Agricultural and Forest Meteorology 249 (2018) 444–456

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

The AmeriFlux network: A coalition of the willing

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ARTICLE INFO

Keywords:
Eddy covariance
Network science
Climate change
Carbon cycle
Water cycle
Big data
Environmental observation networks

ABSTRACT

AmeriFlux scientists were early adopters of a network-enabled approach to ecosystem science that continues to transform the study of land-atmosphere interactions. In the 20 years since its formation, AmeriFlux has grown to include more than 260 flux tower sites in the Americas that support continuous observation of ecosystem carbon, water, and energy fluxes. Many of these sites are co-located within a similar climate regime, and more than 50 have data records that exceed 10 years in length. In this prospective assessment of AmeriFlux's strengths in a new era of network-enabled ecosystem science, we discuss how the longevity and spatial distribution of AmeriFlux data make them exceptionally well suited for disentangling ecosystem response to slowly evolving changes in climate and land-cover, and to rare events like droughts and biological disturbances. More recently, flux towers have also been integrated into environmental observation networks that have broader scientific goals; in North America these include the National Ecological Observatory Network (NEON), Critical Zone Observatory network (CZO), and Long-Term Ecological Research network (LTER). AmeriFlux stands apart from these other networks in its reliance on voluntary participation of individual sites, which receive funding from diverse sources to pursue a wide, transdisciplinary array of research topics. This diffuse, grassroots approach fosters methodological and theoretical innovation, but also challenges network-level data synthesis and data sharing to the network. While AmeriFlux has had strong ties to other regional flux networks and FLUXNET, better integration with networks like NEON, CZO and LTER provides opportunities for new types of cooperation and synergies that could strengthen the scientific output of all these networks.

1. Introduction and overview

Ecosystem science is being transformed by the proliferation of environmental observation networks, which aggregate observations from a large number of biomes, often for long time-periods, and make these data widely available (Baldocchi, 2008; Jones et al., 2010; Peters et al., 2008). Rapid advances in instrument design and cyber-infrastructure have advanced network-enabled approaches by fostering data sharing and reuse through centralized repositories (Hampton et al., 2013; Peters et al., 2014; Rundel et al., 2009). Network-enabled approaches produce generalizable environmental knowledge through integration of distributed observations. This shift towards network science has been motivated by an increasingly complex set of socio-ecological questions – often related to the interactions between humans, ecosystems, and the global climate system – that necessitate synthesis of information from many biomes and at policy- and management-relevant scales (Jones et al., 2010; Schimel, 2011).

Scientists who study land-atmosphere interactions, and in particular those who focus on the biosphere-atmosphere exchange of CO_2 and water, have been at the forefront of this shift towards network-enabled approaches (Baldocchi, 2008). How much CO_2 ecosystems remove from the atmosphere each year, and how much water they use in the process, are critical questions guiding our understanding of trends in climate and water resources (Booth et al., 2012; Friedlingstein et al., 2014; Jung et al., 2010). These ecosystem carbon and water fluxes are sensitive to slowly evolving processes, including ongoing climate change and recovery from disturbance, which frequently occur at large spatial scales. These processes are difficult to study using short-term manipulative experiments, single-factor gradient studies, and other traditional tools of inquiry in the ecological and environmental sciences.

In response to this research challenge, the AmeriFlux network of carbon and water flux tower sites was formed more than 20 years ago

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http://dx.doi.org/10.1016/j.agrformet.2017.10.009
Received 24 May 2017; Received in revised form 11 September 2017; Accepted 8 October 2017
Available online 23 October 2017
0168-1923/

by a pioneering group of scientists who were separately monitoring these fluxes at individual sites and site-clusters. At the same time, other, continental- and international flux tower networks were initiated, including FLUXNET (Baldocchi et al., 2001) and EuroFlux (Aubinet et al., 1999), with others soon to follow (e.g. Oz-flux and Asia-Flux, Beringer et al., 2016; Mizoguchi et al., 2009). Written as AmeriFlux celebrates its 20th anniversary, this paper focuses on science that leverages AmeriFlux observations, while also recognizing present and potential synergies between AmeriFlux and its sister flux networks around the globe.

The individual field sites of AmeriFlux are organized around eddy-covariance flux towers, which support the continuous monitoring of the net ecosystem exchange of CO_2 (NEE), evapotranspiration (ET), and other land-atmosphere fluxes (Baldocchi, 2003; Goulden et al., 1996). Since AmeriFlux was formed, eddy covariance flux towers have also become an important part of other environmental observation networks, including three networks of the National Science Foundation (NSF): the National Ecological Observation Network (NEON, Schimel et al., 2007), the Critical Zone Observatory network (CZO, White et al., 2015), and Long-Term Ecological Research Network (LTER, Hobbie et al., 2003). The missions of NEON, CZO and LTER are supportive of, but not exclusively focused on, understanding land-atmosphere interactions.

While AmeriFlux, NEON, CZO, and LTER all support flux tower measurements, they differ substantially in operational aspects, including research scope, spatial and temporal representativeness of the data, and degree of operational standardization (Table 1). Perhaps the most significant distinction among the networks is their degree of centralization of site activities. AmeriFlux's approach has been described as a "coalition of the willing": tower principal investigators (PIs) receive funding from diverse sources in support of diverse questions, and most data are shared voluntarily to the network (Fig. 1). At the other end of the spectrum is NEON, which has a highly centralized, top-down approach to instrumentation and measurements; this design allows for data to be collected in the same way everywhere, to foster intra- network synthesis, and is not tailored to site-specific questions. LTER and CZO lie between these two extremes; sites in both networks receive their base funding from a centralized source (NSF) and have mandates to collect and share certain types of data as a result. However, specific research questions and methods are PI-driven and linked to the ecological, geological, and topographical context of each site (Hobbie et al., 2003; Richter and Billings, 2015).

A principle objective of this paper is to offer a prospective assessment of the research questions and knowledge gaps that are well matched to the unique operational characteristics of the AmeriFlux network, in the context of the attributes of the other networks. We will also identify some challenges associated with AmeriFlux's grass-roots, bottom-up approach to network science, and the potential to address these challenges through cross-network integration and synergies. Here, we do not provide a thorough review of all the significant knowledge advances already enabled by AmeriFlux and the other networks; those success stories are well described elsewhere (Baldocchi, 2008; Knapp et al., 2012; Law, 2005; Richter and Billings, 2015). Rather, the retrospective sections of this manuscript are focused on identifying the broad research questions that have historically been well-matched to AmeriFlux's operational approach.

To meet our objectives, we will first compare and contrast the scope, size, and organization of the major environmental networks in North America that support flux towers (Section 2), with a particular focus on highlighting the unique attributes of AmeriFlux. In Section 3, we will review the range of scientific inquiry that has been historically supported by AmeriFlux's unique approach to network-enabled science. In Section 4, we will explore the likely future research directions for AmeriFlux scientists. Finally, in Section 5, we review some of the challenges associated with AmeriFlux's approach to network activity, and highlight ways in which those challenges can be overcome through synergies with other networks.

Table 1
Key Network Characteristics.

Network	# of sites	# of sites sharing flux data via central repository	Average length of flux records (years)	# of sites with 10 + years of flux data	Instruments and data processing	Mechanism for site selection	Scope of research questions at the site level
AmeriFlux	> 260	170	7.2	47	Varies by site, some centralized post-processing	Any site may join provided a core set of variables are measured	Diverse site-level questions determined by PIs.
NEON	47	None yet; expected to come online in 2017	< 1	0	Highly centralized and standardized	Sites chosen centrally; no additional sites expected.	To be determined by data end-users
LTER	25	34 towers from 10 LTER sites	7.8	12	Varies by site, no centralized processing	Competitive proposals	Hypothesis-driven research questions chosen by site PIs, but with required inquiry into 'core' research themes.
CZO	9 core, > 20 affiliated	7	7.2	0	Varies by site, no centralized processing	Competitive proposals	Site-level questions driven by PIs, but aligned with overall goals of the CZO network.