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Ideas and perspectives: Research on ecosystem-atmosphere interactions in Asia: early career researcher opinion

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Abstract

Due to a growing recognition of the need to study how ecosystems and the atmosphere interact with each other, many regional networks as well as the global network of regional networks, FLUXNET, were formed. Since 1999, when the AsiaFlux network was established, scientists in the region have been measuring the flux densities of energy, water vapor, and greenhouse gas exchanges to better evaluate ecosystem-atmosphere interactions and understand their underlying mechanisms. The network includes natural and managed ecosystems that span broad climatic and ecological gradients, as well as experience diverse management practices and disturbances. In this ideas and perspectives paper, from the view of early career researchers (ECRs), we synthesize key research foci in this network in recent years, with a focus on the latest AsiaFlux conferences, and highlight selected key discoveries. While achieving significant milestones, ECRs argue that the community should work together to emphasize the importance of long-term observations, rejuvenate the network's shared and open-access database, and actively engage with stakeholders. With many unique ecosystem types in the Asian region, efforts and expertise from AsiaFlux can provide critical insights into the roles of climate change, extreme weather events, soil properties, vegetation physiology and structure, and management practices on the breathing of the biosphere. In closing, we hope this ideas and perspectives paper can inspire the future generation of flux scientists in Asia and promote exchanges between scientists across different cultures and career stages.

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1 Introduction

Ecosystem-atmosphere interactions are defined as the exchanges of energy, water, greenhouse gases, and other materials between the Earth's ecosystems and the atmosphere (Bonan, 1995). These interactions play a crucial role in shaping regional and global climate patterns, as well as influencing various ecosystem processes and human activities (Santanello et al., 2018). Over the past few decades, there has been an increasing recognition of the importance of studying ecosystem-atmosphere interactions (Beamesderfer et al., 2022). These exchanges have been measured using the eddy covariance technique since the late 1960's (e.g., Baldocchi et al., 1988; Hicks and Martin, 1972; Leuning et al., 1982). Since then, the number of eddy covariance flux tower sites has increased substantially, thus improving the spatial and temporal coverage of ecosystem-atmosphere exchange observations across the globe (Baldocchi et al., 2024). However, these bi-directional interactions represent one of the most uncertain components of the terrestrial climate system (Betts and Silva Dias, 2010).

Ecosystems in Asia are characterized by extraordinary biodiversity and complex topography, which include vast rainforests, extensive river systems, and expansive coastal and marine environments (Myers et al., 2000). This region is home to some of the world's most vital carbon sinks, such as the peat swamp forests and mangroves, which play a significant role in the Earth's carbon cycle and climate (Tian et al., 2003). Land cover and land use change in Asia has been dramatic over the last several decades and studies have proven that the role of vegetation shift in the ecosystem-atmosphere exchanges have been substantial (Sarkar et al., 2007; Sodhi et al., 2004). Additionally, the influence of climatic events (e.g., El Niño and La Niña) and disturbances (e.g., drought and intense rainfall) is increasing in this region (Patra et al., 2005). Therefore, a better understanding of how ecosystems in Asia respond to natural variability will reduce uncertainties in understanding the long-term trends and dynamics of the ecosystem-atmosphere exchanges (Cervarich et al., 2016).

The integrated Land Ecosystems Atmospheric Processes Study (iLEAPS) was formed in March 2004 to build an international community of practice to investigate the interactions between terrestrial

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ecosystems and the atmosphere. The first decade of iLEAPS had an emphasis on creating new ways to observe and model the land–atmosphere continuum (Suni et al., 2015). In the second decade, the focus has shifted to the human influence on these ecosystem–atmosphere interactions and the implications for resource use and sustainable development (Hayman et al., 2024). In light of recognizing the importance of ecosystem–atmosphere interactions in Asia, iLEAPS hosted a virtual discussion forum on "South East Asia: Key future challenges in biosphere-atmosphere research" in May 2023 and called for participations of early career researchers (ECR) working on biosphere-atmosphere research in the region of south-east Asia.

The atmosphere of the first meetup was vibrant with enthusiasm as each participant introduced themselves, sharing their unique perspectives and experiences. During the following weeks, we began to delve into the tasks at hand, ideas flowed freely, sparked by the diversity of backgrounds and expertise present. Collaboratively, we sifted through these ideas, targeting those with the most shared research topics among the participants. Inspired by the discussions, iLEAPS invited Stefan Wolff, researcher at the Max Planck Institute for Chemistry, to share experience on the Amazonian Tall Tower Observatory project with the forum participants. Through spirited exchanges and constructive dialogue, we crystallized our thoughts into more concrete action items–proposing scientific sessions on ecosystem-atmosphere interactions of Southeast Asia in the AsiaFlux conference 2023 and the European Geosciences Union (EGU) General Assembly 2024 held in Jeju Island, the Republic of Korea and Vienna, Austria, respectively.

AsiaFlux is a regional research network bringing together scientists from universities and institutions in Asia to study the exchanges of carbon dioxide, water vapor, and energy between terrestrial ecosystems and the atmosphere across daily to inter-annual time scales. Due to COVID-19, in-person AsiaFlux conference was canceled in 2020 and 2021 but returned in 2022 being held in Malaysia. The theme of the AsiaFlux conference 2023 is "The Role of AsiaFlux in the Era of Carbon Neutral and Beyond" and we successfully convened a session on "Biosphere-Atmosphere Interactions in Southeast Asia's (Sub)tropical Ecosystems". In addition, one of the iLEAPS discussion forum ECR participant, Sung-Ching Lee, was invited as a keynote speaker having a talk on "Power of long-term flux observation and synergies in land-atmosphere interactions". In 2024, we submitted a session proposal on "Land-

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atmosphere interactions, biodiversity, and ecohydrology of tropical ecosystems" to EGU General Assembly and successfully attracted 7 abstracts. EGU General Assembly is Europe's largest and most prominent geosciences event. It attracts more than 16,000 scientists each year, more than half of which are at early career stage, from all over the world. To foster exchanges with other scientists from other tropical regions (e.g., Amazon and Africa), we merged our session with another session on "Amazon forest in transition - a biome of global significance", which was also mainly convened by ECRs. In the end, we had 24 abstracts covering various research topics and conducted in multiple tropical areas (BG 1.8, https://meetingorganizer.copernicus.org/EGU24/session/49921).

Kang and Cho (2021) reviewed the water and energy flux studies for the AsiaFlux and discussed three remaining challenges (i.e., surface energy closure, difference between open- and closed-path gas analyzers, and ET partitioning). Chang et al. (2021), more specifically, conducted meta-analyses for understanding forest ecosystem carbon budgets. Different from these existing reviews, this paper provides perspectives on ecosystem-atmosphere interactions in Asia from the experience of the ECRs involved in the iLEAPS discussion forum. This paper is organized as follows: Section 2 highlights selected study in relevant research fields presented in the last two AsiaFlux conferences and recent publications. Section 3 elaborates key challenges in ecosystem-atmosphere interaction study in Asia with evidence from existing and new data. Section 4 highlights opportunities that excited the ECRs most, followed by Section 5, which concludes this perspective paper.

2 Recent foci

In this section, we reviewed the abstracts submitted to AsiaFlux conference 2022 and 2023 as well as recent relevant publications to identify the aspects that scientists working on interactions between ecosystems and the atmosphere in Asia are currently addressing. We categorized them into three groups: (a) natural ecosystems in Section 2.1, (b) managed ecosystems in Section 2.2, and (c) remote sensing and modeling in Section 2.3. We followed the definition of natural and managed ecosystems from iLEAPS, described in Suni et al. (2015).

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2.1 Natural ecosystems

2.1.1 Methane fluxes at wetlands and lakes

Methane is the second-most important anthropogenic greenhouse gas after carbon dioxide, with a concerning increasing trend as atmospheric methane concentration has more than doubled since 1800. The community in Asia has invested efforts in understanding the methane flux dynamics. In the AsiaFlux conference 2022, there were three invited keynote speakers (i.e., Dr. Ülo Mander, Dr. Gavin McNicol, and Dr. Maria Strack) on this topic addressing the need to reduce uncertainty on high spatial and temporal variability of methane emissions. The host, Sarawak Tropical Peat Research Institute, has also been dedicated to wetland studies, such as the long-term (>10 years) swamp forest sites in Maludam and Cermat Ceria. Additionally, there were about 10 other abstracts related to greenhouse gas fluxes of different wetland ecosystems. This emphasis continued in 2023, with 8 abstracts on ecosystem-atmosphere interactions of wetlands. New publications are coming out on this topic as well such as carbon and water flux dynamics of Zoige peatlands on the Qinghai-Tibetan Plateau (X. Liu et al., 2022) and methane emissions of a subtropical wetland in Hubei, China (Zhang et al., 2022). Another emerging topic related to this is the ecosystem-atmosphere interactions of aquatic ecosystems such as lakes and ponds. Considering that their methane emissions constitute a significant portion of natural methane emissions, it is crucial to provide accurate estimates and better understanding of drivers. For example, during the conference, seven-year variability of methane emissions from a shallow eutrophic lake in Japan were presented as well as model simulations on methane fluxes of Lake Suwa using flux measurements, satellite observations, and machine learning model. Multiple studies on carbon flux dynamics of China's third largest freshwater lake (Lake Taihu) were published (e.g., Xiao et al., 2020 and Xiao et al., 2022). Methane emissions from ponds and lakes on Qinghai-Tibet Plateau (Yang Li et al., 2024) and aquaculture ponds at different locations in China (Dong et al., 2022; Xiao et al., 2024) are being quantified and investigated. Using flux data to reduce uncertainty in the methane budget and understand underlying mechanisms of methane flux dynamics are important to help slow down global methane emission.

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2.1.2 Impacts of extremes on ecosystem-atmosphere fluxes

As extreme events are becoming more frequent and severe in the Asian region, assessing how ecosystem-atmosphere exchanges respond to extremes is therefore an urgent question to be addressed. In the AsiaFlux conference 2022, there was a session, "Impacts of extreme events and disturbance such as hurricanes, droughts, insect outbreaks and flooding on ecosystem processes", designated to this topic. Presentations in this session cover a variety of issues such as impacts of El Niño-Southern Oscillation (ENSO) drought on carbon and energy fluxes of a tropical peat swamp forest as well as typhoon attack and insect diseases on forest carbon budget in Japan. During the next year, despite there being no specific session, multiple abstracts related to this direction were still observed. For example, water processes in a subtropical forest in China following extreme snow events were assessed. Moreover, discussions on crop damage caused by agrometeorological disasters such as freeze damage and floods happened in the conference as well. In terms of recent publications, Lee et al. (2021) analyzed the resilience of the carbon cycles of temperate coniferous and broadleaved forests to the 2016 drought event using eddy covariance measurements. Himawari-8 satellite was used to detect anomalies in diurnal surface temperature changes correlated with decreases in surface soil moisture during the 2018 East Asia heatwave (Yamamoto et al., 2023). Compared to tropical America, tropical Asia was found to experience stronger green-up during the 2015/16 El Niño driven either by anomalously warmer temperatures or drier soil moisture (Satriawan et al., 2024). These highlight that continuous research on responses of ecosystems in Asia to various extremes is needed as they can be quite complex and different from the results observed elsewhere.

2.1.3 Ecosystem services of forests

Long-term carbon dioxide flux observations have been conducted in multiple forest ecosystems in Asia. Results using 20-year data collected in a tropical rainforest in Xishuangbannna, China were presented. In addition, lessons learned from 17 years of monitoring carbon dioxide flux in Japanese larch forests were shared. Impacts of managements on ecosystem-scale and soil carbon fluxes in Bornean tropical rainforest, the lowland rainforest extending into all three countries, were continuously assessed. Temporal dynamics of carbon uptake of a boreal forest ecosystem in Northeast China were analyzed

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using decade-long eddy covariance observation (Yan et al., 2023). Besides carbon dioxide, there are enduring efforts on quantifying methane uptake of Asian forest soils, and it is evident in the conference presentations and publications (Hu et al., 2023; Sha et al., 2021). Beyond carbon exchanges, multiple abstracts pointed out the importance of co-benefits such as biodiversity provided by forests. Study has been done to understand the effects of long-term nutrient fertilization on biodiversity in a subtropical forest in Zhejiang, China. More importantly, the theme of the AsiaFlux conference 2023 was set as "the role of AsiaFlux in the era of carbon neutral and beyond" with multiple abstracts showing increasing recognition on the importance of nature-based climate solutions in Asia. Furthermore, as climate change mitigation strategies gain prominence, precise estimation of forest carbon flux on a national scale becomes imperative. A new initiative, the National Reserve Forest Project, was launched in China, which is a forestry project to ensure the safety of timber supply and create a carbon sink, hence contributing to China's future carbon neutrality goals (Zhang et al., 2024). From 2022, supported by several research projects, three national institutes in Japan have started to estimate forest carbon budgets at 100-m grid scale for the country, including the potential effects of forest disturbance and human management. Scientists in South Korea have tried to obtain estimates of national-scale forest carbon flux with machine learning models using satellite imagery and eddy covariance flux data (Cho et al., 2021), and developed the Korea Forest Carbon Offset System to expand sustainable forest management and harvested wood products (Woo et al., 2020, 2021). Therefore, the rich flux data in forests are important to establish the use of it in the era of carbon neutral and beyond.

2.2 Managed ecosystems

2.2.1 Greenhouse gas fluxes of agricultural ecosystems

Quantifying the emissions of the three main biogenic greenhouse gases, carbon dioxide, methane, and nitrous oxide from agricultural ecosystems is crucial. Rice has substantial economic importance in most Asian countries and paddy fields cover large cultivated land. It is not surprising that there has been lots of work being conducted to quantify ecosystem-atmosphere interactions of rice paddy fields. There were more than 20 abstracts per year in the AsiaFlux conferences 2022 and 2023, respectively. Monitoring the dynamic of carbon dioxide and methane flux of irrigated paddy fields with alternate

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wetting and drying water management has been under the spotlight in recent years considering its potential to reduce water use and greenhouse gas emissions (Yan et al., 2024). For example, Hoang et al. (2023) observed that higher rice grain yield and lower methane emission were achieved by alternate wetting and drying in central Vietnam. Higher rice yield and lower greenhouse gas emissions under alternate wetting and drying were also seen in a study conducted in Indonesia (Pramono et al., 2024). High-resolution methane flux estimates across Monsoon Asia were achieved using 23 eddy covariance sites, MODIS remote sensing data, and machine learning (Ouyang et al., 2023). By using the results, they found that methane emissions from paddy rice in this region have been declining from 2007 through 2015 following declines in both paddy-rice growing area and emission rates per unit area. Additionally, researchers in Asia evaluated impacts of heat waves on carbon and water fluxes in sugarcane agroeceosystems, assessed influences of management strategies on microenvironment and flux patterns in tea fields (e.g., Wang and Juang, 2024), measured carbon dioxide and energy exchanges in soybean fields, tracked crop growth using canopy light extinction ratio in garlic and maize fields, and simulated the growth of onion under climate change using process-based modeling. Other strategies for lowering greenhouse gas emissions are also being explored, such as applying biochar at maize fields and alternative fertilizer in rice paddy. Flux techniques are powerful tools for evaluating various climate change mitigation strategies implemented in agricultural ecosystems.

2.2.2 Impacts of plantation on ecosystem-atmosphere interactions

During the past decades, rising global demand for cheap oils and fats has promoted the expansion of oil palm (*Elaeis guineensis* Jacq.) plantations in tropical regions due to the plant's high yield. Indonesia and Malaysia are, by far, the largest producers of palm oil. Thus, there were two keynote talks, one titled "Changes in greenhouse gas fluxes by converting from disturbed secondary peat swamp forest to oil palm plantation" by Dr. Ryuichi Hirata and another with a title of "Impacts of land transformation from forest to oil palm plantation on land-atmosphere exchange processes in Indonesia" by Dr. Alexander Knohl, presented in the AsiaFlux conference 2022. Furthermore, there were other related presentations such as carbon dioxide fluxes in oil palm cultivation on peat, soil carbon dioxide flux dynamics of oil palm following replanting, and changes in soil chemical properties by compost application in oil palm

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plantation in Malaysia. In this regard, a publication on reducing measurement bias on soil carbon dioxide emissions when using manual chambers was discussed via a case study on a mature oil palm plantation on tropical peatland in Malaysia (Basri et al., 2024). A potential mitigation strategy, raising water tables nearer to the soil surface at oil palm plantation in peatlands, was evaluated. The results indicated that it can have a substantial decrease in carbon dioxide emissions without negatively impacting yields and enhance resilience to increasing atmospheric vapour deficit in Malaysia (McCalmont et al., 2023). Reduced net carbon dioxide emissions by rewetting oil palm plantations were also observed in Indonesia. Besides carbon dioxide, methane exchange rates in response to environmental change at a young oil palm plantation and a mature oil palm plantation in Malaysia were measured. Seasonal dynamics of nitrous oxide fluxes in the drainage ditch water of oil palm plantation in Malaysia. Stiegler et al. (2023) quantified temporal variation in nitrous oxide fluxes from an oil palm plantation in Indonesia. Substantial isoprene emissions from oil palm have been reported, and a presentation showed a study on isoprene emission of different oil palm individuals to find the low-emitting candidates. Beyond oil palm plantation, impacts of other plantation types are being assessed such as carbon dioxide flux of coconut plantation in a tropical peatland in Indonesia and that of rubber plantations in Thailand. Net ecosystem exchanges of carbon dioxide, methane and soil nitrous oxide fluxes between October 2016 and May 2022 from fibre wood (*Acacia crassicarpa*) plantation, degraded forest, and intact forest, within the same peat landscape, were monitored in Sumatra, Indonesia (Deshmukh et al., 2023). These results provide an estimate of how land-use change impact on tropical natural lands and can be used to develop science-based management practice in tropical Asia.

2.2.3 Greenhouse gas fluxes of green space in city

Around 50% of the global population lives in cities and this percentage is expected to increase to 70% by 2050 (Johnson and Munshi-South, 2017). As a result, cities have become a major source of greenhouse gases. A correct quantification of these emissions is crucial for developing climate action plans and monitoring their effectiveness. Japan established a monitoring project called the CONTRAIL (Comprehensive Observation Network for TRace gases by AIrLiners), in which high-resolution vertical atmospheric carbon dioxide data are obtained using onboard commercial aircraft (Umezawa et al.,

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2020). Yuxuan Li (2024) reviewed 127 studies that employed the eddy covariance technique to observe urban carbon dioxide and energy fluxes from 2009 to 2022. The results show that carbon emissions in urban areas vary greatly at different times and seasons and the heterogeneity of the underlying surface in urban areas has a great influence on the energy fluxes. Presentations in the AsiaFlux conference 2022 and 2023 show continuous advancements in this aspect. The role of urban greenery in ecosystem-atmosphere exchanges has become more important, thus carbon fluxes, soil carbon storage, and soil microbial diversity of urban green spaces are being investigated. Because the urban environment is a mixture of various emission sources, 10 urban flux stations with different ground characteristics in the Seoul Metropolitan Area of Korea were operated during 2017-2020. In Hangzhou, China, vehicle-measured atmospheric carbon dioxide and methane concentrations from 2020 to 2022 were used to estimate fluxes at 100-m resolution. Furthermore, nitrous oxide fluxes of an urban center in Japan were monitored using the eddy covariance method and urbanization effects on vegetation were assessed in China using the PhenoCam images. Lastly, $PM_{2.5}$ mitigation and management plans for creating urban forests based on different tree species are evaluated in Korea. In summary, city planners design urban futures by considering environmental degradation and climate mitigation can take advantage of existing flux data.

2.3 Remote sensing and modeling

2.3.1 Geo-stationary satellite observations

Flux towers are a powerful tool to monitor ecosystem-atmosphere interactions but they cannot cover the global land surface due to their relatively small footprints, and their sparse geographic distribution is biased (Schimel et al., 2019; Xiao et al., 2021). This is the reason that remote sensing observations, mainly polar-orbiting satellites, have been widely used in the past two decades to estimate global carbon and water fluxes based on different approaches (Ryu et al., 2019) with one of the greatest challenges coming from their long revisit frequencies and frequent clouds. The diurnal sampling capability of geostationary satellites provides unprecedented opportunities to help minimize data gaps at multiple temporal scales. Recognizing the importance, in the AsiaFlux conference 2022, Dr. Paul Stoy was invited to give a keynote talk on “Toward a geostationary satellite network to monitor global gross

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primary productivity in real time". Additionally, two more presentations used geostationary satellite data to investigate diurnal carbon and water fluxes in the Asian region. With growing interest and developing expertise, the AsiaFlux conference 2023 had a designated session on "leveraging third-generation geostationary satellites for terrestrial ecosystem monitoring: advances, challenges, and applications". With more than 10 abstracts, this session focuses on the utilization of third-generation geostationary satellites, such as Himawari-8/9, GeoKompsat-2A, Fengyun-4, and GOES-16/17/18, for terrestrial ecosystem monitoring. Yamamoto et al. (2022) evaluated uncertainties of sub-hourly land surface temperatures retrieved by three operational algorithms from Advanced Himawari Imager data using in-situ observations from AsiaFlux and OzFlux networks. Data from the Geostationary Korea Multi-Purpose Satellite-2A, together with ground flux measurements, was also used to track diurnal to seasonal variations of gross primary productivity in South Korea (Jeong et al., 2023). These studies demonstrate the unique observation characteristics of geostationary satellites can contribute to large-scale monitoring of ecosystem-atmosphere interactions from diurnal to seasonal scales.

2.3.2 Solar-induced chlorophyll fluorescence

Extending from the previous section, quantifying global photosynthesis is a crucial but challenging problem in the ecosystem-atmosphere interaction study. In the past decades, various models such as the light use efficiency model, vegetation indices models, and process-based models have been used to estimate global photosynthesis using remote sensing observations. Solar-induced chlorophyll fluorescence (SIF), as a signal emitted in photosynthesis, is a promising proxy for photosynthesis and it has been demonstrated to outperform traditional vegetation indices in tracking the photosynthesis dynamics (Meroni et al., 2009). The research community on carbon flux in Asia has on-going studies of SIF observed by GOSAT series including analyzing the use of GOSAT SIF in Japan and GOSAT-2 SIF products in the Mongolian Plateau and Borneo Island. To obtain a better understanding of how SIF-photosynthesis relationship is influenced by meteorological variations and leaf-phenological growth stages, multiple sites (e.g., evergreen broadleaved forest, deciduous needle-leaved forest, and deciduous broadleaved forest) in Asia continuously collect ground SIF measurements and researchers are evaluating differences in the temporal patterns of SIF between in-situ and satellite observations (e.g.,

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GOSAT-2 and TROPOMI). By using ground SIF measurements, Chen et al. (2024) developed a parsimonious mechanistic model for SIF-based photosynthesis estimation in evergreen needle forests in Canada, South Korea, and United States by considering the seasonal variation in maximum photochemical efficiency. Beyond forest ecosystems, there is a potential decoupling between SIF and photosynthesis under subtle plant physiological changes from agricultural practices. Therefore, ongoing projects are working on linking physiological SIF yield with photosynthesis for reliable remote sensing of crop productivity. In addition, novel hyperspectral systems to measure SIF in-situ are also being developed. Retrieving physiological signals from SIF measurements is challenging due to the confounding effects of canopy structure and soil background. A new strategy that incorporates near-infrared reflectance of vegetation to minimize those effects on physiological signal retrieval, using bidirectional reflectance factor from Sentinel-2 and Landsat-7/8 imagery, are proposed and assessed (Wan et al., 2024). These efforts greatly advance the utility of SIF data, from various measuring scales, in ecosystem-atmosphere interaction studies.

2.3.3 Machine learning in flux science

The rapid development of various algorithms and high public availability of programming tools in the field of machine learning have made these techniques easily available to more researchers, community of ecosystem-atmosphere interaction is not an exception. Due to unfavorable weather conditions and sensor failures, gaps exist in continuous time series. Despite a standard gap-filling procedure has been established (Pastorello et al., 2020), it still has limitations and weaknesses. Therefore, efforts are being invested to find better approaches to fill flux data gaps, especially for gas species beyond carbon dioxide and for underrepresented ecosystem types (e.g., rice paddy and tropical peatland). Additionally, net ecosystem exchanges of carbon dioxide are an important indicator of carbon cycling in terrestrial ecosystems, but having gross primary productivity and ecosystem respiration accurately estimated (i.e., flux partitioning) is essential to improve our process understanding. Various partitioning methods have been proposed in recent years, among all, two methods are widely applied in the flux community: the nighttime method (Reichstein et al., 2005) and the daytime method (Lasslop et al., 2010). Both methods rely on simplified empirical models leading to errors and biases. Recently, a group of AsiaFlux scientists with collaborators developed neural networks informed by SIF observations that can successfully partition NEE, while simultaneously learning the ecosystem-scale SIF-photosynthesis relationship (Zhan et al., 2022). Moreover, as mentioned, to provide carbon flux estimates at scales beyond the ecosystem scale, lots of people are trying to combine flux observations and meteorological, biophysical, and ancillary predictors using machine learning techniques. Shi et al. (2022) performed a meta-analysis of these simulations with 178 model records included. They found the impact of timescale on model performance is significant and there are significant differences in the impacts of predictors on model accuracy for different vegetation types. There are more ongoing studies that are further exploiting the power of machine learning such as incorporating physical knowledge to obtain more knowledge out from the rich flux dataset, which we elaborate more in Section 4.3.

3 Challenges

In this section, we outlined the challenges for ECRs conducting ecosystem–atmosphere interaction research and stressed the need to tackle these via interdisciplinary and international collaborations.

3.1 Long-term observations

With an increasing number of time series exceeding 20 years in duration, we are now able to start capturing ecosystem-scale trends in the breathing of a changing biosphere and addressing questions about attributions on flux exchanges with more statistical confidence. Baldocchi (2020) highlighted the contributions of eddy covariance flux measurements to our understanding of ecosystem–atmosphere interaction with one part focused on lessons learned from the long-term data records. First, on average, the subsample of undisturbed sites with more than 10 years of data did not experience trends that were significantly different than the detection limit of the method. In addition, via synthesizing literature, the sensitivity of ecosystem-atmosphere fluxes to physical and biological factors was discussed. Here we would like to add 2 very recent publications that used 20 years of eddy covariance data to understand carbon and water flux dynamics. An actively-managed naturally regenerated pine ecosystem in the southeastern United States was a continuous carbon sink for 21 years; however, different responses of forest photosynthesis to water availability led to different net carbon budgets between the two decades

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despite the same management (i.e., cutting) was performed (Bracho et al., 2023). With continuous flux measurements in a coastal Douglas-fir forest at an age of about 25 years old, it finally became clear that it would take ~35 years for the stand to compensate for the carbon lost due to clearcutting with the benefit of nitrogen fertilization (Lee et al., 2024). Long-term eddy covariance measurements have radically altered how we study ecosystem-atmosphere interactions in a changing world and allowed us to continue finding surprises and discoveries by serendipity. In Asia, few sites have data exceeding 15 years and work has been conducted to assess the relationship between extreme events and changes in ecosystem-atmosphere fluxes. Results based on 15-year (2006-2020) flux data measured in a deciduous old-growth forest in Korea indicated that the forest switched back-and-forth between sink and source of carbon dioxide, which was likely caused by the changing growing season length (Yang et al., 2021). On average, the Tibetan alpine steppe ecosystem in China was a very weak net carbon sink from 2005 to 2019, which highlights the special vulnerability of this ecosystem type to become a source of carbon dioxide due to global warming (Nieberding et al., 2020). In Japan, presented in the AsiaFlux conference 2023, long-term flux observations at 10 forests have been conducted with a mobile flux observation system developed to collect measurements at disturbed sites. This information will be combined with risk assessment using a disturbance model to evaluate changes in carbon dynamics associated with disturbance events. With many sites accumulating time series that are reaching multiple decades in duration, their value is virtually priceless, as we cannot turn back the clock. ECRs would like to advocate again that we should continue to fund and conduct these flux measurements for a longer period but also have the flexibility to accommodate new research questions and their associated design requirements. More importantly, we emphasize that careful data processing and flagging are essential to reduce uncertainties stemming from technical and logistical constraints of long-term tower operation (Jung et al., 2024; Kang et al., 2023; Mauder et al., 2013).

3.2 Open data

Promoting a paradigm of open, free, and timely data sharing is not new; however, ECRs find the communities of ecosystem-atmosphere interaction study in Asia are still somewhat lagging behind. Dai et al. (2018) assessed how data sharing is related to scientific impact and found significant majorities of

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the most influential top 30 and top 100 flux researchers were data sharers. In addition, the results showed regional differences and agreed with Peng et al. (2016) that AsiaFlux communities are notably less oriented to data sharing than their counterparts in North America and Europe. Bond-Lamberty (2018) looked at the FLUXNET2015 dataset, if not the most impactful shared dataset in ecosystem-atmosphere interaction study released from the global FLUXNET network, and noted that many flux data, in particular from Asia, do not appear at all in the dataset. In this perspective paper, ECRs used literature search on SCOPUS to collect yearly publication and citation history of the main flux communities, namely FLUXNET, AmeriFlux, Integrated Carbon Observation System (ICOS), and AsiaFlux (Figure 1). The results indicated continuous growth of all three flux networks except AsiaFlux which has decreasing publications and plateaued citation counts (Figure 1). We also reviewed the data policy of the top 20 journals included in Bond-Lamberty (2018). Different from the previous investigation that indicated the leading journals presented a very mixed picture in data sharing, as of May 2024, 13 of these journals require research data to be shared in a public repository, while the remaining journals highly encourage it. This shows that, as science becomes increasingly collaborative and data-intensive, practices with respect to data sharing and archiving are changing quickly. Moreover, with open data, we can reduce the implementation cost of flux towers as the data can be used by wider communities for more diverse purposes. One final note in this section, as pointed out by Dai et al. (2018), it is still very difficult to access data from the key roles of AsiaFlux (i.e., ChinaFlux, JapanFlux, and KoFlux). ChinaFlux and JapanFlux have their websites in English, but KoFlux is still not searchable online. Moreover, a recent publication in the ChinaFlux special issue on *Agricultural and Forest Meteorology* presented a map showing more than 80 flux towers (Yu et al., 2024). However, data from only 8 sites are shared on the ChinaFlux data portal, which is only available in Chinese, and applications are required before data download. We understand data-sharing culture is different among regions but ECRs urge the community to build a more sustainable open, free, and timely data sharing, especially in the era of big data. This will not only have broader use of data and scientific products by the global community but also foster deeper interdisciplinary integration, which is critical to address the grand societal challenges we are facing (Petzold et al., 2024).

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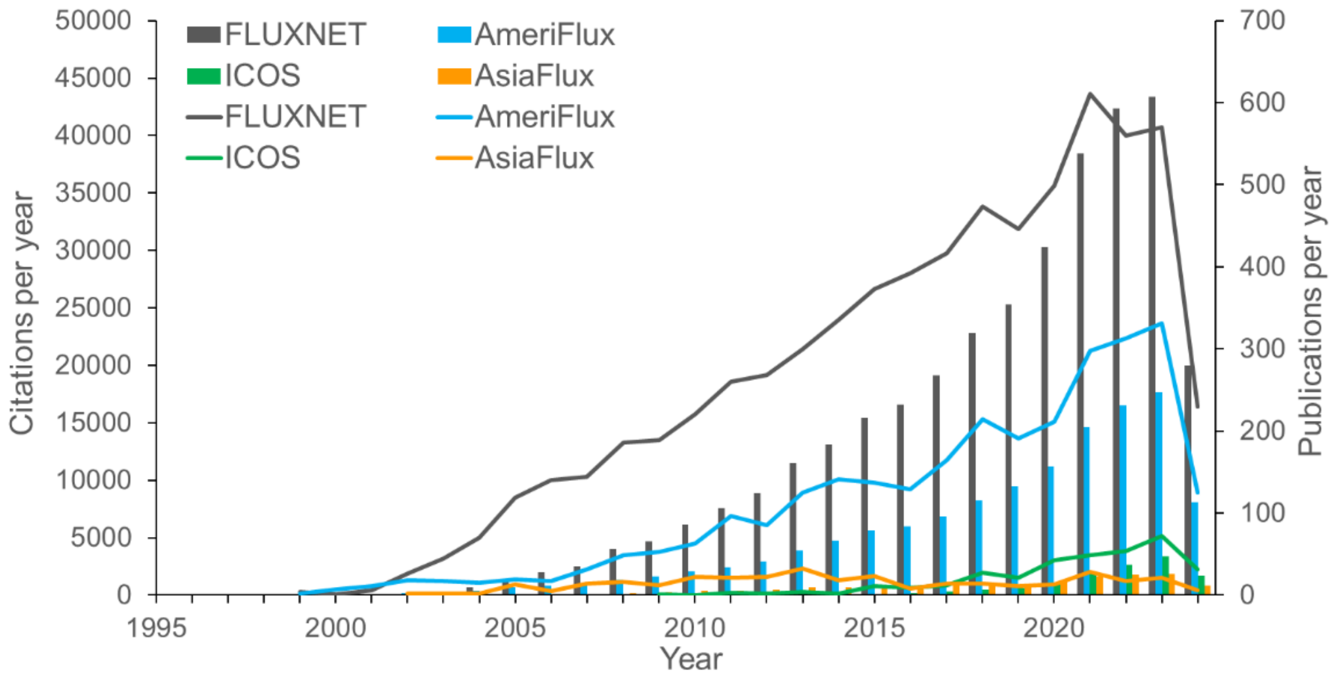

405 Figure 1. Yearly publication (lines) and citation (bars) history of the term 'FLUXNET', 'AmeriFlux', 'ICOS', and 'AsiaFlux' for the period 1999 through 2024. These data are from a literature search using SCOPUS on 31 May 2024.

3.3 Data processing among flux networks

Besides emphasizing the value of data sharing, ECRs would like to note the importance of standardized data post-processing methods. Post-processing of flux data is crucial for gap-filling measured net exchanges of carbon dioxide and partitioning them into respiration and photosynthesis. FLUXNET employs standardized methods for data post-processing, enabling comprehensive analysis across multiple sites. Particularly, ICOS and AmeriFlux networks are already doing flux data post-processing using the same steps (i.e., ONEFlux; Pastorello et al., 2020) in their respective portals. However, in Asia, post-processing methods vary by sub-regional networks, leading to significant uncertainties depending on the specific methods used. In Japan, software for flux calculation and analysis is available (Ichii et al., 2017; Ueyama et al., 2012). Studies utilizing this software indicate that approximately 6% of differences in annual respiration and photosynthesis arise depending on the choice of respiration models for flux partitioning (Ichii et al., 2017; Ueyama et al., 2014). In Korea, the post-processing

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methods for flux data offer various options for flux partitioning (Kang et al., 2018). In complex mountainous terrains, the choice of flux partitioning methods can lead to significant differences in the annual net exchange of carbon dioxide (i.e., between -411 and 13 gC m^{-2} yr^{-1}) (Kang et al., 2014). Recent analyses comparing the REddyProc package (Wutzler et al., 2018) and KoFlux post-processing methods in the complex terrains over 8 years from ECRs revealed no substantial differences (i.e., 45.1±45.2 gC m^{-2} yr^{-1}) in annual net carbon dioxide exchange during daytime (Figure. 2a), but significant discrepancies (i.e., the difference between KoFlux and REddyProc_DT is 241.5±83.2 gC m^{-2} yr^{-1} and the difference between KoFlux and REddyProc_NT is 124.6±43.9 gC m^{-2} yr^{-1}) were observed in nighttime estimations (Figure. 2b). This is a critical issue to solve as the new strategy on how to submit data from regional flux networks to FLUXNET was proposed and it heavily relies on each network cluster to provide the most updated processed data (Papale, 2020). To leverage this concept of making data from Asia flux communities more accessible, it is important to discuss how to follow and implement the standardized methods (Figure 3). Enhancing the functionality of the AsiaFlux database is necessary for flux reprocessing using the standard ONEFlux data processing pipeline and implementing the FLUXNET shuttle concept for regional and global synthesis research. One possible option can be having a designated data scientist team in AsiaFlux as what have been done by ICOS and AmeriFlux. This not only can improve the data sharing issue but can promote future community collaborative activity such as FLUXNET-CH4 Community Product (Delwiche et al. 2021). ECRs would like to highlight the benefits and support from the free training offered by Li-COR and Campbell Scientific before each AsiaFlux conference, and propose it may be a good venue to provide training on flux post-processing that aligns FLUXNET strategies. Moreover, ECRs also want to highlight that FLUXNET Early Career Network seminars and workshops can also focus on this crucial issue that ECRs in global flux communities can explore feasible solutions together.

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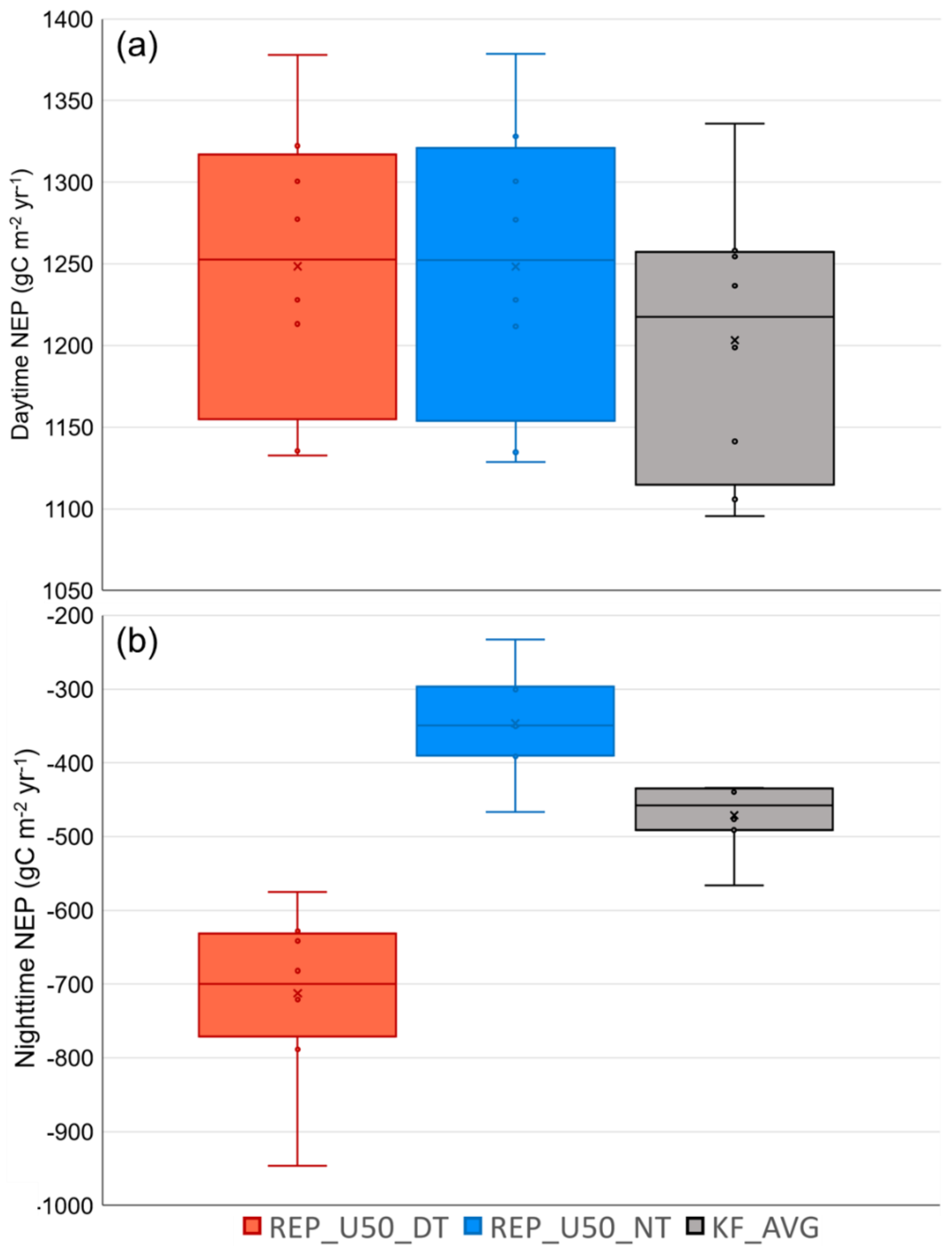

Figure 2. Annual net ecosystem production (NEP) estimations during (a) daytime and (b) nighttime
445 from different post-processing methods at one of the AsiaFlux sites located in a complex mountainous terrain over 8 years. REP_U50_DT is REddyProc daytime-based method with median friction velocity threshold. REP_U50_NT is REddyProc nighttime-based method with median friction velocity threshold. KF_AVG is an average value of three KoFlux post-processing methods.

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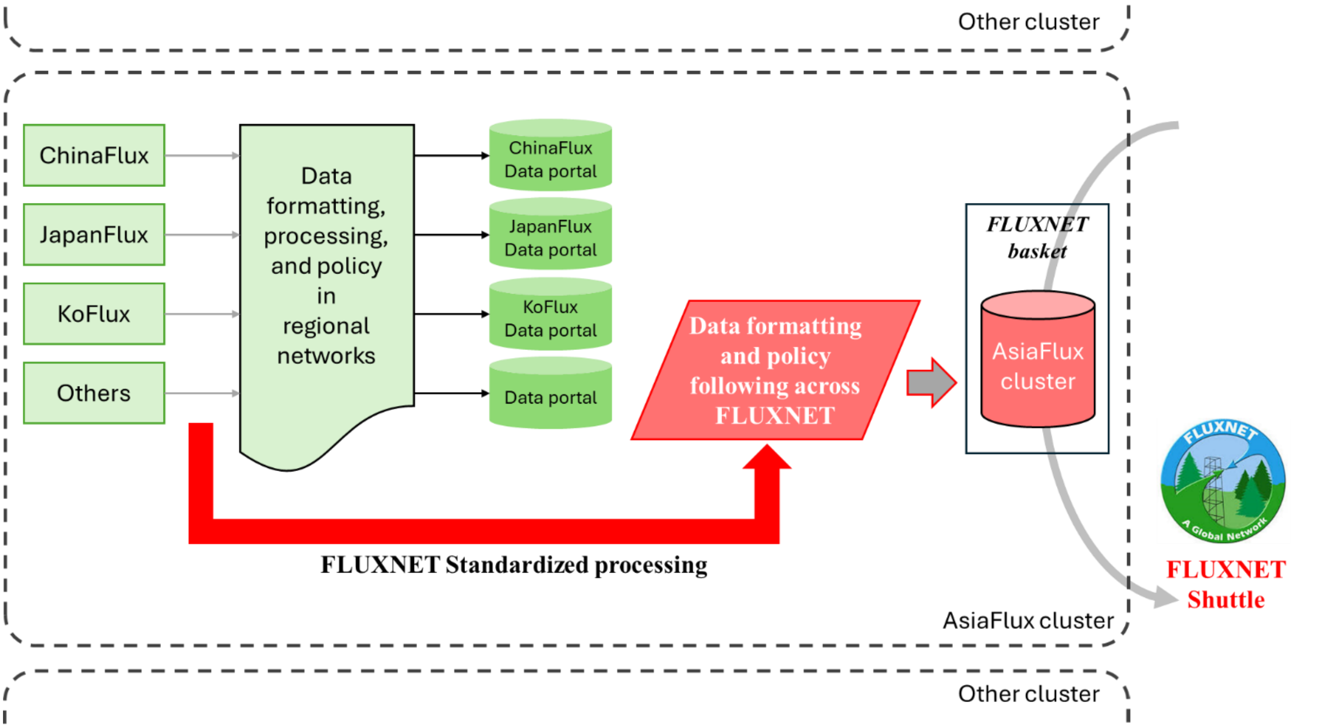

Figure 3. Schematic figure to show data flow from the sites in the Asian region to the new data submission concept, FLUXNET shuttle. The principal investigators of the sites continue to submit data to sub-regional networks with which they are associated. Each regional network can organize its own data processing, data policy and data distribution system. Selected data will be processed using the standard FLUXNET processing and then shared in the FLUXNET basket where the FLUXNET shuttle can collect it for the user upon request. The figure is crafted following the one proposed by Papale (2020).

3.4 Stakeholders engagement

Countries need to monitor, report and verify what they are doing individually and collectively to reduce greenhouse gas emissions. To track efficiency of various actions, a system performing Monitoring, Reporting and Verification (MRV) is needed to provide evidence supporting stakeholders to mitigate climate change. Monitoring, as known as measurement, refers to data regarding trace gas emissions. Reporting is the act of compiling this information into inventories ensuring that it can be accessed by a variety of users. Verification is done by a third party independently verifying the reported information

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to check the accuracy. Observational data play a key part in MRV, and observation-based MRV systems have the potential to complement inventories. By having observations, we can reconcile estimates from models using atmospheric records (i.e., measurement data) with reported emissions (i.e., inventories). Therefore, robust observation-based MRV systems benefit decision makers across the local to global scales. It is still very challenging to incorporate observations into an MRV system, particularly from a global perspective. First, MRV systems are not simple to set up and maintain, and they need to be supported by proper infrastructure and funding. A tricky part in terms of funding is that an observation-based MRV system requires research to function, but it should not be run as a research project as it demands operational staff to support and maintain it long-term. Second, some parts of the world, such as Europe and North America, have well-developed ground-based observation networks and the people to operate them. For example, ICOS atmospheric data are used to verify inverse modeling and ICOS ecosystem and ocean data are used to calculate natural greenhouse gas exchanges between ecosystems and the atmosphere. However, even these well-established networks have gaps in their coverage. To tackle these challenges, the World Meteorological Organization Executive Council approved a Global Greenhouse Gas Watch implementation plan in June 2024 to strengthen monitoring of greenhouse gases and support countries in climate change mitigation actions (World Meteorological Organization, 2024). Lastly, communication among stakeholders is critical to make sure the exchanges of information continue. In the AsiaFlux conferences, ECRs recognized this is urgently needed, on top of the open data concern, as many stakeholders are not aware of the rich data collected by flux towers and other facilities. MRV systems that are science- and measurement-based can help countries, cities, organisations and companies monitor, report and verify their individual and collective actions to reduce greenhouse gas emissions. As shown by the TERrestrial ENvironmental Observatories (TERENO) (Zacharias et al., 2024), scientific community in Asia can increase projects that are co-designed and executed with stakeholder communities to demonstrate relevance and contributions of flux tower measurements to society.

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4 Opportunities

In this section, we highlighted some emerging research directions based on the ECRs' experience and interactions in the conferences. In the meantime, we also pointed out some unknowns and uncertainties that can be further investigated.

4.1 Unique ecosystem type

Some ecosystem types in the Asian region are rarely observed elsewhere, here we show some selected results emphasizing their importance. First, it is very well known that tropical forests are a reservoir for about 25% of the global terrestrial carbon (Bonan, 2008); however, despite accounting for about 40% of all tropical forests and vast ecological significance, tropical dry forests remain overlooked from research as compared to their wet counterparts (Bhadouria et al., 2016). Tropical dry forests are mostly seen in Africa, Latin America, and the Asia Pacific (Miles et al., 2006). Recently, carbon balance of a 65-year-old tropical dry deciduous forest in central India was reported using the 8 years of eddy covariance measurements (Rodda et al., 2021). The forest was a substantial carbon sink but experienced large interannual variations caused by canopy greenness and temperature.

Second, mangrove forest plays a key role in global carbon cycling and Asia-Pacific mangroves make up around 48% of the 15 million ha of mangroves that cover the Earth's surface (Jahnke, 2010). Knowledge of ecosystem-atmosphere interactions for mangroves in this biodiversity-rich region is largely lacking, as highlighted in a review (Sharma et al., 2023). Thus, various teams in the AsiaFlux community are dedicated to improving this. By using year-round data collected at a 10 m-tall flux tower in a mangrove located on the southeast coast of India, it has been found that evapotranspiration only became stronger than sensible heat flux in the wet season (Deb Burman et al., 2022). Carbon dioxide and water fluxes were measured in a subtropical mangrove forest in southern China from 2010 to 2019. The results indicated that the mangrove forest acted as a strong carbon dioxide sink and the importance of certain environmental conditions (e.g., solar radiation and tidal inundation) on carbon dioxide and water fluxes changed over the ten years (Gou et al., 2023). Going beyond, ecosystem-scale methane flux was measured using an eddy covariance system in a subtropical estuarine mangrove in Hong Kong for two years. By applying nonparametric statistical approaches, J. Liu et al. (2022) found that methane

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fluxes were dominantly coupled to plant activities through synchronous processes at the diel scale and primarily controlled by soil temperature and water salinity at the seasonal scale.

Another overlooked managed ecosystem in Asia is agroforestry, an agroecosystem that integrates crops and trees. Agroforestry is estimated to comprise up to 80% of the total agricultural land in Southeast Asia (Zomer et al., 2016). It has been widely practiced by farmers in the region as an important climate change mitigation strategy (Martin et al., 2020; Terasaki Hart et al., 2023). While there is an old study measuring water fluxes in a cacao agroforestry system in Indonesia (Falk et al., 2005), most flux studies in agroforestry systems have been conducted outside Asia. For example, a study found additional carbon storage associated with tree belts in a 'belt and alley' system compared to conventional cropland in Australia (Ward et al., 2012). Another study demonstrated the potential of using lower-cost eddy covariance systems to study heterogeneous alley cropping systems in Northern Germany (Callejas-Rodelas, 2024). There is a need to further explore ecosystem-atmosphere interactions in agroforestry systems in Asia to better establish their role as a nature-based climate solution. Lastly, as mentioned in the Section 2.2, better understanding of ecosystem-atmosphere interaction in managed ecosystems like rice paddy and plantation forests in Asia is urgently needed, thus the AsiaFlux and other relevant communities play an important role in pushing this forward.

Lastly, cloud forests, defined as forest ecosystems characterized by frequent cloud and fog immersion, cover only 1.4% of global tropical forests (Bruijnzeel et al. 2011), but they harbor a disproportionately wide variety of species and are characterized by a unique hydroclimatological cycle. Gu et al. (2021) found that latent heat fluxes reached the peak earlier than other forests and regulated diurnal temperature range in montane cloud forests in Southeast Asia. This ecosystem type is facing many challenges thus accurate prediction of the fog occurrence dynamics is important and it has been found that random forests modeling, with ground measurements, can explain substantial amount of fog occurrence data variation (Li et al. 2022). Furthermore, responses of water vapor exchanges in cloud forests to different climate change scenario are critical to understand and the results indicated that evapotranspiration decreased due to multiple combined factors, in contrast to the expected intensification (Yang et al. 2022).

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4.2 Combination of ground and satellite measurements

Flux measurements represent net exchanges of carbon, water and energy at the ecosystem scale. Therefore, flux data alone do not tell us explicitly the spatiotemporal contributions to, nor the partitioning of fluxes between, different ecosystem components. Further, flux tower measurements are site specific, resulting in underrepresentation of key ecosystems globally. Remote sensing can help scientists interpret site specific flux measurements by providing contextual information on community composition and vegetation function, as well as scale estimate fluxes globally. Additionally, flux data can inform remote sensing measurements which do not directly measure carbon and water fluxes. Cho et al. (2021) estimated regional ecosystem-atmosphere carbon fluxes by combining eddy covariance flux data from 10 sites in South Korea with remote sensing data through a machine learning algorithm for the period 2000–2018. They found the results were consistent with the biometric-based estimates and highlighted that this combination has a great potential to be used to estimate forest carbon fluxes on a national scale. In addition, Chang et al. (2023) estimated gross primary productivity over 9 sites in China via random forest regression models using remote sensing and eddy covariance data. Despite the models performing differently in simulating temporal changes and magnitude for different vegetation types, they can be further explored to predict regional carbon fluxes and for calibration and evaluation of land surface process models. Therefore, the utility of remote sensing for informing flux science provides a great opportunity but is still limited by a lack of awareness of what remote sensing data can and cannot tell us and how it can be used in conjunction with flux tower data. There is a need for improved access, standardization, and usability of remote sensing data at flux tower sites. When cross-disciplinary relationships between these two fields are strengthened (e.g., the KoSpec network), this will ultimately improve our ability to address critical questions in ecosystem-atmosphere interaction study.

4.3 Process understanding from data-driven models

As shown by several papers in the previous sections, the community in Asia has taken advantage of data-driven approaches such as machine learning to achieve good performance for various research topics in the ecosystem-atmosphere interaction realm. However, such newly-developed machine learning models can fit an observational dataset very well but do not accurately represent lagged

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dependencies (Kim et al., 2020) and are mostly not driven by causal relationships (Runge et al., 2019). We must be cautious that machine learning models are limited by their inability to produce physically interpretable and consistent predictions. Considering process-based models in general are restricted by the ad hoc assumptions of the system, new modeling approaches, such as hybrid models, have been proposed to better represent physics in machine learning models that allows physically interpretable performance of predicting and infers intermediate (or latent) states and variables by merging the advantages of the causal understanding of physics-based models and the predictive power of machine learning. The hybrid approaches aim at harvesting the information in observation data efficiently by replacing parameter estimation with a machine learning model, while still maintaining model interpretability and physical consistency (Reichstein et al., 2019). Therefore, the synergy of both techniques offers promising solutions to the shortcomings encountered in using both techniques separately, and this should be further developed and tested for simulating fluxes of a variety of ecosystems. There are several other methods to achieve it as the machine learning community has been making significant progress in developing strategies to improve model interpretability for the past few years, leading to the evolution like interpretable machine learning and explainable artificial intelligence (Jiang et al., 2024). These allow pure data-driven models to go beyond the predictive power, and will have a great potential to significantly improve our understanding of Earth's complex environmental systems (Yang et al., 2023). In addition, it is also important to leverage multiple data streams in this new modeling technique to provide better understanding of ecosystem-atmosphere interactions.

4.4 Interactions between established scientists and early career scientists

The interactions between established scientists and ECRs are crucial for the advancement of scientific knowledge and the development of future leaders in research. AsiaFlux conference highly values this and has been inviting well-known scientists from prestigious universities or institutes to present their work in keynote talk sessions. Established scientists possess a wealth of experience and expertise, through these talks, they can provide invaluable insights of latest research methods and results to ECRs. Beyond skill transfer, these exchanges also stimulate innovation. ECRs bring fresh perspectives and novel ideas, which can inspire established scientists to explore new directions in their research. This

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bidirectional flow of ideas encourages a dynamic and collaborative research environment, leading to groundbreaking discoveries. Besides the invited talks, AsiaFlux conference has also been organizing young scientists meeting during the conference. Senior scientists are invited to share their academic journey with junior scientists and students. This offers insights into the nuances of academic publishing, job searching, securing research funding, and building a professional network, which are often challenging for ECRs to master independently. Via Q&A session and conference dinner after young scientists meeting, further interactions among scientists across different career stages foster the transfer of critical skills and knowledge and this informal mentorship from established scientists helps ECRs build confidence and resilience, essential traits for navigating the often uncertain and competitive nature of scientific careers. Such networking opportunities facilitated through these interactions play a significant role in career advancement. Collaborations can be initiated during these exchanges that can lead to co-authored publications, joint grant applications, and invitations to present at conferences, enhancing the visibility and reputation of ECRs within the scientific community. For example, a 3rd-year PhD from China managed to find a host university in Germany for a scholarship application during the AsiaFlux conference 2023. Additionally, the authors of this perspective paper, Sung-Ching and Hojin, are working together on a newly funded project together in Germany. Moreover, these relationships often extend beyond professional development, providing emotional and moral support, which is crucial for maintaining motivation and enthusiasm in the face of research challenges. In summary, the interactions between established and ECRs are essential for the growth of both individuals and the broader scientific communities in Asia. They promote the continuity of knowledge, foster innovation, and support the professional and personal development of emerging scientists, ultimately contributing to the sustained progress of science. Therefore, ECRs propose that having something similar to the FLUXNET secondment program (https://fluxnet.org/community/secondment-program/) in AsiaFlux community can be a very nice initiative to further promote exchanges among scientists across different career stages.

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5 Conclusion

This ideas and perspectives paper presents an overview of the research on ecosystem-atmosphere interactions in Asia, with a particular focus on the opinions of ECRs. The vibrant discussions among ECRs during an iLEAPS virtual forum, leading to concrete action items such as convening scientific sessions for the AsiaFlux conference 2023 and the EGU General Assembly 2024. Shown by presentations in conferences and publications, the diverse ecosystems such as forests and mangroves in Asia are vital carbon sinks but influence of climatic events and disturbances in the region is rapidly increasing. To better understand how ecosystems respond, recent research foci on natural ecosystems, managed ecosystems, and remote sensing and modeling improve our knowledge of processing mechanisms and provide potential mitigation strategies. However, challenges faced by ECRs include the sustainability of long-term observations, lagging open data sharing, uncertain standardized data processing, and lack of stakeholder engagement that would need collective efforts from all relevant communities to find feasible solutions. Despite challenges, research directions such as the study of unique ecosystem types in Asia, the integration of ground and satellite measurements, and physics-informed data-driven modeling excite and motivate ECRs to advance ecosystem atmosphere interaction study. The interactions between established scientists and ECRs, which has been highly valued, will continue to be the key to the future success of AsiaFlux. In conclusion, the paper emphasizes the complexity and significance of ecosystem-atmosphere interaction research in Asia and calls for continued investment and interdisciplinary collaboration to enhance understanding of these processes and inform sustainable development.

Code and data availability

We share the data used in this paper on: https://doi.org/10.6084/m9.figshare.26491729

Competing interests

The contact author has declared that none of the authors has any competing interests.

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