, and sand and clay contents) obtained from previous reports and filed measurements made in this study (Table 2). These parameters are important for characterising hydrological and biogeochemical properties to evaluate the C stock of soil and C sequestration following the land-use change using the VISIT model. Soil solid volumes within 100 mL soil care samples were measured using a three-phase metre (DIK-1121; Daiki Rika Kogyo Co. Ltd., Japan). The fresh weight of each soil sample was measured and the material was dried at 105 °C for 48 h. The dry weight was measured to calculate the volumes of the water and gas phases within the core samples (Hillel, 1998).

2.4 Input and validation data for the VISIT model

The model simulations were conducted at a daily time step, using daily average meteorological forcing data (Table 3). For this study, daily data were derived from a reanalysis global climate dataset produced by the US National Centres for Environmental Prediction and the US National Centre for Atmospheric Research (NCEP/NCAR; Kistler et al., 2001) for the period from 1 January 1948 to 31 December 2008. These data have a coarse spatial resolution, but they provide a representative long-term time series of meteorological conditions. Figure 2 shows the difference of annual air temperature and precipitation pattern in RF and DEF from 1997 to 2008.

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The diurnal patterns of GPP from 2003 to 2005 were compared with GPP data gathered by two satellites at a 1 km resolution. Data subsets for the RF and DEF were obtained from the Moderate Resolution Imaging Spectrometer (MODIS), Collection 5, onboard the Terra and Aqua satellites. The data were provided by the US Oak Ridge National Laboratory (http://daac.ornl.gov/MODIS/). Terra and Aqua pass the equator same day at 10:30 and 13:30 LT, respectively. Data that passed the quality assurance were used for the comparison.

3 Results

3.1 C budget in the primary forests

The C stock and C fluxes between RF and DEF were simulated using the VISIT model (Fig. 3). Because the ecophysiological parameters of these forests were set at the same values in the model simulations (Table 1), the difference in their C budgets occurred mainly because of the differences in air temperatures, precipitation and soil parameters (Fig. 3; Table 4). The more humid RF had a higher total C stock (plant biomass and soil organic matter, 301.5 t C ha^{-1}) than the drier in DEF (266.5 t C ha^{-1}) in 2008 (Fig. 3a,b). Similarly, the soil C stocks in RF in 2008 was estimated as 73.7 t C ha^{-1}, which was higher than that in DEF (70.0 t C ha^{-1}). Based on the field data, soil carbon content at soil surface in RF (2.92%) was also higher than that in DEF (2.48%). The seasonal variations in NEP and SR were clearer in DEF than in RF, probably because of the large seasonality of precipitation at DEF (Fig. 3c,f). The standard variation (SD) of NEP in 2002–2006 was 1.27 g C m^{-2} day^{-1} in DEF and 0.66 g C m^{-2} day^{-1} in RF. The SDs of SR were 0.29 and 0.20 g C m^{-2} day^{-1} in DEF and RF, respectively. Table 4 presents the forest C budgets based on field measurements versus model estimates for DEF and RF. As compared to tropical ecosystems in general, relatively high photosynthetic uptakes (GPP) of 31.5–35.5 t C ha^{-1} yr^{-1}, were observed and estimated at both sites, although the model slightly underestimated GPP

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for DEF. In this case, the model slightly underestimated the plant aboveground biomass at each site.

3.2 Effect of plantation formation on C stock

The VISIT model was able to capture appropriately the impacts of disturbances, namely the effect of land-use conversion, on the C budget. Table 5 shows results of a sensitivity analysis of the VISIT model for the RF in terms of changes in the ratios of remaining residual debris for stem, leaf and root when a plantation is formed. Here, the proportions of the stem, leaf, and root C pools were individually changed from 0% to 100%. This finding indicates that the proportion of remaining residual debris of stems was more important than those of leaves and roots because most of the standing biomass in the primary forest was dominated by woody stems. The estimation of total C flux 10 yr after land-use conversion was lower than in the undisturbed forest ecosystems, irrespective of the proportions, because the supply of litter and its decomposition rate were decreased in OPP.

The estimated values of soil C emission after disturbance are expected to be underestimated, however, because the calculation does not account for decomposition acceleration at the soil surface due to the change in the radiation budget. In general, the soil surface becomes warmer and dryer after a clear-cut because it receives more direct solar radiation (Ritter et al., 2005). We evaluated the total C emission caused by deforestation and land-use change, using a conventional method for model estimation (McGuire et al., 2001) that assumes that 33% of the total biomass remains as residue. Correspondingly, soil C emission in the 1 yr after the disturbance was estimated as 106.8 t C ha^{-1} when the proportion of total biomass as residue was about 33%. In that case, the 100% of leaves, 16.5% of stems and 100% of roots remained (Table 5). In addition, 40% of harvested C was released to the atmosphere within 10 yr in a tropical region (McGuire et al., 2001). For all the combinations analysed, the estimates of C flux at 10 yr after land-use conversion were lower than that in the undisturbed forest (Table 5).

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Figure 4 shows the temporal variations (from 1948 to 2008) in the C stock and C efflux for land-use conversion from a primary forest (RF) to an oil-palm plantation (OPP) in 1976, simulated by the VISIT model. Note, however, that there were few field data from the plantation (Table 4). The values of aboveground biomass C in OPP was similar for filed measurements and model estimates of 27.5 yr-old oil palms in 2003 and half year. Our findings indicated that the total C stock (total biomass and soil C) in OPP (139.8 $\mathrm{t\,C\,ha^{-1}}$) at 30 yr following the initiation of the plantation was about 46% that of the RF (302.4 $\mathrm{t\,C\,ha^{-1}}$) in 2006.

Figure 5a shows the seasonal variation in SR estimated using the VISIT model and field data from RF and OPP. According to the field data, the spatial variation in SR was greater than the seasonal variation. Adachi et al. (2005) reported that the spatial variation in SR in RF and OPP was higher than in the temperate forest. Moreover, the seasonal variation of SR in the model simulation is less than that observed in the field. The estimated annual SR according to the model was similar to that of filed observations (Table 4), but the spatial variation in SR was not considered in the VISIT model. The soil water content in RF estimated by the VISIT model was higher than that measured in the field (Fig. 5b), mainly because precipitation data tended to be high (Fig. 2).

A comparison of the VISIT model estimates with MODIS data showed that the seasonal variation range of GPP in DEF was more similar to the data gathered by the Terra satellite than that from the Aqua satellite (Fig. 6). Because oil palm seedlings were replanted in 2002, therefore the disturbance event in the VISIT model was set for 2001. The differences between Terra and Aqua data for OPP were not consistent, however, these data were not suitable for validation of the model simulation.

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4 Discussion

4.1 Comparison of two primary forests

The model simulation results were consistent with field data from the rainforest and dry evergreen forest, indicating that the VISIT model is applicable to various forest types in the tropics of Southeast Asia. The model parameters of the forests (Table 1) are based on Ito and Oikawa (2002), and they do not differ according to plant ecophysiological properties in DEF and RF. For instance, mean downward shortwave radiation of NCEP/NCAR in RF was 234 $W m^{-2}$ from 1948 to 2008, and this rate was higher than that in DEF (222 $W m^{-2}$). However, actual plant properties (e.g., the maximum photosynthetic rate) differed from the model estimates and showed seasonal variation. Some reports noted that the maximum photosynthetic rate differs according to tree species, leaf maturity, and the wet/dry season (Ishida et al., 2006; Kosugi et al., 2009). Despite these differences, the VISIT model accurately simulated the C budgets both of a tropical seasonal forest and a rainforest. One of the reasons, coefficient of plant growth and/or maintenance respiration in the VISIT model could be higher than these of real rate.

The annual patterns revealed by VISIT model simulations would be more useful than the seasonal patterns. For instance, the seasonal variation in the SR rate based on field data was greater than that estimated by the model (Fig. 5), whereas the aboveground C stocks of the two primary forests were similar between field data and model estimates (Table 4). According to the VISIT model, total biomass C (aboveground and belowground) in RF was estimated as 227 $t C ha^{-1}$ in 2008, a rate that is similar to that estimated using another model simulations (e.g., 250 $t C ha^{-1}$; Ramankutty et al., 2007). These results indicate that tropical rainforests of Southeast Asia are among the most C-abundant ecosystems in the world, surpassing Amazonian rainforest (161.4 $t C ha^{-1}$; Malhi et al., 2006). Based on the comparison of the VISIT model estimates with MODIS data, the maximum GPP rate in DEF was higher than that in RF (Fig. 6). In RF, the GPP rate showed a large difference between the results based on

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Terra versus Aqua data due to the formation of cumulus clouds before the Aqua overpass (Miettinen and Liew, 2008). In the temperate forest, Ito (2010) compared VISIT model estimates with MODIS data of LAI, and both of them could estimate the seasonal variation in LAI. These results were supported by data based on the eddy covariance method (Table 4). However, Ohtsuka et al. (2009) reported that the difference of NEP between the biometric method and the eddy-covariance method was ±2 t C ha^{-1} y^{-1} in a cool-temperate deciduous broad-leaved forest. Saleska et al. (2003) reported that, in the Amazonian rainforest, the observed seasonal pattern of NEE was opposite to the simulated pattern, although the proper precipitation pattern was used in the models. In the present study, SR in DEF was estimated to have litter seasonal variation (Fig. 3e). The SR rate in the wet season was almost twice that in the dry season in another dry evergreen forest in Thailand (Adachi et al., 2009). Estimates of soil water content showed a large variation for DEF (Fig. 5b), meaning that seasonal variation in soil water content would not significantly affect the SR rates in the VISIT model.

More validation data gathered in tropical regions using various methods are needed to improve the VISIT model simulations. Data obtained by the biometric method, eddy covariance method and remote-sensing have different spatiotemporal scales. For instance, field measurements of SR rates are expected not only to vary temporally due to meteorological conditions, but also to show spatial variation among the limited number of SR chambers.

4.2 Effect of land-use change to an oil palm plantation on the ecosystem C budget

Although the oil palm plantations are structurally simpler than the primary forest ecosystems, agricultural tasks performed by people are expected to engender complexity and make model simulations of this system more difficult. The estimated and observed values of aboveground biomass of oil palms were similar because the photosynthesis rate and stomatal conductance do not differ significantly among various leaf ages (Dufrene and Saugier, 1993). In the present study, however, the field measurements

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of SR data were conducted at a location with no pruned fronds. We added the event of leaf harvest and removal to compare the simulated and observed SR rates. In plantations, however, the pruned fronds are piled up and left between the oil palms (Melling et al., 2008). Thus, the C stock in OPP might have been underestimated in the VISIT model.

Several studies have shown that the soil organic matter data are sensitive to land-use change in tropical ecosystems (Chaplot et al., 2005; Fujii et al., 2009; Marin-Spiotta et al., 2009). Sheng et al. (2010) reported that the temperature sensitivity of SR rates (i.e., Q_{10} value) was higher in sloping tilled land than in a subtropical natural forest in China. Solomon et al. (2007) found that soil organic C loss occurred during the first 4 yr after land-use change in the tropical region and the forest soil was more sensitive to environmental conditions than that of native grasslands. However, Tanaka et al. (2009) reported finding no significant difference in total C contents among the secondary forests and some types of plantations, including trees of different ages in Malaysia.

Our field measurements indicated that soil physical parameters change when primary forest is converted to an oil palm plantation. Using the VISIT model and the deforestation rate reported by FAO (2010), we estimated the total C emissions induced by land-use change in Malaysia were estimated as 1.47 Mt C ($M = 10^6$) between 1995 and 2004. This finding would provide useful information for activities related to the Reduce Emissions from Deforestation and Forest Degradation (REDD). Detecting the effects of land-use change on soil biochemical and physical characteristics requires long-term measurements, however, because it is necessary to examine when and how these soil characteristics change. For instance, the oil palm trees were clear-cut and seedlings were replanted at 25 to 30 yr rotations in Southeast Asia (Corley and Tinker, 2003). Unfortunately, we lack sufficient information about how fast soil physical properties are expected to change after disturbances in tropical forests. More detailed estimations are needed to evaluate the amount of C emission induced by comprehensive deforestation or land-use of the entire Southeast Asian region.

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References

Adachi, M. and Koizumi, H.: Soil organic carbon dynamics of different land use in Southeast Asia, in: Forest Canopies: Forest Production, Ecosystem Health and Climate Conditions, edited by: Creighton, J. D. and Roney, P. J., Nova Science Publishers Inc., New York, NY, USA, 85–101, 2009.

Adachi, M., Bekku, S. Y., Konuma, A., Kadir, W. R., Okuda, T., and Koizumi, H.: Required sample size for estimating soil respiration rates in large areas of two tropical forests and of two types of plantation in Malaysia, Forest Ecol. Manag., 210, 455–459, 2005.

Adachi, M., Bekku, Y. S., Kadir, W. R., Okuda, T., and Koizumi, H.: Differences in soil respiration between different tropical ecosystems, Appl. Soil. Ecol., 34, 258–265, 2006.

Adachi, M., Ishida, A., Bunyavejchewin, S., Okuda, T., and Koizumi, H.: Spatial and temporal variation in soil respiration in a seasonally dry tropical forest, Thailand, J. Trop. Ecol., 25, 532–539, 2009.

Bekku, S. Y., Nakatsubo, T., Kume, A., Adachi, M., and Koizumi, H.: Effect of warming on the temperature dependence of soil respiration rate in arctic, temperate and tropical soils, Appl. Soil. Ecol., 22, 205–210, 2003.

Chapin, F. S. III, Woodwell, G. M., Randerson, J. T., Rastetter, E. B., Lovett, G. M., Baldocchi, D. D., Clark, D. A., Harmon, M. E., Schimel, D. S., Valentini, R., Wirth, C., Aber, J. D., Cole, J. J., Goulden, M. L., Harden, J. W., Heimann, M., Howarth, R. W., Matson, P. A., McGuire, A. D., Melillo, J. M., Mooney, H. A., Neff, J. C., Houghton, R. A., Pace, M. L., Ryan, M. G., Running, S. W., Sala, O. E., Schelesinger, W. H., and Schulze, E. D.: Reconciling carbon-cycle concepts, terminology, and methods, Ecosystems, 9, 1041–1050, 2006.

Chaplot, V. A. M., Rumpel, C., and Valentin, C.: Water erosion impact on soil and carbon redistributions within uplands of Mekong River, Global Biogeochem. Cy., 19, GB4004, doi:10.1029/2005GB002493, 2005.

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Corley, R. H. V. and Tinker, P. B. (Eds.): The Oil Palm, Blackwell Science, Oxford, UK, 2003.
Cramer, W., Bondeau, A., Schaphoff, S., Lucht, W., Smith, B., and Sitch, S.: Tropical forests and the global carbon cycle: impacts of atmospheric carbon dioxide, climate change and rate of deforestation, Philos. T. R. Soc. Lon. B, 359, 331–343, 2004.
Dufrene, E. and Saugier, B.: Gas exchange of oil palm in relation to light, vapour pressure deficit, temperature and leaf age, Funct. Ecol., 7, 97–104, 1993.
Fitzherbert, E. B., Struebig, M. J., Morel, A., Danielsen, F., Brühl, C. A., Donald, P. F., and Phalan, B.: How will oil palm expansion affect biodiversity?, Trends Ecol. Evol., 23, 538–545, 2008.
Food and Agriculture Organization (FAO): Global Forest Resources Assessment 2010, Country report, Food and Agriculture Organization of the United Nations, Rome, Italy, 2010.
Fujii, K., Funakawa, S., Hayakawa, C., Sukartiningsih, and Kosaki, T.: Quantification of proton budgets in soil of cropland and adjacent forest in Thailand and Indonesia, Plant Soil, 316, 241–255, 2009.
Hillel, D. (Ed.): Environmental Soil Physics, Elsevier, New York, NY, USA, 1998.
Hirata, R., Saigusa, N., Yamamoto, S., Ohtani, Y., Ide, R., Asanuma, J., Gamo, M., Hirano, T., Kondo, H., Kosugi, Y., Li, S. G., Nakai, Y., Takagi, K., Tani, M., and Wang, H.: Spatial distribution of carbon balance in forest ecosystems across East Asia, Agr. Forest Meteorol., 148, 761–775, 2008.
Hoshizaki, H., Niiyama, K., Kimura, K., Yamashita, T., Bekku, Y., Okuda, T., Quah, E. S., and Nur Supardi, M. N.: Recent biomass change in relation to stand dynamics in a lowland tropical rain forest, Pasoh Forest Reserve, Malaysia, Ecol. Res., 19, 357–363, 2004.
Houghton, R. A.: The annual net flux of carbon to the atmosphere from changes in land use 1850–1990, Tellus, B51, 298–313, 1999.
Houghton, R. A., Hobbie, J. E., Melillo, J. M., Moore, B., Peterson, B. J., Shaver, G. R., and Woodwell, G. M.: Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: a net release of CO_2 to the atmosphere, Ecol. Monogr., 53(3), 235–262, 1983.
Huang, M., Asner, G. P., Keller, M., and Berry, J. A.: An ecosystem model for tropical forest disturbance and selective logging, J. Geophys. Res., 113, G01002, doi:10.1029/2007JG000438, 2008.
Inatomi, M., Ito, A., Ishijima, K., and Murayama, S.: Greenhouse gas budget of a cool-temperate deciduous broad-leaved forest in Japan estimated using a process-based model, Ecosystems, 13, 472–483, 2010.

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8, 3051–3079, 2011

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Intergovernmental Panel on Climate Change (IPCC): Climate Change 2007: The Physical Science Basis, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, Cambridge, UK, 2007.

Ishida, A., Diloksumpun, S., Ladpala, P., Staporn, D., Panuthai, S., Gamo, M., Yazaki, K., Ishizuka, M., and Puangchit, L.: Contrasting seasonal leaf habits of canopy trees between tropical dry-deciduous and evergreen forests in Thailand, Tree Physiol., 26, 643–656, 2006.

Ito, A.: Evaluation of the impacts of defoliation by tropical cyclones on a Japanese forest's carbon budget using flux data and a process-based model, J. Geophys. Res-Biogeo., 115, G04013, doi:10.1029/2010JG001314, 2010.

Ito, A. and Oikawa, T.: A simulation model of the carbon cycle in land ecosystems (Sim-CYCLE): a description based on dry matter production theory and plot-scale validation, Ecol. Model., 151, 143–176, 2002.

Ito, A., Saigusa, N., Murayama, S., and Yamamoto, S.: Modeling of gross and net carbon dioxide exchange over a cool-temperate deciduous broad-leaved forest in Japan: analysis of seasonal and interannual change, Agr. Forest Meteorol., 134, 122–134, 2005.

Kanzaki, M., Kawaguchi, H., Kiyohara, S., Kajiwara, T., Kaneko, T., Ohta, S., Sangpalee, W. and Wachrinrat, C.: Long- term study on the carbon storage and dynamics in a tropical seasonal evergreen forest of Thailand, in: Tropical Forestry Change in a Changing World, FORTROP II International Conference, 17–20 November 2008, edited by: Pirangchit, L. and Diloksumpun, S., Royal Forest Department and Kasetart University, Bangkok, Thailand, 37–51, 2009.

Kato, T., Ito, A., and Kawamiya, M.: Multiple temporal scale variability during the twentieth century in global carbon dynamics simulated by a coupled climate-terrestrial carbon cycle model, Clim. Dynam., 32, 901–923, 2009.

Kistler, R., Kalnay, E., Collins, W., Saha, S., White, G., Woollen, J., Chelliah, M., Ebisuzaki, W., Kanamitsu, M., Kousky, V., van den Dool, H., Jenne, R., and Fiorino, M.: The NCEP-NCAR 50-year reanalysis: monthly means CD-ROM and documentation, B. Am. Meteorol. Soc., 82, 247–267, 2001.

Kosugi, Y., Takanashi, S., Ohkubo, S., Matsuo, N., Tani, M., Mitani, T., Tsutsumi, D., and Nik, A. R.: CO_2 exchange of a tropical rainforest at Pasoh in Peninsular Malaysia, Agr. Forest Meteorol., 148, 439–452, 2008.

Kosugi, Y., Takanashi, S., Matsuo, N., and Nik, A. R.: Middy depression of leaf CO_2 exchange within the crown of *Dipterocarpus sublamellatus* in a lowland dipterocarp forest in Peninsular Malaysia, Tree Physiol., 29, 505–515, 2009.

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Malhi, Y., Wood, D., Baker, T. R., Wright, J., Phillips, O. L., Cochrane, T., Meir, P., Chave, J., Almeida, S., Arroyo, L., Higuchi, N., Killeen, T. J., Laurance, S. G., Laurance, W. F., Lewis, S. L., Monteagudo, A., Neill, D. A., Vargas, P. N., Pitman, N. C. A., Quesada, C. A., Salomao, R., Silva, J. N. M., Lezama, A. T., Terborgh, J., Martinez, R. V., and Vinceti, B.: The regional variation of aboveground live biomass in old-growth Amazonian forests, Glob. Change Biol., 12, 1107–1138, 2006.

Malhi, Y., Roberts, J. T., Betts, R. A., Killeen, T. J., Li, W., and Nobre, C. A.: Climate change, deforestation, and the fate of the Amazon, Science, 319, 169–172, 2008.

Manokaran, N., Quah, E. S., Ashton, P. S., LaFrankie, J. V., Nur Supardi, M. N., Ahmad, W. M. S. W., and Okuda, T.: Pasoh forest dynamics plot, Peninsular Malaysia, in: Tropical Forest Diversity and Dynamism, edited by: Losos, E. C. and Leigh, J. E. G., The University of Chicago Press, Chicago, USA, 585–598, 2004.

Marin-Spiotta, E., Silver, W., Swanston, C., and Ostertag, R.: Soil organic matter dynamics during 80 years of reforestation of tropical pastures, Glob. Change Biol., 15, 1584–1597, 2009.

McGuire, A. D., Sitch, S., Clein, J. S., Dargaville, R., Esser, G., Foley, J., Heimann, M., Joos, F., Kaplan, J., Kicklighter, D. W., Meier, R. A., Melillo, J. M., Moore III, B., Prentice, I. C., Ramankutty, N., Reichenau, T., Schloss, A., Tian, H., Williams, L. J., and Wittenberg, U.: Carbon balance of the terrestrial biosphere in the twentieth century: analyses of CO_2, climate and land use effects with four process-based ecosystem models, Glob. Change Biol., 15, 183–206, 2001.

Melling, L., Goh, K. J., Constance, B., and Hatano, R.: Carbon flow and budget in a young mature oil palm agroecosystem on deep tropical peat, Planter, 84, 21–25, 2008.

Miettinen, J. and Liew, S. C.: Comparison of multitemporal compositing methods for burnt area detection in Southeast Asian conditions, Int. J. Remote Sens., 29, 1075–1092, 2008.

Ohtsuka, T., Saigusa, N., and Koizumi, H.: On linking multiyear biometric measurements of tree growth with eddy covariance-based net ecosystem production, Glob. Change Biol., 15, 1015–1024, 2009.

Poulter, B., Aragao, L., Heyder, U., Gumpenberger, M., Heinke, J., Langerwisch, F., Rammig, A., Thonicke, K., and Cramer, W.: Net biome production of the Amazon Basin in the 21st century, Glob. Change Biol., 16, 2062–2075, 2010.

Ramankutty, N., Gibbs, H. K., Achard, F., Defries, R., Foley, J. A., and Houghton, R. A.: Challenges to estimating carbon emissions from tropical deforestation, Glob. Change Biol., 13,

51–66, 2007.
Ritter, E., Dalsgaard, L., and Einhorn, K. S.: Light, temperature and soil moisture regimes following gap formation in a semi-natural beech-dominated forest in Denmark, Forest Ecol. Manag., 206, 15–33, 2005.
Saleska, S. R., Miller, S. D., Matross, D. M., Goulden, M. L., Wofsy, S. C., da Rocha, H. R., de Camargo, P. B., Crill, P., Daube, B. C., de Freitas, H. C., Hutyra, L., Keller, M., Kirchhoff, V., Menton, M., Munger, J. W., Pyle, E. H., Rice, A. H., and Silva, H.: Carbon in Amazon forests: unexpected seasonal fluxes and disturbance-induced losses, Science, 302, 1554–1557, 2003.
Shevliakova, E., Pacala, S. W., Malyshev, S., Hurtt, G. C., Milly, P. C. D., Caspersen, J. P., Sentman, L. T., Fisk, J. P., Wirth, C., and Crevoisier, C.: Carbon cycling under 300 years of land use change: importance of the secondary vegetation sink, Global Biogeochem. Cy., 23, GB2022 doi:10.1029/2007GB003176, 2009.
Sheng, H., Yang, Y., Yang, Z., Chen, G., Xie, J., Guo, J., and Zou, S.: The dynamic response of soil respiration to land-use changes in subtropical China, Glob. Change Biol., 16, 1107–1121, 2010.
Solomon, D., Lehmann, J., Kinyangi, J., Amelung, W., Lobe, I., Pell, A., Riha, S., Ngoze, S., Verchot, L., Mbugua, D., Skjemstad, J., and Schäfer, T.: Long-term impacts of anthropogenic perturbations on dynamics and speciation of organic carbon in tropical forest and subtropical grassland ecosystems, Glob. Change Biol., 13, 511–530, 2007.
Tanaka, S., Tachibe, S., Wasli, M. E. B., Lat, J., Seman, L., Kendawang, J. J., Iwasaki, K., and Sakurai, K.: Soil characteristics under cash crop farming in upland areas of Sarawaku, Malaysia, Agr. Ecosyst. Environ., 129, 293–301, 2009.
van der Werf, G. R., Morton, D. C., DeFries, R. S., Olivier, J. G. J., Kasibhatla, P. S., Jackson, R. B., Collatz, G. J., and Randerson, J. T.: CO_2 emissions from forest loss, Nat. Geosci., 2, 737–738, 2009.
Yamashita, N., Ohta, S., Sase, H., Luangjame, J., Visaratana, T., Kievuttinon, B., Garivait, H., and Kanzaki, M.: Seasonal and spatial variation of nitrogen dynamics in the litter and surface soil layers on a tropical dry evergreen forest slope, Forest Ecol. Manag., 259, 1502–1512, 2010.
Yashiro, Y., Kadir, W. R., Adachi, M., Okuda, T., and Koizumi, H.: Emission of nitrous oxide from tropical forest and plantation soils in Peninsular Malaysia, Tropics, 17, 17–23, 2007.

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Table 1. Model parameters for the primary forest (dry evergreen forest and rainforest) and oil palm plantation.

Parameters	Unit	Forest	Oil palm plantation
Maximum photosynthetic rate	$\mu mol\ CO_2\ m^{-2}\ s^{-1}$	20	18
Leaf allocation coefficient	fraction	0.1	0.2
Aboveground allocation coefficient	fraction	0.55	0.60
Specific leaf area	$cm^2\ g^{-1}$	170	150
Stem growth respiration coefficient	fraction allocated carbon	0.25	0.18
Root growth respiration coefficient	fraction allocated carbon	0.35	0.32
Leaf maintenance respiration coefficient	0.001 fraction biomass (15 °C)	1.57	1.30
Sapwood maintenance respiration coefficient	0.001 fraction biomass (15 °C)	0.25	0.06
Fine root maintenance respiration coefficient	0.001 fraction biomass (15 °C)	0.35	0.60
Heartwood maintenance respiration coefficient	0.001 fraction biomass (15 °C)	0.014	0.008
Coarse root maintenance respiration coefficient	0.001 fraction biomass (15 °C)	0.055	0.150
Harvest leaf every year[1]	% of leaves yr^{-1}	–	5.0
Harvest oil palm (from stem) every year[2]	$t\ C\ ha^{-1} 1\ yr^{-1}$	–	3.3

[1] Conducted 5 yr after planting.
[2] Conducted 10 yr after planting.

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Table 2. Model soil parameters at the dry evergreen forest (DEF) in Thailand and the rainforest (RF) and oil palm plantation (OPP) in Malaysia.

Site	Sakaerate, Thailand	Pasoh, Malaysia	
Vegetation	Dry evergreen forest	Evergreen forest	Oil palm plantation
Bulk density	1.05[1]	0.74[3]	1.06[3]
pH (H_2O)	4.85[2]	3.8[4]	4.7[4]
Sand content (%)	61.2[2]	16.6[1]	67.2[1]
Clay content (%)	24.9[2]	57.8[1]	21.0[1]

[1] Measured in the present study.
[2] Yamashita et al. (2010).
[3] Yashiro et al. (2007).
[4] Adachi et al. (2006).

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Table 3. Input climate parameters from NCEP/NCAR to the VISIT model.

Parameters	Unit
Air temperature at 2 m hight	K
Maximum air temperature	K
Minimum air temperature	K
Specific humidity at 2 m	$kg\,kg^{-1}$
Precipitation	$kg\,m^{-2}\,s^{-1}$
Downward shortwave radiation	$W\,m^{-2}$
Cloud cover	%
Soil surface temperature	K
Soil temperature at 0–10 cm depth	K
Soil temperature at 10–200 cm depth	K
Soil temperature at 300 cm depth	K
U wind (component of west-east)	$m\,s^{-1}$
V wind (component of north-south)	$m\,s^{-1}$
Air pressure (Pa)	Pa

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Table 4. Comparisons of gross primary production (GPP), net ecosystem production (NEP), soil respiration rate (SR) and aboveground biomass carbon (AGB) between the VISIT model simulations and field measurements. AGB carbon values were estimated as half of the above-ground biomass.

	DEF site			RF site			OPP site		
$t\,C\,ha^{-1}\,y^{-1}$	VISIT[1]	Field data	Year of field data	VISIT[1]	Field data	Year of field data	VISIT[1]	Field data	Year of field data
GPP	31.5	35.6[2]	2002	35.1	32.6[4]	2003	nd	nd	
	34.8	39.6[2]	2003	35.5	32.8[4]	2004	nd	nd	
	nd	nd	nd	35.0	32.0[4]	2005	nd	nd	
NEP	0.3	−1.8[2]	2002	1.50	−0.4[4]	2003	−0.80	1.06[7]	5 yr old
	2.8	0.9[2]	2003	1.70	2.4[4]	2004	nd	nd	
	nd	nd	nd	1.20	2.8[4]	2005	nd	nd	
SR	18.23	nd	2001	18.3	18.1[5]	2001	12.9	14.4[5]	2001
AGB	145.5	226.3[3]	1993	180.9	201.5[6]	1998	34.0	33.9[8]	27.5 yr old

[1] Same year or period as field data.
[2] Hirata et al. (2008).
[3] Half of above ground biomass, Kanzaki et al. (2009).
[4] Kosugi et al. (2008).
[5] Adachi and Koizumi (2009).
[6] Half of above ground biomass, Hoshizaki et al. (2004).
[7] Melling et al. (2008).
[8] half of above ground biomass, Corley and Tinker (2003).
nd: no data.

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Table 5. Results of sensitivity analysis of the carbon flux performed in 1 yr (1977) and total carbon flux in 10 yr after deforestation in the VISIT model. Deforestation occurs in 1976 in this simulation. Shown are the harvest rate changes along with the changes in the proportions of remaining leaves, stems, and roots.

Proportion remaining			Harvest	C flux from soil	Total carbon flux
Leaf (%)	Stem (%)	Root (%)	($t\,C\,ha^{-1}$)	($t\,C\,ha^{-1}$ in 1 yr)	($t\,C\,ha^{-1}$ in 10 yr)
100	100	100	0	34.0	9.5
80	80	80	43.8	54.5	20.4
60	60	60	87.7	75.0	31.4
50	50	50	109.6	86.3	38.3
40	40	40	131.5	95.5	42.3
20	20	20	175.4	116.0	53.2
0	0	0	219.2	136.4	64.2
0	100	0	43.7	50.5	20.7
100	16.5	100	140.4	106.8	46.9
No disturbance (Forest)			0	18.2	18.1

Disturbance year was 1976. Of the total carbon, 67% was assumed to be released to the atmosphere, with 40% in the 1st year and 27% in the 10th year.

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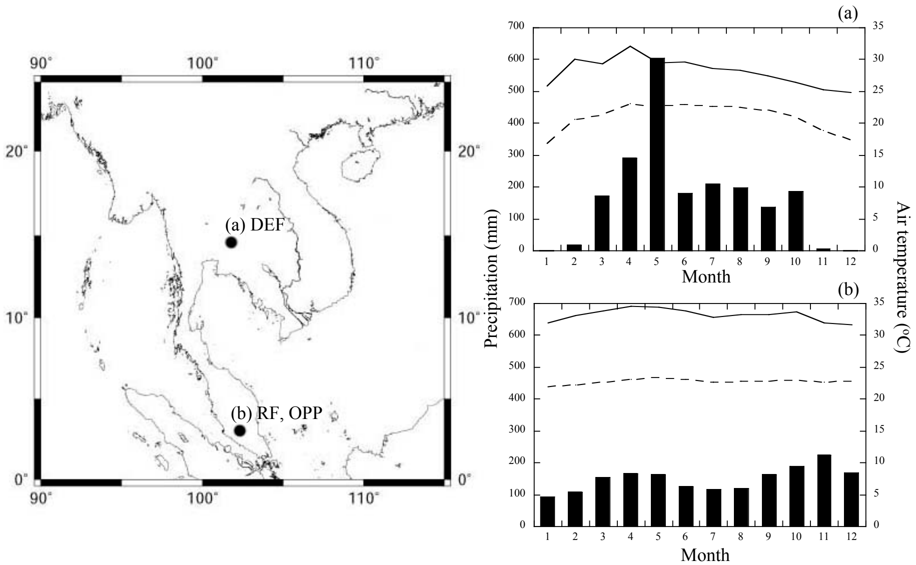

Fig. 1. Locations map of the dry evergreen forest (DEF) in Thailand and the rainforest (RF) and the oil palm plantation (OPP) in Peninsular Malaysia. Climate data for **(a)** the DEF (2001–2003; from the AsiaFlux Database) and **(b)** the RF (1991–1997; from Manokaran et al. 2004). Solid and broken lines show the monthly means of daily maximum and minimum air temperatures, respectively; vertical bars show the monthly precipitation.

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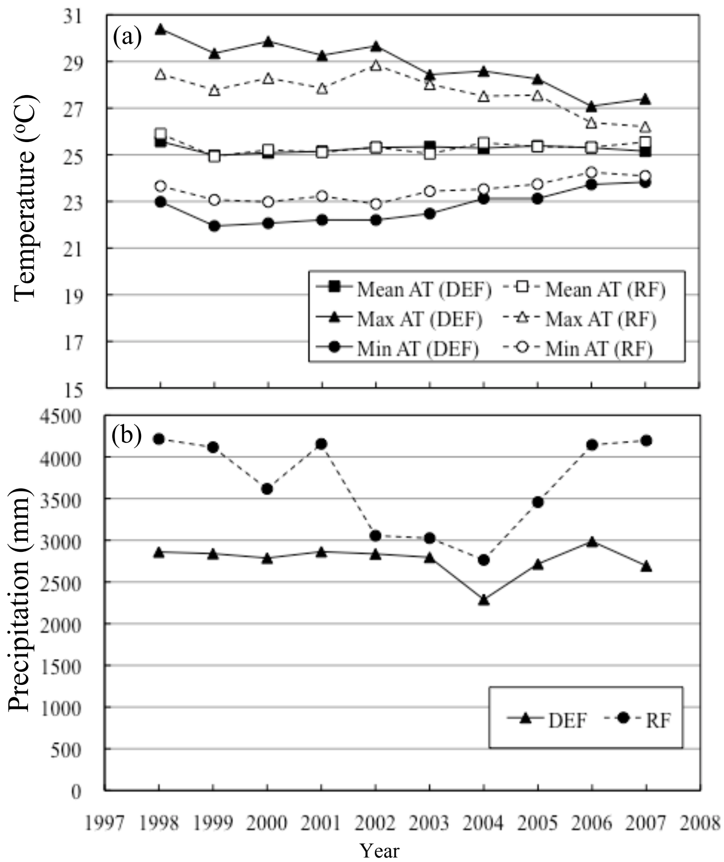

Fig. 2. (a) Annual mean, maximum and minimum air temperatures and **(b)** annual mean precipitation in dry evergreen forest (DEF) in Thailand and the rainforest (RF) in Malaysia based on US National Centres for Environmental Prediction and the US National Centre for Atmospheric Research (NCEP/NCAR) data.

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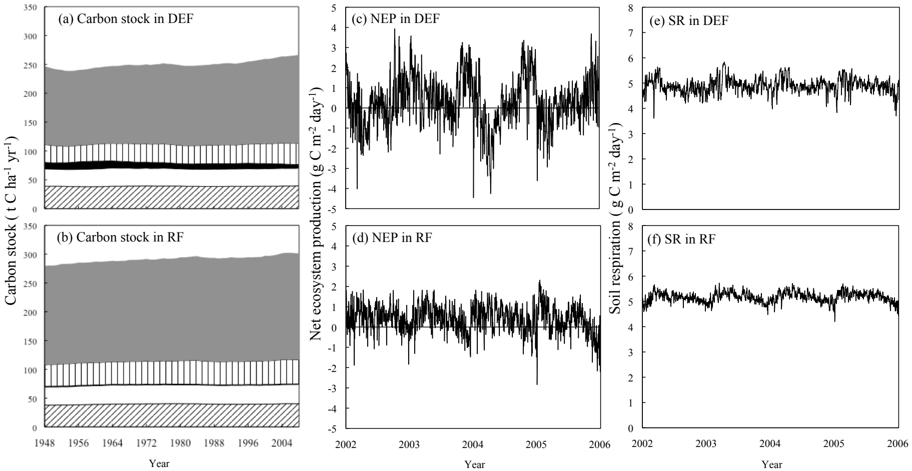

Fig. 3. Temporal variations in **(a, b)** carbon stock, **(c, d)** net ecosystem production (NEP) and **(e, f)** soil respiration (SR) in dry evergreen forest (DEF) in Thailand (top) and the rainforest (RF) in Malaysia (bottom) simulated by the VISIT model. The classified subclasses of C stock were: aboveground biomass, belowground biomass, tree biomass under the canopy, dead biomass and detritus (litter and humus).

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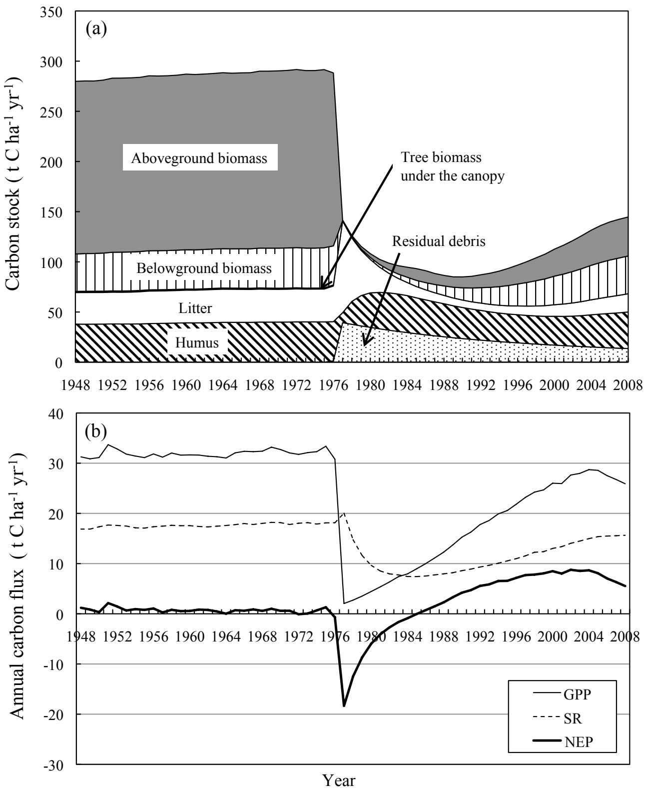

Fig. 4. Temporal variation in C stock **(a)** and C flux **(b)** within the rainforest (RF) during 1948–2008, including land-use conversion from a primary forest to oil palm plantation in 1976. The classified subclasses of C stock are aboveground biomass (gray), belowground biomass (vertical), tree biomass under the canopy (black), dead biomass and detritus (litter: white), humus (diagonal line) and residual debris (dotted). The subclasses of C flux are gross primary production (GPP: solid line), soil respiration (SR: broken line) and net primary production (NEP: bold line).

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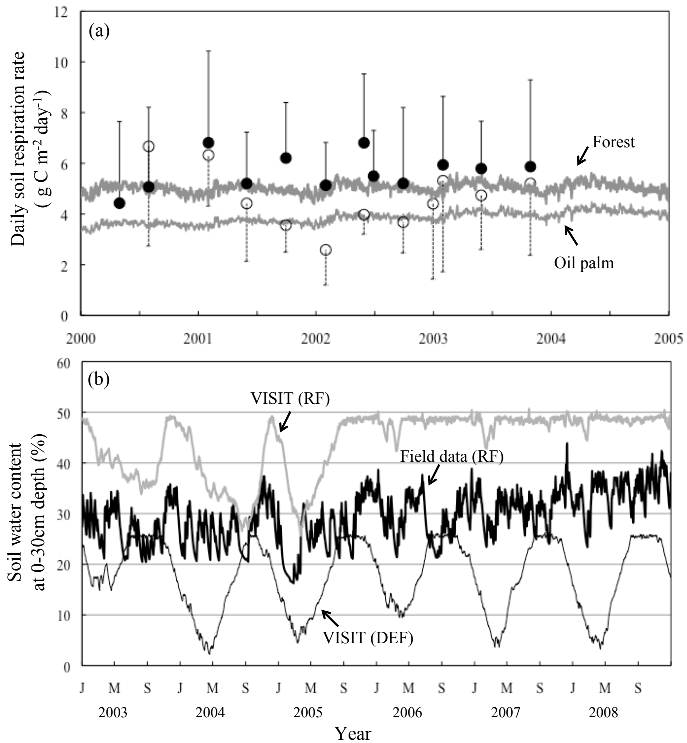

Fig. 5. Comparisons of the VISIT model simulation and field measurements of **(a)** soil respiration rates (SR) in the rainforest (RF) and oil palm plantation (OPP) from 2000 to 2004 and **(b)** daily mean soil water content at 0 to 30 cm depth in RF from 2003 to 2008. In **(a)**, model simulation for RF (bold line), model simulation for OPP (gray line), observed mean SR in RF (filled circles), observed mean SR in OPP (open circles); error bars show the standard deviation ($n = 16$). See Adachi and Koizumi (2009) for field measurements. In **(b)**, field observation from Kosugi et al. (2009) (bold line) and VISIT model estimates in dry evergreen forest (DEF; black line) and RF (gray line).

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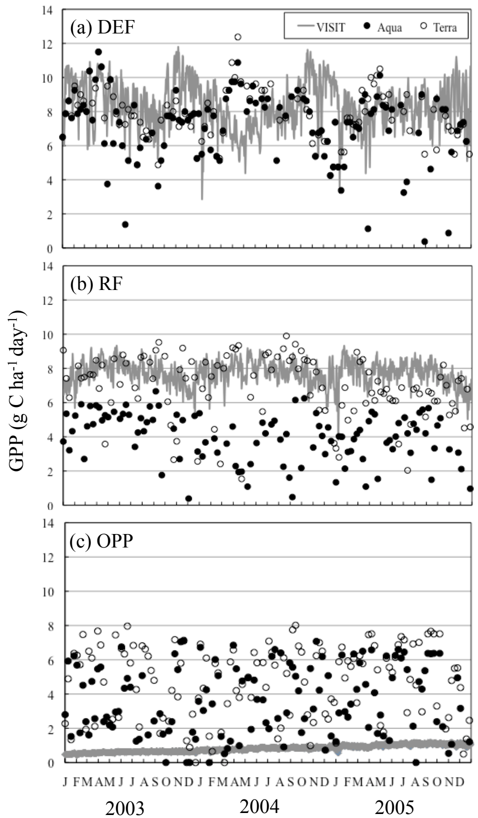

Fig. 6. Seasonal variations in gross primary production (GPP) based on satellite observations (Aqua and Terra MODIS values) and the VISIT model simulation in **(a)** the dry evergreen forest (DEF) in Thailand, and **(b)** the rainforest (RF) in Malaysia, and **(c)** the oil palm plantation (OPP) in Malaysia. The gray line represents the VISIT model simulations; closed and open circles represent Aqua and Terra observations, respectively.

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