DOI: 10.1007/s11430-006-8001-3

Recent progress and future directions of ChinaFLUX

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Received October 27, 2005; accepted March 10, 2006

Abstract The eddy covariance technique has emerged as an important tool to directly measure carbon dioxide, water vapor and heat fluxes between the terrestrial ecosystem and the atmosphere after a long history of fundamental research and technological developments. With the realization of regional networks of flux measurements in North American, European, Asia, Brazil, Australia and Africa, a global-scale network of micrometeorological flux measurement (FLUXNET) was established in 1998. FLUXNET has made great progresses in investigating the environmental mechanisms controlling carbon and water cycles, quantifying spatial-temporal patterns of carbon budget and seeking the "missing carbon sink" in global terrestrial ecosystems in the past ten years. The global-scale flux measurement also built a platform for international communication in the fields of resource, ecology and environment sciences. With the continuous development of flux research, FLUXNET will introduce and explore new techniques to extend the application fields of flux measurement and to answer questions in the fields of bio-geography, eco-hydrology, meteorology, climate change, remote sensing and modeling with eddy covariance flux data. As an important part of FLUXNET, ChinaFLUX has made significant progresses in the past three years on the methodology and technique of eddy covariance flux measurement, on the responses of CO_2 and H_2O exchange between the terrestrial ecosystem and the atmosphere to environmental change, and on flux modeling development. Results showed that the major forests on the North-South Transect of Eastern China (NSTEC) were all carbon sinks during 2003 to 2005, and the alpine meadows on the Tibet Plateau were also small carbon sinks. However, the reserved natural grassland, *Leymus chinensis* steppe in Inner Mongolia, was a carbon source. On a regional scale, temperature and precipitation are the primary climatic factors that determined the carbon balance in major terrestrial ecosystems in China. Finally, the current research emphasis and future directions of ChinaFLUX were presented. By combining flux network and terrestrial transect, ChinaFLUX will develop integrated research with multi-scale, multi-process, multi-subject observations, placing emphasis on the mechanism and coupling relationships between water, carbon and nitrogen cycles in terrestrial ecosystems.

Keywords: eddy covariance, flux measurement, carbon budget, terrestrial ecosystem, FLUXNET, ChinaFLUX.

Climate changes such as global warming, polar ice melting, rising sea level and the change of ecosystem species composition caused by the enrichment of atmospheric greenhouse gases such as CO_2 and CH_4 have been the key environmental problems receiving worldwide attention in recent years[1]. Currently, the mechanism of the carbon cycle and carbon budget in terrestrial ecosystems is one of the core issues of many international research projects. There is a famous "missing sink" in global carbon budget research[2], and some studies indicate that the missing carbon is sequestrated by terrestrial ecosystems[3]. Therefore, the accurate evaluation of net carbon exchange between vegetation and atmosphere is critical for quantifying the spatial pattern of carbon budget in terrestrial ecosystems, also a major issue that global bio geochemical scientists are attempting to resolve[4].

Traditional tools used to measure the components of net ecosystem carbon exchange include biomass inventory, assimilation chamber, modeling and remote sensing, etc. But all these methods could not be applied to large scale and long-term continuous measurement because of their own limitations[5]. With a long history of theoretical development and technical improvement, the eddy covariance technique can directly measure net CO_2, water vapor and energy exchange of forest, grassland and agriculture ecosystems with minimal disturbance to the underlying vegetation and ambient environment[6]. With the worldwide application of eddy covariance flux measurement and the establishment of regional and national flux observational networks, a global-scale network of micrometeorological flux measurement (FLUXNET) emerged as the time requires and became a major organization to measure CO_2, water vapor and energy fluxes on a regional scale[7]. FLUXNET plays an important role in exploring soil-plant-atmosphere interactions, evaluating the role of terrestrial ecosystems in the global carbon cycle, and investigating the response of the terrestrial ecosystem carbon exchange to global environmental changes.

The objectives of this paper are to: (1) present an overview of the historical development of flux measurement; (2) assess the scientific contribution of global flux measurement and future directions of FLUXNET; (3) summarize the main achievements of ChinaFLUX in the technique of flux measurement, the controlling mechanism of environmental factors on terrestrial ecosystem carbon budget and the modeling of carbon and water fluxes in terrestrial ecosystems; and (4) discuss the future directions of ChinaFLUX.

1 History development of flux measurement

1.1 Historical development

In recent years, the eddy covariance (EC) technique has been widely used to quantify the fluxes of CO_2, H_2O and energy between ecosystem and atmosphere. This technique is built on a long history of the fundamental research in the fields of fluid dynamics and micrometeorology and on the technological development associated with meteorological instruments, computers and data acquisition systems. As early as 1895, Osborne Reynolds established the theoretical framework for the eddy covariance technique (Reynolds decomposition)[8], however, the lack of instrumentation hindered the application of the eddy covariance method. In 1926, however, a study on momentum transfer, the so-called Reynolds' stress, was conducted for the fist time with simple analog instruments and strip-chart data logging[9].

After World War II, the development of fast responding hot-wire anemometry and thermometry and digital computers brought the second wave of advancement in eddy covariance technique. During this time, application of the eddy covariance method was still limited to areas over short vegetation with extremely level terrain, and to windy, sunny days, focusing on the research of structure of turbulence in atmospheric boundary layer and the transfer of heat and momentum, rather than CO_2 flux[10]. During the late 1950s and early 1960s, some pioneering studies on CO_2 flux were conducted using the flux-gradient method rather than the eddy covariance technique by Japanese, British and American scientists over short and ideal cropland due to a lack of fast-responding anemometers and CO_2 sensors[11−13].

The first CO_2 flux measurements over some native ecosystems, such as tundra, grassland, wetland [14,15], and forest[16,17] did not occur until the late 1960s and early 1970 s. Application of flux-gradient theory over tall vegetation was found to be problematic at the beginning[18] because turbulent mixing is efficient and vertical gradients of CO_2 are small over tall vegetation. In addition, the presence of a roughness sublayer invalidates the Monin-Obukhov similarity theory above forests[18,19]. At this point, the wide use of the eddy covariance technique needed to wait for further technical developments.

The first eddy covariance measurement of CO_2 exchange did not occur until the early 1970s[20,21], with a propeller anemometer and a modified, closed-path infrared gas analyzer over cropland. But these measurements suffered from large errors (~40%) due to the slow time-response of the sensors[22]. During the late 1970 s and early 1980 s, critical technological improvements were made on commercial sonic anemometers and rapid-responding, open path infrared gas analyzers, which greatly promoted the development of the eddy covariance technique [23−25]. Open-path CO_2 sensors using solid-state, lead-selenium (PbSe) detectors were a key innovation as they can sense CO_2 fluctuations as rapidly as 10 times per second with minimal aerodynamic disturbance. This technique was first used to measure CO_2 fluxes over crops such as soybeans[26], sorghum[27], rice[28] and corn[29], and soon expanded to native vegetation, such as forests[30−32] and grasslands[33,34],. Prior to 1990, limitations in sensor performance and data acquisition systems restricted the duration of the eddy covariance technology in field measurements. Subsequent production of commercial infrared spectrometers that were stable and had short time constants enabled scientists to conduct eddy covariance measurements 24 h a day, 7 days a week and 365 days a year. Since 1993, many additional studies measuring CO_2 and water vapor exchange based on the eddy covariance technique began operating over forests, grasslands and other native ecosystems in North America[35−37], Japan[38], and Europe[39]. All of these studies lay a foundation for the establishment of FLUXNET.

1.2 The construction and development of FLUXNET

The global network of long-term flux measurement sites as a scientific concept was first noted as early as 1993, in the science plan of the International Geosphere-Biosphere Program/Biospheric Aspects of the Hydrological Cycle (BAHC Core Project Office 1993). This concept was next formally discussed among the international scientific community at the following 1995 La Thuile workshop. After this meeting, more flux towers and regional flux measurement networks were established quickly. The Euroflux and AmeriFlux, two of the early large regional flux measurement networks, were established in 1996 and 1997, respectively. With the success of European and American regional networks and the anticipations of the Earth Observation Satellite (*EOS/Terra*), the National Aeronautics and Space Administration (NASA) decided to fund the global-scale project, popularly known as FLUXNET, as a means of validating EOS products in 1998[7].

The FLUXNET project comprises seven main regional networks, AmeriFlux, AsiaFlux, CarboEurope, ChinaFLUX, Fluxnet-Canada, KoFlux and OzFlux, and some special research projects such as CAROMONT, GREENGRASS, OzNet, Safari2000, TCOS-Sibeia, TroiFlux, etc. There are over 400 flux sites (as shown on the FLUXNET website) registered at FLUXNET existing on six continents; their latitudinal distribution ranges from 70°N to 40°S . Vegetation under study includes tropical and boreal forests, temperate coniferous and broadleaved (deciduous and evergreen) forests, mixed forests, crops, savanna, grasslands, chaparrals, crops, badlands and urban ecosystems.

Besides the continuous measurement of CO_2, water vapor and energy fluxes, the site information of vegetation, soil, land cover, hydrology and micrometeorology were also collected periodically at each site. As a global network of long-term flux measurement, FLUXNET has produced reliable data for research on carbon and water cycles between the terrestrial biosphere and the atmosphere, the spatial-temporal patterns of carbon sources or sinks in terrestrial ecosystems and their responses to climate changes. FLUXNET also established a platform for international cooperation in resource, ecology and environmental sciences.

1.3 Establishment and development of ChinaFLUX

Multiple climate types and complex topography and terrain results in a diversity of ecosystem types in China, with the Tibet Plateau famous as "the third peak on earth", large areas of temperate grassland and alpine meadow, and integrated seral forests from tropical to cold temperate zone; this diversity provides a natural laboratory for the research on terrestrial ecosystem carbon and water cycles. The Chinese Terrestrial Ecosystem Flux Research Network (ChinaFLUX) relies on the Chinese Ecosystem Research Network (CERN) and was established in 2002, funded by the Knowledge Innovation Program of the Chinese Academy of Sciences (CAS) and the National 973 project. The construction of ChinaFLUX refers to the criterion of most international flux networks, with uniform observation instruments, standardized measuring items and methods at each site. It took both ecosystem integrality and regional representativeness, research innovation and foresee into account [5].

At present, ChinaFLUX has four forest sites (Changbaishan (CBS), Qianyanzhou (QYZ), Dinghushan (DHS) and Xishuangbanna (XSBN)), three grassland sites (Haibei (HB), Inner Mongolia (NMG) and Dangxiong (DX)) and one cropland site (Yucheng (YC)) (Fig.1) that are conducting long-term flux observation of carbon dioxide, water and heat. In addition, the chamber method was used at 16 sites to measure soil efflux of greenhouse gases such as CO_2, CH_4, N_2O, etc. At the same time, the site information about vegetation, soil, hydrology and meteorology sites were collected periodically. The four forest sites of ChinaFLUX are influenced by the East-Asia monsoon climate, while the three different grassland sites were influenced by different temperate continental climates. For example, the NMG site represents the temperate steppe, while the flux sites at HB (three types of alpine vegetation) and DX represent different alpine meadows on the Tibet Plateau. As an important component of FLUXNET, ChinaFLUX has taken the lead in flux observation and research in China and received worldwide attention from the international flux community. In the past two years, many new flux sites were set up by academic institutes and universities, greatly enhancing the extension and intensity of flux research in China.

2 Scientific contribution and hot topics of flux research

2.1 Technical advancement of flux measurement

Currently, numerous techniques exist for studying biosphere–atmosphere CO_2 and water vapor exchange, each with distinct advantages and disadvantages. The traditional inventory method estimates ecosystem carbon flux by measuring the change of above- and

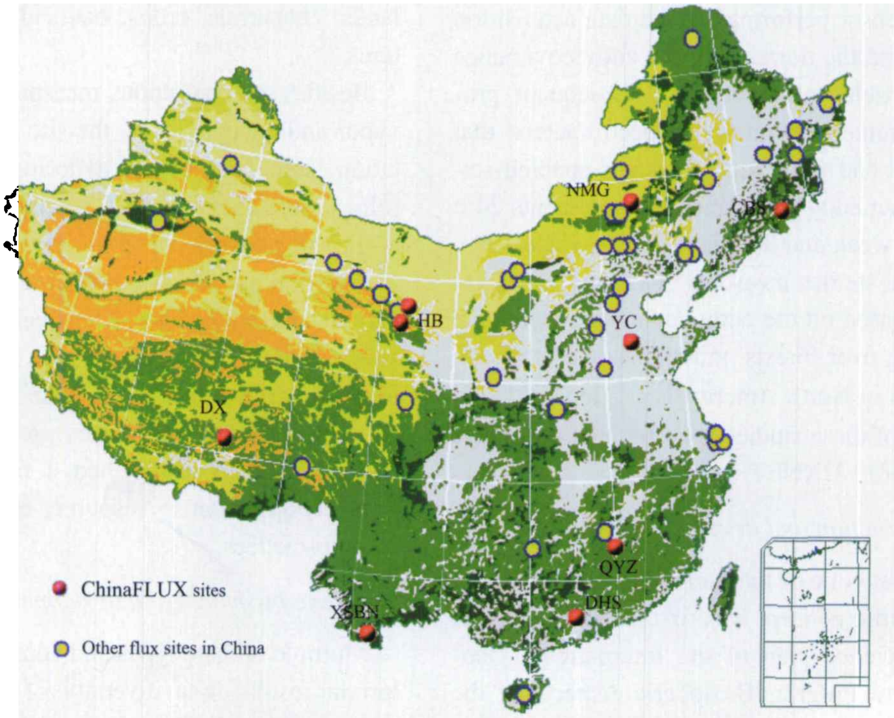

Fig. 1. The distribution of flux observation sites in China.

below-ground carbon pools during certain periods[40]. However, biomass surveys provide information on multiyear to decadal timescales for detecting the small changes in carbon pools[41], so they do not provide information on shorter-term physiological forcings and mechanisms. Furthermore, forest inventory studies are inferential estimates of net carbon exchange and could induce significant bias[5]. Dynamic chamber or static chamber is another method to assess the components of ecosystem carbon flux by directly measuring leaf photosynthesis or soil respiration. This chamber method is inexpensive and provides for easy comparisons among different ecotypes or managing modes. In addition, it allows accurate indoor analysis of efflux of other trace gases (e.g. CO_2、N_2O and CH_4) by sampling gas from the field. However, the chamber method is difficult to apply to tall vegetation such as forest and tall-stalk cropland. On the other hand, placing a chamber over the soil to measure respiration could introduce bias errors due to perturbations of local micro-meteorological conditions (e.g. air press, wind, CO_2 density, temperature, energy balance etc) around the plant measured[42,43]. Consequently, the responses of ecosystems to environmental perturbations on a canopy scale differ from those detected with independent micrometeorological measurements [5]. At the landscape to regional scale we can use instruments mounted on aircraft to assess carbon and water fluxes. Aircraft-based flux measurements give good information on carbon and water fluxes by sampling relatively large areas of land across transects tens to hundreds of kilometers long. However, they do not provide information continuous in time, nor do they provide insights on the physiological mechanisms that govern ecosystem carbon and water fluxes. At the continental and global scales, scientists assess carbon dioxide flux using atmospheric inversion models. But this approach is subject to errors due to the sparseness of the trace gas measurement network, their biased placement in the marine boundary layer, and the accuracy of the atmospheric transport models[2,44,45]. Satellite-based remote sensing technique estimates CO_2 and H_2O flux between global land surface and the atmosphere with the use of a radiation-driven model by sensing the dispersion radiation and reflected radiation[46]. However, this approach is easily affected by the accuracy of model algorithms, the frequency of satellite observational images and the spectrum information contained in the images[7].

The eddy covariance technique ascertains the exchange of CO_2 and water vapor between the atmosphere and vegetated canopies by measuring the covariance between fluctuations in trace gas mixing ration and vertical wind velocity. One advantage of this technique is its ability to measure mass and energy fluxes over short and long timescales with minimal disturbance to the underlying vegetation. Compared to other methods, the eddy covariance technique has many advantages:

(1) The flux-gradient method could not be applied to tall vegetation because it is hard to detect the tiny CO_2 concentration gradient or variation[18]. However, the eddy covariance technique can measure the small fluctuations in concentration of trace gases with infrared gas analyzers, so it can measure the CO_2 flux between the atmosphere and the terrestrial ecosystem more accurately.

(2) The eddy covariance technique supplies the gaps of traditional methods, such as temporal discontinuousness of measurement, time-consuming to get data. This technique can attain a mass of data over short or long time periods to investigate how ecosystem CO_2 exchange responds to environmental perturbations on different time scales.

(3) The eddy covariance method is particularly useful for studying physiological questions at a canopy scale due to its large spatial representative[47], which offsets the scale mismatch between aircraft / satellite measurement and ground surveys. In addition, it could help us to understand the response of different ecosystems to environmental gradients using multi-site flux measurement across terrestrial transects[4].

(4) The eddy covariance technique is a key technological innovation for research on the terrestrial ecosystem water cycle, as it can directly and exactly measure ecosystem evaporation with high time resolution. It can supply plenty of data for improving the regional water budget model, evaluating the spatial-temporal variation of regional water balance and studying the effect of the water cycle on the carbon cycle.

2.2 Scientific contributions of flux measurement

In the last two decades, FLUXNET has achieved great success in the fields of carbon cycling, water cycling, global change and atmospheric boundary layer science. The major contributions of flux observations are as follows:

(1) Carbon budgets in different terrestrial ecosystems were estimated by using long-term observation data from global flux sites. Many studies found that the forests distributed at middle to high latitude regions in North American and Europe are important carbon sinks[7,48] while, most temperate grasslands have reached the stage of carbon equilibrium; net annual carbon exchange in grassland ecosystems shows large fluctuation with response to climate change[49,50]. Croplands are significantly influenced by human activities and their function as carbon sinks/sources changed with human management, thus, some croplands are carbon sinks[51,52] and some are carbon sources[53].

(2) With the observed long-term flux data, the seasonal and interannual variation of carbon and water balance of different terrestrial ecosystems and their response to environmental (radiation, temperature, water and soil nutrient) and biotic (photosynthesis, canopy structure, ecosystem function type and growing season) factors were investigated [54,55]. Temperature is the primary factor determining annual ecosystem respiration[48,56], while on a daily scale ecosystem photosynthesis was mainly determined by synthetic influences of multiple factors such as radiation, temperature and water etc[51].

(3) Long-term canopy flux data was widely applied to validate and parameterize various process- or mechanism–based ecosystem carbon cycle models and soil-vegetation-atmosphere transfer models [57 – 60]. Furthermore, great efforts have been made to develop and improve terrestrial ecosystem carbon and water cycle models, and flux data were used to validate CO_2 and H_2O flux modeled with a land surface model based on GCMs and global dynamical vegetation model[61,62]. According to optimization of model algorithms, modeling accuracy of seasonal change of carbon and water fluxes and its response to global warming, precipitation variability and nitrogen deposition was improved [63,64].

(4) The FLUXNET Data and Information System (DIS) was established by integrating the measured flux data, micrometeorology data and vegetation investigation data from regional flux networks after standardized data processing. The FLUXNETDIS provides a platform for international cooperation in the fields of terrestrial ecosystem and global change[65].

2.3 Hot topics of flux observation

Early studies of flux measurement mainly focused on the development of the techniques and the theory of the eddy covariance method, extension of flux research regions and accumulation of long-term flux data. Recently, more efforts were made to investigate environmental controls on the spatial-temporal variation of CO_2 and H_2O fluxes between the terrestrial biosphere and the atmosphere, and evaluation of the effects of climate change on ecosystem carbon balance. Significant results have been achieved through global flux observation; however, many problems are still unsolved concerning ecosystem carbon and water cycles. At present, flux observation is paying more attention to the following issues:

(1) Flux measurement in difficult conditions. Flux measurement using the eddy covariance method requires well-mixed atmospheric turbulence and a horizontally homogeneous surface with long upwind area. But many flux sites located in complex terrain suffer from non-ideal micrometeorological conditions, which could introduce significant uncertainties into the evaluation of the ecosystem carbon budget. The technical improvement of flux measurements in difficult conditions, the ecological explanation of measuring results and the evaluation and correction of observation data under complex conditions are still unsolved problems. These questions, which have received worldwide attention among researchers of FLUXNET, are important directions of flux research at present and for the future,.

(2) Ecosystem respiration measurement. Respiration is one of the major carbon fluxes between ecosystem and atmosphere. The reliability of ecosystem respiration measurement could affect the evaluation of net ecosystem carbon balance, and different limitations or disadvantages exist in the commonly-used methods for measuring respiration. The dynamic and

static chamber method can not be used for long-term observation and the separation of auto- and hetero-respiration. The chamber is inclined to change the atmospheric and soil conditions inside or outside the chamber, which leads to disagreement between real and measured values. Measuring ecosystem respiration with the eddy covariance method at night is often influenced by both instrumental and micrometeorological limitation, which could induce significant bias error to the evaluation of ecosystem respiration. In addition, the separation of plant auto-respiration and soil hetero-respiration is another technical difficulty of ecosystem respiration measurement. Therefore, it is of great significance to develop new techniques and improve the accuracy of ecosystem respiration measurement for global carbon cycle and carbon balance research.

(3) Developing new techniques of flux observation. Although great progresses has been achieved by FLUXNET, many issues still could not be resolved without combining the eddy covariance method with other observation techniques. These limitations are due to the limited spatial representativeness of flux measurement (about 100−3000 m) and the difficulty in separating the components of ecosystem CO_2 and H_2O fluxes. In recent years, the stable isotope technique was combined with eddy covariance flux measurement to separate the components of carbon flux into photosynthesis, auto-respiration and hetero-respiration and H_2O flux into soil evaporation and plant transpiration[66,67]. The stable isotope technique has a unique role in ecological studies and has been applied from leaf level to vegetation canopy, ecosystem and even global scales[68]. The aircraft is another new technique used to study carbon and water fluxes from landscape to regional scales[69]. Scientists are improving the aircraft technique and attempting to integrate the aircraft with the eddy covariance technique so as to improve the spatial representativeness of global flux observation. The wireless sensor and wireless data transfer technique is not limited by the disadvantages of electric power and signal attenuation with distance existing in present flux observation. The wireless technique helps achieve real-time monitoring on the observation system to insure data quality and temporal continuity.

(4) Integration of flux observation with remote sensing and global carbon modeling. The flux measurement based on ground observation towers or aircrafts are capable of measuring fluxes from every patch on earth. However, satellite-based remote sensing technique could sense all the vegetation on earth on daily intervals, but it could not obtain ecosystem CO_2 flux data directly and large uncertainties exits in measured radiation, air temperature, air humidity and plant physiological characteristics. The results derived from ground measurement could be scaled up to regional or global areas with global carbon modeling, an important approach to study regional or global carbon cycles. FLUXNET provides effective observation data with high time resolution for the parameterization and validation of various carbon cycle models, and global land classification, vegetation index and meteorology data can be obtained from remote sensing observation. Therefore, combining the ground flux measurement, remote sensing observation and global carbon cycle model is an alternative way to extend ground observation results to regional and global scales to study the spatial-temporal pattern of terrestrial ecosystem carbon and water budget and their response to global change[46].

(5) The extension of flux application. In recent years, many other scientists also participated in the flux observation and research due to its advantage in explaining many ecological questions. The international flux community has realized the wide application of flux measurement in many other fields and has begun associated flux research to study problems in biogeography, biogeochemistry, ecological hydrology, meteorology/climate, remote sensing and global carbon modeling by using the ecosystem carbon, water and energy flux data[70]. For example, multi-site flux observation could allow researchers to investigate the variability of ecosystem evapotranspiration at different spatial and temporal scales, evaluate local or basin water balance more accurately and discuss the water use efficiency of plant under different climate conditions. Furthermore, flux observation can also be applied to boundary layer meteorological problems such as large-scale advection, deep convection and nocturnal flow motion so as to reveal the primary processes controlling convective boundary layer and nocturnal boundary layer.

3 Major progresses of ChinaFLUX

A mass of first-hand flux data in major terrestrial ecosystems of China has been obtained since the establishment of ChinaFLUX in 2002. Great efforts have been made on carbon/vapor balances in different ecosystems, environmental controls on carbon/vapor flux, development of the mechanism-based models of carbon/water cycles and techniques of field flux observation.

3.1 Flux observation technique, data processing and evaluation

As with any technique, the eddy covariance method does have disadvantages. Errors appear when the natural condition cannot meet the requirements of the eddy covariance flux measurement[6]. Main causes of error are: loss of high and low frequency signal due to the limitation of the sensor's physical attribute[71], underestimation of long-term carbon balance by choosing an improper coordinate system and due to low turbulence during the nighttime[72,73]. These problems have attracted interest and many studies were conducted to seek proper correction methods to reduce these errors. At present, widely accepted data processing approaches include frequency response correction[71,74,75], tilt correction[76,77], WPL correction[78], canopy storage correction[79−81] and advection correction[72−81]. Furthermore, the average period of flux calculation, nighttime flux correction and gap-filling of missing data could also impose significant effects on the estimation of ecosystem carbon budget.

ChinaFLUX has developed a relatively sound flux data processing procedure after long-term exploration and practice, including data collection and storage and flux calculation and correction (Fig. 2). Coordinate rotation, evaluation of system performance, flux data correction and gap-filling methods of missing data are particularly important for obtaining reliable data to estimate ecosystem carbon budgets at different temporal scales; each of these steps, however, require further investigation and discussion.

3.1.1 Data collection and storage

The eddy covariance technique requires a high sampling frequency and a long enough sampling period to catch the eddy motion that has significant contribution to flux transfer. But high sampling

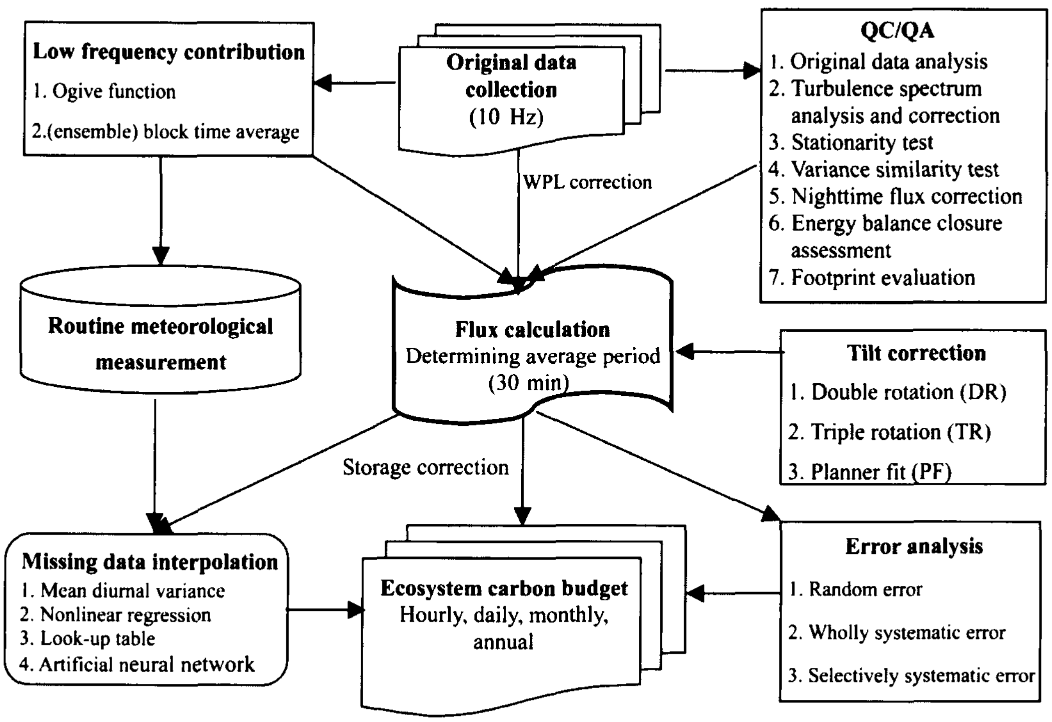

Fig. 2. Procedure of data processing for ChinaFLUX.

frequency will produce a large volume of original data, which brings about difficulties in data storage and flux calculation. Generally, 10 Hz can meet the requirements to catch most high frequency signals and avoid producing too much excessive data [36]. Therefore, all sites of ChinaFLUX use the sampling frequency of 10 Hz. Original data files from each site are directly deposited on a PC card at first, then transferred to the ChinaFLUX database.

3.1.2 Data quality analysis and quality control

To accurately estimate the ecosystem carbon budget with the eddy covariance technique, the measured flux data have to go through quality control and quality analysis (QC/QA). When analyzing the accuracy of data measured by the eddy covariance method, the instrumental physical limitation (which is mostly related to the response frequency of sonic anemometers and infrared gas analyzer), and the satisfaction of natural condition for the eddy covariance technique (which is mostly related to the conditions of atmospheric turbulence and terrain) should be carefully considered [73].

(1) Analysis of sensor frequency response of EC. Frequency response analysis can diagnose the capacity of instruments responding to high-frequency eddy signals. At the QYZ site of ChinaFLUX, the power spectra and cospectra of 3-dimensional wind speeds, virtual temperature (measured by sonic anemometer) and CO_2 / H_2O density (measured by open-path infrared gas analyzer) shows that the eddy covariance systems of ChinaFLUX are capable of detecting high-frequency (10 Hz) eddy signals to meet the requirement of eddy flux measurement[82]. Low-frequency eddy motion also has an important effect on flux transportation and a sufficiently long sampling period is needed in order to catch the low-frequency eddy movement. However, some information on the diurnal variation of ecosystem CO_2 exchange may be lost with too long a sampling period. Therefore, a proper sampling period should be chosen for flux calculation. Wen *et al.* assessed the contribution of the low-frequency component of CO_2 flux with "ensemble block time average" and "Ogive function", respectively [83]. The results showed that the CO_2 flux calculated with the sampling period of 60 min was 2.8%−3.5% higher than that of 30 min, and flux calculated with 120 min was 4.5%−6.1% higher than that of 30 min. On average, low-frequency eddy turbulence has more effect on carbon flux (<6%) than on latent and sensible flux. Therefore, a sampling period of 30 min is appropriate for long-term flux measurement studies, and most sites of FLUXNET use 30−60 min sampling period for flux calculation. However, a longer sampling period might be needed at night because of the existence of intermittent turbulence[73].

(2) Stationarity and variance similarity tests. The constant flux layer hypothesis of the eddy covariance technique requires stationarity and homogeneity of the atmosphere. Stationarity means that the statistic characters of atmospheric turbulence show no change with time. Homogeneity means that there is spatial similarity in the statistical characters of atmospheric turbulence. Generally, the instability of turbulence has a significant effect on eddy flux measurement, and heterogeneity often results in the instability of atmospheric turbulence[84]. In addition, turbulent variance similarity can be used to test whether or not the development of turbulence is consistent with Monin-Obukhov theory, thus helping us to understand the effects of natural condition and instruments' spatial arrangement on flux measurement. Both stationarity and variance similarity tests can be used as the standards for QC/QA of eddy covariance flux data. For the details of these two methods and classification standard of data quality analysis refer to Foken *et al.* [85]. The stationarity and variance similarity tests at the QYZ site indicated that the very small proportion of invalid data mostly occurred at night, mainly resulting from the instrumental limitations and disadvantageous meteorological conditions at night. Furthermore, the comparison among the open path, close path eddy covariance systems and routine meteorological measurement system confirmed that performance of observing instruments at QYZ could meet the requirements for long-term flux research [84].

(3) Nighttime flux evaluation and correction. The eddy covariance technique tends to underestimate the turbulent CO_2 flux at night since it cannot detect the nonturbulent flux transportation when turbulent motions shift becomes more intermittent and turbulent mixing is relatively weak. A common phenomenon at long-term

flux sites is that measured turbulent CO_2 flux is evidently correlated with friction velocity u_*[86]. In this word, a common practice is to screen and correct the measured flux during low turbulent conditions with a threshold of friction velocity u_{*c} (mostly 0.15−0.3 m s^{-1}). The flux data during the periods with $u_* < u_{*c}$ is replaced by the value estimated with a temperature and moisture function established using data obtained during well-mixed, windy periods ($u_* < u_{*c}$)[4, 87]. Wen *et al.* studied the relationship between variance similarity and atmospheric stationarity and found that the value of u_* was correlated with measurement height, suggesting that nighttime flux correction with friction velocity still has some shortage [84]. Zhu *et al.* summarized the theory and methods dealing with nighttime flux data and proposed using the average varying ratio of carbon flux to u_* (i.e. $\partial F_c / \partial u_*$) to determine the threshold friction velocity[88]. This method could be an alternative choice for nighttime flux correction.

(4) Tilt correction. When the EC technique is used to measure flux over complex terrain, a tilt correction (i.e. coordinate rotation) has to be applied before using the data to analyze ecological questions for the following three reasons: (1) the sonic anemometer is tilted; (2) the local terrain is not level; and (3) the average vertical wind speed is not zero and cannot satisfy the hypothesis of the EC technique. It is of significant importance to choose a proper coordinate rotation method for tilt correction. At present, there are three methods commonly used known as double rotation, triple rotation and planner fit. Zhu *et al.* compared the effects of these three coordinate rotation methods on flux calculation at YC (crop), NMG (grassland), CBS (deciduous forest) and QYZ sites (evergreen forest) sites of ChinaFLUX[89,90]. Results showed that the three methods could correct the carbon flux rationally, but the performance of each method depended on local conditions such as slop degree, slop direction, wind speed ,wind direction, etc.[89].

(5) Canopy storage. At night the thermal stratification of the atmosphere is stable and the turbulent mixing is weak; thus the CO_2 exiting leaves and soil may not reach the observing instruments at a reference height and a proportion of the CO_2 will be stored within the canopy air space. Under this non-steady condition, the storage of CO_2 in the underlying airspace is non-zero. Storage must be assessed and added to the eddy covariance measurement if we expect to obtain accurate estimates of net CO_2 flowing into or out of the soil and vegetation. Generally, the influence of canopy storage is very small and negligible for short vegetation (e.g. crop and grassland) but is important for forest. On daily and annual time scales the storage term is approximately zero so errors of its evaluation are not critical[73,81]; however, it should be considered when analyzing environmental mechanism of CO_2 flux on short time scales.

(6) Gap-filling of missing data. Data loss is inevitable during long-term measurement due to system malfunction and data rejection in bad weather. Therefore, gap-filling procedures need to be established for providing complete data sets to estimate net ecosystem CO_2 exchange on different time scales. Different gap filling procedures will produce different estimations of daily, monthly and annual NEE with bias. Therefore, it is important to choose proper gap-filling procedure for estimating each ecosystem carbon budget. At present, the flux measurement community has agreed on several data processing routines, such as "nonlinear regression", "look-up table" and "mean diurnal variation"[91,92]. Yu and Sun have compared these methods in detail[5]. The ChinaFLUX community mainly uses these three methods to fill the missing data gaps. In recent years, the artificial neural network (ANN) has also been used for gap-fill studies[93].

3.1.3 Evaluation of ecosystem NEE

(1) Error analysis of flux measurement. After the data processing mentioned above (i.e. data quality control, tilt correction and gap filling), we can acquire a relatively complete dataset, which could be used for NEE calculation on various time scales and for ecological study. However, the limitation of instruments and imperfect meteorological and topographical conditions may reduce the reliability of flux measurement. In addition, the above data processing procedures will also induce significant errors to flux calculation. Moncrieff *et al.* discuss the effects of random errors and systematic errors associated with the measurement of fluxes[80]. These errors may be large enough to change the carbon source/sink status of an ecosys-

tem. Error analysis is an important tool for assessing possible aberrant results caused by errors. Therefore, special attention should be given to the errors produced by data processing in any long-term flux measurement to estimate net ecosystem carbon budgets.

(2) Footprint analysis. Spatial representation of flux measurement indicates to what extent the values measured at the height of installed instrument reflect the average condition of the underlying surface. The underlying area that contributes to the measured value is called the flux footprint. Footprint analysis is an important tool for assessing the spatial representation of measured flux at certain sites. It also provides a theoretical foundation for data quality control and scale conversion of flux measurement. Mi et al found that the footprint area was about 160—200 m in crop and grassland ecosystems of ChinaFLUX, and 1600—3000 m for forest ecosystems [94]. The footprint area increases as the atmosphere becomes stable and instrument height increases, and decreases with courser upwind land surfaces.

3.2 Environmental controls on ecosystem carbon budget

3.2.1 Evaluation of carbon budget in major ecosystem

Most sites of ChinaFLUX have continuously measured CO_2 flux for 2—3 years. Table 1 shows net annual CO_2 budgets in major terrestrial ecosystems of ChinaFLUX[95−100]. The three forest sites in eastern China (CBS, QYZ and DHS) are big carbon sinks. NEE of the CBS temperate mixed forest is similar to other forest ecosystems of the same type[95]. The subtropical coniferous forest at the QYZ site is larger than most temperate or higher latitude evergreen coniferous forests, and is similar to the evergreen coniferous forests at Duke and Wind River in the U.S.A. and Bordeaux in France[51]. This may be because the planted coniferous forest at QYZ is a young community with relatively rapid growth rate and has a strong capacity to sequester carbon. The NEE of a subtropical evergreen broad-leaved forest at the DHS site is slightly less than that of the Manaus tropical evergreen broad-leaved

Table 1 Site characteristics, including mean annual temperature (MAT), mean annual precipitation (MAP), net ecosystem CO_2 exchane (N_{EE}), ecosystem respiration (R_E) and gross ecosystem productivity (GEP) in major ecosystems of ChinaFLUX

Site	Vegetation type	Location and elevation	MAT (℃)	MAP (mm)	NEE	RE	GEP	Year	Reference
					(gC · m^{-2} · yr^{-1})				
CBS	Temperate deciduous mixed forest	128°28'E, 42°24' N 738 m	4.66	774	−242	1285.8	−1527.8	2003	[95]
			4.88	707	−257.1	1247.8	−1504.8	2004	
			3.35	690	−278.9	1047.6	−1326.5	2005	
QYZ	Sub-tropical planted forest	26°44"N, 115°03'E 102 m	18.9	945	−387	1223	−1610	2003	[96]
			18.6	1485	−424	1442	−1866	2004	
			18.0	1330	−315.9	1345.4	−1661.3	2005	[95]
DHS	Evergreen broad-leaved forest	23°10'N, 112°32'E 200—500 m	20.7	1289.4	−435.6	1094.4	−1530	2003	[95]
			20.5	1297.5	−499.4	1012.4	−1511.8	2004	
			20.2	1423.7	−368.1	1030.1	−1398.2	2005	
XSBN	Tropical seasonal rainforest.	21°57'N, 101°12'E 756 m	22	1149.2	320	2247	−1927	2003	[97]
DX	Alpine meadow	30°51'N, 91°05'E 4250 m	1.7	550.4	15.7	205.8	−190	2004	[98]
			2.4	489.9	39.4	183.2	−144	2005	
HB	Alpine shrub-meadow	37°40'N, 101°20'E 3293 m	−1.35	531.3	−63.1	441.35	−450.90	2003	[98]
			−1.9	493.5	−85.3	416.20	−501.50	2004	[99]
			−1.31	541.5	−51.7	502.20	−553.90	2005	
	Alpine meadow	37°37'N, 101°18'E 3148 m	−1.0	484	−76.9	621.8	−698.7	2003	[98, 100]
	Alpine swamp	37°36'N,101°19'E, 3160 m	−1.35	531.3	67.9	499.5	−431.6	2003	[98]
			−1.8	493.5	70.6	475	−404.5	2004	
			−1.1	541.5	104.7	540.3	−432.4	2005	
NMG	Temperate steppe	44°30'N, 117°10'E 1189 m	1.7	364.1	109.9	421.1	−311.2	2004	[98]
			1.0	143.8	139	179.8	−40.8	2005	
YC	Cropland	36°57'N, 116°38'E 50°m	12.6	674.5	−198	1172	−1370	2003	[52]
			13.4	860.8	−318	1213	−1531	2004	

forest in Brazil and Castelporziano in Italy, which is influenced by Mediterranean climate[48]. The observation data indicated that the tropic seasonal rain forest ecosystem at the XSBN site is a net carbon source. However, studies showed that the tropical rain forest in Brazil is in carbon balance or a carbon sink[95]. The flux tower of XSBN site is located in a valley with complex terrain and drainage flow as well as frequent advection. Therefore, significant uncertainty and errors might exits in the eddy covariance measurement results in this region. More studies and longer-term measurements are needed to precisely evaluate the carbon budgets of the tropical seasonal rain forest at the XSBN site.

The observation results show that the semi-arid *Leymus chinensis* steppe in Inner Mongolia was evidently a carbon source in both 2004 and 2005, while studies indicate that the tallgrass prairie in North America is in carbon equilibrium[49,101,102]. The carbon exchange in grassland ecosystems is easily affected by the variation in precipitation; they serve as small carbon sinks in wet years and carbon sources in dry years[49,50]. The semi-arid *Leymus chinensis* steppe of ChinaFLUX has been protected from grazing for 20 years and the vegetation has reached the climax community. The decrease in annual precipitation may obviously constrain the carbon uptake in the semi-arid ecosystem. At the same time, the thick litterfall on the surface due to the protection from grazing also enhanced heterotrophic respiration and resulted in net carbon release in the steppe[103]. In contrast with the temperate steppe, the alpine meadow and alpine shrub at HB, located at north-eastern Tibet Plateau, were net carbon sinks during the observed years. The alpine swamp meadow at Haibei, rich in soil organic matter, has relatively high soil respiration during the long dormant season and lower photosynthetic carbon uptake during the growing season, compared to the alpine meadow and shrub; its annual total carbon budget seems to be a stable carbon source[100]. The alpine meadow at Dangxiong, located at the south edge of Tibet Plateau with the highest altitude, is a small carbon source as well. Study sites of the protected *Leymus chinensis* steppe at NMG and the alpine swamp meadow at HB have limited spatial representative due to their small area.

The winter wheat-corn rotation farmland ecosystem at YC was sequestering carbon during the 2 measurement years. The cropland at YC would become a carbon source if the carbon loss due to human harvest was considered. Actually, human management such as irrigation, fertilization and harvest may change annual carbon budgets of cropland ecosystems greatly. Flux measurement at all the sites of ChinaFLUX only continues for a few years, and more data from longer-term measurement (for example over 5 − 10 years) are needed to accurately evaluate the net carbon budget of the major ecosystems in China.

3.2.2 Response of ecosystem CO_2 exchange to environment

(1) Response of Gross Ecosystem Photosynthesis (GEP) to environmental factors

Differences in ecosystem carbon flux among sites might be attributed to biome type, disturbance history, succession stage of a community, soil nutrition condition and the eco-physiological characteristic of vegetation. Radiation, temperature and moisture conditions are primary environmental factors that affect ecosystem carbon uptake and release[51]. Valentini *et al.* found that GEP of a European forest ecosystem varied little with increasing latitude [48]. Similarly, the GEP of forest ecosystems on the North-South Transect of Eastern China (NSTEC) shows no increase with latitude, but the NEE decreases with increasing latitude in the order of DHS > QYZ > CBS (Table 1). This is similar to the forest ecosystems in Europe. Using the flux data obtained from forest, grassland and crop ecosystems in Europe, America and Asia, Law *et al.* found that mean temperature during the growing season and site water balance are primary factors that govern ecosystem GEP and that the impact of temperature on GEP is larger than that of moisture. Moisture determines the potential available leaf area, which represents the community photosynthetic ability on long time scales and controls the seasonal variation of GEP on short-time scale[51]. GEP reflects the integrated response of an ecosystem to climate, nutrition, disturbance and other factors, varying greatly among various ecosystems within a small latitude range.

The growth of vegetation is easily limited by low temperature and moisture stress with ample radiation in high latitude or altitude regions where the vegetation experiences a distinct growing season (usually from May to September) and dormant season. The seasonal variation and annual total GEP of temperate mixed forest at the CBS site are mainly affected by temperature and leaf area index[97,104]. The alpine meadow on the Tibet Plateau is also mainly controlled by temperature [99]. Moisture is the basic factor to affect vegetation growth for most terrestrial ecosystems. In the growing season with enough radiation, moisture is the primary factor determining the GEP of a forest ecosystem, and annual precipitation as well as its temporal variability is the key factor that affects the GPP of temperate grasslands[105]. For example, the GEP of a coniferous forest at QYZ decreased distinctly under drought stress in July, 2003, and as a result GEP and NEE in 2003 were lower in 2003 than in 2004[96,97]. The GEP of the *Leymus chinensis* steppe at NMG decreases sharply due to less precipitation and the change of seasonal distribution of rain, which also alters ecosystem vegetation phenology[103,106]. Actually, GEP of the ecosystem during the growing season is mostly determined by the coordination of temperature and moisture. With ample precipitation, ecosystems in subtropical and tropical regions are in a growth season during the entire year, where the slight seasonal changes in GEP are more likely controlled by solar radiation, as the GEP of evergreen broad-leaved forest at the DHS site is often constrained by heavy fog and less radiation in summer[97]. NSTEC spans the wide region from tropic, subtropical, temperate zone to frigid-temperate zone, showing distinctly different ecosystem response to environmental factors.

Table 2 shows the ecosystem quantum yield (α) and the maximal ecosystem photosynthesis (P_{max}), as well as their time of occurrence at each site of ChinaFLUX[52,95,97,107,108]. P_{max} of cropland is much higher than that of forests or grasslands, and forest P_{max} is higher than grassland P_{max} generally. The biggest α appears at CBS, and the alpine meadow at HB has the greatest photosynthetic productivity among grassland ecosystems. Table 2 also shows that the P_{max} of temperate ecosystems mostly appears in the active growth season, while the timing of P_{max} in tropic or subtropical ecosystems differs due to the effects of various environmental factors.

(2) Response of ecosystem respiration (RE) to environment

Ecosystem respiration (RE) is an important part of CO_2 flux between the biosphere and the atmosphere, which determines net ecosystem CO_2 exchange to a certain extent[48]. Table 1 also gives the estimated annual RE at each site of ChinaFLUX based on eddy covariance measurements, which could account for more than 60% of GEP on average. The ratio of RE and GEP in major terrestrial ecosystems on NSTEC increases with latitude (Fig. 3), similar to sites studied by EuroFLUX. The forests in Europe are mostly located in the mid- and high- latitude region and are influenced by temperate oceanic climate. The ratio of RE and GEP of EuroFLUX increases faster than that of ChinaFLUX.

Many studies have found that temperature is the primary factor that governs ecosystem RE among various environmental factors, and it is widely accepted that RE increases exponentially with temperature[56]. Q_{10} is temperature sensitivity of RE or the factor of increase of RE for every 10℃ increment of

Table 2 Comparing of photosynthesis parameters of each ecosystem at ChinaFLUX sites in 2003

Site	Vegetation	α (mg · CO_2 · μmol^{-1})	P_{max} (mg · CO_2 · m^{-2}s^{-1})	Timing	Reference
XSBN	tropical seasonal rain-forest	0.0006	1.64	March—April	[95]
DHS	evergreen broad-leaved forest	0.0027	1.1	October—March	[95]
QYZ	sub-tropical planted forest	0.0019	1.43	May—June	[107]
CBS	temperate deciduous mixed forest	0.0041	1.40	July—August	[108]
NMG	temperate steppe	0.0009	0.29	July—August	[97]
HB	alpine meadow	0.0017	0.9	July—August	
	alpine shrub-meadow	0.0016	0.65	July—August	
	alpine swamp	0.0018	0.61	July—August	
DX	alpine meadow	0.001	0.2	July—August	
YC	wheat	0.0015	2.42	March—May	[52]
	maize	0.0021	3.76	July—September	

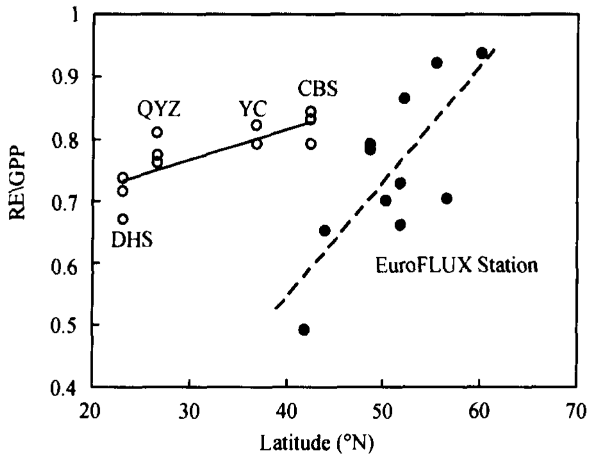

Fig. 3. The ratio of annual total ecosystem respiration (RE) and gross ecosystem production (GPP) plotted against latitude. Open symbols are ChinaFLUX sites; closed symbols are EuroFLUX sites[48].

temperature. The Q_{10} at each site of ChinaFLUX is presented in Table 3. Referring to Table 1, we see that the Q_{10} and annual total respiration of forest ecosystems follow the order XSBN > CBS > QYZ > DHS, which shows that Q_{10} decreases with increasing temperature[109]. Results show that the Q_{10} of grassland ecosystems is usually higher than that of forest ecosystems. In this study, only the semi-arid *Leymus chinensis* steppe (NMG) belongs to temperate grassland, the Q_{10} of which is similar to that of temperate grassland in North America. The alpine meadows at HB and DX sites have higher Q_{10} than forest ecosystems due to the rich organic carbon in alpine soil and its high temperature sensitivity[110].

It is has long been recognized that soil temperature is just one of a host of variables that influence ecosystem respiration and other factors such as soil moisture, soil organic matter and microbes are also known to influence soil respiration. Soil moisture deficit can restrain ecosystem autotrophic and heterotrophic respiration by limiting plant and microbial activity at low soil water content, particularly in arid or semi-arid ecosystems. Fu *et al.* found that the Q_{10} of semi-arid steppe decreases distinctly under moisture stress[103]. Yu *et al.* also suggested that moisture may become the key factor that controls RE under serious drought stress[90]. When describing the synthetic effects of temperature and moisture on ecosystem respiration simultaneously, two different models were used, a multiplicative model and a Q_{10} model. In the multiplicative model, ER is described as multiplicatively dependent on temperature and soil water content, supposing that Q_{10} is independent on soil water content. In the Q_{10} model, the temperature sensitivity coefficient of RE (Q_{10}) is expressed as a function of soil temperature and moisture. Thus, the impact of moisture on Q_{10} is accounted for when analyzing the synthetic effects of temperature and moisture on RE [90]. With both the eddy covariance and chamber method, the response of RE in typical forest, grassland and farmland ecosystems to temperature[111−115] has been studied, and results suggest that the Q_{10} model is better than the multiplicative model in describing the seasonal variation of RE in ecosystems that often experience drought stress [90].

(3) Environmental controls of net ecosystem CO_2 exchange

Net ecosystem CO_2 exchange (NEE) is the balance between ecosystem photosynthetic uptake and ecosystem respiratory effluxes. The quite different responses of photosynthesis and respiration to environmental changes results in the spatial-temporal variation of NEE[51]. Most ecosystems in the east of China experi-

Table 3 Ecosystem respiration at reference temperature (RE_{Tref}) and its temperature sensitivity (Q_{10}) at different sites ChinaFLUX

	Site	Q_{10}	$RE_{T_{ref}}$ (mg C m^{-2} s^{-1})	T_s/℃ (5cm)	Reference temperature (℃)	Year	Reference
	XSBN	3.03	0.144	22.3	T_{ref}=15℃	2003	[95]
	CBS	2.9	0.275	6.6			
	QYZ	1.7	0.113	18.2			
	DHS	1.6	0.08	19.9			
HB	Alpine shrub-meadow	3.94	0.09	2.3	T_{ref}=10℃	2003	[98]
HB	Alpine meadow	3.46	0.09	5.1		2003	
HB	Alpine swamp	2.2	0.095	2.4		2004	
	DX	2.59	0.04	5.8		2004	
	NMG	2.09	0.05	4.2			
	YC	2.94	0.13	13.2	T_{ref}=0℃	2003	[52]
		2.4	0.21	13.4		2004	

enced a drier and warmer year in 2003, with less annual precipitation at four sites (CBS, QYZ, YC, NMG) in 2003 than in 2004 (Table 1). But these ecosystems showed different responses to seasonal and interannual changes in temperature and precipitation. The GEP and RE of the evergreen coniferous forest at QYZ and the *Leymus chinensis* steppe at NMG were significantly restrained by water stress and NEE decreased during the drought summer in 2003[96,102,105]. The Yucheng cropland ecosystem, which suffers more influence from human activities, had higher production in wet years than in dry years. But the distinct lower precipitation at CBS in 2003 did not reduce its NEE, the value of which was comparable in 2003 and 2004, and larger than in 2005. This result might be ascribed to the increase of RE due to higher temperature during the growing season in 2004 that counteracted the increase of GEP with ample precipitation[104]. The vegetation growth of the alpine meadows at HB and DX are usually restrained by low temperature and a short growing season, although there is abundant precipitation in the warm season at the two sites. But most of the alpine plants have adapted to the low-temperature condition and can grow rapidly to sequester CO_2 during the short growing season with appropriate temperature and moisture. On the other side, the carbon efflux from ecosystem respiration of alpine meadows will be weakened during the cold winter. Therefore, the alpine meadows have better capacity for carbon sequestration than temperate grassland. This also indicates that the NEE of alpine grasslands is mainly controlled by temperature, whereas the precipitation and soil moisture have greater effects on temperate semi-arid grassland than does temperature.

The relationships between observed annual total NEE and annual mean temperature and annual precipitation among the typical terrestrial ecosystems of ChinaFLUX are plotted in Fig. 4. There is a significant positive relationship between net ecosystem carbon uptake and temperature or precipitation among various ecosystems such as forest, grassland and cropland ($R^2 \approx 0.8$). This suggests that temperature and moisture are the key factors controlling the pattern of ecosystem budget on large spatial scales. This also suggests the possibility that NEE can be estimated on a large scale with a simple method, but this still needs to be confirmed with further observation and investigation.

Observed data shows that the seasonal pattern and the response of NEE to temperature and precipitation for the tropical seasonal rainforest at XSBN are quite different from the evergreen broad-leaved forest at DHS and other tropical forests in Brazil. The GEP of XSBN is high in dry-hot and wet-warm seasons, but the increasing rate of GEP is apparently less than that of RE, causing the ecosystem to convert from a carbon sink to a carbon source. However, the seasonal rainforest converts to a carbon sink in the cool season due to the faster decrease in RE than GEP [97]. There is much uncertainty in the eddy covariance measurement at XSBN site due to its complex topography. Long-term observation and additional studies are needed to evaluate the carbon budget exactly in this tropic seasonal rainforest ecosystem more reliably.

3.3 Research on carbon and water fluxes modeling

Ecological modeling is an important tool for research on carbon flux and carbon cycling in global terrestrial ecosystems because of the impossibility of

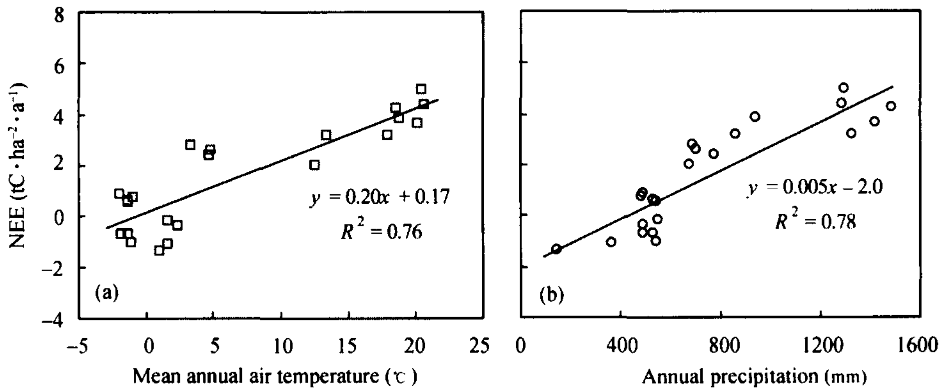

Fig. 4. The relationship between the annual total NEE and annual mean temperature (a) and annual mean precipitation(b) among the typical ecosystems of ChinaFLUX (Data source is the same as table 1 but not including Xishuangbanna site).

measuring all ecosystems on earth. Some ecological results derived from experimental sites could be extrapolated to regional and even global scales with modeling methods to estimate and evaluate the varying trend of terrestrial ecosystem carbon flux on larger spatial and temporal scales. ChinaFLUX has attached importance to research on ecosystem carbon and water flux modeling, as well as research on long-term flux observation. Ren *et al.*[116] and Zhang *et al.*[117] established a photosynthesis-transpiration coupling model on a canopy scale by using the observed flux data from CBS and YC sites. Wang *et al.* simulated the variation of ecosystem carbon and water fluxes during the growing season at CBS in 2003 at hourly intervals based on the BEPS model. The scenario analysis suggested that the capacity of the CBS forest ecosystem to function as a carbon sink would decrease with climatic warming[118]. He *et al.* simulated the CO_2 flux of three different ecosystems (cropland, forest and grassland) of ChinaFLUX with BP artificial neural network (ANN) by using energy flux, temperature and surface soil water data[119]. The results suggested ANN is not completely a black box model and could reveal the mechanism of variation in CO_2 flux. CEVSA (Carbon Exchange between Vegetation, Soil and Atmosphere) is a physiologically process-based mechanism model that can simulate energy exchange among a plant-soil-atmosphere continuum and the response and adaptation of carbon-water coupling cycle to environmental change. CEVSA has been widely used on regional and global scales[120–122]. Gu *et al.* parameterized and validated the CEVSA model by using the flux data from the ground investigation at the QYZ site in 2003. The simulated relationship between water, carbon fluxes and environmental factors is consistent with the observation results. But the model needs to be improved in simulating the effects of extreme temperature and water stress on ecosystem CO_2/H_2O flux[123]. These studies lay a foundation for developing coupling models of carbon-water-nitrogen cycles in a soil-plant-atmosphere system from canopy to regional and global scales.

4 Key issues and future direction of ChinaFLUX

The diversity of climate and vegetation in China provides a natural lab for research on terrestrial ecosystem carbon flux observation, but the complex vegetation and topography also bring many difficulties and challenges for eddy covariance flux observation. ChinaFLUX has obtained some significant results during the first three years of its development, and has received worldwide attention from the flux research community. Compared with other countries or regional networks, flux observation and research in China is still at the primary phase and much more effort is needed for further research on following issues.

4.1 Technique and methodology of flux observation in difficult conditions

Flux observation in terrestrial ecosystem based on the EC technique has been recognized by scientists in the fields of meteorology, bionomics and global change, but many technical problems still exist in flux observation with the EC method. The EC technique requires well-mixed atmospheric turbulence and flat land surface with homogeneous vegetation. But most natural vegetation grows in mountainous areas characterized by complex topography and airflow movement and relatively weak convection during night. These disadvantages bring many difficulties for long-term flux observation. The issues about the representativeness and reliability of observed flux data with the EC technique under difficult topography, vegetation and climate conditions have yet to be resolved. The three forest sites of QYZ, DHS and XSBN of ChinaFLUX are all located in complex terrain, which not only brings challenge for flux observation and research in China but also provides advantages for research on the technique and methodology of flux observation over complex terrain. ChinaFLUX will make more efforts on followings issues: ① the evaluation and correction method of flux observation over complex terrain; ② flux observational technique under complex meteorological conditions and the correction methods for flux underestimation during nighttime based on the EC technique, ③ the parallel comparison between biology inventory and eddy covariance flux observation, chamber method and aerodynamic method.

4.2 Environmental controls on CO_2 and H_2O fluxes in terrestrial ecosystems

The major goal of flux measurement is to study the key processes and physiological mechanisms of carbon and water cycles. Further knowledge of the mechanisms and processes of ecosystem carbon/water flux is needed to explain the flux observation results scientifically, abstract ecology knowledge, and apply the results to region scale. The net exchange of ecosystem carbon and water vapor can be obtained directly by long-term continuous measurement, and the environmental effects/controls on carbon and water vapor flux in terrestrial ecosystem is well studied. However, it is still difficult to partition the components of CO_2 flux into photosynthesis and respiration, as well as H_2O flux into plant transpiration and soil evaporation. Meanwhile, the effects of environmental change on the key processes of ecosystem carbon and water exchange at different spatial and time scales are still unknown. Many other observation methods (such as isotope technique, soil respiration measurement, aviation observation in atmospheric boundary layer and remote sensing etc.) are needed furthering order to obtain a deeper understanding of biological and environmental mechanisms that control different components of ecosystem carbon and water flux, combined with the dynamic models of the carbon cycle.

4.3 Development of multi-scale data-model fusion system

Observational data at different spatial and time scales by means of a certain method (such as field investigation, remote sensing, digital technique, historical recorder, statistical and inventory data and integration data) are needed to study the processes of ecosystem carbon and water cycles. Generally, ground single point observation could provide continuous data with high temporal resolution, but the observed data from limited ground points can not reflect the spatial- temporal pattern because of the spatial heterogeneity of natural terrestrial vegetation. Ecological models are able to distinguish and to quantify variation in physical and ecological processes at different scales or cross-scales. The data-model fusion system could greatly accelerate the work efficiency of research on ecosystem processes. As a result, the research on a multi-scale data-model fusion system is receiving attention from ecosystem and global change scientists and has been broadly applied to carbon and water cycles on different scales. International scientists are carrying out studies to develop the data-model fusion system, to improve the precision of simulating ecosystem production, estimate the sink and source of terrestrial ecosystems and the spatial pattern of greenhouse gases, forecast the change of ecosystems using the flux data of FLUXNET, and report the uncertainty of modeling results. ChinaFLUX has carried out some primary studies on flux data-model fusion [119]. As one of the major research participants, ChinaFLUX will continue with its efforts to develop a data-model fusion system that is applicable for terrestrial ecosystem in China in order to infer the historical variation of terrestrial ecosystem production and to predict the future trends of the ecosystem carbon budget under possible climate scenarios.

4.4 The patterns of CO_2 source/sink on large scale

At present, there are over 400 flux sites registered on FLUXNET. The measurement results of FLUXNET indicate that the terrestrial ecosystems in mid-latitude of north earth are atmospheric CO_2 sinks[44,45]. Because of the complex structure of natural vegetation and the disorder of the spatial distribution of flux site among vegetation types, the results derived from FLUXNET can not represent all the vegetation on earth. Therefore, there is large uncertainty existing in assessing the range and distribution of carbon sink/source of global terrestrial ecosystems[124]. The primary results of ChinaFLUX showed much interannual variation in carbon sequestration capacity as well as variation between different ecosystems.. Therefore, we still need long-term (5—10 years) measurements to determine whether different terrestrial ecosystems function as CO_2 sinks or sources. In addition, for the complex vegetation type in China, there is large uncertainty in evaluating the ecosystem carbon budget on a national scale using only the observed data from ChinaFLUX sites. Therefore, at present the emergent task for ChinaFLUX is to extend the diversity of biomes and climate for flux research by adding more flux observation sites.

4.5 Future directions of ChinaFLUX

As a national research network, ChinaFLUX has promoted the development of flux research in China.

With the wide extension and application of flux research, many new flux sites have been established by other institutes and universities in China (such as the institute of Chinese Academy Science, China Meteorological Administration, Chinese Forestry Academy) (Fig. 1). ChinaFLUX needs more cooperation with domestic and international flux networks to advance research on the coupling mechanism of carbon, water and nitrogen cycles by combining flux observation with transect research and carrying out synthetic research plans based on multi-scale, multi-process, multi- approach and cross-subjects.

Terrestrial transect is a bridge to link site observation with regional research and a media of scale conversion between different spatial and time scales. It can make full use of the site measurement data to improve work efficiency and shorten the time for understanding some scientific problems by using spatial information instead of temporal series data, the displacement experiments of ecosystem composition and transect research[125]. IGBP start-ups 15 transects in 4 critical regions, including the North East Chinese Transect (NECT) and the North South Transect East Chinese (NSTEC). Influenced by the monsoon and the high elevation of Tibet Plateau, the grasslands in China form a natural transect driven by the change of water and heat conditions spatially (Chinese Grassland Transect, CGT)[5]. The range of CGT is about 200—300 km in width and 5000 km in length from Fuyuan in Northeast of China (135°E, 48.5°N) to Pulan in the west of Tibet Plateau (81°E,30.3°N), across North-East Plain, Mongolia Plateau, Loess Plateau and Tibet Plateau from north-east to south-west of China. Most flux sites in China are located on the three terrestrial transects (Fig. 5).

EACEEFT (Euro-Asian Continental Eastern Edge Forests Transect) and EACGT (Euro-Asian Continental Grassland Transect) are both basic platforms for

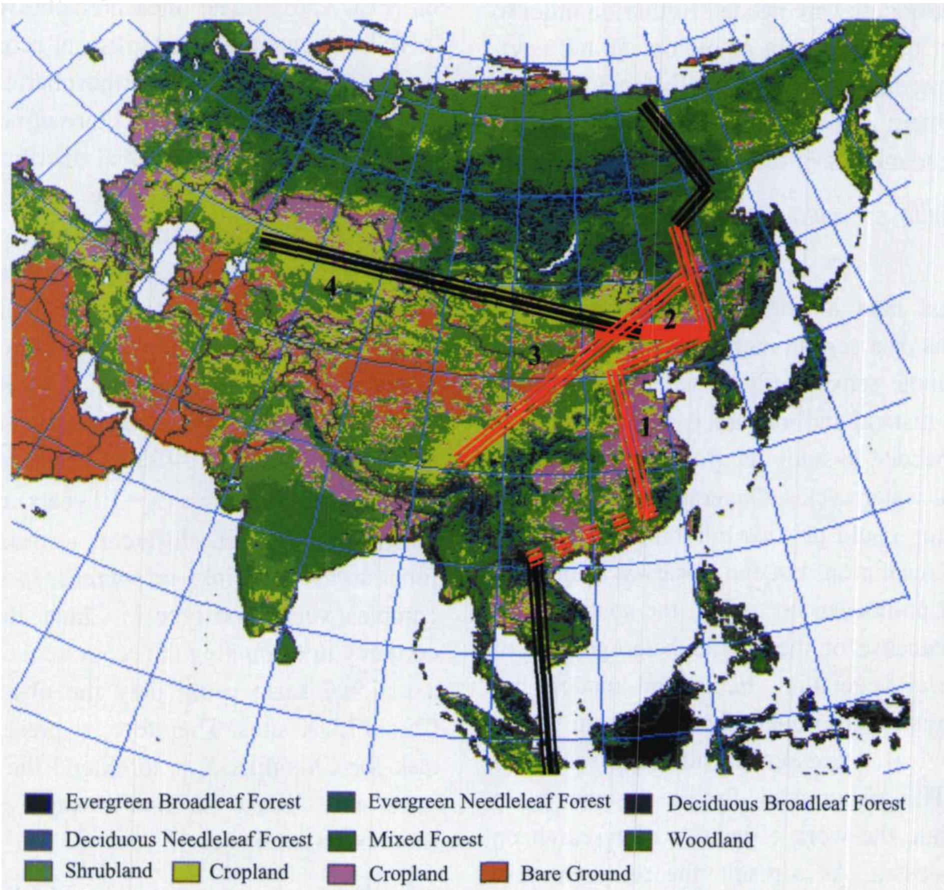

Fig. 5. Spatial distributions of Euro-Asian Continental Eastern Edge Forests Transect, Euro-Asia Continental Grassland Transect and China mainly land transect. 1, North-South Transect of Eastern China (NSTEC); 2, North-East China Transect (NECT); 3, China Grassland Transect (CGT); 4, Euro-Asia Continental Grassland Transect (EACGT).

cooperative international research on global change and terrestrial ecosystems on a continental scale[5]. NECT, NSTEC and CGT are important parts of EACEEFT and EACGT, and are also the core research region of ChinaFLUX. Some of the major future directions of ChinaFLUX include researches on understanding the response and adaptation of water, carbon and nitrogen cycles to global change, and to discovering the formative mechanisms of the spatial pattern of terr estrial ecosystem structure, function and process.

Carbon, water and nitrogen cycles are coupled ecosystem processes. In recent years, singnificant progress has been made in water and carbon cycles from different aspects, and scientists are devoting themselves to developing the carbon-water coupling cycle models. However, most current carbon-water coupled models simplify the coupling relationship of carbon and water cycles and have difficulty exactly simulating the processes of ecosystem carbon and water cycles[126]. Nitrogen as a nutrient could affect plant photosysnthesis directly, and the effective nitrogen in soil determines the capacity of ecosystem carbon sequestration. Global change has increased ecosystem primary production, however, it also results in more effective nitrogen absorbed by vegetation and fixed by soil organic matter, and eventually limiting ecosystem production[127]. Atmospheric nitrogen deposition is an abiotic method for an ecosystem to capture nitrogen. Although it can imporve carbon sequestration in nitrogen-poor ecosystems, its long-term ecological effect is still unkown[128]. ChinaFLUX has not carried out the integrated research on water-carbon-nitrogen cycles yet. However, it is a key issue to observe ecosystem water-carbon-nitrogen coupling cycles, explore the relationships between water, carbon and nitrogen cycles and the response and adaptation of terrestrial ecosystem to global changes in critical regions of NSTEC, NECT and GCT.

As a main part of FLUXNET, ChinaFLUX will play an important role in assessing the carbon budget on the Euro-Asian Continent and global ecosystems and in exploring the response and adaptation of terrestrial ecosystems to global changes. In order to study the terrestrial ecosystem carbon cycle, carbon budget and the interaction between carbon cycle and global change, ChinaFLUX should cooperate with not only the domestic organization of flux research, but also other national/regional fluxnet (AsiaFlux, KoFlux, AmeriFlux, CarboEurope, OzFlux).

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