BAMS
Meeting Summary

Charting the Future of the FLUXNET Network

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FLUXNET Meeting 2023

What: FLUXNET scientists gathered to share insights from eddy covariance research on ecosystem functioning, discuss future plans for data sharing, and establish future priorities for FLUXNET community building.

When: 11–13 July 2023

Where: Brno, Czech Republic

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FLUXNET is a global network of micrometeorological tower sites that employ eddy covariance (EC) methods to measure the exchanges of greenhouse gases, water vapor, and energy between terrestrial and aquatic ecosystems and the atmosphere. FLUXNET has played a critical role in advancing our understanding of ecosystem functioning, carbon cycling, and land–atmosphere interactions circa 1997 (Baldocchi 2020) and is now poised to develop an advanced data sharing infrastructure aiming to increase global data availability and accessibility. By providing high-frequency, long-term data across a diverse range of ecosystems, FLUXNET enables researchers to study temporal and spatial variations in fluxes between the Earth surface and atmosphere, thereby contributing to more accurate climate models and better-informed environmental policies.

On 11–13 July 2023, FLUXNET scientists gathered in Brno, Czech Republic, for the first FLUXNET meeting since 2017. The meeting was hosted at Mendel University, sponsored by Integrated Carbon Observation System (ICOS; www.icos-cp.eu/) and company representatives, and planned by colleagues from the Global Change Research Institute CAS and the FLUXNET Community Council (FCC). Ninety-one people joined as in-person participants from 24 countries, with another 126 people registering to join virtually. Attendees represented a range of career stages with 22% being students. The 3-day meeting consisted of plenary speakers, lightning talks, poster sessions, breakout discussions, and informal time for peer-to-peer networking. After 3 days of science, participants joined for an optional visit to the Lanzhot ecosystem station and a tour of the nearby Lednice Castle.

The FLUXNET meeting catalyzed a wealth of scientific discussion on current and future applications of FLUXNET data, and culminated with a large group discussion to lay out future priorities and goals for the community. Key future goals include building the next generation of data sharing infrastructure to allow more timely releases of standardized data, expanding outreach and educational initiatives to support underserved research communities, and helping early career scientists establish thriving professional networks to ensure their research success in flux-related fields.

Current and historical FLUXNET activities

Network development. Since the 1980s, scientists have used eddy covariance techniques to measure carbon, water, and energy cycles between the biosphere and atmosphere. This method gained popularity after the pivotal La Thuile workshop in 1995, leading to the formation of regional networks like AmeriFlux, OzFlux, AsiaFlux, and EuroFlux for data sharing

(Beringer et al. 2016, 2022; Kang and Cho 2021; Novick et al. 2018; Yamamoto et al. 2005), along with other regional networks for knowledge and data sharing and community building (Kim et al. 2002; Vargas et al. 2013; Yu et al. 2006). FLUXNET emerged as a network of networks, standardizing data from these regional networks to facilitate global studies. Its key data collections were released in 2001 (Marconi), 2007 (La Thuile), and 2016 (FLUXNET2015), each expanding in number of available sites and years. More recently, the need to streamline data processing and release across networks led to the development of the Open Network-Enabled Flux (ONEFlux) codebase (Pastorello et al. 2020). ONEFlux code has since been used to process and release data from over 150 sites through AmeriFlux and >200 site years of data from 105 sites through ICOS, with more sites being added continuously. These data products are available as the "AmeriFlux FLUXNET" data product at https://ameriflux.lbl.gov/, and through the ICOS data portal at www.icos-cp.eu/data-services/about-data-portal.

In 2020, FLUXNET's expansion was bolstered by a National Science Foundation (NSF) AccelNet grant, leading to the formation of the FCC which is composed of members from major regional networks. The FCC focuses on education, data development, and community building, with projects like the FLUXNET Secondment program for early career U.S. researchers, support for the annual Fluxcourse at Niwot Ridge, Colorado, and various community-led workshops and committees.

Applications of FLUXNET data. The FLUXNET meeting showcased the diverse research within the flux community. Meeting presentations and posters highlighted the use of flux data in understanding carbon exchanges, carbon sequestration, and ecosystem productivity across a wide range of ecosystem types and management regimes. The data's role in water and evapotranspiration studies was also noted, including developments in evapotranspiration partitioning approaches. Presentations covered advances in eddy covariance data processing and gap filling, as well as new machine learning data analysis tools. Advances in remote sensing technologies are providing more opportunities to understand and upscale flux data. The expanding geographical coverage of the network is fueling integration of eddy covariance data with land surface models. This breadth of research promises to further our understanding of how ecosystems respond to land-use change and climate change.

Future opportunities for FLUXNET data

Future opportunities and goals elicited by the attendees at the FLUXNET Annual Meeting included multiple strategies to increase the visibility and applications of FLUXNET data as well as bolster its long-term viability.

Eddy covariance data could be used in an emerging global carbon trading market. Rising interest to inform carbon accounting with eddy covariance data led participants to discuss what role the FLUXNET community should play as a network of scientists—either as knowledge brokers, data suppliers, or advocates. The long legacy of monitoring infrastructure, high-quality data, and expert training in carbon cycle processes in the FLUXNET community means it is ideally placed to advise on carbon accounting methods being developed, and contribute important datasets to help fine-tune these methods. Indeed, eddy covariance data are already being used in some places to validate carbon accounting models (Bona et al. 2020; Marino and Bautista 2022), and we expect this practice to grow as the carbon trading markets expand. While there are gaps in the FLUXNET network, such as underrepresented regions or ecosystem types that could and should be addressed (Baldocchi et al. 2018), the FLUXNET road map and goals ("FLUXNET road map and goals" section) demonstrate how the community is working toward a data product that will become invaluable for carbon accounting work.

At the meeting, four key emerging themes arose from our carbon accounting discussions. These included 1) a need to keep pushing forward the foundational scientific enquiry, which will continue the improvement of the eddy covariance method; 2) the importance of national networks that provide regular, standardized measurements at the highest quality for verification of carbon accounting protocols; 3) expansion of lower-quality but cheaper sensor networks to fill gaps in coverage in the existing network; and 4) development of outreach and education materials for the wider community to expand FLUXNET and ensure the eddy covariance method is applied as correctly as possible.

Remote sensing observations can be ground-truthed with eddy covariance data. The timing of the meeting coincided with the Moderate Resolution Imaging Spectroradiometer (MODIS) products approaching their end of life, which is significant because a key motivation for the original FLUXNET idea was the need for a ground validation dataset for MODIS data (Running et al. 1999). While MODIS data are no longer being collected, the successful pairing of FLUXNET data with MODIS has proven the value in consistent ground truth data and opens the opportunities for the next generation of remote sensing products (Chu et al. 2021; Running et al. 1999; Walther et al. 2022). New technologies, such as the high spatial/temporal resolutions of the Sentinel fleet, new physiological parameters such as spaceborne sun-induced fluorescence (SIF), and up-and-coming hyperspectral and laser data will allow new insights into ecosystem diversity and functioning (Calders et al. 2023; Shirkey et al. 2022). All of these new data streams will need not only data from eddy covariance, but also the knowledge and expertise the community brings with it.

Eddy covariance data can be used to train and validate land surface models. Eddy covariance is one of the few methods providing measurements integrated over sufficiently large geographic areas and at fine enough temporal resolution to serve as an evaluation dataset for the land surface models (LSMs) (Ukkola et al. 2022). Models then serve as a key tool to understand not only current water, carbon, and energy fluxes, but also the potential outcomes of future climate scenarios such as those outlined in IPCC reports. Apart from process-based models, FLUXNET data have also been a key source of training data for data-driven models and machine learning which are useful in understanding larger-scale patterns without making assumptions on biological functioning (Burton et al. 2023; Dannenberg et al. 2023; Ichii et al. 2017; Virkkala et al. 2021). Going forward, increasing the representativeness of the network by adding more towers in underrepresented ecosystems [see Pastorello et al. (2020) for map of FLUXNET2015 sites] and lowering boundaries in using large amounts of eddy covariance data by both process and machine learning modeling communities will allow for both greater ecophysiological understanding and reduced uncertainties in global processes under a changing climate.

Long-term studies show how ecosystems respond to climate change. As we approach the 30 year anniversary of the first international gathering of flux scientists in La Thuile, FLUXNET is uniquely poised to offer critical insights into long-term ecosystem trends (Chen et al. 2022) and drivers of interannual flux variability (Barcza et al. 2020; Liu et al. 2022; Niu et al. 2017; Xu et al. 2023). The FLUXNET2015 dataset already contained numerous sites with 20+ years of data, and the network has continued to expand since then (Fig. 1). Long-term continuous datasets are increasingly valuable as climate change accelerates the occurrence of drought, heat waves, and other climatological events that will significantly

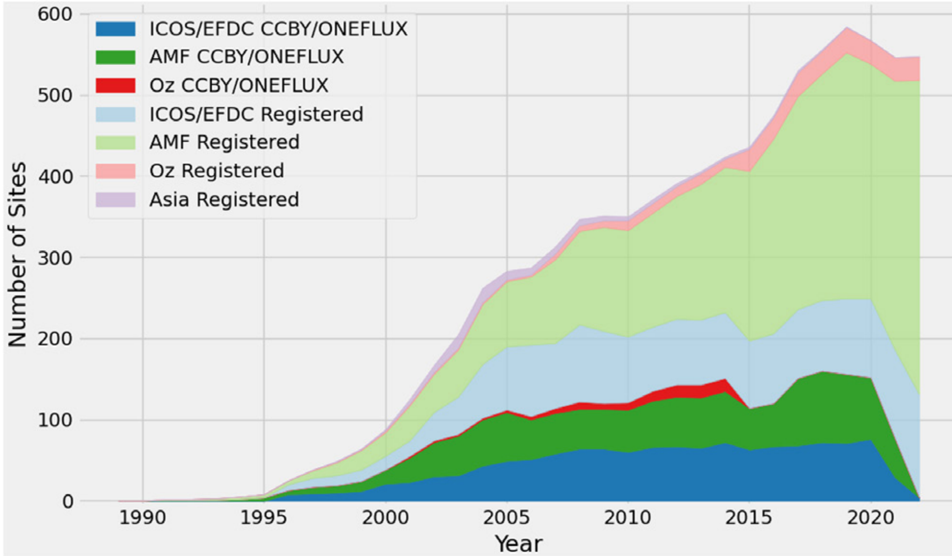

Fig. 1. **Overview of the current expanse of the network, both in terms of sites registered with either the European Fluxes Database Cluster or AmeriFlux (registered sites), as well as data that are registered *and* fully released using the ONEFlux (FLUXNET) processing chain and a CC BY 4.0 license (CC BY/ONEFlux).**

impact ecosystem functioning. Long-term data are also particularly critical for quantifying the success of nature-based climate solutions alterations (Hemes et al. 2021; Novick et al. 2022). Maintaining the operational status of flux towers with multidecadal time series is therefore an important goal for future FLUXNET work.

FLUXNET road map and goals

Data processing and distribution. One of the largest recognized needs and goals for the FLUXNET community is the development and adoption of standardized data processing across all regional network data providers. Standardization of variable naming, variable units, QA/QC procedures, u-star (friction velocity) filtering, gap-filling protocols, and partitioning protocols will enable more comparison studies from regional to global scales, and expand the scientific potential of eddy covariance data. The latest and largest collection of globally standardized EC data is the FLUXNET2015 dataset (Pastorello et al. 2020). These data were processed using the open-source code package ONEFlux. Since then, AmeriFlux and ICOS have continued to release datasets processed with the ONEFlux pipeline, and AsiaFlux and OzFlux have plans to incorporate ONEFlux processing [M. Kang (2023, personal communication) on AsiaFlux plans; P. Isaac (2023, personal communication) on OzFlux plans] in addition to alternative processing approaches.

Since standardized processing chains are vital for global synthesis studies, ONEFlux continues to be modified for use across a wider range of ecosystems and applications. For example, OzFlux has historically used PyFluxPro for data processing (Isaac et al. 2017), which accommodates the extreme climatological conditions at some OzFlux sites. Furthermore, new approaches for quality control, flux partitioning, and additional postprocessing are constantly being developed to produce improved and innovative applications for eddy covariance data (https://fluxnet.org/2017/10/10/toolbox-a-rolling-list-of-softwarepackages-for-flux-related-data-processing/). Going forward, the community strives to grow the available standardized datasets while facilitating further innovation.

Another major FLUXNET goal is making data sharing easier and more timely through a globally agreed upon processing pipeline and distribution infrastructure. Currently, outside of the FLUXNET2015 dataset, data are shared across various regional platforms with different hosting methods and often delayed availability. FLUXNET needs to work toward a formal data sharing infrastructure that will promote timely delivery of standardized data. A possibility for this type of infrastructure was highlighted in Papale (2020). This infrastructure proposal includes the global adoption of ONEFlux processing software to achieve data standardization regardless of regional network. Users could then use a database query functionality to download current existing data from one or more regional networks.

As FLUXNET develops this data sharing infrastructure, it must overcome adoption barriers and incentivize global data sharing. Historically, dedicated funding from ICOS and AmeriFlux has stabilized long-term sites and increased openly shared datasets, but that has led to a global eddy covariance data bias toward North America and Europe. We need to leverage the success of existing network infrastructures to support smaller regional networks. Another means of incentivizing global data sharing will be to promote proper data citation to give PIs appropriate credit for their data using licensing under a CC BY 4.0 data usage license [Attribution 4.0 International (CC BY 4.0); https://creativecommons.org/licenses/by/4.0/].

Education, outreach, and community building. FLUXNET's future priorities include a strong emphasis on education, outreach, and community building, and regional networks host regular training events with both in-person and remote options. Fluxcourse is a 2-week-long in-person workshop where participants from all over the world come together in Niwot Ridge to learn fundamentals and applications of eddy covariance measurements. Scholarships for Fluxcourse participants enable an international representation, but while Fluxcourse has hosted more than 350 participants from every continent (except Antarctica) and has forged enduring professional ties between participants, the in-person nature of the course has practical restrictions on the number of people that can attend. To allow the benefits of Fluxcourse education to more scientists, FLUXNET is working on packaging and disseminating existing Fluxcourse educational materials (https://fluxnet.org/fluxcourse_educational_materials/). To further enhance accessibility, FLUXNET community members have begun an initiative to translate Fluxcourse materials into other languages, starting with Spanish.

Community building is a fundamental necessity of future FLUXNET goals. The successful development, adoption, and execution of standardized data processing and data sharing infrastructure will depend on strong community relationships within and across regional networks. The FCC itself serves as a community-building entity by building professional relationships between FCC members, and thereby facilitating communication across regional networks. The Secondment and workshop initiatives build community, particularly among early career scientists, which supports the next generation of FLUXNET leaders. In addition to strengthening existing networks, FLUXNET aims to increase outreach beyond the traditional flux scientist community. This outreach will begin with a pilot artist-residency program, where artists are paired with flux towers and supported to create multimedia art inspired by flux science (recently funded by supplemental funding to the 2020 NSF AccelNet grant to FLUXNET).

Distributing physical/financial/expertise resources from overstudied areas to understudied areas. FLUXNET faces uneven challenges across different countries, especially in low- and medium-income nations. These challenges are educational, financial, and technical. Educational issues include language barriers, limited access to scholarships, training, and outreach facilities. Financially, these countries struggle with maintaining long-term sites, staffing, minimal maintenance funding, and higher costs for third-party equipment. While financially maintaining eddy flux sites is difficult regardless of site location, sites in low- and medium- income countries typically face steeper challenges. Technically, the people operating these sites also face difficulties in instrument replacement and factory calibration, as well as accessing remote sites. While these challenges are significant and difficult to address, there are opportunities for

FLUXNET to help. For example, recent FLUXNET efforts have focused on releasing Fluxcourse educational materials online, and translating these materials (starting with Spanish). Fluxcourse continues to provide international scholarships to increase the diversity of attendees, and the recent NSF grant has allowed more scholarships than before.

Supporting the next generation of flux scientists. The FLUXNET Early Career Network (ECN), comprising 377 early career flux scientists from 57 countries, focuses on supporting the global flux community. The network, mainly consisting of graduate students (56.5%), postdocs (26%), and independent researchers (18%), is active in raising FLUXNET awareness and data use through webinars, workshops, and mentorship programs. However, to enhance its impact, the ECN needs more support for participation in meetings and training in program management. Cross-cultural mentorship by FLUXNET's senior members is essential for building a more cohesive global team and strengthening leadership. Although the FLUXNET Coordination Project supports ECN travel, current funding is U.S.-centric, limiting global reach. Expanding funding sources is vital for enabling broader global collaboration.

Conclusions

The FLUXNET meeting in Brno showcased the vibrant, collaborative nature of the FLUXNET community which has been the cornerstone of its success. Further deepening and expanding the community's connections and willingness to collaborate and share data will ensure that FLUXNET data continue to be used to answer critically important questions about ecosystem functioning in the face of climate change. FLUXNET data will continue to be important for remote sensing integration and model development, and new opportunities such as informing carbon markets will ensure that FLUXNET data remains crucial for scientific and policy endeavors. The establishment and success of the FLUXNET Community Council will enhance cross-regional collaboration and ultimately strengthen the global network.

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