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Influence of the Asian Monsoon on net ecosystem carbon exchange in two major plant functional types in Korea

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Abstract

Considering the feedback loops in radiation, temperature, and soil moisture with alterations in rainfall patterns, the influence of the changing monsoon on net ecosystem CO_2 exchange can be critical to the estimation of carbon balance in Asia. In this paper, we examined the eddy covariance CO_2 fluxes observed from 2004 to 2008 in two major plant functional types in KoFlux, i.e., the Gwangneung deciduous forest (GDK) site and the Haenam farmland (HFK) site. The objectives of the study were to (1) quantify the net ecosystem CO_2 exchange (NEE), ecosystem respiration (RE), and gross primary production (GPP), (2) examine their interannual patterns, and (3) assess the mechanism for the coupling of carbon and water exchange associated with the summer monsoon. The GDK site, which had a maximum leaf area index (LAI) of ~5, was on average a relatively weak carbon sink with NEE of $-84\,\mathrm{gC\,m^{-2}\,y^{-1}}$, RE of $1028\,\mathrm{gC\,m^{-2}\,y^{-1}}$, and GPP of $1113\,\mathrm{gC\,m^{-2}\,y^{-1}}$. Despite about 20% larger GPP (of $1321\,\mathrm{gC\,m^{-2}\,y^{-1}}$) in comparison with the GDK site, the HFK site (with the maximum LAI of 3 to 4) was a weaker carbon sink with NEE of $-58\,\mathrm{gC\,m^{-2}\,y^{-1}}$ because of greater RE of $1263\,\mathrm{gC\,m^{-2}\,y^{-1}}$. In both sites, the annual patterns of NEE and GPP had a striking "mid-season depression" each year with two distinctive peaks of different timing and magnitude, whereas RE did not. The mid-season depression at the GDK site occurred typically from early June to late August, coinciding with the season of summer monsoon when the solar radiation decreased substantially due to frequent rainfalls and cloudiness. At the HFK site, the mid-season depression began earlier in May and continued until the end of July due to land use management (e.g., crop rotation) in addition to such disturbances as summer monsoon and typhoons. Other flux observation sites in East Asia also show a decline in radiation but with a lesser degree during the monsoon season, resulting in less pronounced depression in NEE. In our study, however, the observed depression in NEE changed the forest and farmland from a carbon sink to a source in the middle of the growing season. Consequently, the annually integrated values of NEE lies on the low end of the range reported in the literature. Such a delicate coupling between

carbon and water cycles may turn these ecosystems into a stronger carbon sink with the projected trends of less frequent but more intensive rainfalls in this region.

1 Introduction

The Asian continent consists of diverse ecosystems from tropical forests to boreal forests and from temperate grasslands to deserts to tundra. It also contains agricultural lands including mixed croplands and rice paddies. These ecosystems explain about 20% of potential global terrestrial net primary productivity (Melillo et al., 1993; McGuire et al., 2001) and undergo rapid land use and cover change for economic developments. Under the current climate and environmental changes, one of the main concerns lies in the potential role of terrestrial ecosystems in Asia on global carbon balance.

The monsoon climate in Asia has been suggested as a major factor controlling carbon budget. Based on modeling results, Esser (1995) showed that the Asian monsoon region acted as a carbon source to the atmosphere due to land use changes since the mid 19th century. Fu and Wen (1999) reported that variation in monsoon climate had a strong correlation with net primary production (NPP). Yang and Wang (2000) suggested that an increase of precipitation with enhanced clouds reduces seasonal NPP and causes a higher carbon emission. Considering the inter-connected changes in radiation, temperature, and soil moisture with alterations in precipitation, the influence of changing monsoon climate on carbon balance in Asia is critical to ascertain the regional and global carbon balance.

The Asian summer monsoon (June to August) is divided into three subsystems (i.e., Indian monsoon, East Asian monsoon, and western North Pacific monsoon) and the Korean Peninsular is under the subsystem of East Asian monsoon. During the monsoon period such as "*Changma*" (i.e., an intensive rainy periods) and a subsequent typhoon season in Korea, the solar radiation is expected to decrease due to frequent and concentrated rainfalls. The climate normal (averaged for the 1971–2000 period) in solar radiation at two different latitudes in Korea shows a substantial decrease particularly in July during *Changma* (Fig. 1). Kwon et al. (2009) reported that such a reduced radiation caused a significant mid-season depression in net ecosystem carbon exchange (NEE) in two major plant functional types (i.e., a deciduous forest and farmland) at these latitudes. Under the global warming scenario, the precipitation during the East Asian monsoon is to be intensified (except a part of northern region) and the duration of *Changma* is expected to change with more intensive rainfalls in the Korean Peninsula (e.g., Yun et al., 2008). The likely changes in precipitation regime are expected to alter the feedback loop in carbon balance between the atmosphere and the ecosystems in East Asia.

Previous studies indicate diverse determinants controlling the interannual variations in ecosystem carbon budget in different climate regimes. For example, in a boreal coniferous forest, Dum et al. (2007) reported that the interannual variability of carbon exchange was determined by the variations in water table elevation, soil temperature, and summertime solar radiation. The carbon budget of a moist tussock tundra in Alaska was strongly temperature dependent, accentuating the importance of ecosystem respiration (Kwon et al., 2006). In a sagebrush-steppe ecosystem, the interannual variability of NEE was linked to precipitation timing and amount of total annual precipitation (Gilmanov et al., 2006). In oak/grass savanna and grassland ecosystems, the length of the growing season was important (Ma et al., 2007). In an evergreen Mediterranean forest, the interannual variability of NEE was affected by drought and/or defoliation during March–June period (Allard et al., 2008).

In East Asia, based on almost a decade-long record of flux measurements in a deciduous forest, Saigusa et al. (2005) attributed the observed large interannual variations in carbon budget to those in radiation. The seasonal variation of carbon exchange at grazed steppe ecosystem in central Mongolia was closely associated with precipitation and soil moisture (Li et al., 2005). Hirata et al. (2007) ascribed the interannual variation of carbon budget to changes in radiation in the summer and temperature in the spring and summer. Despite the apparent influence of the summer monsoon, however, it is rare to find its clear impact seen in the seasonal and annual variations of NEE from the literature. This may have been due to the confounding effects of the controlling factors with rainfall changes on NEE, the difficulty in separating their roles, and potential errors in gap-filling of the missing fluxes for the rainy periods.

Based on a single year's flux observation in 2006, Kwon et al. (2009) reported a significant "mid-season depression" in NEE and gross primary production (GPP) in both deciduous forest and farmland ecosystems in Korea. The consequent bimodal seasonality was attributed to different timing and intensity of the disturbances encountered during the summer monsoon, the passage of typhoons after *Changma* and the land use management (e.g., crop rotation). The objective of this study is to further scrutinize the patterns and interannaul variability of the observed mid-season depression in NEE by using multi-year observations in two important ecosystems. We have extended the eddy covariance flux measurement and analysis from 2006 to 2008 for the deciduous forest site and added two more years' data (i.e., 2004 and 2008) for the farmland site. The flux observation during the years with low data retrieval rates (e.g., 2004 and 2005 for the deciduous forest site and 2005 and 2007 for the farmland site) were excluded in the data analysis in this study.

2 Materials and methods

2.1 The study sites

Measurements of CO_2 flux were conducted at two KoFlux sites: the Gwangneung deciduous forest (GDK) and the Haenam farmland (HFK). The GDK site is located in the west-central part of the Korean Peninsular (37°45′25.37″ N, 127°9′11.62″ E, 90–470 m.s.l). This site is in a complex, hilly catchment with a mean slope of 10–20°. The vegetation is dominated by an old natural forest of *Quercus* sp. and *Carpinus* sp. (80–200 years old) with a mean canopy height of ∼18m. Soil depth is 0.4 to 0.8 m and soil texture is mainly sandy loam (Lim et al., 2003). Further description of the GDK site can be found in Lee et al. (2007).

The HFK site is located near the southwestern coast of the Korean Peninsula (34°33′17.70′′ N, 126°34′ 7.11′′ E, 13.74 m.s.l.) with heterogeneous land cover types consisting of scattered rice paddies and a different patch of various land use (Moon et al., 2007). Based on our footprint analysis (Kwon et al., 2009) and the Landsat 7 land cover classification from national water resources management system (http://www.wamis.go.kr), the footprint area (600 m×600 m with the flux tower centered) was composed with 44% rice paddy, 27% forest, 19% cropland, and the remaining 10% being grassland, urban and bare soil (Choi et al., 2009). The flux tower was located in cropland, covering with crops and rice paddies as the representative footprint area (Kwon et al., 2009). Topography at the HFK site is relatively flat at regional scale (e.g., ∼20 km) and the site was about 30 km away from the ocean.

2.2 Field measurements

Eddy covariance technique was used to measure CO_2 flux from a 40 m tower at the GDK site and a 20 m tower at the HFK. The fluctuations in wind velocity (e.g., vertical, streamwise, and lateral wind speed) and temperature were measured with a three-dimensional sonic anemometer (Model CSAT3, Campbell Scientific Inc., Logan, Utah, USA) at 10 Hz sampling rates for both sites. To measure the fluctuations in CO_2 concentration, an open-path infrared gas analyzer (IRGA; Model LI-7500, LI-COR Inc., Lincoln, Nebraska, USA) was used for both sites. Half-hourly eddy covariances and the associated statistics were calculated online from 10 Hz raw data and stored on the dataloggers (Model CR-5000, Campbell Scientific Inc.). Other measurements such as net radiation, air temperature, soil temperature, and soil water content were sampled every minute, averaged over 30 min, and logged in the dataloggers (Model CR-23X and CR-5000 at the GDK site and CR-5000 at the HFK site, Campbell Scientific Inc.). More information can be found in Lee et al. (2007), Kwon et al. (2009), and the KoFlux website (http://koflux.org).

In order to determine the climatological characteristics of the studied years for each site, the 30-year normals (averaged for 1971–2000) for solar radiation, air temperature, and precipitation were estimated by interpolation for the GDK site using the closest weather station (KMA #108) using half-hourly data. For the HFK site, the temperature and precipitation normals were obtained directly from the on-site weather station (KMA #261) except solar radiation, which was estimated from the closest weather station (KMA #165). The estimates from the nearby weather stations and the on-site measurements were in good agreement. For example, the relationship between solar radiation from KMA #165 weather station (X_{KMA}) and that from the tower at the HFK site (Y_{HFK}) was $Y_{\mathrm{HFK}}=0.93X_{\mathrm{KMA}}+8$ with R^2 of 0.91 for 2008.

2.3 Leaf area measurements

The measurements of the plant area index (PAI) were conducted every two or three weeks at the GDK site using plant canopy analyzers (Model LAI-2000, LI-COR Inc.) under diffuse light conditions at 12 sampling points with 50×50m grid interval. The PAI measurements were not conducted at the HFK site. Instead, the 1 km global data product from moderate-resolution imaging spectroradiometer (MODIS) was used to illustrate the annual pattern of leaf area index (LAI; Myneni et al., 2002; https://lpdaac.usgs.gov/lpdaac/products/modis_products_table). The additional information (on cloud, aerosol, overall product quality, etc.) provided with MODIS LAI was utilized for quality control.

2.4 Data processing, quality control, and gap-filling

The eddy covariance data were reprocessed, quality-controlled, and then gap-filled using the standardized KoFlux protocol (Hong et al., 2009), which is similar to that of FLUXNET (Papale et al., 2006). The standardized protocol includes planar fit rotation (PFR), WPL correction, spike detection, storage correction, nighttime correction, gap-filling, and the estimation of GPP and ecosystem respiration (RE). The PFR was applied to determine the angles necessary to place the sonic anemometer into a streamwise coordinate system (Wilczak et al., 2001; Yuan et al., 2007). In order to consider the effect of rolling topography around the flux towers, the PFR was applied to each 30° of wind direction sectors. The flux was corrected for the variation in air density due to simultaneous transfers of water vapor and sensible heat (Webb et al., 1980).

After the quality control, the data retrieval rate was 52–74% at the GDK site and 55–85% at the HFK site during the study period. In order to fill the missing CO_2 fluxes, the meteorological data were prefilled. At the GDK site, solar radiation (R_g), air temperature (T_a), vapor pressure deficit (VPD), and wind speed were filled from the linear relationships with either the auxiliary data observed at the site or the data observed at the second tower (∼1.2km apart). The meteorological data at the HFK site were filled with the data from the KMA weather station at the site. For storage correction for CO_2 flux calculation (Papale et al., 2006; Kwon et al., 2009), the CO_2 concentration data were gap-filled using those measured simultaneously by the profile system (i.e., a closed-path system, Model LI-6262, LI-COR; Yoo et al., 2009) at the GDK site. The mean diurnal variation method was used to fill the gaps at the HFK site because no additional CO_2 concentration measurements were available.

Spike detection was conducted and then storage correction was applied to the CO_2 flux dataset, following Papale et al. (2006). Gap-filling was performed for nighttime ($R_g<1\,\mathrm{W\,m^{-2}}$) and daytime ($R_g\geq1\,\mathrm{W\,m^{-2}}$) data separately. Instead of using the u^*-threshold filtering technique (e.g., Gu et al., 2005), we adopted the method suggested by van Gorsel et al. (2007) to estimate nighttime CO_2 flux (RE). This method selects the maximum nocturnal CO_2 flux (i.e., $\mathrm{RE_{max}}$) in the early evening when the sum of the turbulent flux and change in storage of CO_2 becomes maximum and the advection is relatively negligible. The $\mathrm{RE_{max}}$ was used to derive a temperature response function for the CO_2 fluxes. In this study, the $\mathrm{RE_{max}}$ occurred mostly from 18:00 to 20:00 h and all the available $\mathrm{RE_{max}}$ data over a fixed period (e.g., 20 days for the GDK site and 32 days for the HFK site) were used to estimate RE using the exponential regression model of Lloyd and Taylor (1994).

Marginal distribution sample (MDS), which is an advanced look-up table method, was used to do the gap-filling for the daytime CO_2 data (Reichstein et al., 2005). NEE data were binned by meteorological variables controlling NEE such as net radiation (R_n), T_a, and VPD over a time-window with the same number of days used for RE estimation. The binning intervals for the variables were 40 $\mathrm{W\,m^{-2}}$ for R_n, 2.5°C for T_a, and 0.5 kPa for VPD. When there was a missing NEE value, it was replaced with the binned NEE with the similar meteorological conditions. Finally, the half-hourly data are aggregated to make daily to annual values of NEE, RE, and GPP (=NEE−RE).

The uncertainty associated with a given gap-filling method was assessed by comparing the annual estimation of NEE, RE, and GPP in 2006 between the KoFlux and FLUXNET protocols. The comparison illustrated a good agreement with the difference of 20% for the individual carbon components, and unusual peaks of GPP and RE generated by the FLUXNET protocol during the non-growing season were absent with the KoFlux protocol (data not shown). Different artificial gaps (i.e., 30–50%) were randomly created to investigate the sensitivity to the gap-filling method for the annual estimation of NEE. The annual NEE varied about 20 $\mathrm{g\,C\,m^{-2}\,y^{-1}}$ with the increasing artificial gaps (Hong et al., 2009). These results suggest that the artificial errors associated with the gap-filling are relatively minor in the estimation of annual carbon budget in this study.

2.5 Energy budget

Energy budget closure was assessed using energy balance ratio ($\mathrm{EBR}=\sum(R_n-G)/\sum(LE+H)$, here G, LE, and H are ground, latent, and sensible heat fluxes, respectively; Wilson et al., 2000) calculated from daily integrated values of each energy flux component (Fig. 2). The EBR varied from 0.5 to 1.8 with an average of 0.68 at the GDK site and 0.7 to 2.0 with an average of 0.92 at the HFK site throughout the measurement periods (see Kang et al., 2009 for more details). The values of the EBR were within the ranges reported from other forest and agricultural sites (e.g., Wilson et al., 2000). The water balance at the site is an additional constraint to examine the quality of flux measurements by the same eddy covariance system. At the GDK site, it was closed within 10%, providing more assurance in the quality of the flux measurements used in this study (see Fig. 3 in Kang et al., 2009).

3 Result

3.1 Climate conditions

The annual averages of T_a at the GDK and HFK sites had a minor year-to-year variation ($<0.5^\circ$C) during the measurement period (Table 1). Annual precipitation (P) varied from 1356 to 1625 mm with an average of 1487 mm at the GDK site, and from 1060 to 1585 mm with an average of 1341 mm at the HFK site. Intensive rainfalls occurred mainly during the summer season including *Changma*, defined as the intensive rainy spell in summer (mostly from late June to July), accounting 53–74% of the annual P. The annual sums of R_g at both sites also showed a minor variation (of $<200\,\mathrm{MJ\,m^{-2}}$) from year to year. The annual mean of surface soil water content (SWC) also changed little at the GDK site, whereas that of SWC in 2008 was low at the HFK site, reflecting the decreased rainfalls and the absence of typhoons encountered during and after the summer monsoon.

The 30-year normals of T_a and P are, respectively 9.9°C and 1344 mm at the GDK site and 13.3°C and 1306 mm at the HFK site. In general, T_a was about 2–3°C higher and P was 10–15% higher than the normal for both sites. Monthly deviations of P and R_g from their 30-year normals are shown in Fig. 3. At the GDK site, P showed positive deviations during *Changma* but negative deviations after *Changma* from August to October in 2006 and 2008, corresponding to variation in SWC (Table 1). On the contrary, the year of 2007 had a negative deviation during *Changma*, resulting in lower SWC at the site, and had a positive deviation in August and September due to frequent typhoons. The HFK site showed a positive deviation during *Changma* for all three years. In 2008, however, the HFK site had lower P from July to September, resulting in a decreasing annual amount of P (about 20%) compared to the normal climate condition and consequently a fall drought. The deviation of monthly averaged R_g generally followed the opposite patterns of P deviation. Monthly T_a was mostly higher than the corresponding monthly normal for both sites (not shown).

The overall seasonal trend of PAI was similar each year at the GDK site: the leaf-out occurred in early to mid April and grew to the full size around mid June with PAI of 5–6 (Fig. 4). The consistent rainfall events of substantial amount and intensity in summer resulted in a decrease of PAI to almost 4. After the leaf-fall, PAI declined to about 1.2 in the winter, suggesting that the maximum LAI in June would be 4 to 5. The subtle differences in PAI among the study years are worth noting such as a consistently higher PAI in 2006 compared to 2007 throughout the year and the earlier leaf-out with a rapid increase in the spring of 2008. At the HFK site, the variation of MODIS LAI was related with the management practice (i.e., two crop rotation) conducted. MODIS LAI reached around 1 in late April but declined to <1 in late May to early June, corresponding to the growth of barley in spring and the harvest in late May. MODIS LAI in June 2004 and 2006 showed an earlier increase than in June 2008 and this may be related with the different timing of rice transplanting each year. During the peak growth stage of rice and other crops (in July to August), MODIS LAI showed the maximum of 3–4 and the year 2008 had a higher LAI than 2006. The typical values of maximum LAI reported for croplands are on average ~4 (e.g., Scurlock et al., 2001).

3.2 Seasonal and interannual variations of NEE, RE, and GPP

GDK site: each year, the daily NEE demonstrated a bimodal seasonal pattern with a mid-season depression in carbon uptake, as has been observed by Kwon et al. (2009). Until the leaf-out in mid April, the forest ecosystem was a carbon source. With rapidly increasing LAI in May to early June, NEE reached its first peak of carbon uptake (-4 to $-6\,\mathrm{gC\,m^{-2}\,d^{-1}}$). Then in June, the mid-season depression in NEE started and turned the forest ecosystem to a weak carbon sink or even a carbon source ($\sim 2\,\mathrm{gC\,m^{-2}\,d^{-1}}$) during the summer monsoon. In September, the second peak of carbon uptake occurred but was less pronounced (-2 to $-3\,\mathrm{gC\,m^{-2}\,d^{-1}}$) (Fig. 5). The distinctive phases are reflected in the cumulative NEE (Fig. 6), showing a consistent transition during *Changma* from higher rate of carbon uptake in May-June to a lower rate in July–October. The relative contribution of the first and the second peaks to the annual carbon sink strength was on average 70 and 30%, respectively.

The variation of RE followed the general trend of T_a (and soil temperature, not shown) with its maximum in July and August. A bimodal pattern was not observed but the magnitude of RE decreased during the mid-season depression due to either excessive rainfalls (and thus high SWC) or lack of rainfalls (and thus dry spell with low SWC) (e.g., Chae, 2008). The influence of higher T_a in March and April in 2008 was reflected in an early and rapid rise in RE. As shown in the trend of NEE, GPP manifested a bimodal pattern with the first peak of 6 to $8\,\mathrm{gC\,m^{-2}\,d^{-1}}$ in May-early June and the second peak of $4\,\mathrm{gC\,m^{-2}\,d^{-1}}$ in September and October. During the mid-season depression, GPP decreased substantially to $<2\,\mathrm{gC\,m^{-2}\,d^{-1}}$.

HFK site: interannual patterns of NEE were similar for the three years. The farmland was a carbon source until February and became a carbon sink (of -1 to $-4\,\mathrm{gC\,m^{-2}\,d^{-1}}$) from April to May (the first peak of a carbon sink) during the growing season of barley crop. With the barley harvest followed by weeding and sowing, the farmland became again a carbon source of 1 to $3\,\mathrm{gC\,m^{-2}\,d^{-1}}$ (i.e., a mid-season depression) in late May to early July. During the growing season of rice and other crops in the summer and fall, NEE reached the second peak of carbon uptake of $-6\,\mathrm{gC\,m^{-2}\,d^{-1}}$. After the rice harvest in late September to early October, the farmland remained as a carbon source. Theses phases are well represented in the patterns of the cumulative NEE (Fig. 6). The relative contribution of the first and second peaks to the annual carbon sink strength was on average 10 and 90%, respectively. As observed at the GDK site, the HFK site also exhibited a bimodality but the timing, magnitudes, and patterns were different. The interannual variation of RE was similar for the three years, following the trend of T_a. Consequentially, the variation of GPP also showed the similar bimodal peaks each year.

3.3 Annual carbon budget

GDK site: annually integrated values of carbon budget components varied from year to year, ranging from −246 to 66 $\mathrm{g\,C\,m^{-2}\,y^{-1}}$ for NEE, from 947 to 1034 for RE, and from 1020 to 1281 $\mathrm{g\,C\,m^{-2}\,y^{-1}}$ for GPP (Table 2). For the whole three years studied here, the mean values of NEE, RE, and GPP were, respectively −84, 1028, and 1113 $\mathrm{g\,C\,m^{-2}\,y^{-1}}$, indicating that about 8% of GPP was sequestered by this forest ecosystem (Fig. 6).

HFK site: the annual NEE, RE, and GPP ranged from −172 to 10 $\mathrm{g\,C\,m^{-2}\,y^{-1}}$, from 1222 to 1293 $\mathrm{g\,C\,m^{-2}\,y^{-1}}$, and from 1212 to 1465 $\mathrm{g\,C\,m^{-2}\,y^{-1}}$, respectively (Table 2). The three-year average of GPP was 1321 $\mathrm{g\,C\,m^{-2}\,y^{-1}}$, which was about 20% greater than that at the GDK site. However, the averaged RE (of 1263 $\mathrm{g\,C\,m^{-2}\,y^{-1}}$) was as large as that of GPP, resulting in the averaged NEE (of −58 $\mathrm{g\,C\,m^{-2}\,y^{-1}}$) lower than that of the forest. This result shows that RE was an important determinant of the annual NEE in this farmland ecosystem.

4 Discussion

The observed mid-season depressions of NEE at the GDK site are mainly the results of intensive and consecutive rainfalls that reduced R_g during the summer monsoon. Accordingly, the duration of the mid-season depression shifted with changes in the frequency and intensity of rainfall events. For example, even after the typical *Changma* in July, unusually heavy rainfalls continued in August and September in 2007, which produced a prolonged and pronounced mid-season depression in NEE (Figs. 5 and 6). Consequently in 2007, the forest turned into a carbon source. In 2008, the weakened mid-season depression brought the forest back to a moderate carbon sink. This was associated with lower numbers of rainy days (e.g., 45 days in 2006, 46 days in 2007, and 38 days in 2008 from June to August) with more intermittent rainfall patterns (e.g., 12 consecutive rainy days in 2006, 14 days in 2007, and 8 days in 2008), resulting in higher R_g during the summer (Table 1).

At the HFK site, the mid-season depression of NEE was associated more with management intervention throughout the growing seasons of barley, rice, and other crops. The decreased R_g during the summer monsoon also contributed to the reduced NEE later in the season. The rice at the early growth stage under irrigated conditions seemed less affected by the reduced radiation especially during *Changma*. The latter half of the year 2008 was characterized by local droughts in the southern part of Korea due to the decline in precipitation from July to September and the absence of typhoons (Fig. 3). The patterns and magnitudes of NEE, however, differed marginally from those observed in previous years. This was due to human intervention through irrigation to maintain rice growth under water-stressed conditions. Aubinet et al. (2009) also indicated the significance of intercropping and farmers' interventions on carbon sequestration in a cropland with rotation cycle. Overall, the changes in the patterns of phenology and mid-season depression at the HFK site were closely related to the combined effects of management intervention (e.g., sowing, transplanting, harvest, and applications of fertilizer and pesticide) and natural disturbances (e.g., *Changma*, drought, and typhoons).

Despite the prevalent influence of summer monsoon on the annual NEE observed in our study, such a distinct depression in NEE in the middle of the season has been seldom reported in other regions of the monsoon Asia. Hirano et al. (2003) and Hirata et al. (2008) reported a reduced NEE in August in their multi-year observations from a larch plantation in Tomakomai, Japan. They attributed, however, the reduced NEE to the enhanced RE with increased soil temperature. At Takayama, Japan, Saigusa et al. (2005) presented the decreased carbon uptake during the rainy season (in July) at a secondary deciduous forest but the degree of the decreasing NEE was not as prominent as seen in this study. We examined the seasonal patterns of solar radiation and precipitation for these two sites by obtaining the monthly data from Japan Meteorological Agency (http://www.data.jma.go.jp/). Long-term solar radiation data were not available at Tomakomai and the data at Muroran (i.e., the nearest weather station at about 70 km from Tomakomai) were used for the analysis. Precipitation considerably increased at both sites during the Asian summer monsoon (Fig. 7). Only the Takayama station demonstrated a weak bimodal seasonality in R_g associated with the summer monsoon. The reductions in R_g at both sites were, however, not as distinct as those observed at the two KoFlux sites reported in this study.

The causation of the observed mid-season depression in NEE can be manifold and includes, *inter alia*, reduction in GPP and NEE under low light conditions, increase in RE under warmer conditions, reduction in RE under anaerobic soil condition with excessive soil moisture, and defoliation under heavy rainfalls. Changes in precipitation are closely inter-connected with those in radiation, temperature, and soil moisture, thus the confounding effects drive the carbon dynamics in these complex ecosystems.

It should be noted that the periods associated with the mid-season depression reported in this study are those when the field measurements were largely missing due to rainfall events, for which the gap-filling method was employed. This might have resulted in biases in the estimation of carbon budget component, especially when the mean diurnal variation method was used for the gap-filling because it used the data representing mostly clear and sunny conditions. Considering NEE being the subtle balance between two large carbon fluxes, the RE estimation (based on a relationship between temperature and nighttime carbon flux) may cause additional errors in ascertaining the observed mid-season depression. In order to scrutinize the processes causing mid-season depression, a careful examination is needed with independent datasets (i.e., NEE and RE) collected during the rainy periods (instead of gap-filled data). Measuring fluxes in the rain is therefore an important issue in monsoon regions, for which attempts have been made recently by employing closed-path sensors in conjunction with a modified aerodynamic method, or instance (e.g., Dias et al., 2009).

The net CO_2 uptake at the GDK site averaged $84\,\mathrm{g\,C\,m^{-2}}$ with a large variability during the study years (Table 2 and Fig. 6). Plant phenology was different to some extent for the three years. The leaf-out occurred on 12 April 2006 and 15 April 2007, whereas in 2008 it occurred on 8 April. The earlier leaf expansion may have yielded a longer period of a carbon uptake during the first peak. This is also supported by the rapid increase of LAI during April in 2008 (Fig. 4). The extended length of the growing season, in conjunction with the weakened mid-season depression, probably resulted in a substantial increase in carbon uptake in 2008 (Table 2 and Fig. 5). Other data, however, did not seem to support such an interpretation. For example, the annul growth rates of the major species at the site were, respectively 5.2 and 5.5 mm y^{-1} in 2006 and 2007, but it was 3.44 mm y^{-1} in 2008 (Jong-Hwan Lim, personal communication, 2009). Despite the similar growth rates in 2006 and 2007, the annual carbon budget changed its sign from carbon sink in 2006 to source in 2007. In addition to the extended period of mid-season depression of carbon uptake, the net carbon loss in 2007 is also attributed to a lower LAI. The month-long dry spell encountered in the early summer (e.g., no rain in June) may also have played a role here (Table 1 and Fig. 5).

The annual NEE of the deciduous forest at the GDK site was near the low end of the ranges reported from other forests in similar latitudes in the monsoon Asia. For deciduous forests, Saigusa et al. (2005) reported the annual NEE varying from −59 to $-346\,\mathrm{gC\,m^{-2}\,y^{-1}}$ whereas Shibata et al. (2005) reported NEE ranging from −219 to $-288\,\mathrm{gC\,m^{-2}\,y^{-1}}$. For coniferous forests, Ohtani et al. (2005) found NEE varying from −318 to $-459\,\mathrm{gC\,m^{-2}\,y^{-1}}$, which is similar to the range (−316 to $-424\,\mathrm{gC\,m^{-2}\,y^{-1}}$) reported by Yu et al. (2006).

The farmland at the HFK site exhibited virtually a balance in carbon budget except 2008 when it became a weak carbon sink. Again, the occurrence of mid-season depression in NEE played a major role in this farmland ecosystem. On the other hand, larger magnitudes of NEE have been reported for other agricultural sites in monsoon Asia (e.g., −102 to $-301\,\mathrm{gC\,m^{-2}\,y^{-1}}$ for rice paddies: Miyata et al., 2005; −198 to $-318\,\mathrm{gC\,m^{-2}\,y^{-1}}$ for croplands: Yoshikoshi et al., 2006; Yu et al., 2006). In terms of the relationships between the major environmental factors and the annual carbon budgets over the cross-biomes (Kato and Tang, 2008), NEE, RE and GPP at both GDK and HFK sites fall onto lower ranges with given P and T_a except the relationship between RE and T_a (Kwon et al., 2009).

5 Summary and conclusions

We reported the seasonal variations of ecosystem carbon budget observed in the two major plant functional types in Korea, that were very sensitive to hydrometeorological changes associated with the Asian monsoon and the local land use management (e.g., crop rotation, irrigation). During the three-year measurement periods, the deciduous forest and farmland ecosystems acted as a weak carbon sink or even a source with the annual NEE ranging from -246 to $66\,\mathrm{gC\,m^{-2}}$ for the forest and from -173 to $10\,\mathrm{gC\,m^{-2}}$ for the farmland. Based on the analysis of a global data across ecological gradient (Baldocchi, 2008), the relationships between GPP and RE at the GDK and HFK sites showed the characteristics of the disturbed ecosystems.

According to the studies on precipitation changes in the Asian monsoon (e.g., Kripalani et al., 2007; Lee et al., 2008; Yun et al. 2008), alterations in precipitation magnitude and patterns occur not only on local scale but also on continental scale through the *Meiyu-Changma-Baiu* band covering the China-Korea-Japan region in East Asia. The results of our study encourage both scientists and policymakers to better appreciate the sensitive couplings between land and water, between the carbon cycle and the hydrological cycle, and between the integrated ecosystem management and climate change (e.g., Battin et al., 2009).

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Table 1. Monthly average of air temperature (T_a) and soil water content (SWC), and monthly sum of precipitation (P) and solar radiation (R_g) for the GDK site (2006 to 2008) and for the HFK site (2004, 2006, and 2008).

	T_a (°C)	SWC (%)	P (mm)	R_g (MJm^{-2})	T_a (°C)	SWC (%)	P (mm)	R_g (MJm^{-2})	T_a (°C)	SWC (%)	P (mm)	R_g (MJm^{-2})
GDK		2006				2007				2008		
1	–1.6	24	40	252	–0.8	20	2	268	–2.9	24	7	260
2	–1.4	25	17	321	3.0	20	8	316	–2.7	18	8	371
3	3.7	25	22	468	5.2	23	107	351	6.5	24	50	422
4	10.6	26	68	401	10.7	24	46	478	13.5	25	28	515
5	17.9	27	158	557	17.7	25	157	554	17.7	23	82	572
6	22.1	27	197	499	23.2	19	7	541	21.8	25	195	560
7	24.3	34	910	295	24.8	26	233	404	26.7	33	630	362
8	27.8	25	94	533	27.3	28	506	366	26.7	32	292	496
9	20.6	20	18	462	22.0	29	234	303	23.4	28	121	446
10	17.4	14	38	352	14.6	27	30	358	17.0	19	13	375
11	7.4	19	52	238	6.0	–	20	276	7.6	20	32	256
12	0.3	–[a]	12	229	0.7	–	6	202	0.9	28	23	218
	12.4	24	1625	4703	12.9	24	1356	4417	13.0	25	1480	4852
HFK		2004				2006				2008		
1	1.2	33	29	284	2.6	35	15	247	2.4	–	48	230
2	4.5	33	41	348	2.7	37	31	319	1.2	–	17	371
3	7.2	33	51	472	7.0	36	34	505	8.1	–	62	469
4	12.7	33	61	541	12.2	38	121	471	13.3	25	56	475
5	18.4	34	111	498	18.1	37	235	472	18.1	26	195	560
6	23.1	32	192	499	22.9	37	244	498	21.8	29	344	420
7	28.1	36	313	523	26.7	38	375	387	28.4	26	127	499
8	28.9	–	429	562	29.4	24	136	578	27.6	20	95	574
9	24.6	35	275	387	21.3	25	79	428	24.2	20	33	406
10	16.8	24	1	491	18.5	27	39	439	18.0	19	34	416
11	11.4	30	58	323	11.8	31	34	270	10.7	24	41	270
12	6.4	32	27	272	5.3	35	37	247	5.0	26	9	265
	15.3	32	1585	5200	14.9	33	1378	4940	14.9	24	1060	4954

[a] Indicates "not available"

Table 2. Seasonal and annual budgets of net ecosystem CO_2 exchange (NEE), gross primary production (GPP), and ecosystem respiration (RE) for the GDK and HFK sites.

	Year		2006			2007			2008	
		NEE	GPP	RE	NEE	GPP	RE	NEE	GPP	RE
GDK	Winter	59	74	133	88	109	197	16	148	164
	Spring	–13	245	233	31	254	284	–73	358	285
	Summer	–121	422	302	–75	412	337	–154	490	336
	Fall	1	279	280	22	261	284	–36	285	249
Annual Sum		–73	1020	947	66	1037	1103	–246	1281	1034
	Year		2004			2006			2008	
HFK	Winter	66	166	231	86	142	229	56	169	224
	Spring	36	286	322	–16	310	294	–39	371	333
	Summer	–175	567	392	–145	514	369	–208	594	386
	Fall	60	266	327	85	247	332	19	331	350
Annual Sum		–13	1287	1274	10	1212	1222	–172	1465	1293

Unit of NEE, RE, and GPP is (gCm^{-2}) per season or year.
Each season includes months as follow: January, February, and December for winter; March to May for spring; June to August for summer; and September to November for fall.

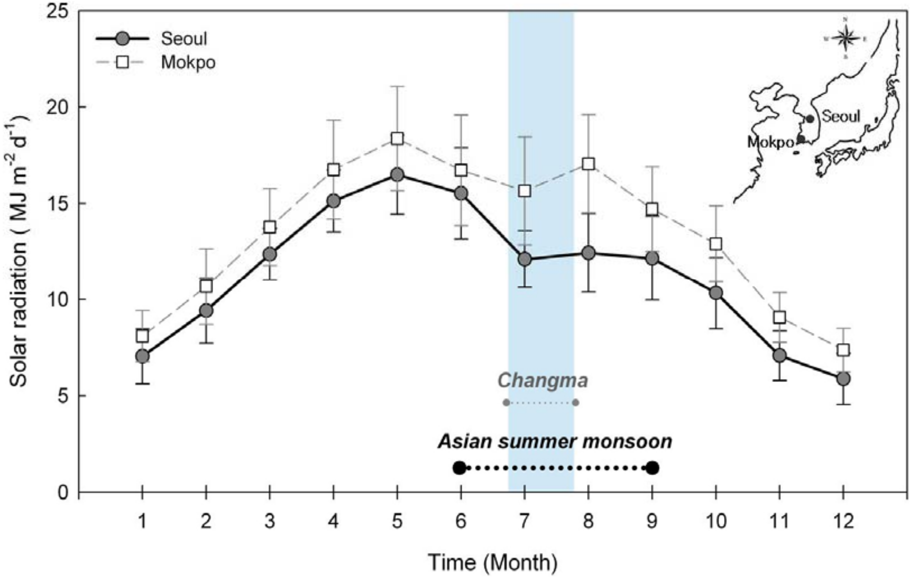

Fig. 1. Variations of 30-year (1971–2000) averaged daily sum of solar radiation over each month at Seoul and Mokpo in Korea. Seoul is located near the deciduous forest (the GDK site), while Mokpo is located near the farmland site (the HFK site).

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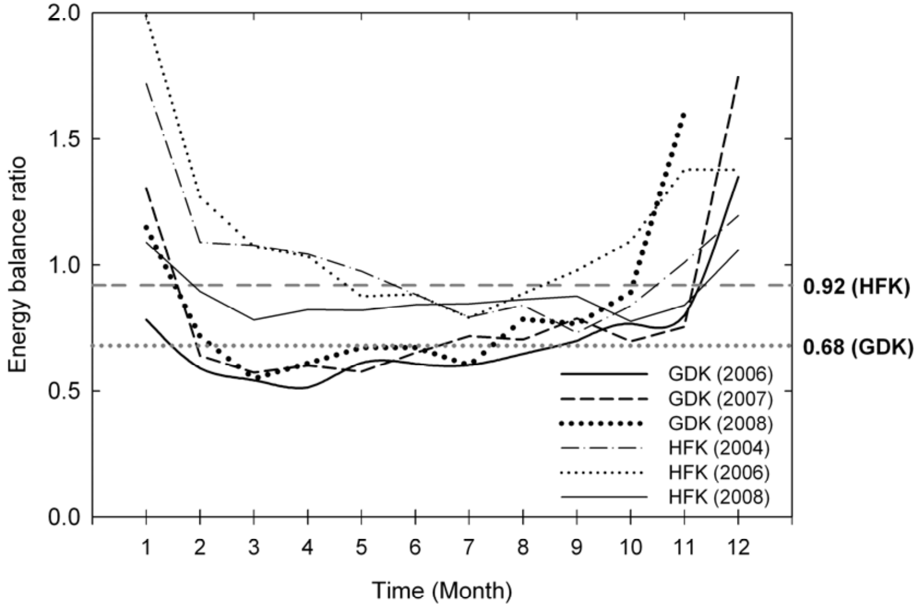

Fig. 2. Monthly energy balance ratio (EBR) at the GDK site (2006 to 2008) and at the HFK site (2004, 2006, and 2008). The short-dotted line represents the annual average value for the GDK site, whereas the long-dotted line represents the annual average for the HFK site.

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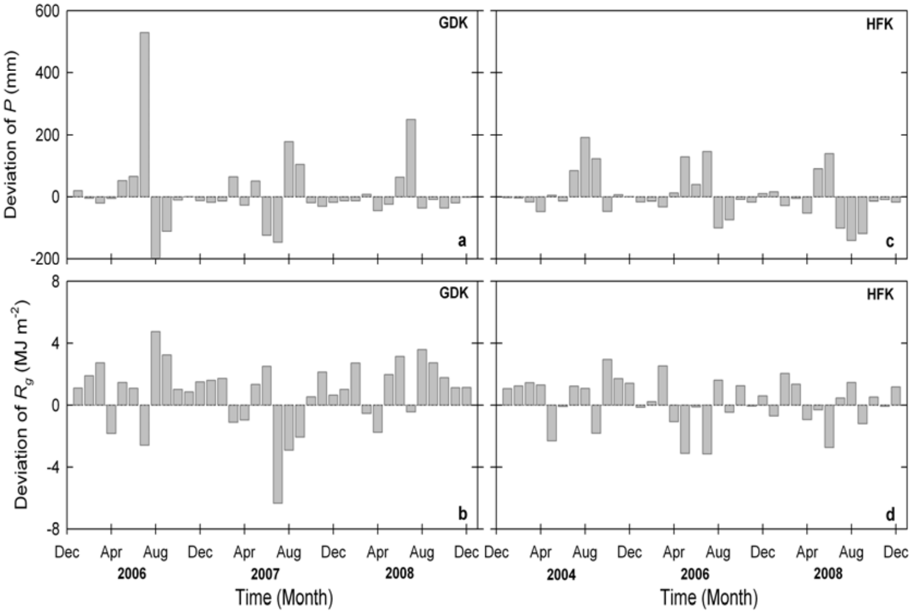

Fig. 3. Deviation of cumulative monthly precipitation (P) from the climate normal sum and deviation of mean monthly radiation (R_g) from the climate normal mean at the GDK and HFK sites. The climate normal was calculated using the data from 1971–2000.

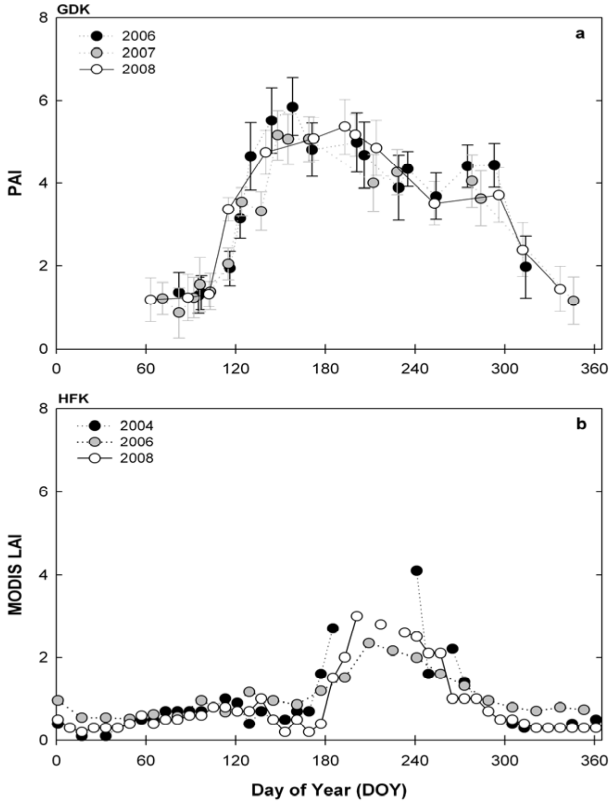

Fig. 4. Seasonal variation of plant area index (PAI) at the GDK site (2006 to 2008) and leaf area index (LAI) at the HFK site (2006 and 2008). PAI was measured from a plant canopy analyzer (LAI-2000) at the GDK site and the error bar indicates standard deviation of each measurement. LAI was obtained from moderate-resolution imaging spectroradiometer (MODIS) at the HFK site.

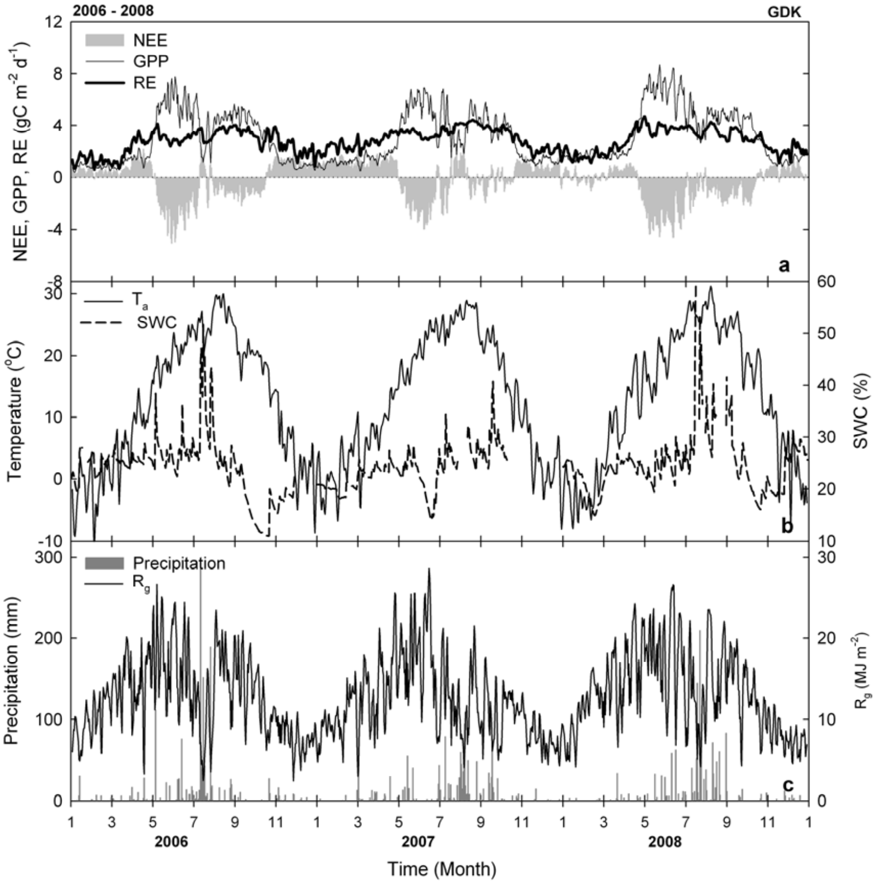

Fig. 5. Seasonal variation of net ecosystem exchange (NEE), gross primary productivity (GPP), ecosystem respiration (RE), air temperature (T_a), soil water content (SWC), precipitation, and solar radiation (R_g) at the GDK site (2006 to 2008) and the HFK site (2004, 2006, and 2008).

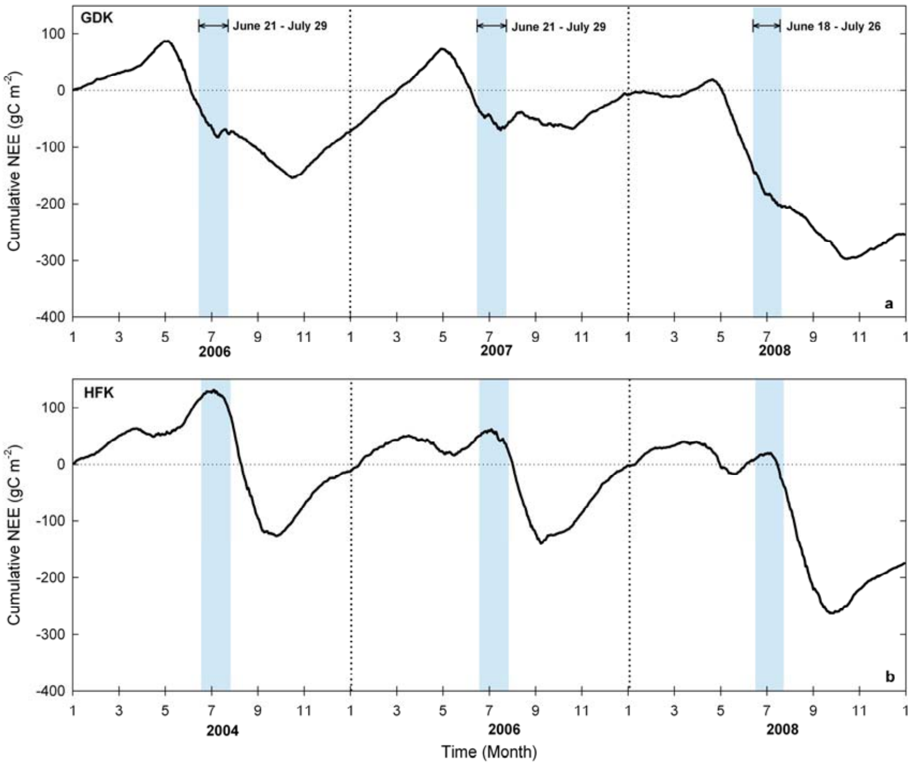

Fig. 6. Cumulative net ecosystem exchange (NEE) at the GDK site (2006 to 2008) and the HFK site (2004, 2006, and 2008). The shaded column indicates the period of *Changma* occurred each year.

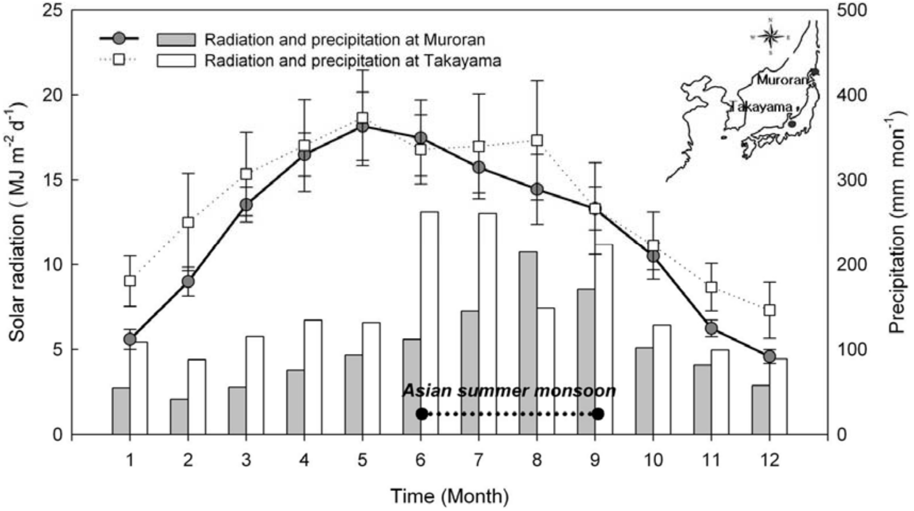

Fig. 7. Variations of averaged daily sum of solar radiation and monthly sum of precipitation over each month at Muroran and Takayama in Japan. The period of solar radiation data used was 1973–2003 for Muroran and 1961–1973 for Takayama (http://www.data.jma.go.jp/).