Progress in water and energy flux studies in Asia: A review focused on eddy covariance measurements

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Abstract

The eddy covariance (EC) technique-based observation system allows for researchers to determine latent and sensible heat fluxes, which are key components of the surface energy balance. The number of water and energy flux studies in Asia has increased as the number of flux measurement sites and the length of the observation periods have grown. To retrace the footprints of the AsiaFlux network and predict future research directions, we reviewed the progress in water and energy flux studies in Asia from the 1990s to the present day. This included studies on continuous evapotranspiration (ET) and surface energy balance measurements in various ecosystems, from the tropics to the polar regions. We also reviewed comparative experiments between the EC technique and other observation techniques including the use of a lysimeter or scintillometer, data processing techniques, connections between carbon and water fluxes, and multi-site syntheses. This paper discusses three remaining challenges that are hindering the derivation of scientific knowledge for ET and the surface energy balance, namely: the non-closure of the surface energy budget, imperfect compatibility between open- and closed-path gas analyzers, and difficulty in partitioning ET into evaporation and transpiration. If we leverage the advantages of the EC technique (i.e., high sampling rates of \(\geq 10\) Hz and continuous measurement capabilities), standardized methods for correcting and partitioning can be developed in the near future.

Key words: AsiaFlux, Eddy covariance, Energy flux, Evapotranspiration, Synthesis

1. Introduction

Latent and sensible heat fluxes are the main targets of the application of an eddy covariance (EC) technique-based observation system. These fluxes are key components of the surface energy balance. In particular, latent heat flux is critically important, as it can be converted to evapotranspiration (ET), which is also a primary component of the surface water balance. Sensible heat flux is related to convection and determines mass and heat transfer to the free atmosphere through the planetary boundary layer. If an open-path type gas analyzer is used to measure trace gas fluxes (e.g., carbon dioxide, methane), it is imperative to measure both fluxes to enable the application of air density fluctuation corrections (e.g., Webb \textit{et al.}, 1980). For these reasons, both latent and sensible heat flux measurements have been conducted for most of the observing sites around the world, including in Asia.

The number of water and energy flux studies in Asia has increased along with both the number of flux measurement sites and the length of observation periods. The 20th anniversary workshop of AsiaFlux (i.e., the continental network of flux tower measurements in Asia, http://www.asiaflux.net) was held in Takayama, Japan from October 2 to October 5, 2019. Although the history of AsiaFlux is relatively short compared with similar networks in Europe and America, the number of AsiaFlux sites increased to 110 as of January 2020. During this period, the number of publications related to water and energy flux studies in Asia had risen to over 530, largely because more multi-year observation data are now available for synthetic analyses and validations of various models and satellite algorithms (Fig. 1).

To date, several regional networks have been established to monitor carbon and water cycles in terrestrial ecosystems. AsiaFlux is a regional research network in Asia, and it was established in 1999 to study the exchanges of carbon, water, and energy between terrestrial ecosystems and the atmosphere; this network shares data with several national networks such as ChinaFLUX, JapanFlux, and KoFlux. Several papers have provided introductions to such networks. Notably, Mizoguchi \textit{et al.} (2009) reviewed the state of tower flux observation sites in Asia including AsiaFlux. Yu \textit{et al.} (2006) introduced ChinaFLUX which has been led by a government knowledge innovation program to support ecosystem integration and local representation, for innovation, research, and forecasting. Lee \textit{et al.} (2014) established the Lake Taihu Eddy Flux Network, the first lake EC network, and it was launched to monitor the temporal and spatial patterns of lake air fluxes in Lake Taihu, China. These networks are playing increasingly important roles in Earth and environmental sciences. Such network-based studies are providing more opportunities to improve and generalize environmental knowledge through the integration of distributed observations.
To retrace the footprints of the AsiaFlux network and predict future research directions, we reviewed the progress in water and energy flux studies in Asia from the 1990s to the present. In section 2, we classify publications into a number of categories. These publications included observations, technique inter-comparisons, data processing studies, evaluations of the connection between carbon and water fluxes, multi-site syntheses, model-data fusion studies, satellite remote sensing analyses, and finally, other publications that did not fit into any of the previous categories. Among those previous studies, we mainly focused on EC flux measurements in this review. In section 3, we discuss the observations of continuous ET and surface energy balance measurements in various ecosystems (e.g., forest, cropland, grassland, urban) from the tropics to the polar regions. In section 4, we discuss comparative experiments between EC and other observation techniques, such as lysimeters or scintillometers. In section 5, we discuss data processing techniques such as flux calculation or gap-filling. In section 6, we discuss the connections between carbon and water fluxes. In section 7, we discuss multi-site synthesis methods, such as inter-comparison and upscaling. Finally, in section 8, we outline and discuss the remaining challenges that remain in the field of water and energy flux studies in Asia.

2. Literature review

To identify what research has been conducted in which field, we classified publications according to the following subjects.

Observations: A study primarily based on observation, including documentation and analyses of the diurnal/seasonal/inter-annual variations of various land cover types and climates.

Inter-comparison with other techniques: A study primarily based on inter-comparison between EC and other flux observation techniques, such as lysimeter and scintillometer evaluations.

Data processing: A study primarily based on data processing techniques, including gap-filling and partitioning of ET into evaporation and transpiration.

Connections between carbon and water fluxes: A study primarily based on connections between carbon and water fluxes, such as quantifying the efficiency of water use of various land cover types and climates.

Multi-site synthesis: A study primarily based on multi-site observations, such as inter-comparison and upscaling using an observation network.

Model-data fusion: A study primarily based on analytical or numerical modeling of the surface energy balance or hydrology, such as calibration and validation of the land surface-hydrology model.

Satellite remote sensing: A study primarily based on satellite remote sensing, such as ET mapping using satellite imagery.

Other: A study that does not belong to the above categories, such as aerodynamic parameters of boundary layer meteorology.

From 1998 to 2019, the percentage of studies classified as observation (39%) was the largest among the water and energy flux studies in Asia (Fig. 2). Those classified as model-data fusion (19%) made up the second largest portion, followed by satellite remote sensing (13%). The total number of publications has more than doubled since 2012 (Fig. 1), and such increases occurred in the whole field of research, with the exception of inter-comparison with other techniques. Such overall trends support the postulation that the sharp increase since 2012 was caused by more multi-year observation data becoming available for the whole research field. It should be noted that the boundaries between categories have been becoming ambiguous. In such cases, we judged the category subjectively after checking the journal in which the article was published and reading the abstract. Hereafter, we have reviewed each category, with the exception of the model-data fusion category, the satellite remote sensing category, and the Other category, which were reviewed by Ito (in this special issue) and Kobayashi (in this special issue), respectively.

3. Observations

We identified a number of studies that reported long-term (e.g., annual, whole growing season) ET observations from 131 sites across Asia. These applied the EC technique for measuring water and energy fluxes in a wide range of regions from Siberia to Southeast Asia (10°–80°N, 60°–80°E). The EC towers are distributed in tropical, arid, temperate, and boreal climate zones. Figure 3a shows the relationship between the annual mean air temperature and annual precipitation for the 109 sites. The annual mean air temperature ranges from −4°C to 28°C and the annual precipitation ranges from below 30 mm to

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**Fig. 1.** Number of publications related to water and energy flux studies in Asia from 1998 to 2020. (Peer-reviewed international journals only; Source: Scopus database, https://www.scopus.com, last accessed: February 25, 2020, key search words: eddy covariance, energy flux, evapotranspiration, Asia).

**Fig. 2.** Classification of the publications in Fig. 1. The number in parentheses represents the number of publications for each category.
2,600 mm. Nevertheless, EC flux sites within Asia do not appear to be representative of the climate zone as a whole (e.g., in polar and tropical regions). Some regions, such as East Asia, are more densely instrumented than other regions (e.g., Siberia and South Asia). However, the total number of sites for each biome seems to be fairly representative. The sites span a wide variety of plant functional types (PFTs) including evergreen needleleaf forest (ENF), evergreen broadleaf forest (EBF), deciduous needleleaf forest (DNF), deciduous broadleaf forest (DBF), mixed forest (MF), shrublands (SH), grasslands (GRA), permanent wetlands (WET), croplands (CRO), deserts (Barren), and water bodies (WAT). The studies conducted in croplands and forests (i.e., ENF, EBF, DNF, DBF, and MF) are the most dominant types (25% and 24%, respectively).

We used the Budyko hypothesis (Budyko, 1974) to examine the water balance controlled by the supply and demand of water from the atmosphere. The Budyko curve describes the relationship between potential ET and its actual ET, each normalized by precipitation. The slope of the Budyko curve is steep in energy-limited regions (i.e., evaporation index as a function of ET/precipitation < 1), and becomes flat in water-limited regions (i.e., aridity index as a function of potential ET/precipitation > 1). Figure 3b plots the original Budyko curve for the EC observations across Asia. The EC observations showed that the relationship between water and energy is consistent with the original Budyko hypothesis. However, there were regions where the amount of actual ET has exceeded local precipitation such as hyper-arid regions and irrigated crop plantations.

3.1 Forests

Forest ecosystems exert a significant influence on regional and global water cycling (Baldocchi et al., 1988). The ET from forest ecosystems constitutes nearly one half of the total terrestrial ET (Oki and Kanae, 2006). Forests are believed to function as a “green dam” that (1) prevents flooding and soil erosion via buffering actions that reduce the rate of run-off by intercepting and evaporating precipitation, and (2) conserves the moisture contents in the surface soil by controlling the transpiration rate. For this reason, many long-term field experiments have been performed to measure the exchange of water and energy between forest ecosystems and the atmosphere in various areas of woody PFTs and climates.

The annual ET rate ranged from 330 mm year$^{-1}$ to 1,600 mm year$^{-1}$ in 32 forest regions in Asia (Table 1). At the biome level, EBF had the highest mean annual ET rate, followed by ENF, DBF, MF, and DNF (Fig. 4). The annual ET rate gradually decreased from tropical to temperate and boreal zones. The daily ET rate in tropical forests was 2.8–6 mm day$^{-1}$ and showed little seasonal variation (Igarashi et al., 2015; Takanashi et al., 2010), and the annual water loss via ET was > 1,100 mm year$^{-1}$ (Hirano et al., 2015; Kosugi et al., 2012; Kumagai et al., 2005; Kume et al., 2011). For the other climatic zones, the peak daily rate was comparable, but strong seasonal variations resulted in much less water loss via ET (330–1030 mm year$^{-1}$). It should be noted that there has been a lack of observations in the arid regions compared to the other regions even though large-scale
| Location (City, Country) | Latitude, Longitude | AsiaFlux site code | Vegetation type | Period (season) | Climate | Köppen climate | LAI_{MAX} | P | T_a | ET | EBR | System type | Reference |
|-------------------------|---------------------|-------------------|----------------|----------------|---------|----------------|-----------|-----|------|-----|-----|-------------|-----------|
| Paseo, Malaysia | 2°58′N, 102°18′E | MY-PSO        | MF             | 2003–2005 (Whole year) | Tropical | Af              | 5.76             | 1733 | -   | 1318 | 0.78 | OPEC         | Takanashi et al. (2010) |
| Kalangpangan, Indonesia | 2°20′N, 114°02′E | ID-PDF     | EBF            | 2004.08–2008.07 (Whole year) | Tropical | Af              | 2446             | 26.3  | -   | -    | -   | OPEC         | Hirano et al. (2015) |
| Miri, Malaysia | 4°12′N, 114°56′E | MY-LHP       | EBF            | 2001.07–2002.06 (Whole year) | Tropical | Af              | 2151             | 27    | 1545 | 0.82 | OPEC         | Kumagai et al. (2005) |
| Lampang, Thailand | 18°25′N, 99°43′E | TH-MMP      | DBF            | 2006–2012 (Whole year) | Tropical | Aw              | 1335             | 25.4  | 977  | 0.68 | OPEC         | Igarashi et al. (2015) |
| Xishuangbanna, China | 21°55′N, 101°16′E | CN-BNS | EBF | 2003–2006 (Whole year) | Tropical | Cwa            | 1322             | 20.1  | 1029 | 0.64 | OPEC         | Li et al. (2010) |
| Beijing, China | 40°22′N, 115°56′E | -             | MF             | 2012–2015 (Whole year) | Arid    | Bsk            | 325              | 9.7   | 329  | 0.59 | OPEC         | Ma et al. (2018) |
| Heihe, China | 41°59′N, 101°07′E | -             | DBF            | 2014 (Whole year) | Arid    | BWk            | 16.4             | 10.8  | 653.4 | 0.72 | OPEC         | Ma et al. (2017) |
| Pu’er, China | 24°32′N, 101°01′E | -             | EBF            | 2009–2013 (Whole year) | Temperate | Cwb           | 1637             | 11.6  | 863  | 0.70 | OPEC         | Song et al. (2017a) |
| Yueyang, China | 29°31′N, 112°55′E | -             | DBF            | 2010 (Whole year) | Temperate | Cfa            | 2184             | 17.0  | 1033 | -    | OPEC         | Gao et al. (2017) |
| Taihe, China | 26°44′N, 115°03′E | CN-QYZ       | ENF            | 2003–2010 (Whole year) | Temperate | Cfa            | 1381             | 18.1  | 787  | -    | OPEC         | Xu et al. (2014) |
| Jiyuan, China | 35°01′N, 112°28′E | -             | DBF            | 2004 (Whole year) | Temperate | Cfa            | 1324             | 17.8  | 736  | -    | OPEC         | Li et al. (2006a) |
| Kiryu, Japan | 34°58′N, 136°00′E | JP-KEW      | ENF            | 2001–2003 (Whole year) | Temperate | Cfa            | 1592             | 13.2  | 729  | 0.9  | OPEC and CPEC | Kosugi et al. (2007) |
| Jiyuan, China | 35°01′N, 112°28′E | -             | DBF            | 2006–2009 (Growing) | Temperate | Cfa            | 1536             | 13.3  | 752  | -    | OPEC         | Tsuruta et al. (2016) |
| Beijing, China | 39°32′N, 116°16′E | -             | DBF            | 2006–2009 (Growing) | Temperate | Cfa            | 1592             | 13.2  | 729  | 0.9  | OPEC and CPEC | Kosugi et al. (2007) |
| Beijing, China | 40°06′N, 116°42′E | -             | DBF            | 2014–2015 (Growing) | Temperate | Cfa            | 1536             | 13.3  | 752  | -    | OPEC         | Xu et al. (2018a) |
| Hokkaido, Japan | 42°44′N, 141°31′E | JP-TMK      | DNF            | 2002–2003 (Whole year) | Temperate | Dfb            | 1001             | 6.8   | 494  | 0.94 | OPEC         | Hirano et al. (2017) |
| Sichuan, China | 33°09′N, 103°52′E | -             | MF             | 2014–2015 (Whole year) | Temperate | Dwb            | 893              | 7.3   | 720  | -    | OPEC         | Yan et al. (2017) |
| Anju, China | 42°24′N, 128°05′E | -             | MF             | 2003 (Whole year) | Boreal   | Dwa            | 6.9              | 524   | 13.4 | 579  | 0.71 | OPEC         | Tong et al. (2017) |

1*Abbreviations of vegetation type as follows: EBF: evergreen broadleaf forest, ENF: evergreen needleleaf forest, DBF: deciduous broadleaf forest, DNF: deciduous needleleaf forest, MF: mixed forest. Abbreviations of Köppen climate are as follows: Af: tropical rainforest climate, Aw: tropical savanna climate with dry-winter characteristics, Bsk: cold semi-arid climate, BWk: cold desert climate, Cfa: humid subtropical climate, Cwa: monsoon-influenced humid subtropical climate, Cwb: subtropical highland climate, Dfb: warm-summer humid continental climate, Dwa: monsoon-influenced hot-summer humid continental climate, and Dwb: monsoon-influenced warm-summer humid continental climate based on the Beck et al. (2018) 1-km resolution map.*
afforestation/reforestation areas in vulnerable arid/semi-arid regions has resulted in a higher demand for ET measurements (Cao et al., 2016, 2009; Chen et al., 2010; Cho et al., 2019).

### 3.2 Cropland

Agricultural intensification over the past 50 years, along with green revolution trends, have resulted in an approximate doubling in agricultural productivity. A single plant pumps 200–500 g of water from soil to leaves to photosynthesize one gram of sugar. This means that water scarcity due to the doubling of crop productivity and the subsequent increase in water consumption remains problematic. In Asia, more than 70% of freshwater resources are used to irrigate agricultural lands (Dubois, 2011), particularly rice paddies. Moreover, crop irrigation is expected to continue increasing in response to the expansion of irrigated areas (Siebert et al., 2015) and future global warming (Wada et al., 2014). In this context, information on ET for agricultural ecosystems is critical, as such data can allow for better water management, e.g., through adjustments to the timings, amounts, and types of irrigation.

The ET rate ranged from 210 mm to 1,370 mm over the growing season in the 34 cropland sites in Asia (Table 2). Among the types of crops, cacao had the highest mean growing season ET rate, followed by rice, cotton, maize, vineyards, and wheat (Fig. 5). The highest daily ET rate occurred in the cotton fields and maize fields (7.8 mm day\(^{-1}\), Jiang et al., 2014; Yang et al., 2016), followed by the rice paddies (6.57 mm day\(^{-1}\), Hossen et al., 2011), wheat fields (4.7 mm day\(^{-1}\), Yang et al., 2014), and vineyards (3.3 mm day\(^{-1}\), Gao et al., 2019). The growing season mean ET rate of the croplands was highest in the tropical zone (1,215 mm) and was within a comparable range in the other climatic zones (400–650 mm).

The crop coefficient (\(K_c\)) method is an approach that has been widely used for the estimation of water consumption by crops, because of its simplicity and robustness. The \(K_c\) is the ratio of the crop evapotranspiration (\(ET_c\), mm day\(^{-1}\)) to the reference crop evapotranspiration (\(ET_o\), mm day\(^{-1}\)), and it represents the ET of plants under growing conditions (Allen et al., 1998).
Table 2. Locations and brief descriptions of the eddy covariance-based evapotranspiration (ET, mm) in the cropland sites reviewed in this study. LAI_{max} is the maximum leaf area index (m² m⁻²), P is the mean annual/growing season precipitation (mm), T_r is the mean annual/growing season temperature in (°C), K_r is the measured crop coefficients of whole season growing, and EBR is the mean energy balance ratio (unitless). System types are shown as an open-path eddy covariance (OPEC) or a closed-path eddy covariance (CPEC).

| Location (City, Country) | Latitude, Longitude | Asia/Flux site code | Crop | Period (season) | Climate | Köppen climate | LAI_{max} | P (irrigation) | T_r | ET | K_r | EBR | System type | Reference |
|--------------------------|---------------------|---------------------|------|-----------------|---------|-----------------|-----------|---------------|-----|-----|-----|-----|-------------|-----------|
| Nogu Rahmat, Indonesia   | 1°08′S, 102°50′E    | -                   | Cacao | 2002 (Whole year) | Tropical | Cfa             | 7.2       | 1970          | 24.5 | 1058 | -   | -   | OPEC       | Falk et al. (2005) |
| Los Banaos, Philippines  | 14°14′N, 120°26′E   | PH-IRI              | Paddy rice/ Upland rice | 2008–2009 (Growing) | Tropical | Aw              | 6.9       | 2396          | 27.2 | 1371 | 1.02 | 0.99 | OPEC       | Alberto et al. (2011) |
| Deir Ala, Jordan         | 32°18′N, 35°52′E   | -                   | Tomato | 2001–2002 (Growing) | Arid | BSh             | -         | 10            | 23   | -   | 0.69 | -   | OPEC       | Amayreh and Al-Abed (2005) |
| Gansu, China             | 37°51′N, 102°53′E   | -                   | Vineyard | 2017–2018 (Growing) | Arid | BWk             | 1.4       | 164 (407)     | 19.6 | 355  | -   | 0.85 | OPEC       | Gao et al. (2019) |
| Wuwei, China             | 37°52′N, 102°50′E   | -                   | Maize | 2013–2014 (Growing) | Arid | BWk             | -         | 123 (118)     | 218  | -   | 0.78 | -   | OPEC       | Li et al. (2008a) |
| Weishan, China           | 36°39′N, 116°03′E   | -                   | Wheat | 2005–2007 (Growing) | Arid | BSk             | 4.6       | 131 (211)     | 11.1 | 374  | -   | 0.75 | OPEC       | Lei and Yang (2010) |
| Wuwei, China             | 37°52′N, 102°50′E   | -                   | Maize | 2014–2015 (Growing) | Arid | BWk             | 4.9       | 140 (407)     | 18.4 | 498  | -   | -   | OPEC       | Qin et al. (2016) |
| Loess Plateau, China      | 38°44′N, 113°12′E   | -                   | Maize | 2012–2013 (Growing) | Arid | Dwa             | 4.5       | 466 (811)     | 18.1 | 371  | 0.83 | -   | OPEC       | Feng et al. (2016) |
| Shouyang, China          | 37°45′N, 113°12′E   | -                   | Maize | 2011–2013 (Growing) | Arid | Dwa             | 4.5       | 481 (734)     | 7.4  | 363  | 0.84 | -   | OPEC       | Gong et al. (2017a) |
| Daxing, China            | 39°37′N, 116°26′E   | -                   | Wheat | 2008–2009 (Growing) | Arid | Dwa             | -         | 540 (660)     | 12.1 | 56   | 0.79 | -   | OPEC       | Zhang et al. (2013a) |
| Zhangye, China           | 38°38′N, 100°41′E   | -                   | Maize | 2008 (Growing)     | Arid | BWk             | 4.9       | 116 (660)     | 4.7  | 658  | 0.71 | 0.81 | OPEC       | Gu et al. (2017) |
| DC, China                | 40°37′N, 81°11′E    | -                   | Cotton | 2013–2014 (Growing) | Arid | BWk             | 4.9       | 105 (875)     | 18.8 | 472  | 0.36 | -   | OPEC       | Ji et al. (2017) |
| Aler, China              | 41°53′N, 86°12′E    | -                   | Cotton | 2012–2013 (Growing) | Arid | BWk             | 4.9       | 51.5 (430)    | 20.9 | -   | 0.54 | -   | OPEC       | Az et al. (2018) |
| Kofu, China              | 41°53′N, 86°12′E    | -                   | Cotton | 2012–2013 (Growing) | Arid | BWk             | 4.9       | 60 (566)      | 11.5 | 543  | 0.53 | -   | OPEC       | Tian et al. (2016) |
| Shihzei, China           | 41°17′N, 85°49′E    | -                   | Cotton | 2008–2009 (Growing) | Arid | BWk             | 7.3       | 216 (490)     | 8.4  | 337  | 0.5  | -   | OPEC       | Zhou et al. (2012) |
| Nanchang, China          | 28°26′N, 116°00′E   | -                   | Milk vetch Paddy early rice | 2016–2017 (Growing) | Temperate | Cfa | 6.4       | 1748 (389)    | 18.1 | 349  | -   | 0.77 | OPEC       | Liu et al. (2019a) |
| Mymensingh, Bangladesh   | 24°37′N, 90°42′E    | BD-MYM              | Paddy rice | 2007 (Whole year) | Temperate | Cwa | 5.9       | 2763 (674)    | 24   | 997  | -   | -   | OPEC       | Hossen et al. (2011) |
| Tsukuba, Japan           | 36°03′N, 140°01′E   | JP-MSE              | Paddy rice | 2002–2014 (Growing) | Temperate | Cfa | 3         | 543.3 (1103) | 22.0 | 419  | 0.79 | -   | CPEC      | Ikawa et al. (2017) |
| Dingxi, China            | 35°33′N, 104°35′E   | -                   | Wheat | 2010 (Growing)     | Boreal | Dwb | -         | 286     | -    | 252  | 0.46 | -   | OPEC       | Yang et al. (2014a) |
| Duanl Innere Mongolia, China | 42°02′N, 116°16′E | CN-D02              | Wheat | 2006–2007 (Growing) | Boreal | Dwb | 2.4       | 542     | 3.3  | 241  | -   | -   | OPEC       | Miao et al. (2009) |
| Loess Plateau, China     | 35°33′N, 104°35′E   | -                   | Wheat, Potato, Maize | 2009–2011 (Growing) | Boreal | Dwb | 3.0       | 303     | 7.3  | 280  | -   | -   | OPEC       | Yang et al. (2019a) |
| Jinhou, China            | 41°09′N, 121°12′E   | -                   | Maize | 2005–2014 (Growing) | Boreal | Dwa | 3.1       | 575     | 10.3 | 397  | -   | -   | OPEC       | Zhou et al. (2019) |
| Panjin, China            | 40°56′N, 121°58′E   | CN-PRW              | Paddy rice | 2013–2014 (Growing) | Boreal | Dwb | 12.7     | 252     | 3.3  | 241  | -   | -   | OPEC       | Wang et al. (2017) |

Abbreviations of Köppen climate are as follows: Af: tropical rainforest climate, Aw: tropical savanna climate with dry-winter characteristics, BSk: cold semi-arid climate, BWk: warm-summer humid continental climate, Dwb: warm-summer humid continental climate, and Dwc: warm-summer humid continental climate based on the Beck et al. (2018) 1-km resolution map.

The crop coefficients (K_r) in FAO-56 (Allen et al., 1998) as follows for cotton (0.71), tomato (0.85), maize (0.71), wheat (0.65), and vineyards (0.51).
\[ K_c = \frac{ET}{ET_{g}} \] (1)

The Food and Agricultural Organization (FAO) of the United Nations recommended calculation of the ET (FAO56) by multiplying the ET value by \( K_c \) as a relatively simple method for assessments (Allen et al., 1998). However, the FAO56 approach can overestimate ET by more than 20% as a result of various factors such as crop variety differences, planting density, and quality of the input dataset (Allen, 2000). In addition, the \( K_c \) values can vary significantly depending on crop characteristics (e.g., leaf area, height, growth stages, and leaf physiological properties) and field management strategies (e.g., irrigation control, mulching), or environmental conditions, and so data need to be adjusted to reflect the actual conditions (Gharsallah et al., 2013; Hunsaker et al., 2003; Katerji and Rana, 2006).

Table 2 also shows the seasonally averaged \( K_c \) values for various crops. As expected, there was a difference in the \( K_c \) values between the measured values, and values reported by the FAO (Allen et al., 1998). For example, the \( K_c \) of cotton and tomato under mulch and drip irrigation was substantially decreased compared to open field conditions. Similarly, in the case of maize, plastic mulch was shown to have a beneficial effect on improving water use (Gong et al., 2017a; Li et al., 2008c). Therefore, to accurately estimate \( K_c \), it is still prudent to measure the amount of ET directly and continuously as a reference for calibrating and updating the value of \( K_c \).

### 3.3 Grassland

Grassland ecosystems are the most dominant ecosystem type throughout the Northern Hemisphere, and these account for approximately 32% of natural global vegetation (Parton et al., 1995). Grasslands not only provide livestock products and plant resources (O’Mara, 2012), but also a wide variety of critical ecosystem services, such as soil erosion reductions, carbon storage, and wildlife habitat (FAO, 2010; Fu et al., 2011). Despite their importance, grasslands are an endangered biome, that is being threatened by land conversion practices, agricultural intensification, fire suppression activities, and abandonment. In addition, grasslands are declining in response to warming from climate change, changed patterns of precipitation, and other trends (Guo et al., 2017).

The annual ET rate ranged from 160 to 630 mm year\(^{-1}\) in 26 grassland areas across Asia (Table 3). The mean annual ET rate for meadows was 200 mm higher than that for steppes (Fig. 6). The annual ET rate for the different climate regions was lowest in the arid region, followed by the boreal, and polar regions. The daily ET value during the growing season was 1–1.5 mm day\(^{-1}\), and it was less than 0.5 mm day\(^{-1}\) during the non-growing season in the arid area. In the boreal zone, the daily ET rate varied from 1.4 to 2.9 mm day\(^{-1}\) during the growing season and was lower than 0.5 mm day\(^{-1}\) during the non-growing season. The daily ET rate in the polar area was 0.9–1.3 mm day\(^{-1}\) throughout the whole year. The grasslands have short growing seasons and intense rainfall in the summer regardless of climate region, and the available water during the intensive rainy period is used for vegetation growth.

### 3.4 Others

Measurements of ET also have been conducted for the other types of land cover. The annual ET rate from the other ecosystems ranged from 70 to 3,030 mm year\(^{-1}\) over Asia (Table 4). Depending on the land cover type, the daily ET rate showed large differences, which ranged from less than 0.2 mm day\(^{-1}\) in the desert (Kimura et al., 2016) to 8.3 mm day\(^{-1}\) in natural mangrove reserves (Liang et al., 2019). The annual ET rate was also reported for the desert (117 ± 70 mm year\(^{-1}\)), lake (1,150 ± 253 mm year\(^{-1}\)), shrubland (400 ± 218 mm year\(^{-1}\)), and wetland (1,000 ± 829 mm year\(^{-1}\)) ecosystems (Fig. 7). In the desert, as expected, the ET rate was extremely low compared to that at the other sites because of the scarcity of water. However, the wetland ecosystem contained open water and much vegetation, and thus, it showed higher ET rates and large variations.

![Figure 6](image-url)

**Fig. 6.** Annual ET (mm) of each (a) grass type and (b) climatic zone for the 26 grassland sites in Asia. Each box represents the quartile below (Q1) and above (Q3) the median value, and dots indicate outliers, which are defined as observations more than 1.5 times the inter-quartile range away from the top or bottom of the box.
3.5 Relationship between ET and precipitation

We identified a trend in which the observed annual ET generally increased with annual precipitation over various ecosystems and climates in Asia (Fig. 8). It is well-known that ET dynamics are complex because ET depends on various controlling factors such as the radiation, temperature, vapor pressure deficit, soil water content, and leaf area index. From the synthetic analysis using the data in this review (Tables 1–5), it was difficult to find general relationships between the ET and controlling factors, except for precipitation, which could explain (with statistical significance) the annual ET trends over various ecosystems and climates in Asia. The likely reasons are as follows: (1) primary limiting factors for ET are site-specific, and (2) the Asian monsoon with intensive rainy spells (e.g., “Meiyu” in China, “Baiu” in Japan, “Changma” in Korea) changes the controlling factors overall. In the same context, the observed annual ET (except in wetlands) generally followed the Budyko curve (Fig. 3b).

4. Inter-comparison with other techniques

The EC technique is a micrometeorological measurement method used to monitor the vertical turbulent transport of

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Table 3. Locations and brief descriptions of the eddy covariance-based evapotranspiration (ET, mm) in the grassland sites reviewed in this study. \( \text{LAI}_{\text{max}} \) is the maximum leaf area index (m \(^2\)/m \(^2\)), \( \bar{P} \) is the mean annual/growing season precipitation (mm), \( T_e \) is the mean annual/growing season temperature in \(^\circ\)C, and EBR is the mean energy balance ratio (unitless). System types are shown as an open-path eddy covariance (OPEC) or a closed-path eddy covariance (CPEC).

| Location (City, Country) | Latitude, Longitude | AsiaFlux site code | Vegetation type | Period (season) | Climate | Köppen climate | \( \text{LAI}_{\text{max}} \) | \( \bar{P} \) | \( T_e \) | EBR | System type | Reference |
|--------------------------|---------------------|--------------------|----------------|----------------|---------|----------------|-----------------|------|------|------|----------|-----------|
| Loess Plateau, China     | 35°57′N, 104°08′E  | -                  | Steppe         | 2007–2012      | Arid     | BSk            | 372             | 7.3  | 386  | 0.77 | OPEC     | Yue et al. (2019) |
| Inner Mongolia, China   | 44°95′N, 113°34′E  | CN-DSX            | Steppe         | 2008–2009      | Arid     | BSk            | -               | 162  | 5.9  | 207  | 0.77     | OPEC     | Zhang et al. (2012a) |
| Loess Plateau, China     | 37°57′N, 104°08′E  | -                  | Steppe         | 2007–2012      | Arid     | BSk            | -               | 372  | 7.3  | 359  | 0.77     | OPEC     | Ping et al. (2018) |
| Kherlenbayan-Ulaan, Mongolia | 47°12′N, 108°44′E | MN-KBU            | Steppe         | 2003.03–2004.03| Arid     | BSk            | 0.54            | 260  | -0.2 | 166  | 0.77     | OPEC     | Li et al. (2006b) |
| Inner Mongolia, China   | 41°47′N, 111°53′E | -                  | Steppe (ungrazed) | 2010.05–2012.05| Boreal   | Dwc            | 0.7             | 217  | 2.9  | 312  | 0.98     | OPEC     | Shao et al. (2017) |
| Doulun Inner Mongolia, China | 42°02′N, 116°16′E | CN-D01            | Steppe         | 2006–2007      | Boreal   | Dwb            | 0.97            | 541  | 3.3  | 274  | 0.77     | OPEC     | Miao et al. (2009) |
| Xilinhot Inner Mongolia, China | 43°33′N, 116°40′E | -                  | Steppe         | 2006–2007      | Boreal   | Dwb            | 0.52            | 632  | 0.6  | 220  | 0.77     | OPEC     | Shang et al. (2015) |
| Inner Mongolia Plateau, China | 43°32′N, 116°40′E | -                  | Steppe         | 2004–2005      | Boreal   | Dwb            | 1.5             | 235  | -0.4 | 268  | 0.77     | OPEC     | Hsiao et al. (2008) |
| Inner Mongolia, China   | 44°95′N, 113°34′E  | CN-DSX            | Steppe         | 2008          | Boreal   | BSk            | 0.29            | 136  | 3.2  | 190  | 0.87     | OPEC     | Yang and Zhou (2010) |
| Lijiang, China          | 27°10′N, 100°14′E | -                  | Meadow         | 2012–2013      | Boreal   | Dwb            | -               | 1128 | 5.9  | 434  | 0.88     | OPEC     | Wang et al. (2016a) |
| Gannan Tibetan Autonomous, China | 33°89′N, 102°14′E | -                  | Meadow         | 2010          | Boreal   | Dwc            | 2.4             | 562  | 3.3  | 580  | 0.77     | OPEC     | Shang et al. (2015) |
| Qinghai-Tibetan Plateau, China | 37°36′N, 101°18′E | -                  | Meadow         | 2002–2005      | Boreal   | Dwc            | 3.8             | 637  | -390 | 0.77 | OPEC     | Li et al. (2013) |
| Qinghai-Tibetan Plateau, China | 37°37′N, 101°19′E | -                  | Meadow         | 2002–2004      | Boreal   | Dwc            | 3               | 642  | -1.2 | 397  | 0.77     | OPEC     | Gu et al. (2008) |
| Haibei, China           | 37°37′N, 101°19′E | -                  | Meadow         | 2014–2015      | Boreal   | Dwc            | 3.7             | 473  | 0.2  | 598  | 0.77     | OPEC     | Li et al. (2018) |
| Inner Mongolia, China   | 43°17′N, 122°16′E | -                  | Meadow         | 2008–2013      | Boreal   | Dwa            | 6.6             | 342  | 6.8  | 631  | 0.79     | OPEC     | Li et al. (2016a) |
| Changling, China        | 44°32′N, 123°30′E | -                  | Meadow         | 2007–2010      | Boreal   | Dwa            | 3.1             | 288  | 7.2  | 398  | 0.95     | OPEC     | Chen et al. (2019) |
| Qilian, China           | 38°09′N, 100°46′E | -                  | Meadow         | 2015–2016      | Boreal   | Dwc            | 6.5             | 464  | 0.6  | 505  | -        | OPEC     | Sun et al. (2019) |
| Qilian, China           | 38°84′N, 98°54′E | -                  | Meadow         | 2015–2016      | Boreal   | BWk            | 1.1             | 389  | -3.4 | 484  | 0.77     | OPEC     | Sun et al. (2019) |
| Naqu, China             | 31°64′N, 92°01′E | -                  | Meadow (ungrazed) | 2014, 2017    | Polar    | ET             | 0.9             | 480  | -4.2 | 386  | -        | OPEC     | Zhang et al. (2019) |
| Qinghai, China          | 34°04′N, 91°56′E | -                  | Meadow         | 2005          | Polar    | ET             | -               | 478  | -1.9 | 417  | 0.77     | OPEC     | Yao et al. (2008) |
mass and energy between the surface and atmosphere, and it requires data from both a fast response (≥ 10 Hz) sonic anemometer-thermometer (SAT) and an infrared gas analyzer (IRGA) placed on an observation tower. Based on a mass conservation equation, the value of ET can be expressed as follows (e.g., Baldocchi et al., 1988; Hong et al., 2008):

### Table 4. Locations and brief descriptions of the eddy covariance-based evapotranspiration (ET, mm) in the other land cover sites reviewed in this study. LAI_{max} is the maximum leaf area index (m² m⁻²), P is the mean annual/growing season precipitation (mm), T_a is the mean annual/growing season temperature in (°C), and EBR is the mean energy balance ratio (unitless). System types are shown as an open-path eddy covariance (OPEC) or a closed-path eddy covariance (CPEC).

| Location (City, Country) | Latitude, Longitude | AsiaFlux site code | Vegetation type | Period (season) | Climate | Köppen climate | LAI_{max} | P | T_a | ET | EBR | System type | Reference |
|-------------------------|---------------------|--------------------|----------------|----------------|---------|----------------|---------|---|-----|----|-----|-------------|-----------|
| Hainan Tibetan, China   | 23°15′N, 107°53′E   | -                  | Lake           | 2013.06-2015.06 (Whole year) | Arid    | BWk             | -       | 367 | 3.51 | 828 | -   | OPEC        | Li et al. (2016c) |
| Inner Mongolia, China   | 39°50′N, 102°27′E   | -                  | Lake           | 2012.04-2013.03 (Whole year) | Arid    | BWk             | -       | 145 | -   | 1445 | - | OPEC        | Sun et al. (2018) |
| Ningxia, China          | 37°42′N, 107°13′E   | -                  | Shrubland      | 2012 (Growing)  | Arid    | BWk             | -       | 296 | -   | 238 | 0.67 | OPEC        | Guo et al. (2016) |
| Chongqing, China        | 30°42′N, 107°14′E   | -                  | Shrubland      | 2014-2016       | Arid    | BWk             | 1.2     | 330 | 8.1 | 311 | -   | OPEC        | Jia et al. (2016a) |
| Loess Plateau, China    | 38°26′N, 109°28′E   | -                  | Shrubland      | 2011.07-2014.07 (Whole year) | Arid    | BWk             | -       | 357 | 20.0 | 256 | 0.87 | OPEC        | Gong et al. (2017b) |
| Xinjiang, China         | 40°27′N, 87°54′E    | -                  | Shrubland      | 2012-2013.11 (Whole year) | Arid    | BWk             | 1.2     | 105 | 5.10 | -   | 0.46 | OPEC        | Yuan et al. (2014) |
| Ejin, China             | 40°02′N, 101°03′E   | -                  | Shrubland      | 2011.05-2012 (Growing) | Arid    | BWk             | 1.7     | 28  | -   | 684 | 0.75 | OPEC        | Yu et al. (2017) |
| Zhongwei, China         | 37°32′N, 105°02′E   | -                  | Desert         | 2009-2012 (Growing) | Arid    | BWk             | -       | 164 | 9.6  | 167 | 0.79 | OPEC        | Guo et al. (2016) |
| Ningxia, China          | 39°47′N, 102°26′E   | -                  | Desert         | 2012.04-2012.10 (Whole year) | Arid    | BWk             | -       | 145 | -   | 150 | -   | OPEC        | Hu et al. (2015) |
| Tsegt-Ovoo, Mongolia    | 44°22′N, 105°17′E   | -                  | Desert         | 2011.05-2011.10 (Growing) | Arid    | BWk             | -       | 62.5 | 3.8  | 68  | 0.8 | OPEC        | Kimura et al. (2016) |
| Zhangye, China          | 38°58′N, 100°12′E   | -                  | Wetland        | 2012.07-2014.06 (Whole year) | Arid    | BWk             | 2.1     | 105 | 6   | 1300 | 0.69 | OPEC        | Zhang et al. (2016) |
| Dali, China             | 25°46′N, 106°10′E   | -                  | Lake           | 2012 (Whole year)  | Temperate Cwb | -       | 818  | 15.1| 1165 | -   | OPEC        | Liu et al. (2015) |
| Anji, China             | 30°28′N, 119°40′E   | -                  | Shrubland      | 2011 (Whole year)  | Temperate Cfb | -       | 1543 | 16.6| 745  | -   | OPEC        | Liu et al. (2014) |
| Guangdong, China        | 20°56′N, 110°09′E   | -                  | Shrubland      | 2012-2013 (Growing) | Temperate Cfa | -       | 1668 | 16.6| 701  | -   | OPEC        | Sha et al. (2016) |
| Guangdong, China        | 21°35′N, 109°45′E   | -                  | Wetland        | 2010-2016 (Whole year) | Temperate Cwa | 2.8     | 1480 | 23  | 2336 | 0.7 | OPEC        | Liang et al. (2019) |
| Boyang, China           | 28°30′N, 115°70′E   | -                  | Wetland        | 2013-2016 (Whole year) | Temperate Cfb | -       | 1748 | 18.2| 951  | 0.8 | OPEC        | Zhao and Liu (2018) |
| Wuxi, China             | 31°25′N, 120°13′E   | -                  | Wetland        | 2011.09-2012.08 | Temperate Cfb | -       | 1124 | 16.6| 1061 | -   | OPEC        | Wang et al. (2014) |
| Yixing, China           | 31°15′N, 119°55′E   | -                  | Wetland        | 2011.09-2012.08 | Temperate Cfb | -       | 1124 | 16.6| 1090 | -   | OPEC        | Sun and Song (2008) |
| Snajiang, China         | 47°35′N, 133°31′E   | -                  | Wetland        | 2005 (Growing)   | Temperate Cwa | 2.9     | 1560 | 22  | 219  | 0.63 | OPEC        | Li et al. (2019) |
| Haisbei, China          | 37°37′N, 101°19′E   | -                  | Shrubland      | 2002 (Growing)   | Temperate Dwc | 4.6     | 461  | 7.7 | 278  | 1   | OPEC        | Zhao et al. (2010) |
| Panjin, China           | 41°08′N, 121°54′E   | CN-NRW             | Wetland        | 2004 (Whole year) | Temperate Dwa | 3.0     | 529  | 8.6 | 577  | 1   | OPEC        | Li et al. (2016b) |
| Sanjiang, China         | 47°35′N, 133°31′E   | -                  | Wetland        | 2005-2006 (Growing) | Temperate Dwa | 3.0     | 464  | 1.9 | 340  | 0.83 | OPEC        | Zhao et al. (2008) |

Notes: abbreviations of Köppen climate are as follows: BSk: cold semi-arid climate, BWk: cold desert climate, Cfa: humid subtropical climate, Cwa: monsoon-influenced humid subtropical climate, Cwb: subtropical highland climate, Dwa: monsoon-influenced hot-summer humid continental climate, Dwb: monsoon-influenced warm-summer humid continental climate, and Dwc: monsoon-influenced subarctic climate based on the Beck et al. (2018) 1-km resolution map.

1 Abbreviations of Köppen climate are as follows: BSk: cold semi-arid climate, BWk: cold desert climate, Cfa: humid subtropical climate, Cwa: monsoon-influenced humid subtropical climate, Cwb: subtropical highland climate, Dwa: monsoon-influenced hot-summer humid continental climate, Dwb: monsoon-influenced warm-summer humid continental climate, and Dwc: monsoon-influenced subarctic climate based on the Beck et al. (2018) 1-km resolution map.

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where \( h \) is the measurement height; an overbar denotes Reynolds averaging; a prime (e.g., \( w' \)) denotes the deviation from the mean; and \( r \) is time. Term I (i.e., eddy flux) represents the flux via vertical turbulence, term II (i.e., storage flux) is the flux stored below the measurement height, term III (i.e., vertical advective flux) is the flux advected by the mean vertical flow in the presence of a vertical \( H_2O \) gradient, and term IV (i.e., horizontal advective flux) represents the fluxes transported by the horizontal mean flow and turbulence in the presence of a horizontal \( H_2O \) gradient beneath the height of the measurement. Assuming that the site is flat and homogeneous, and under well-developed turbulent conditions (III \( \approx IV \approx 0 \)), ET can be quantified as the sum of terms I and II. The ET measured by the EC technique typically represents the sum of the eddy flux and the storage flux, or the eddy flux only, in cases where the storage flux can be considered negligible on timescales longer than the daily timescale (e.g., Moon et al., 2015). In the same context, the EC technique can also provide the sensible heat flux if the air temperature is measured by using a SAT instead of with the \( H_2O \) concentration.

Often, the EC technique is used to quantify latent and sensible heat fluxes in conjunction with other methods because it has both advantages and disadvantages. The EC technique can provide both fluxes over a relatively large area (< 1 km\(^2\)) continuously without artificial disturbance, but the experimental field must be large enough; additionally, the EC technique only can provide a spatially averaged value. In this section, we have reviewed studies that were primarily based on the inter-comparison between the EC technique and other flux observation techniques such as those employing a lysimeter and scintillometer. We review the differences in ET fluxes between a closed-path EC system and an open-path EC system in section 8.2.

Lysimeter and pan evaporation techniques are traditional methods that measure the evaporative water loss in the soil or from an evaporation pan. Liu et al. (2009) found that the ET from a winter wheat and summer maize rotation agricultural system in the northwestern Shandong Plain, China, as determined by the EC technique was systematically underestimated by approximately 20% in comparison to that measured by the weighing lysimeter method. Ding et al. (2010) also reported that the ET of a maize field in Northwest China as measured by the EC technique was underestimated by 21.8% during the daytime and by 30.2% during the nighttime in comparison to values measured by a large-scale weighing lysimeter. After adjustments of the daytime ET data by using the Bowen ratio forced energy balance closure method, and adjustments of the nighttime ET data by using the filtering/interpolation method, the differences between the EC technique and the lysimeter method decreased to 4.8% during the daytime and 10.3% during the nighttime. The remaining discrepancy after the adjustments further decreased to 3.2% after discarding overestimated ET data measured by the lysimeter during periods of irrigation and heavy rainfall events. Zuo et al. (2016) showed that the actual evaporation measured by the EC technique and the pan evaporation technique in the arid region of Northwest China presented a clear asymmetrical complementary relationship due to the significant non-uniformity of heat and moisture between the pan water surface and the

\[
y = 0.388x + 377.818 \\
\rho^2 = 0.70, \ p < 0.001
\]
surrounding land surface.

Latent and sensible heat fluxes can be measured by other micrometeorological methods. The Bowen ratio-energy balance (BREB) method is based on the surface energy conservation equation and the gradient diffusion equation (e.g., Zhu et al., 2003). It estimates latent (LE) and sensible heat (H) fluxes by measuring the vertical gradients of temperature (∆T) and water vapor pressure (∆e) to determine the Bowen ratio (= H/LE ≈ γ∆T/∆e, where γ is the psychometric constant) and the other surface energy components (i.e., net radiation and ground heat flux) that allow for the quantification of available energy (= net radiation – ground heat flux = LE + H). Inter-comparison experiments between the BREB and EC methods have been conducted in various ecosystems such as heterogeneous grasslands (Zhu et al., 2003), forests (Shi et al., 2008; Wu et al., 2005), and oases (Zhang et al., 2011a) in China. The discrepancies between the EC and BREB methods depended on water vapor gradient (Wu et al., 2005), vapor pressure deficit (Shi et al., 2008), resolution of slow-response sensors, and atmospheric stability (Zhang et al., 2011a). There were a few studies that compared the EC technique with other micrometeorological techniques such as the variational method (Yang et al., 2006) and the flux variance, and surface renewal methods (Zhao et al., 2010).

Large aperture scintillometers (LAS) also can be used to measure turbulent characteristics, including H, at regional scales. An LAS transmits near-infrared light over the optical path (from the transmitter to the receiver) and measures fluctuations of the beam irradiance, which can be used to estimate the refractive index of air caused by turbulent eddies (Asanuma and Iemoto, 2007). With an LAS, one can adjust the field of view of the measurement by up to several kilometers by locating the transmitter and the receiver, whereas the footprint of ECs (~1 km²) depends on the wind direction and atmospheric stability, which cannot be controlled. Most inter-comparison experiments between an LAS and the EC method were conducted in large areas displaying landscape heterogeneity (e.g., Li et al., 2017; Liu et al., 2011; 2013). The discrepancies between the results of the two methods were mainly caused by surface energy imbalances (Liu et al., 2011) and different fields of view over heterogeneous surfaces (Li et al., 2017; Liu et al., 2011; 2013), whereas the measurements agreed well over homogeneous surfaces (Xu et al., 2013).

The ET measurements from ECs were also validated by comparing measurements from the other methods in terms of various spatial and temporal scales. The daily ET rate measured by ECs in the oasis was in good agreement with that estimated by the water balance (WB) method based on soil moisture measurements (Nad et al., 2006). Kosugi and Katsuyama (2007) compared daily ET rates measured by ECs in a Japanese cypress forest, while using a correction for the surface energy balance closure to those estimated by the WB method based on precipitation and runoff measurements (catchment ET = precipitation – runoff) for the inter-validation of both measurements. Li et al. (2008b) reported that the EC, WB, and BREB methods provided similar estimates of total ET from a vineyard in the arid desert region of Northwest China. Multi-scale ET measurements using multiple techniques, such as leaf chambers (at the leaf scale), sap flow meters (at the plant scale), ECs (at the field scale), and the WB (at the catchment scale), were also conducted in a cotton field (Zhang et al., 2014), a planted coniferous forest (Shimizu et al., 2015), and a sub-humid mountainous forest (Tie et al., 2018).

5. Data processing

Data processing consists of the following three main steps: flux calculation, quality assurance and quality control (QA/QC), and gap-filling and partitioning. Among the previous studies on flux calculations, Asanuma et al. (2005) introduced the advanced band-pass covariance technique for frequency extrapolation with LE measurements collected by using a relatively slow-response hygrometer. Multiple methods were tested on sites with various topographic and vegetation conditions (Wang and Wang, 2016; Zheng et al., 2015; Zhu et al., 2005), including double rotation (rotating the coordinate to set v = w = 0, Wesely et al., 1970), triple rotation (rotating the coordinate to set v = w = Vw = 0, McMillen, 1988), and planar fit rotation (rotating based on the measured mean wind vector during the entire experimental period as well as a fitted plane obtained by using multiple-linear regression for constructing a stable coordinate frame, Wilczak et al., 2001) methods. It should be noted that most studies found that there was better surface energy balance closure (or greater LE) after applying the suitable coordination rotation method for the specific site. Yuan et al. (2007 and 2011) introduced a sector-wise planar fit rotation (i.e., applying planar fit rotation with each sector of the wind direction) to consider the effect of the rolling topography around the flux tower.

The QA/QC and gap-filling steps are essential for constructing high-quality time series data and quantifying diurnal, seasonal, and annual budgets for comparisons with modeling or remote-sensing results. Mano et al. (2007) tested several QC methods for open-path EC flux data, including steady state tests and integral turbulent characteristic tests, and results showed that a higher quality of flux data led to better surface energy balance closure. Many traditional gap-filling techniques, such as mean diurnal variation, nonlinear regression, and marginal distribution sampling (MDS, one of the standard gap-filling methods in the global flux network, FLUXNET, Reichstein et al., 2005) were evaluated for sites with various climate conditions and land cover types (Du et al., 2014; Park et al., 2015). In particular, Kang et al. (2012) showed that the gap-filled ET data, derived by using MDS under wet canopy conditions, were underestimated because the data used in the gap-filling methods were mostly collected during dry or partially wet canopy conditions; MDS also failed in regard to the consideration of the aerodynamic coupling, advection of sensible heat, and heat storage. Because MDS performed poorly for long-period flux data gaps (i.e., gaps longer than a month) because of the absence of marginally distributed data around gaps, Kang et al. (2019a) suggested that researchers apply a data-driven approach using machine learning and remote-sensing data to apply gap-filling for the long gaps.

In addition to the above research, there have been a considerable number of studies aimed at improving the data quality and usability. He et al. (2010) reported on the random...
sampling errors for the flux data from six EC sites in ChinaFLUX. Instrument heating corrections for an open-path gas analyzer (Burba et al., 2008) where shown to have an insignificant effect on the ET and surface energy balance closure, contrary to the findings for the carbon dioxide (CO2) flux (Zhu et al., 2012). Ono and Maruyama (2015) developed an onsite computation scheme for EC fluxes in real-time assessments. Liu et al. (2016b) introduced flux calculations and QA/QC procedures for an EC system installed on a 325 m meteorology tower in an urban area. The studies associated with correcting the surface energy balance closure and partitioning ET into evaporation and transpiration are discussed in sections 8.1 and 8.3.

6. Connections between carbon and water fluxes

Carbon and water fluxes are key aspects of the functioning of an ecosystem. The ratio of carbon gain to water loss, known as water use efficiency (WUE), is an important physiological parameter linking carbon and water cycles. The WUE has been defined in various ways because the spatiotemporal scales and measurement methods used are research-specific. Considering the original definition of the WUE (i.e., the ratio of CO2 flux to H2O flux) and the spatiotemporal scale of EC measurements, the ecosystem-level WUE and canopy-level WUE can be defined as the ratio of net ecosystem production (NEP) to ET (NEP/ET), and the ratio of net primary production (NPP) to transpiration, respectively (Kang et al., 2018). Because of the difficulties associated with the partitioning of the ET into evaporation and transpiration, and in estimating NPP from ECs, most studies based on ECs have reported the ratio of gross primary production (GPP) to ET (GPP/ET) for the canopy-level WUE, with the exception of a few studies (e.g., Huang et al., 2010; Kang et al., 2018).

The assessments of the WUE using NEP/ET were conducted mainly in arid regions suffering from water scarcity. For the croplands in arid regions, NEP/ET during the growing season ranged from 0.54 to 1.68 g [C] kg⁻¹ [H2O] (i.e., values corresponding to pear orchards in the arid region and maize in arid cropland), where the unit “g [C] kg⁻¹ [H2O]” refers to grams of carbon per kilogram of water (Table 5). The measured value of 0.24 g [C] kg⁻¹ [H2O] for NEP/ET in desert shrubland (Liu et al., 2012b) was smaller than that measured for croplands in arid regions. Meanwhile, the evaluations of the WUE using GPP/ET were performed mainly in forest ecosystems with a high photosynthesis rate. For the forests, GPP/ET ranged from 1.71 to 2.57 g [C] kg⁻¹ [H2O] with a mean of 2.2 ± 0.4 g [C] kg⁻¹ [H2O] (Table 5). The measured value of 1.36 g [C] kg⁻¹ [H2O] for GPP/ET in rice paddies with high water consumption was considerably smaller than the values from the forests (Wang et al., 2017).

Such WUE values are largely regulated by environmental conditions such as the amount of radiation and water. Tong et al. (2014), based on a 5-year experimental dataset, showed that the GPP/ET was approximately 30% higher under cloudy skies as result of the increase in the proportion of diffuse radiation. Ma et al. (2019) found that drought reduced the GPP/ET in a young plantation, whereas Liu et al. (2017) found that drought enhanced the GPP/ET in an old-growth sub-tropical forest. These findings suggest that the resilience of ecosystem functions to drought might be system-specific.

7. Multi-site synthesis

In the early stages of multi-site synthesis, the main objective of most studies was to simply compare the water and energy fluxes among sites with different or similar land cover to obtain a better understanding of the surface energy partitioning process. For example, Kang et al. (2009) quantified the ET from deciduous forest and farmland under a monsoon climate and documented its temporal variations and control mechanisms by using multi-year observations. There have been other studies that have shown differences in water and heat exchanges due to the distinctiveness in surface properties, or meteorological conditions, for two different PFTs (e.g., an alpine meadow and banana plantation, Ding et al., 2017; or maize farmland and reed wetland, Li et al., 2009). Zhang et al. (2018b) compared the water budget of two typical agricultural ecosystems (i.e., winter wheat–summer maize and pear orchard) to compute the sustainable usage of groundwater in the North China Plain. In these previous studies, the point was raised that the spatiotemporal variability for water and energy fluxes may depend on climate, PFT, and ecophysiology.

Climate has a significant impact on the seasonal and inter-annual variations of ET via various environmental factors. In Southeast Asia peatland, Hirano et al. (2015) found that drainage and fires caused by low groundwater levels in El Niño years decreased the ET and increased the annual discharge. The rubber trees, a major economic tree crop in tropical areas, exhibited limited water use as a result of their strict regulation of stomatal conductance under seasonal water stress due to the monsoon changes and El Niño–Southern Oscillation (ENSO) changes (Giambelluca et al., 2016; Kumagai et al., 2015). Li et al. (2015) showed that the surface energy partitioning of four sites in the Tibetan Plateau was clearly influenced by the Asian summer monsoon (i.e., H was dominant in the pre-monsoon period, whereas LE was greater during the monsoon season). Xiao et al. (2013) synthesized EC fluxes and micrometeorological data from 22 flux sites across China to investigate the variations in water and carbon fluxes, including the WUE, and they found that these processes were being controlled by the annual temperature, precipitation, and growing season length with increasing latitude.

In dry grasslands under water-limited conditions, the available energy, precipitation, and soil water content were found to be the primary factors driving the inter-annual variability of water and energy fluxes during the growing season (Liu et al., 2010; Wang et al., 2018; Wilske et al., 2010; Yang et al., 2018b). Therefore, many studies have been conducted to improve our understanding of the interactions and coupling mechanisms among the energy, soil, water, and vegetation. Wang et al. (2018) showed that the main factors controlling the daily LE were net radiation in normal years and soil water content in the dry season. Yang et al. (2019b) argued that leaf area index (LAI) is not suitable for estimating the ET of semi-arid natural vegetation, even though it is useful for identifying the physiological constraints on ET. Wilske et al. (2010) found that, among the inputs of
Table 5. Locations and brief descriptions of the water use efficiency (WUE, g [C] kg⁻¹ [H₂O]) based on the eddy covariance measurements in Asia. LAI_MAX is the maximum leaf area index (m² m⁻²), P is the mean annual/growing season precipitation (mm), Tₑ is the mean annual/growing season temperature in (°C), ET is the mean annual/growing season evapotranspiration (mm). NEP is the mean annual/growing season net ecosystem production (g C m⁻²), GPP is the mean annual/growing season gross primary production (g C m⁻²), and EBR is the mean energy balance ratio (unitless). System types are shown as an open-path eddy covariance (OPEC) or a closed-path eddy covariance (CPEC). WUE is defined as the NEP/ET or GPP/ET. Vegetation type is defined based on the International Geosphere Biosphere Program (IGBP) definitions as described in Fig. 3.

| Location (City, Country) | Latitude, Longitude | AsiaFlux site code | Spp. | Vegetation type | Climate | LAI_MAX | P | Tₑ | ET | WUE | NEP or GPP | EBR | System type | Reference |
|--------------------------|---------------------|--------------------|------|----------------|---------|---------|---|----|----|-----|-----------|-----|-------------|-----------|
| Dzungarian, China        | 44°17N, 87°56E      | -                  | SH   | T. ramosissima, S. nitaria | Arid    | --      | 3.5| 173| 6.6| 205| 0.24 | 49  | OPEC        | Liu et al. (2012a) |
| Xinjiang, China          | 44°17N, 85°49E      | -                  | CRO  | G. hirsutum L. | 2009-2010 (Growing) | 8.8 | 144| 19| 501| 1   | 479 | 0.53 OPEC  | Bai et al. (2015) |
| Shijiazhuang, China      | 37°52N, 114°40E     | -                  | CRO  | T. aestivum L. | 2008-2011 (Growing) | 6   | 114| 12.8| 410| 0.96 | 392 | 0.95 OPEC  | Shen et al. (2013) |
| Liaocheng, China         | 36°39N, 116°03E     | -                  | CRO  | Z. mays L. | 2008-2012 (Growing) | 5   | 341| 12.8| 275| 1.33 | 365 | 0.95 OPEC  |                       |
| Shijiazhuang, China      | 37°47N, 114°55E     | -                  | CRO  | P. betuloides | 2011-10 (Whole year) | 3   | 507| 12.9| 759| 0.54 | 408 | 0.88 OPEC  | Zhang et al. (2013b) |
| Simpang Pertang, Malaysia | 2°58N, 102°18E      | MV-PSO             | EBF  | S. rupicaulis | 2003-2009 (Whole year) | 185 | -   | 1287| 2.46 | 3164 | 0.7 OPEC |                       |
| Guangdong, China         | 23°10N, 112°31E     | -                  | EBF  | C. chinensis, C. trachilepis | 2003-2009 (Whole year) | 5.6 | -   | 20.2| 407 | 1.6 | 2.03 | 799 | 0.53 OPEC | Liu et al. (2017) |
| Pu`er, China             | 24°32N, 101°91E     | -                  | EBF  | L. hancei, M. bombycina | 2009-2013 (Whole year) | 1681 | -   | 863 | 2.48 | 2139 | 0.7 OPEC | Song et al. (2017b) |
| Dingshusan, China        | 23°10N, 112°34E     | -                  | EBF  | S. superboides, P. maximowicziana | 2003-2005 (Whole year) | 1287 | -   | 1.88 | 1287 | 0.8 OPEC |                       |
| Taibe, China             | 26°44N, 115°33E     | -                  | EBF  | P. massoniana, P. elliottii, C. lanceolata | 2003-2005 (Whole year) | 3.5 | 1485| 17.9| 633 | 2.53 | 1555 | 0.8 OPEC | Yu et al. (2008) |
| Erdzaoehle, China        | 42°24N, 128°05E     | -                  | MF   | Q. variabilis, R. pseudoacacia, P. orientalis | 2003-2005 (Whole year) | 6.1 | 695| 3.6 | 481 | 2.57 | 1233 | 0.8 OPEC |                       |
| Juyuan, China            | 35°01N, 112°28E     | -                  | MF   | Q. variabilis, R. pseudoacacia, P. orientalis | 2006-2010 (Whole year) | 6.3 | 528| 14.8| 579 | 1.9 | 1196 | OPEC |                       |
| Beijing, China           | 40°37N, 115°94E     | -                  | MF   | P. tabuliformis, A. trucatula | 2012-2013 (Whole year) | 359 | 9.4 | 336 | 1.71 | 580 | 0.7 OPEC |                       |
| Panjin, China            | 40°56N, 121°58E     | -                  | CRO  | P. tatarica | 2012-2013 (Growing) | 6.65 | 631| 8.6 | 608 | 1.36 | 603 | 0.76 OPEC | Wang et al. (2017) |

Because the number of EC flux towers is relatively limited in terms of the spatial coverage because of cost constraints and operational difficulties, it is critical to assess and correct the spatial representation of the EC network before synthetic analyses. An optimized flux network distribution will more accurately represent major ecosystems and promote the integration of fluxes to improve the accuracy of upscaling water and energy fluxes from local tower observations to regional scales. Wang et al. (2013) assessed the spatial distribution of the existing 85 EC flux sites in China by using a multivariate geographic clustering approach and recommended the addition of EC observations numbering up to 100–150 in total to represent the entire ecoregions of China. In addition, Zheng et al. (2016) constructed the variation of actual ET in China by synthesizing the ecosystem-level EC observation data from 61 sites and argued that additional observation sites are needed for parameterization or validation of global ET products.

Combining observational EC data with satellite remote sensing data is an effective approach for overcoming the limitations posed by a lack of spatial EC observations. Satellite remote sensing is useful for estimating key surface biophysical variables, such as the fraction of photosynthetically active radiation (FPAR), LAI, and land surface temperature for an unobserved area. The scaling-up of the observed ET by using remotely sensed data has facilitated ET estimations at the regional and continental level. Wu et al. (2012) estimated ET for water use reduction management in the Hai Basin (320,000 km²) of North China, within an area that has experienced serious over-exploitation of ground water, and this was accomplished by using new algorithms for ET calculations with remotely sensed data (ETWatch); the results were validated by in situ...
measurements (i.e., lysimeter, EC system, LAS, and water balance calculations). Liu et al. (2016a) analyzed the differences between upsampling methods and proposed a combined method for the acquisition of ground-truth ET data at the satellite pixel scale. Similarly, Xu et al. (2018b) evaluated the upsampling performance of several machine learning methods (e.g., artificial neural network, cubist, deep belief network, random forest, and support vector machine), which were the most popular ones for upsampling from tower-based ET observations to large scales.

As noted, the difficulty in matching the entire EC tower sampling area (footprint) with the satellite pixel scale/model grid scale over a heterogeneous land surface is largely caused by the inherent variability of the EC tower footprint. Xu et al. (2017a) proposed a flux aggregation method for determining the area-averaged EC flux with a high-resolution land-cover map to improve the representativeness of EC towers. In spite of some limitations, the current flux integration scheme is expected to provide a richer understanding of the mechanisms controlling water and energy fluxes on a large scale.

8. Identification of remaining challenges

After navigating a number of publications related to water and energy flux studies in Asia, we noted that there still remain challenges that are hindering the derivation of scientific knowledge on the surface energy balance, namely, (1) the non-closure of the surface energy budget, (2) the imperfection of compatibility between open- and closed-path gas analyzers, and (3) difficulty in partitioning ET into evaporation and transpiration. To identify fruitful directions for future research, we retrace the footprints and summarize the three remaining challenges below.

8.1 Non-closure of the surface energy budget

A discrepancy between the terms of available energy estimated by slow-response sensors and an EC system is unavoidable at most flux sites in Asia. Generally, the energy balance has been examined by using the energy balance ratio (EBR) defined as follows (Wilson et al., 2002):

\[
EBR = \frac{\sum (LE + H)}{\sum (R_{net} - G - S)}
\]

where \(R_{net}\) is the net radiation, \(G\) is the ground heat flux, and \(S\) is the energy storage. Even though EBR should be 1.0 based on the conservation of energy principle (the first law of thermodynamics), an actual EBR of less than or greater than 1.0 often is obtained. The extent of non-closure of the surface energy balance with EC measurements and how to handle this phenomenon is still an open question. This is a well-known issue that has plagued the EC flux community for decades. For a comprehensive analysis and evaluation of the surface energy balance closure, field experiments over homogeneous and/or heterogeneous land surfaces have been conducted in Asia (Kim et al., 2014; Li et al., 2005; Xin et al., 2018; Xu et al., 2017b).

The non-closure of the surface energy budget can result from factors such as a failure to satisfy the fundamental assumptions of the EC technique, a mismatch of the flux footprint, sampling error, instrument biases, incorrect accounting for storage terms, influence of longwave eddies, and advection effects (e.g., Foken, 2008; Leuning et al., 2012; Wilson et al., 2002). Considering that much of the landscape in Asia is not well suited for the ideal application of the EC technique (i.e., the land is not flat and homogeneous), we can expect to encounter such surface energy imbalance problems in the Asian region. The EBR from the studies in this review ranged from 0.5 to 0.99 (Tables 1-5) with a median of 0.79. As expected, the median EBRs for the forest sites (0.77) and other sites (e.g., wetland, 0.76) were less than those for the cropland sites (0.80) and grassland sites (0.84), which were typically located on flat and/or homogeneous surfaces (Fig. 9).

A correction for the surface energy balance closure was often applied to some sites in Asia. Most corrections assume that the measured \(R_{net} - G - S\) is the true value (e.g., Allen, 2008; Pan et al., 2017). Among the correction methods, the Bowen ratio forced energy balance closure method, while assuming that the measured Bowen ratio by the EC technique is preserved, has been widely used in Asia (e.g., Ding et al., 2010; Kosugi and Katsuyama, 2007; Kumagai et al., 2005; Tsuruta et al., 2016). It is also based on the fact that water vapor and heat are transferred by eddies simultaneously, and thus, there are similarities that allow these processes to be compared. It should be noted that the discrepancies between EC and other methods, such as the BREB and WB methods, decreased after applying a correction for the surface energy balance closure (e.g., Ding et al., 2010; Kosugi and Katsuyama, 2007).

Application of a correction for the surface energy balance closure as a standardized procedure is still under debate. Such correction was not applied to most of the flux sites in Asia so far. Leuning et al. (2012) strongly criticized the implicit application of a correction for the surface energy balance closure. They investigated the possible sources of a lack of energy balance closure and found that these were related to (1) too short of an averaging time to capture the low-frequency contributions, (2)
a high frequency contribution loss due to the instrument path length, sensor separation, and tube attenuation, (3) the error of radiation measurements over sloping terrain, and (4) the error of the storage term in soil, air, and biomass. They showed that most of the lack of energy could be taken into account in this way. Whether or not to apply this to the CO\(_2\) flux is another issue since CO\(_2\) also shows similarities with water vapor and heat. We expect that international collaborative efforts, such as the Energy Balance Residual Correction initiative (Mauder et al., 2020), will offer a solid argument on this subject in the near future.

8.2 Imperfections in the compatibility between open- and closed-path gas analyzers

There are two types of gas analyzers, namely, closed-path and open-path gas analyzers. A closed-path analyzer has an internal sample cell (optical path for analyzing the gas concentration) that is flushed by sampled air; in open-path sensors, the sample cell is in the open air (Munger et al., 2012). For a closed-path system, the fluctuation of gas concentrations in the high frequency domain is attenuated while the air is drawn in through a tube. Such attenuation depends on measurement conditions such as the flow rate, tube diameter, wind speed, and atmospheric stability. For recovering the loss of fluctuation, a frequency response correction should be applied (Aubinet et al., 1999; Moncrieff et al., 1997).

The ET measured by a closed-path system can still be underestimated after applying a frequency response correction for tube attenuation. Kosugi et al. (2007) reported that the ET measured by a closed-path system with attenuation correction frequently underestimated the ET measured by an open-path system under wet canopy conditions with high relative humidity (RH). The RH does not affect the CO\(_2\) flux but does affect the H\(_2\)O flux significantly (e.g., Fratini et al., 2012; Ibrom et al., 2007). The attenuation effect is similar to low-pass filtering, such that the attenuation domain expands with the increasing RH from high frequency to medium frequency. It is worth noting that the ET measured by a closed-path system, after applying the attenuation correction that considers RH, still can be considerably underestimated compared to that measured by an open-path system (Fratini et al., 2012; Kang et al., 2019b). Such imperfection in the compatibility between open- and closed-path gas analyzers requires care during synthesizing multi-site measurements and in applying the Bowen ratio forced energy balance closure method to fluxes measured by a closed-path system.

8.3 Difficulty in partitioning the ET into evaporation and transpiration

Partitioning of ET into evaporation and transpiration is essential for an improved understanding of ET dynamics. The EC technique measures net fluxes, i.e., the net ecosystem exchange of CO\(_2\), which consists of ecosystem respiration and GPP, and ET, which consists of plant transpiration (T), soil evaporation (E\(_S\)), and wet canopy evaporation (E\(_{WC}\), intercepted rainfall). The partitioning of ET into \(T, E_S\), and E\(_{WC}\) is required to understand how ET is affected by environmental changes and how the water cycle is connected to the carbon cycle in an ecosystem, since each component is controlled by different mechanisms and processes (e.g, Kang et al., 2018). In particular, Savenije (2004) argued that ET is an outdated terminology that hinders our separate consideration of different evaporative processes in terms of the time scale, time of occurrence, physical characteristics, climatic feedbacks, and isotope compositions.

Practical difficulties still remain for the widespread adoption of ET partitioning. Because of the importance of this subject, there have been a considerable number of previous studies in Asia that partitioned ET by using other supplementary measurements, such as oxygen stable isotopes (Liu et al., 2018; Wei et al., 2015; Xu et al., 2016; Zhang et al., 2011c), sap flow (Liu and Man, 2017; Zhao et al., 2015; 2018), lysimeter data (Gong et al., 2017a; Liu et al., 2018; Yang et al., 2018; Zhao et al., 2015; 2018), and supplementary EC system data inside the canopy (Kang et al., 2018). However, such approaches based on other supplementary measurements are costly and difficult to apply to previous data. Therefore, many studies based on a modeling approach using two-source models (e.g., Shuttleworth-Wallace model) have also been conducted in Asia (Hu et al., 2009; Tian et al., 2016; Wang and Yamanaka, 2014; Xu et al., 2016; Yang et al., 2018; Zhao et al., 2015). However, the modeling approach also requires supplementary measurements to validate the results of ET partitioning. For partitioning the net ecosystem exchange of CO\(_2\) into ecosystem respiration and GPP, most methods are stand-alone and do not require additional data, except for the data from flux towers (e.g., Reichstein et al., 2005; Saigusa et al., 2013). This approach has been applied almost everywhere in the world as a standardized procedure.

Similarly, to activate the partitioning of ET as is done with the CO\(_2\) flux, it will be necessary to develop a stand-alone method for ET partitioning, which can minimize additional but necessary information for application and validation purposes. It should be noted that Wang et al. (2016b) reported on the partitioning results of ET from steppe ecosystems in Inner Mongolia following use of the partitioning method based on the flux-variance similarity developed by Scanlon and Kustas (2010). Their partitioning method is reliant upon the fact that the measured high-frequency time series of CO\(_2\) and H\(_2\)O concentrations are a result of stomatal processes (photosynthesis and transpiration, in which CO\(_2\) and H\(_2\)O concentrations are negatively correlated) and non-stomatal processes (respiration and direct evaporation, in which CO\(_2\) and H\(_2\)O concentrations are positively correlated) and thus requires one parameter only, the leaf-level water use efficiency. Most of the ET partitioning studies have focused on the partitioning of ET into \(E_S\) (or direct evaporation) and \(T\). In this context, it is noteworthy that Kang et al. (2018) developed the gap-filling and partitioning method for forest ecosystems based on a simplified rainfall interception model, which can estimate \(E_{WC}\) using the inputs and parameters from a flux tower measurement and be optimized using available ET data from an EC system under wet canopy conditions. If we continue to capitalize on the advantages and possibilities of the EC technique being capable of a high sampling rate of \(\geq 10\) Hz and continuous observations, a standardized ET partitioning method will be feasible in the near future.
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