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REVIEW

A review of tower flux observation sites in Asia

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Abstract Aggregating and sharing the metadata of flux observation sites results in a strong collaboration among various fields of study. Such data sharing will also be a part of the future design of a tower flux observation network in Asia. The aim of this review is to comprehend the state of tower flux observation sites in Asia. There are 109 tower flux observation sites in Asia including 51 forest sites. There are more new sites under construction in Asia than in America and Europe. These sites range from the taiga in Siberia to the rainforest in Southeast Asia, and from the equatorial to polar Koeppen climate zones. There are many highly humid areas in Asia, not only at low latitudes but also at middle latitudes. This climate condition has developed unique vegetation such as lucidophyllous (evergreen broadleaf) forest, which is distributed in warm areas with high precipitation in the growing season. However, there are only a few observations taking place in lucidophyllous forest. Rice paddy fields are also unique land cover in Asia. It is important to accumulate long-term data for rice fields with their management records, because plant activity depends highly on both climate conditions and land-use management. Flux data, especially net ecosystem exchange and related elements, are used for widespread studies not only within the flux-research community but also in other fields of study, for example remote sensing. At present, however, both the quantity and quality of the data are not sufficient for these studies. Regarding the quantity, there are many recently established sites that have not published data yet; regarding quality, flux data include uncertainties caused by methodological problems. Flux researchers are required not only to obtain flux data but also to improve their quality. Meanwhile, data users must understand there are still uncertainties in flux data.

Keywords Asia · Carbon dioxide · Climate · Flux observation site · Vegetation

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Introduction

The taking of micrometeorological flux measurements has expanded in Asia since the 1960s in croplands (Seo and Yamaguchi 1968) and since the 1970s in forest (Suzuki and Fukushima 1976; Hattori et al. 1981) mainly for determining sensible and latent heats. Historically, flux observations were mostly conducted using conventional micrometeorological methods, for example the Bowen ratio and aerodynamic methods. The eddy covariance method was introduced to mainstream flux observations for various terrestrial ecosystems (Maitani and Ohtaki 1989; Yamanoi and Ohtani 1992; Tsukamoto 1993) as the performance of computers and instruments improved and facilitated measurement of turbulent fluctuations in the early 1990s.

Under the strategy of the Global Energy and Water Cycle Experiment (GEWEX), the GEWEX Asian Monsoon Experiment (GAME) has been implemented since 1996. In this big project, measurements of sensible and latent heat fluxes were conducted in a wide area from taiga in Siberia to rainforest in Thailand. The project produced significant results (The Sixth GAME Conference Program Committee 2004), and in the late 1990s CO_2 flux became a generally measured observable, similar to sensible and latent heat fluxes (Yasuda et al. 1998; Yamamoto et al. 1999).

Although there are presently more than 100 tower flux observation sites in Asia and its surrounding area, information from flux observation sites has been scattered. Understanding scattering in Asia has been desired since AsiaFlux, a flux-observation study network in Asia, was established in 1999. In the last three years, we have intensively collected site information as one of the main AsiaFlux activities. We expect aggregating and sharing metadata from flux observation sites will result in a strong collaboration not only within the flux-research community but also with investigators in other fields of study, for example modeling and remote-sensing. Organized information is also needed for future design of the tower flux observation network in Asia. Therefore we review the state of flux observations in Asia in this article.

World and Asian trends in flux study

In 1998, a workshop for flux researchers was held in Montana, USA. This has gathered momentum towards the establishment of a global flux observation network, currently called FLUXNET (Baldocchi et al. 2001). Prior to FLUXNET, local area networks were established as EUROFLUX and MedeFlu in Europe and AmeriFlux in the USA. Establishment of AsiaFlux in 1999 was an offshoot of this global movement.

Western originators of flux observation networks have managed observation sites with a view to long-term continuous observation. Measurement standardization, data sharing and synthesis analysis among the local networks have been actively conducted with powerful sponsors supporting these networks. Meanwhile, AsiaFlux has not been involved in the operation of flux observation sites, mainly because it has not secured sufficient funds. Therefore, measurement standardization was not a priority in AsiaFlux when its groundwork was laid.

Although most members of AsiaFlux were Korean and Japanese researchers at the inauguration of the network, many researchers from other nations have joined AsiaFlux in the last few years, and the number of sites has increased dramatically. Behind this trend, FLUXNET intensively drives data sharing and synthesis analysis on a global scale (Takagi et al. 2007).

Situation of flux observation sites in Asia

We listed flux observation sites around Asia by quoting websites and publications and obtained a total of 134 sites covering a wide area from Siberia to Southeast Asia. Electronic Supplementary Table s1 lists 51 forest sites and electronic Supplementary Table s2 lists 58 unforested sites such as grassland and cropland sites, where inactive sites and ongoing long-term observation sites are both listed. Electronic Supplementary Table s3 lists 25 temporary and closed observation sites. Sites where a micrometeorological method other than the eddy covariance method was employed are included in the lists.

Table 1 shows the state of sites composed of forest and unforested sites. Eighty-four active ongoing sites exist in Asia. For comparison, the number of active sites is 104 in AmeriFlux and 39 in CarboEurope. The number of active sites shows the Asian potential for flux observation study is not at all low.

There are more temporary observation sites in unforested areas than in forest areas. One of the reasons is that sites in grasslands and croplands are readily established and closed, unlike forest sites, which need tall towers. Another reason is that the target for a forest site, the trees, has a long life compared with grass or crops, so long-term observation is required.

Starting date

Figure 1 shows when the 109 sites in the lists (Electronic Supplementary Tables s1 and s2) were established and began observation. Thirty-three sites (forest: 17, unforested: 16) started flux observations before 1999. For comparison, 35 sites out of 117 in AmeriFlux and 23 out of 41 in CarboEurope registered for FLUXNET before 1999. After 2005, 21 sites (forest: 10, unforested: 11) were established in Asia. There were ten sites in AmeriFlux and none in CarboEurope established after 2005.

Table 1 Number of ongoing and inactive sites in the lists (see details in Electronic supplementary Tables s1–s3 available online)

State	Forest	Un-forested
Ongoing site	41	43
Inactive site with long-term observation	10	15
Inactive site with temporary observation	3	22

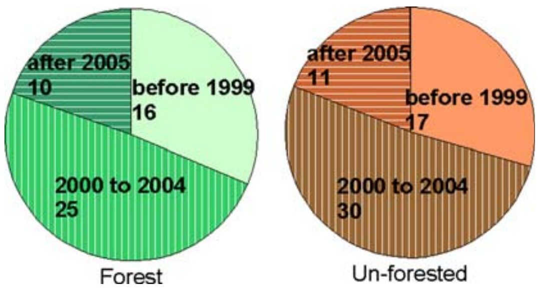

Fig. 1 Year of commencement of operation of the sites in the lists (see details in Electronic Supplementary Tables s1 and s2 available online). *Each digit under a label* shows the number of sites included in each category

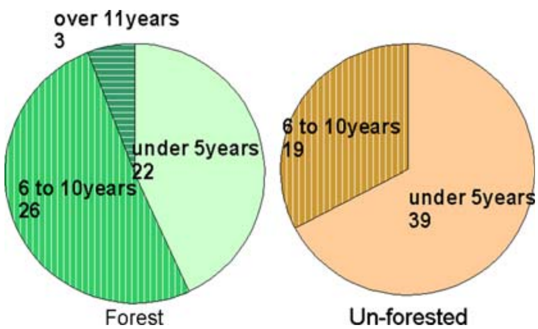

Fig. 2 Observation periods for sites in the lists (see details in Electronic Supplementary Tables s1 and s2 available online). *Each digit under a label* shows the number of sites included in each category

Duration of observation

Figure 2 shows the durations of observation at the 109 sites. Because many sites were established after 2005, it seems there are more sites with short-term observations than for AmeriFlux and CarboEurope. It is expected new flux sites will store flux data with a view towards long-term flux observation.

Measurement periods at unforested sites are shorter than at forest sites in general, owing to a shorter life-time of plants in croplands or grasslands. In addition, investigators at unforested sites are liable to have more interest in the influence of different field-management practices on fluxes than on inter-annual variability. However, observations covering several life stages of crops and grasses are desirable because crops and grasses are affected by climate conditions and land-use management.

Spatial distribution

All five zones of the Koeppen–Geiger climate classification exist in Asia (Kottek et al. 2006). Flux observations are conducted in every climate zone (Fig. 3a, b); nevertheless,

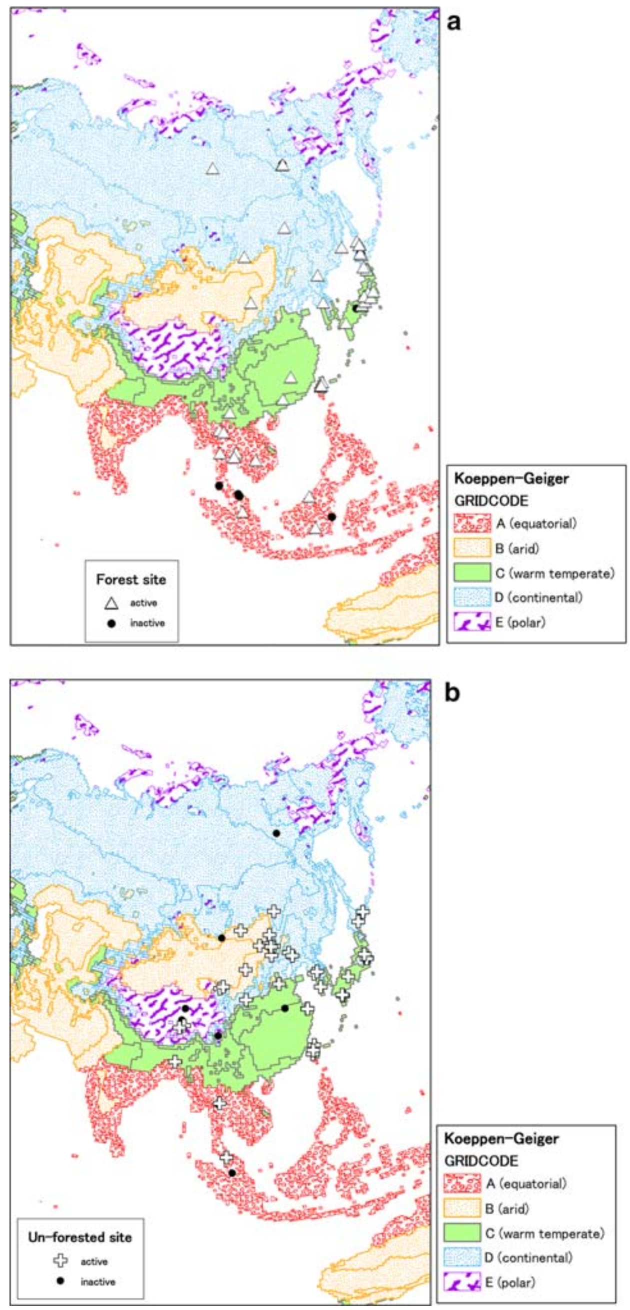

Fig. 3 Tower flux observation sites on the Koeppen–Geiger climate classification map (Kottek et al. 2006). GIS format data for climate classification were downloaded from the Internet (URL: http://koeppen-geiger.vu-wien.ac.at/). (**a**) forest sites, (**b**) unforested (grassland, cropland, and other land cover) sites

most observation sites are distributed in warm temperate (C) and continental (D) zones from East to Southeast Asia.

Climate

Although there are many kinds of classification of climate zones, we have adopted the Koeppen–Geiger classification

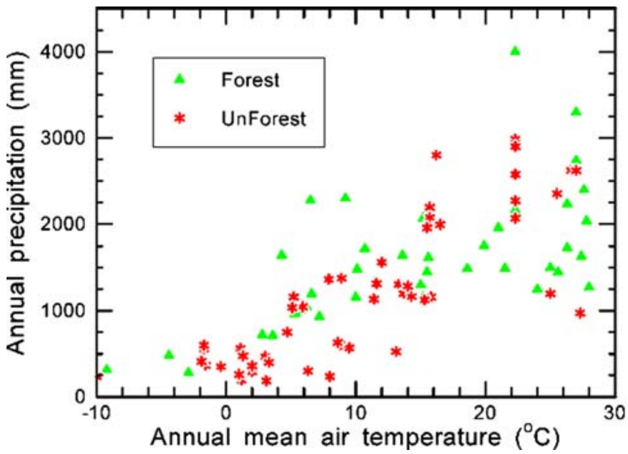

Fig. 4 Annual mean air temperatures and annual precipitation at flux observation sites. When air temperature and precipitation data for a site were not available, JMA (1999) data were substituted

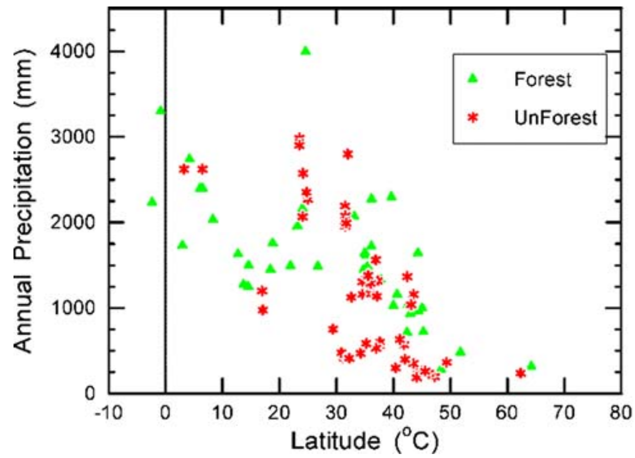

Fig. 5 Annual precipitation at flux observation sites against latitude. When precipitation data for a site were not available, JMA (1999) data were substituted

(Kottek et al. 2006). The climate of each site is quoted from the site website or a publication. When sufficient information was not available, the idea of Kottek et al. (2006) was applied. Twelve forest and five unforested sites are in A (equatorial) zones, zero and five in B (arid) zones, 18 and 22 in C (warm temperate) zones, 21 and 19 in D (continental) zones, and zero and seven in E (polar) zones. Most sites are located in temperate or continental zones. Although there are many forest sites in equatorial regions, there are a few cropland sites, despite its wide coverage.

Figure 4 shows the relationship between the annual mean air temperature and annual precipitation for the 109 sites. When air temperature and precipitation data for individual sites were not available, World Surface Data (Japan Meteorological Agency 1999) were substituted. The annual mean air temperature ranges from −10 to 30°C and annual precipitation ranges from below 200 to 4,000 mm. Forest sites are distributed in humid areas with high temperature and in cold areas with low precipitation.

Figure 5 shows annual precipitation against latitude. Many sites with high precipitation are located in mid-latitudes. This high humidity at mid-latitudes is one of the characteristics of the Asian climate. Forest sites are distributed over a wide range from low to high latitude, whereas unforested sites are few at low latitude.

Vegetation

Fifty-one of the 109 sites are in forest. As shown in Fig. 6, they are divided into evergreen needle-leaf (E_N), evergreen broadleaf (E_B), deciduous needle-leaf (D_N), deciduous broadleaf (D_B), and mixed (M) forests in each

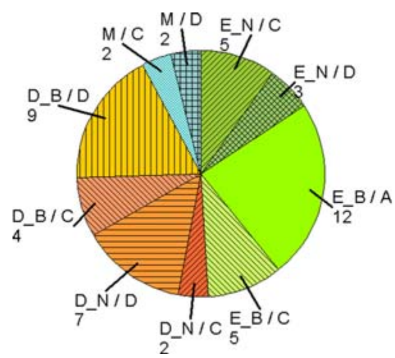

Fig. 6 Occurrence of forest types against climate zones. Label captions: *E* evergreen, *D* deciduous, *M* mixed; *_N* needleleaf, *_B* broadleaf; */A* equatorial, */C* warm temperate, */D* continental climate. *Each digit under a label* shows the number of sites included in each category

climate zone. There are more sites in broadleaf forest (evergreen (E_B): 17, deciduous (D_B): 13) than in needleleaf forest (evergreen (E_N): 8, deciduous (D_N): 9). There are 27 evergreen forest sites and 22 deciduous forest sites. According to the Food and Agriculture Organization's forest classification (FAO 2003), they can be divided into 12 tropical, three subtropical, 30 temperate and six boreal forests.

Most sites in evergreen broadleaf forest are located in subtropical and tropical zones. Sites in lucidophyllous forest in warm temperate zones and boreal forest sites are few. Lucidophyllous forest is a typical forest in warm temperate Asia. In contrast, the fraction of boreal forest area is small in Asia and many sites exist in the other regions such as Europe and North America. Therefore, sites in broadleaf forest in the temperate zone are more expected in Asia.

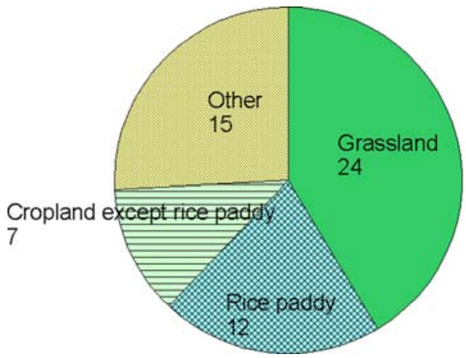

Fig. 7 Land cover at 58 unforested sites

Figure 7 shows land cover for unforested sites. There are twelve rice paddy field sites: two in the equatorial zone, nine in the warm temperate zone, and one in the continental climate zone. Rice paddy fields are typical croplands in Asia and characterized by unique field management in that the fields are flooded for most of the growing season. Paddy fields will provide observations that are different from those in other croplands.

Topography

Flat topography and uniform land-cover is ideal when flux observation is conducted by the micrometeorological method; however, this can rarely be found for natural conditions. We often have to compromise on the topography and land-cover condition when we observe in various vegetation. Forests, especially, usually exist in mountainous area in Asia and we have to conduct flux observations in complex terrain. Figure 8 shows the terrain type of forest and unforested sites. More than 20% of forest sites are classified as having complex terrain and most flat and gentle slope sites are distributed in equatorial zones. Considering most Asian forest is located in mountainous areas, we need to develop a flux evaluation method for complex terrain sites.

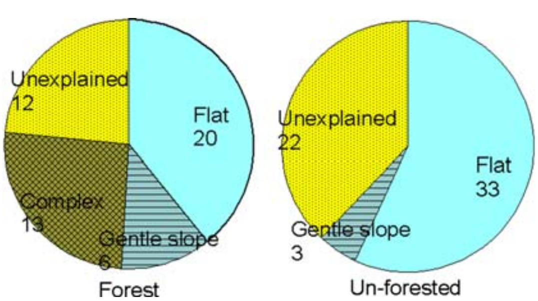

Fig. 8 Terrain type at forested and unforested sites

Measurements

Conventional micrometeorological methods, for example the aerodynamic method and the Bowen ratio method, were generally used for measurement of sensible and latent heat fluxes until the 1980s. The eddy covariance method became the mainstream flux measurement method around the year 2000. In Asia, the eddy covariance method became popular for CO_2 flux measurement in the late 1990s and CO_2 flux is now one of the standard observables measured in tower flux observations.

Eddy covariance method for CO_2 flux observation

There are two main types of measurement system for the CO_2 concentration—the open-path and closed-path systems. The closed-path system has been used since the beginning of CO_2 flux measurement. Although this system demands much work regarding installation and maintenance, it can measure the CO_2 concentration reasonably well under rainy conditions. On the other hand, the open-path system is easy to install and mechanical problems do not happen frequently. Seventy-eight of the 90 sites where CO_2 flux measurements are carried out employ the open-path system (Fig. 9). The system used at nearly half forest sites is the closed-path system whereas most of the unforested sites use the open-path system only. Measurement under rainy conditions is an important difficulty to be overcome for users of the open-path system, especially at sites with frequent precipitation.

Ultrasonic thermo-anemometers, which are essential sensors for the eddy covariance method, are produced by several manufactures including Kaijo Sonic (Hamura, Japan), Gill Instruments (Lymington, UK), Campbell Scientific (Logan, UT, USA) and R.M. Young (Traverse City, MI, USA). Kaijo's sensors for example the DA600 are employed at 34 sites and Campbell's C-SAT3 at 33 sites. Most sites that employ Kaijo thermo-anemometers began flux observations early on. Most recently constructed sites employ the C-SAT3.

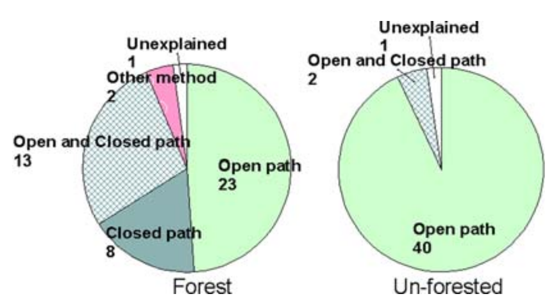

Fig. 9 Measurement system for CO_2 flux

An open-path gas analyzer was developed in the 1980s (Ohtaki and Matsui 1982) and has become an easy to install observation system. Although the E009 (Advanet, Okayama, Japan) and the OP2 (DataDesign Group, La Jolla, CA, USA) used to be the major open-path CO_2/H_2O gas analyzers, the LI-7500 (LI-COR, Lincoln, NE, USA) has taken over nowadays because of its accuracy and stability. A LI-6262 or LI-7000 is employed as a closed-path CO_2/H_2O gas analyzer at most sites. LI-COR's products practically monopolize CO_2/H_2O gas-analyzer use in Asia.

Campbell's data loggers for example the CR-23x and CR-5000 and TEAC's loggers for example the DR-M3 are used at 43 and 14 sites, respectively. Personal computers with analog/digital converters were used to record high-frequency data before these reasonable data loggers appeared.

Analysis

The data analysis method is another important factor in flux measurements. Table 2 shows sampling frequencies and averaging periods for data from different sites. A sampling frequency of 10 Hz and an averaging period of 30 min are adopted at most sites irrespective of vegetation type. The contribution of the high-frequency component in the co-spectrum is not high, so the lower sampling frequency is adopted at some forest sites. Although the averaging period is a basic issue, it is still under discussion e.g. (Moncrieff et al. 2004). It is best to store raw data in case they are required for future re-calculations.

General meteorological instrument using radiation as an example

The survey results show that various micrometeorological elements including solar radiation, wind velocity, air temperature, and precipitation are measured in addition to sensible heat, latent heat, and CO_2 fluxes. Although the CO_2/H_2O gas-analyzer market is almost a monopoly, many manufacturers produce micrometeorological sensors. We have focused on sensors for radiation as an example. Radiation is one of the most important elements in the energy balance because it is only an input term for the surface. This is also important in CO_2 flux study owing to its high impact on plant photosynthesis.

Table 2 Sampling frequency and averaging period for CO_2 flux observations and calculations

Sampling frequency			Averaging period		
Hz	Forest	Un-forested	Minutes	Forest	Un-forested
4	2	0	10	1	0
5	6	0	13.7	1	0
8	1	1	15	1	2
10	27	34	20	1	0
20	1	0	30	32	30
Unexplained	15	22	60	1	0

The products of Kipp & Zonen (Delft, The Netherlands), for example the CNR1 and CM6, and those of EKO Instruments (Tokyo), for example the MR40 and MS42, are used at many sites as pyranometers. The most popular pyrgeometers are the CNR1, PIR (The Eppley Laboratory, Newport, RI, USA), and MR40. There are an increasing number of sites where the four components of radiation (downward and upward shortwave radiation and downward and upward longwave radiation) are measured. All-in-one sensors for the four components, for example the CNR1 and MR40, are often adopted instead of a net radiometer. The LI-190, a photosynthetically active radiometer, is the most used and is recommended by flux research networks including Fluxnet Canada.

Carbon budgets in terrestrial ecosystems

Nowadays global warming receives much public attention. Studies of carbon dioxide, one of the major greenhouse gases, have developed and the field of flux study is no exception. The accurate evaluation of net ecosystem exchanges (NEEs) in various terrestrial ecosystems is one of the final goals of flux study. Therefore, the networking of tower flux observation sites has strengthened recently.

Annual NEE (or net ecosystem production, NEP) is reported from only 23 forest sites and eight un-forested sites out of 109. The growing periods of almost all crops are less than a year. Hence the NEP during the growing period is often considered to be much more meaningful in croplands. This is a reason that the annual NEE at unforested sites is not widely published.

At forest sites in the equatorial zone, NEP ranges from -720 to 700 g cm^{-2} y^{-1} whereas it is between 90 and 830 g cm^{-2} y^{-1} in the warm temperate zone and between 10 and 530 g cm^{-2} y^{-1} in the continental zone. Forest in the equatorial zone has both large emission and absorption of carbon. High air temperature increases ecosystem respiration, sometimes resulting in negative NEP (carbon emission). Sites in the warm temperate zone are often located in complex terrain and diversified ecosystems and the NEP tends to vary widely owing to these uncertainties. NEP in the continental zone has also a wide range. This may indicate the effect of precipitation is large compared with the effect in other climate zones. Although these results suggest a trend for NEP at forest sites, there are still other uncertainties, for example underestimation of nocturnal flux because of low wind velocity.

At unforested and natural vegetation sites in the lists (including grasslands), the annual NEP ranges from −70 to 200 g cm^{-2} y^{-1}. In naturally vegetated areas where trees are not covered, the climate condition is very severe; therefore, NEP is smaller than that for forest. At unforested sites under mild climatic conditions, usually cropland, NEP depends mostly on land-use management. NEP in a rice paddy field in warm temperate zones ranges from −20 to 284 g cm^{-2} y^{-1} and the reason for this difference is not simple as it relates not only to land-use management but also to climatic conditions. More reports with annual data are expected to discuss the land-use management effect.

As described above, micrometeorological flux measurement includes many uncertainties. Despite this difficult situation, data sharing and synthesis analysis are actively taking place, mainly among Euro-American researchers (Luyssaert et al. 2007; Takagi et al. 2007). There is a concern that only numerical values of NEP come up in discussions. Researchers who are conducting synthesis analysis and using flux data should understand this situation surrounding micrometeorological flux measurements. Meanwhile, flux data are also required from remote sensing and model study fields; in Asia, however, the publication of data is very slow. Asian data are extremely valuable because of the diversity of vegetation and climate conditions, especially humid conditions. Hence, it is strongly expected that flux data for Asia will be published in the future.

Conclusion

More than 100 flux observation sites exist in Asia including more than 20 sites established after 2005. From the viewpoint of the number of sites, Asia has a very high level of flux observation. However, the amount of published flux data is small considering the number of the sites. We expect to see flux data from more sites in the near future.

There are still few sites in Lucidophyllous forest, which is one of the distinguishing types of vegetarian in Asia, and more observations are required. On the other hand, there are more than a dozen sites in rice paddy fields, which are also a land cover unique to Asia. It is expected that intensive synthesis analysis will be conducted to understand the effects of climatic conditions and field management on fluxes.

The choice of meteorological instruments seems to have narrowed with flux measurement standardization. Although instrument errors will decrease if all sites use a common sensor, the future development of a new type of sensor may not be possible in a monopoly market.

Although the eddy covariance method is one of the best choices for flux observations, and Asian flux data can be unique and very interesting, this field of study has uncertainties such as those caused by complex terrain and diversified ecosystems. Asian flux sites face this difficult situation while dealing with other worldwide issues such as the energy imbalance and nocturnal underestimation. Flux data have to be used with much understanding of this situation.

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