The AmeriFlux Network: A Coalition of the Willing

K.A. Novick[1,*], J.A. Biederman[2], A.R. Desai[3], M.E. Litvak[4], D.J.P. Moore[5], R.L. Scott[2], M.S. Torn[6]

[1]School of Public and Environmental Affairs, Indiana University – Bloomington
[2] Southwest Watershed Research Center, United States Agricultural Department, Agricultural Research Service, 2000 E Allen Road,
Tucson, AZ 85719 USA.
[3] University of Wisconsin-Madison, Department of Atmospheric and Oceanic Sciences, Madison, WI, United States
[4] Department of Biology, University of New Mexico, Albuquerque, NM 87131, USA
[5]School of Natural Resources, University of Arizona, Tucson, AZ, USA
[6] Climate and Ecosystem Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California, USA

Keywords: eddy covariance, network science, climate change, carbon cycle, water cycle, big data, environmental observation networks

[*]Corresponding author: Kim Novick, knovick@indiana.edu, 812.855.3010

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.

Section 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 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 (Figure 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; 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.

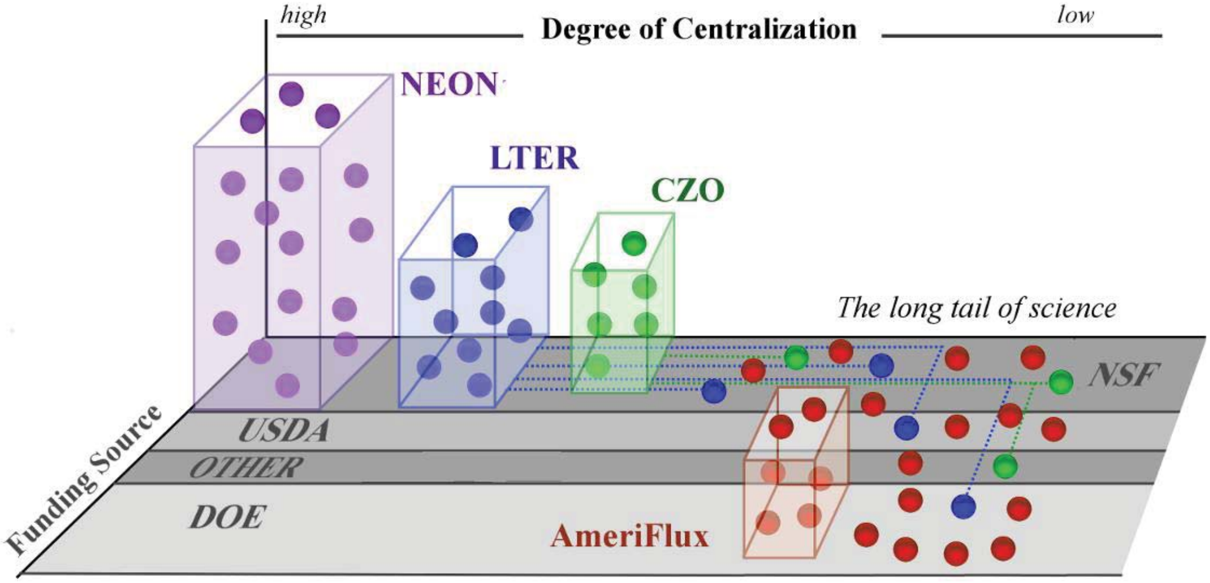


Figure 1: A conceptual illustration of funding sources and organizational approach of the networks considered here, focusing specifically on their flux towers. The spheres represent individual tower sites; those that are contained in boxes represent towers that are funded directly by the network, while those residing outside of boxes leverage funding from a non-centralized source. On one end of the spectrum resides NEON, a network with sites that are funded and maintained exclusively by a central governing body. On the other end the spectrum is AmeriFlux, a distributed network of PI-managed towers largely funded by relatively small grants or allocations from a diverse range of sources. LTER and CZO lie in between – while support for network sites is centralized, site-specific research activities are PI-driven and often leverage funding from other, non-network sources.

Section 2: Comparing and contrasting the flux tower networks. This section focuses on highlighting the key similarities and differences among the flux tower networks operating in North America, with a goal of identifying AmeriFlux's most distinctive operational attributes.

2.1: AmeriFlux's grassroots approach to measuring carbon and water fluxes. Established in 1996, AmeriFlux is a PI-driven 'coalition' of more than 260 registered tower sites, with approximately 170 having shared data to the network at the time of this writing. The domain covers North, South, and Central America, but most sites are located in North America. AmeriFlux relies on a bottom-up organizational approach: PIs establish and maintain sites to answer a diverse set of research questions, but willingly share data in support of broader community efforts to understand, predict, and manage the global carbon cycle. Although funding for individual tower sites comes from a range of sources (Figure 1), the US Department of Energy (US-DOE) has historically invested heavily in centralized support for data quality control, archiving, processing, and distribution (Boden et al., 2013), as well as annual meetings. Since 2013, US-DOE has organized its financial support for the network under the umbrella of the 'AmeriFlux Management Project' (AMP).

The primary objectives of the AMP are to (1) maximize the quality of AmeriFlux data and its usability by a broad community; (2) expand the network's impact as a field laboratory for basic research and Earth System Model (ESM) improvement; (3) foster innovative measurements; and (4) sustain and extend the long-term record of carbon, water and energy fluxes being collected by a cohort of AmeriFlux 'core' sites, (approximately 17% of all sites in the network). AmeriFlux sites are non-standardized with respect to their instrumentation and site-level data processing, though the AMP is actively working to infuse a standardized approach into network-level data organization, post-processing, and quality control. AMP also continues longstanding US-DOE support for a portable eddy covariance system (PECS; Billesbach et al., 2004; Schmidt et al., 2012) that is deployed to 8 to 12 sites per year to compare flux and meteorological measurements, and evaluate calibration protocols and safety practices.

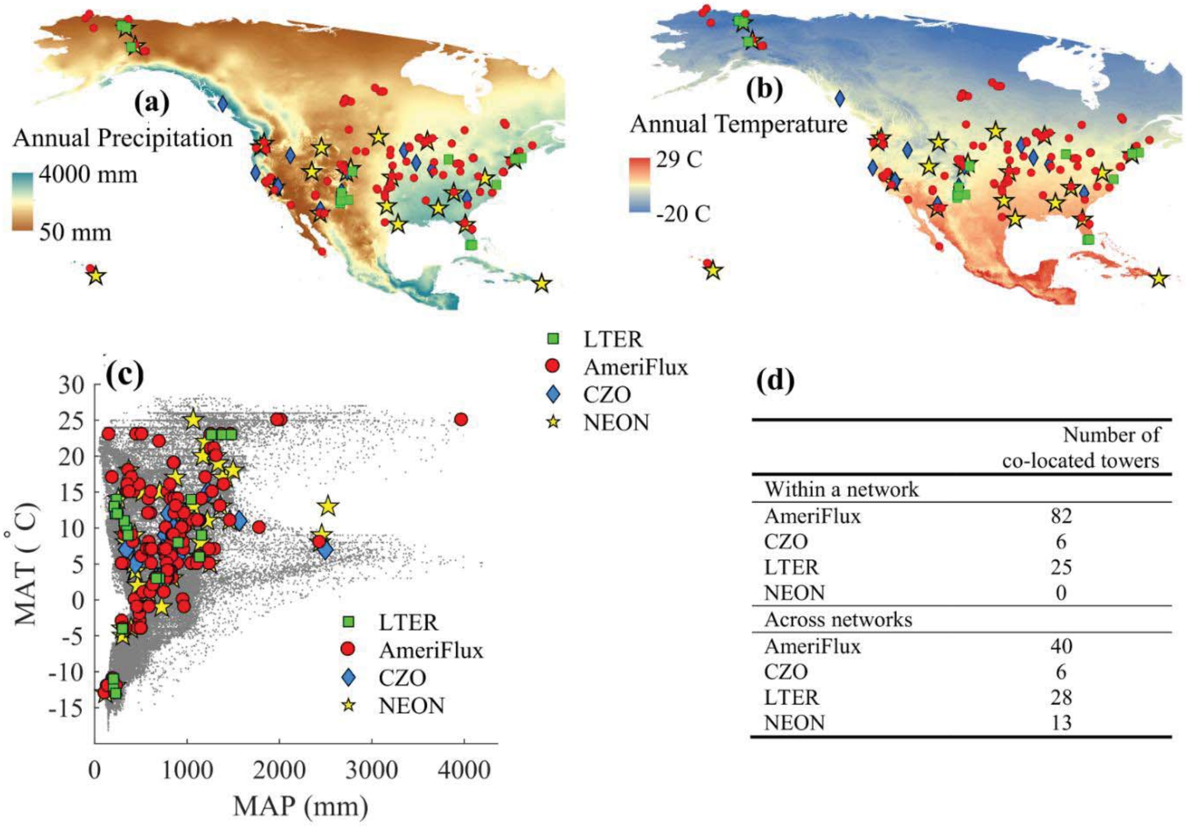
2.2: Systematic sampling with NEON. NEON aims to be a continental-scale ecological network supporting the study of interactions and feedbacks among a complex suite of ecological processes and drivers (Schimel et al., 2007). This network sustains a -coordinated array of 'terrestrial' monitoring sites (incl. EC flux, *n* = 47) and 'aquatic' sites (no EC flux, *n* = 34), alongside in-situ sample collections and airborne remote sensing. NEON terrestrial EC flux sites are classified as "core" (*n* = 20, expected 30-year study period) or "relocatable" (*n = 27*, expected 5- to 10-year study period), and were selected to maximize the network's representativeness of the large gradients in land cover and climate in the study domain (Keller et al., 2008). Flux towers are an important component of the sampling design of the terrestrial sites, where information about soil biophysics and plant phenology, productivity, and species composition will also be routinely collected. In contrast to AmeriFlux, a central technical and governing body manages all sampling, and data are highly standardized. At the mid-point of 2017, turbulent and storage flux data were being collected at many NEON sites, with corresponding data products at four processing levels intended to come online throughout 2017.

2.3: Studying slowly-evolving processes through the Long-Term Ecological Research Network (LTER). NSF's LTER network is the oldest of the four considered here, initiated in 1982 to support research into ecological processes that evolve over long time scales (Franklin et al., 1990; Hobbie et al., 2003). It has grown to include 25 sites representing diverse biomes in the US, the Caribbean, and Antarctica, with new sites added occasionally through a competitive process tailored for a specific biome. Because the LTER program places strong emphasis on context-dependent, hypotheses-driven research questions developed by site-level teams, it can be described as "bottom-up." In contrast to AmeriFlux, however, all LTER funding comes from a single source (NSF), and sites must collect and share data pertaining to one or more of five core research areas. Cross-site collaboration has been a focus of LTER since its inception (Johnson et al. 2010) and is facilitated through a centralized "data portal" and competitive funding for synthesis projects. A portion of LTER sites support eddy covariance measurements, with decisions about instrumentation and data processing are made by the site PIs.

2.4: A common approach to integrating hydrology, geology, and ecology through Critical Zone Observatories (CZOs). The Critical Zone refers to earth's thin outer shell, extending from the bedrock, through aquifers and soils, and upwards to the top of vegetative canopies (Richter and Billings, 2015). Within the last decade, an international network of observatories has been established to study mass and energy flows in the Critical Zone, and to understand their relevance for economic and environmental goods and services (White et al., 2015). NSF funds nine individual sites in the continental US and Puerto Rico, and an additional ~20 sites have registered as CZO affiliates in North America (White et al. 2015). Like LTER, CZO is "bottom-up" in that site-level work is led by cross-disciplinary teams studying links between geological and surface processes that are unique to each site. The site-specific research questions and observations all fall under an umbrella of a shared conceptual framework and a common set of measurements, including flux tower observations (Chorover et al., 2012). Decisions about measurement approach and technique are decentralized and site-specific, but data are shared to a centralized repository.

2.5: Spatial and temporal representativeness of flux towers. AmeriFlux sites are not efficiently distributed to achieve representativeness. Their sheer number, however, spans wide gradients in climate conditions and vegetation communities and affords rich multi-site design (Figure 2). For example, many sites are part of smaller site-clusters that are co-located in similar macro-climate environments (~30 km, Figure 2) but are distributed across a range of land cover and edaphic conditions (Anderson-Teixeira et al., 2011; Novick et al., 2015; Scott et al., 2015). These site-clusters thus allow for investigation of how, for example, land management, hydrologic conditions, or disturbance affect ecosystem fluxes and processes. In contrast, there are 47 planned NEON sites, 34 LTER-affiliated flux towers, and 9 flux-tower CZO sites. By design, NEON sites are distributed to represent the range of bio-climate conditions in North America (Figure 2), and no two NEON sites are co-located to within 30 km of each other. LTER and CZO-affiliated tower sites are smaller in number and represent fewer climate regimes. AmeriFlux is also distinguished by the longevity of its data records. While the average length of tower data records is 7 to 8 years for AmeriFlux, CZO, and LTER (Table 2), AmeriFlux includes more than 50 sites with datasets exceeding 10 years in length – far more than any other network.

There is significant overlap in the spatial representatives of the networks (Figure 2). Many of the 34 LTER towers are also registered in the AmeriFlux network, and some of these dual-affiliation AmeriFlux-LTER towers are located adjacent to new NEON tower sites, including at Harvard Forest (Goulden et al., 1996), Konza Prairie (Nippert et al., 2011) , and the Niwot Ridge alpine zone (Turnipseed et al., 2002).



	Number of co-located towers
Within a network	
AmeriFlux	82
CZO	6
LTER	25
NEON	0
Across networks	
AmeriFlux	40
CZO	6
LTER	28
NEON	13

Figure 2: The location of various network flux towers on a background of mean annual precipitation (panel a), mean annual temperature (b), and the MAP-MAT phase plane (c). The AmeriFlux sites are limited to those that have submitted data to the network. The analysis is also limited to the core CZO sites, excluding CZO "affiliated" sites that do not necessarily host flux towers. LTER sites are limited to those that share flux tower data with the LTER network. Panel d shows the number of network sites co-located to within 30 km of at least one other tower, within and across networks. The maps are restricted to North America, where the majority of AmeriFlux sites is located.

In addition, a new network, the Long-Term Agro-ecosystem Research (LTAR), initiated by the USDA Agricultural Research Service, was recently established to investigate the effects of management on agro-ecosystems (Walbridge and Shafer, 2011). Some of the 23 LTAR network sites already host AmeriFlux-affiliated towers, and plans to instrument many others could significantly increase the richness of agro-ecosystems in the AmeriFlux database. Similarly, new towers are being established in Canada and Alaska as part of the NASA-supported Arctic-Boreal Vulnerability Experiment (ABoVE). Because the operational approach and cyber-infrastructure of these newer networks are still largely under development, they are not a focus of this manuscript, though we recognize the potential for future synergies between AmeriFlux and these new network initiatives.

Section 3: Leveraging the strengths of AmeriFlux. In this section, we discuss challenging research questions that have historically been well matched to AmeriFlux's unique attributes, which include spatial representativeness and site clustering, long data records, and the diversity of research questions that fuel the activities of individual sites.

3.1: Characterizing the interannual variability in carbon and water fluxes . Long-term flux data records are full of surprises, often revealed only after many years of data collection. For example, in the long-running Morgan-Monroe State Forest AmeriFlux site, estimates of the annual net ecosystem exchange of CO_2 (or NEE) were relatively constant for the first 5 years of data record (between -300 and -350 g C m^{-2} year, Figure 3a). Unexpectedly, carbon uptake increased considerably for the second five years (e.g., NEE became more negative, between -375 and -400 g C m^{-2}), driven in part by longer growing seasons (Dragoni et al., 2011). Thereafter, the size of the carbon sink was noticeably reduced, driven in part by a coincident increase in aridity (Brzostek et al., 2014) and a severe drought event in 2012 (Roman et al., 2015).

In fact, most flux records are characterized by significant interannual variability (IAV) of carbon and water-vapor exchange (see Figure 3b-d, Desai, 2010; Hui et al., 2003; Yuan et al., 2009; Zscheischler et al., 2016). This high degree of IAV underscores the need for long-term flux monitoring, as estimates of flux magnitudes and IAV can be biased when based on only a few years of data (Figure 3). In many sites, flux records must reach timescales of decades (or longer) in order to adequately sample the IAV of relevant meteorological drivers (Chu et al., 2017). Many AmeriFlux site data records are now sufficiently long to characterize the statistics of flux IAV and to characterize and quantify its drivers.

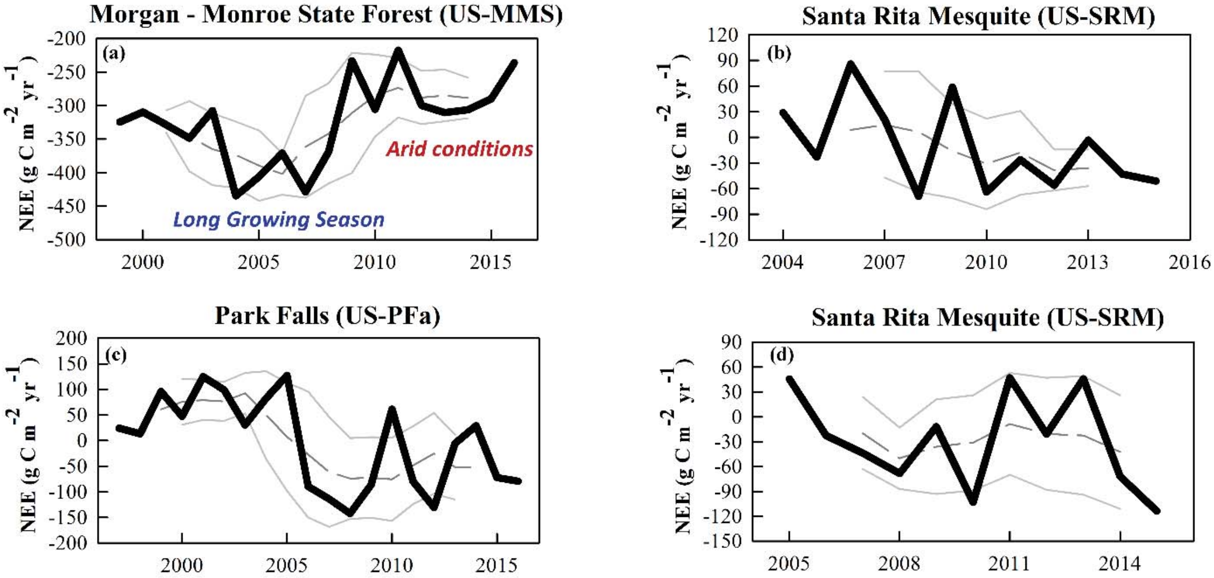


Figure 3: Annual NEE from several long-running AmeriFlux core sites. The thick black line shows the annual data. The dashed gray line shows the 5-year moving average, and the thin gray lines show the 5-year moving standard deviation.

3.2: Detecting the influence of extreme events on ecosystem fluxes: Because AmeriFlux records are long, they contain many unusual events including droughts, floods, wildfires, and insect outbreaks. For example, roughly half of AmeriFlux sites experienced at least one severe spring or summer drought month, defined as a Palmer Drought Severity Index (PSDI, Alley 1984) value less than -3. A quarter of sites have experienced multiple years with at least one drought month (Figure 4). AmeriFlux data collected during these events have already been used to study (1) differential drought impacts on gross primary productivity (GPP) and respiration (Schwalm et al., 2010; Schwalm et al., 2012), (2) interactions between early season phenology and later season drought (Wolf et al., 2016), (3) plant response to drying soil as compared to drying air (Novick et al., 2016a; Rigden and Salvucci, 2017), and (4) ecosystem response to exogenous structural disturbances like insect outbreaks and logging (Amiro et al., 2010).

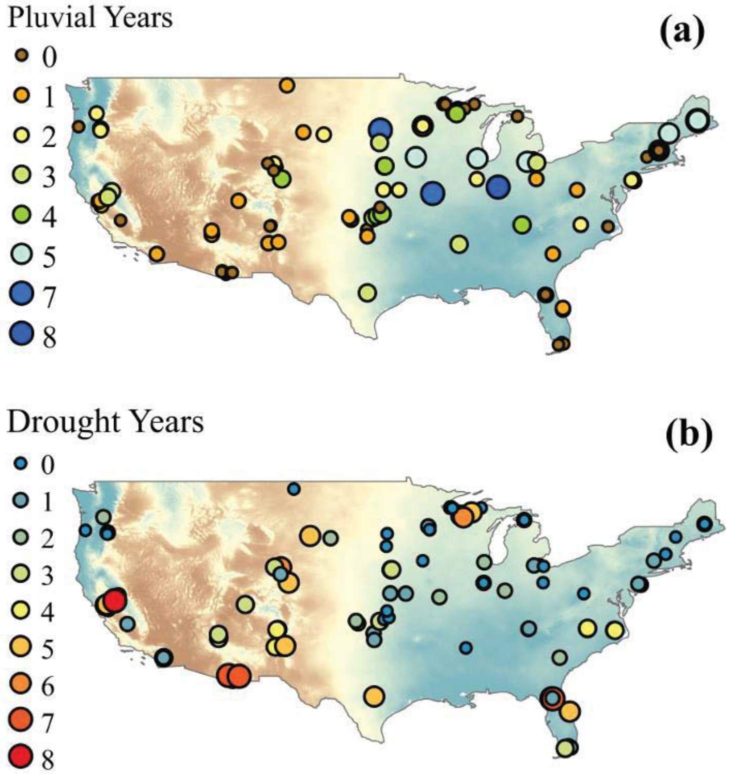


Figure 4 : *Panel a shows the number of pluvial years in AmeriFlux records from the continental United States, where a pluvial years includes at least one growing season month of PDSI>3. Panel b shows the number of drought years at each site, defined as a year with at least one growing season month of PDSI< -3. Background map is mean annual precipitation.*

Future efforts to understanding the flux consequences of rare or extreme events will benefit from a long-term perspective made possible by AmeriFlux's long time series. Changes to canopy structure or plant function by extreme events may produce legacy effects that persist for years, but these effects can only be quantified if data characterizing pre- and post-event conditions are available (Amiro et al., 2006; Anderegg et al., 2015; Chen et al., 2006; Moore et al., 2013; Scott et al., 2010; Shen et al., 2016). Furthermore, multiple extreme events may occur during the same time period, obscuring the impact of each individual event in the absence of a long-term record. For example, in 2012 much of the Midwestern U.S. was affected not only by severe drought but also by a very early start to the growing season (Roman et al., 2015; Wolf et al., 2016). Thus, while the 2012 annual NEE in many drought-affected sites was not particularly anomalous, comparing the drought year fluxes to those recorded in non-drought years allowed for the effects of the early growing season and drought event to be separately quantified (Roman et al., 2015).

3.3: Disentangling land cover effects from climate effects. Because AmeriFlux is a relatively dense network (Figure 2), many sites occupy similar climate envelopes, and approximately 30% of AmeriFlux sites are co-located to within 30 km of at least one other tower site (Figure 2d). Consequently, it is possible to subsample from the AmeriFlux database to form site-clusters that experience similar climate conditions but different land cover, enabling the disentangling of effects of climate and vegetation on fluxes. As an early example of the site-cluster approach, the Boreal Ecosystem-Atmosphere Study (BOREAS) project relied on a series of intensive field campaigns to assess the carbon sink strength of boreal ecosystems of different burn ages and vegetation cover (Sellers et al. 1997). Since then, AmeriFlux site-clusters have been used to evaluate effects of climate and disturbance history on NEE (Law et al., 2004), assess theoretical predictions for the carbon uptake potential of mature forests (Novick et al., 2015; Stoy et al., 2008), and quantify the influence of site-level factors in determining GPP and ET in semi-arid (Biederman et al., 2016) and temperate (Desai et al., 2008a) biomes. Additionally, the Forest Accelerated Succession Experiment (FASET) at the University of Michigan Biological Station used deliberate landscape-scale manipulation within a tower footprint to bridge the gap between observational and experimental approaches for understanding land-atmosphere interactions (Gough et al., 2013).

3.4: Benchmarking models and remote-sensing products. AmeriFlux has a long history of validating remote-sensing products and informing and benchmarking land surface models for plant productivity, water use, and other ecosystem processes (Huntzinger et al., 2012; Levis et al., 2012; Running et al., 2004; Stöckli et al., 2008). Although the spatial resolution of ESMs is much larger than that of eddy covariance tower footprints, AmeriFlux sites broadly sample from the plant functional types represented by models. Thus, network data can be used to characterize rate controls and climate dependencies of CO_2 and water fluxes in different plant communities, providing the means to redress problems with current models and develop new modeling approaches (Huntzinger et al., 2012; Luo et al. 2012). These efforts benefitted from methods to estimate the uncertainties in flux observations (Hollinger et al., 2004; Richardson et al., 2006), a pre-requisite for data-model fusion studies. Additionally, recent advances in scaling methods allow better rectification of tower footprints to model grid cells (Xiao et al. 2011; Xu et al., 2017), and guide the number of sites needed to accurately capture net flux for a given uncertainty (Hill et al., 2017).

Similarly, AmeriFlux data have played an important role in evaluating reanalysis and gridded meteorology products (Decker et al., 2012), downscaling climate model output to local regions (Vuichard and Papale, 2015), and benchmarking the ever-evolving suite of remotely-sensed information on vegetation distribution and function (Nishida et al., 2003; Xiao et al., 2008). Recent advances in detection of plant solar-induced fluorescence (SIF) for mapping plant stress and photosynthesis (Frankenberg et al., 2014; Verma et al., 2017; Yang et al., 2015), hyperspectral visible-to near-IR imaging for mapping of foliar traits and chemistry (Serbin et al., 2015), and detection of moisture variation from satellite platforms (e.g. SMAP, Jones et al. *in press*, and ECOSTRESS, Fisher et al., 2017) all suggest a rich era of future satellite missions that will require a robust ground network like AmeriFlux. Complimenting these efforts, many AmeriFlux sites have installed ancillary sensors to detect ecosystem-scale properties that are linked to satellite observations (including Phenocam cameras, Brown et al., 2016, and COSMOS soil moisture sensors, Zreda et al., 2012).

3.5: Advancing the theory and practice of eddy covariance measurements. By allowing for a diversity of measurement approaches, across a wide range of environmental and infrastructure conditions, AmeriFlux has been a source of innovation in instrumentation and measurement approaches, and continues to act as a testbed as new instruments and processing methods become available. For example, data from many AmeriFlux sites have been useful for understanding instrument-related biases, including tube effects in closed-path analyzers (Burba et al., 2011; Hollinger et al., 1999; Novick et al., 2013; Su et al., 2004), self-heating effects in open path gas analyzers (Burba et al., 2008), and the influence of sonic anemometer orientation on the measurement of vertical wind speed (Frank et al., 2016; Van der Molen et al., 2004). AmeriFlux scientists have also played a critical role in developing approaches to correct for instrument biases and processing procedures, for example by applying spectral corrections (Hollinger et al., 1999; Massman, 2000; Massman, 2001), selecting an appropriate coordinate rotation scheme (Lee et al., 2005; Wilczak et al., 2001), and averaging and detrending eddy covariance time series (Moncrieff et al., 2005).

3.6: Scientific community building . AmeriFlux's grassroots, community-oriented approach to network-enabled science enables interactions across sites, disciplines, and career stages. Because individual sites must choose to opt-in to AmeriFlux, affiliation reflects each PI's recognition of the value of the community enterprise. PIs share technical know-how to elevate the standards of other sites, share their data with a specific goal of advancing science beyond their site-level questions, and pursue broader management- and policy-oriented scientific aims that are best achieved through network-enabled approaches. Historically, AmeriFlux's collaborative data use policy has fostered the development of synthesis products by large collaborative teams (Amiro et al., 2010; Richardson et al., 2012; Xiao et al., 2011). These teams foster inter-personal relationships that benefit other network activities requiring voluntary participation from community members, such as the annual AmeriFlux meetings, technical workshops focused on sharing best practices, coordination of meetings with the U.S. Global Change Research Program's "North American Carbon Program", PECS site visits, active list serves, and AmeriFlux sponsorship of Flux Course (www.fluxcourse.org). Flux Course is a two-week workshop for early career scientists, with many AmeriFlux scientists serving as guest instructors. For early career scientists in particular, network collaboration has many benefits, including increased publication rates, greater visibility, opportunities for extra-institutional mentorship, and the chance to learn best practices for publication and grant writing (Goring et al., 2014). Informal collaborations promoted by interactions at AmeriFlux workshops, PI meetings, and the Flux Course can also lay foundations for future, more formal operational collaborations (Hara et al., 2003; Lewis et al., 2012).

Section 4: Looking forward – Emerging research areas for AmeriFlux scientists.

In this section, we turn to the likely avenues of future research to be conducted by AmeriFlux scientists, again drawing connections between the scope of the research and the network's unique operational characteristics. Towards this end, we performed a keyword analysis on abstracts from more than 60 active grants funded by the US Department of Energy, NSF, USDA, and/or NASA. Projects were initially screened for their mention of keywords like "eddy covariance," "AmeriFlux," "flux tower(s)", and "ecosystem fluxes." Projects were retained in the analysis if it was clear from the abstract that the investigators planned to use AmeriFlux data in project activities, or planned to generate new observations from flux tower sites in North, Central our Latin America. It was not clear whether all of these towers were already registered AmeriFlux sites, though they are all eligible to register with AmeriFlux (i.e. they represent current or potential AmeriFlux sites). After the 60+ abstracts were compiled, they were searched for a wide range of keywords. Those that appeared in at least three (or 5%) of the abstracts are included in Table 2.

4.1: An enduring focus on carbon cycling. The words "carbon" or "CO_2" appeared in nearly 90% of project abstracts, suggesting that AmeriFlux scientists will continue to leverage network data to reduce uncertainty in the global carbon cycle. As AmeriFlux data records continue to grow, richer sets of information will be available to close remaining gaps in our understanding of current and future ecosystem carbon cycling (Friedlingstein et al., 2014), and inform more confident fingerprinting of trends in the fluxes driven by ongoing climate change. The large number of studies that include a modeling focus (85%), remotely sensed data (37%), and evapotranspiration (27%) suggest that understanding of carbon and water cycling at regional and continental scales remains a research priority for the community.

Relatedly, AmeriFlux scientists are poised to advance new methodological approaches for leveraging flux tower data to quantify GPP at landscape and regional scales, moving beyond traditional approaches based on fusing tower data with simple process-based models (Lasslop et al., 2010; Reichstein et al., 2005; van Gorsel et al., 2009). For example, four of the projects surveyed in Table 2 include a focus on GPP estimates derived from SIF. Flux towers provide a platform for near-surface SIF measurements, as well as independent estimates of GPP against which to benchmark SIF observations from towers and satellites (Frankenberg et al., 2014; Yang et al., 2015). Several other active projects include a focus on carbonyl sulfide (COS), which is a "sulfur-containing analogue of CO_2" (Asaf et al., 2013) that can be taken up by plants and thereby serve as a proxy for GPP (Campbell et al., 2015; Seibt et al., 2010). This approach is particularly well suited for testing at flux tower sites, because COS flux can be measured directly using the eddy covariance technique (Billesbach et al., 2014; Wehr et al., 2017).

Table 2: Results from active grant keyword search (n = 61 active projects)

Search term	**Number of grants**	**Percent of grants**
carbon or CO_2	53	0.88
model, models or modeling	51	0.85
remote sensing	22	0.37
management	19	0.32
evapotranspiration	16	0.27
energy balance, energy cycling	14	0.23
tropics, tropical	12	0.20
drought	11	0.18
GPP	11	0.18
disturbance	10	0.17
economic	10	0.17
land cover, land use	10	0.17
agriculture	7	0.12
hydrology	7	0.12
arctic	6	0.10
belowground	5	0.08
methane	5	0.08

physiology	5	0.08
fluorescence or SIF	4	0.07
blue carbon	3	0.05
carbonyl Sulfide (COS or OCS)	3	0.05
nitrous oxide	3	0.05

4.2: An emerging focus on land management. The phrases “land management” and “agricultural systems” were mentioned in a significant number of project abstracts (32% and 12% of projects, respectively), positioning AmeriFlux scientists to better constrain our understanding of how human land use impacts biogeochemical and hydrologic cycling (Bohrer et al., 2015). Numerous AmeriFlux research groups have already demonstrated the usefulness of aggregating flux data from management-oriented site-clusters to investigate carbon cycle impacts of tilling, irrigation, and winter cover crops in the Corn Belt (Baker and Griffis, 2005; Verma et al., 2005), thinning and harvesting in US forests (Clark et al., 2004; Law et al., 2003), and landscape-scale shifts in land use and management regimes (Runkle et al., 2017; Stoy et al., 2008). Moving forward, the newly formed USDA-ARS LTAR network, which includes several AmeriFlux-affiliated towers, may play a critical role in elucidating links between agricultural management and land-atmosphere interactions.

4.3: Energy balance – moving beyond the closure problem. Approximately 14% of the studies in Table 2 made explicit mention of “energy balance” in the project abstract. Energy balance closure (or the lack thereof) in flux tower data has been a subject of investigation since the inception of AmeriFlux (Baldocchi and Vogel, 1996, Wilson et al. 2002). Generalized solutions continuet to remain elusive (Foken et al., 2008; Stoy et al., 2013), and thus will undoubtedly persist as a focus for future research. Nonetheless, despite these methodological challenges, flux tower data are increasingly being used to understand how biophysical mechanisms directly alter energy balance and local temperature. For example, Juang et al. (2007) demonstrated that, in the temperate zone, surface temperature is lower over an evergreen and deciduous forest when compared to an adjacent grassland site, due principally to higher evapotranspiration and sensible heat flux in the forests. In contrast, Lee et al. (2011) demonstrated that in boreal ecosystems, surface temperature tends to be warmer over forested sites compared to nearby grasslands, due to the strong radiative effects of low forest albedo in wintertime when open areas are snow-covered. Using data from two savannah ecosystems, Baldocchi and Ma (2013) explored interactions between land cover, surface and air temperature, and seasonality. These research foci are well-aligned with an emerging recognition of the potential for land management schemes to mitigate climate change not only through their effect on carbon uptake, but also through direct effects on local hydrology and surface temperature (Ellison et al., 2017).

4.4: Other greenhouse gases. A small but significant fraction of active grant proposals are explicitly focused on measuring fluxes of non-CO_2 greenhouse gases like methane (8% of studies) and nitrous oxide (5% of studies), enabled by rapid advancements in gas analyzer technology and data analysis (McDermitt et al., 2011; Detto et al., 2011; Mammarella et al., 2010). As the number of sites reporting these gas fluxes continues to grow, network-enabled approaches for understanding CO_2 and H_2O fluxes will be applied to better understand and predict the dynamics of the biosphere-atmosphere exchange.

Section 5: Challenges associated with a grassroots approach to network science, and opportunities for cross-network syntheses and synergies.

Our discussion thus far has highlighted how AmeriFlux's 20 year history of PI-driven network science positions the network to continue addressing pressing knowledge gaps in our understanding of carbon and water cycle science. However, AmeriFlux's "bottom-up approach" also presents significant challenges to network operations and syntheses (see Table 3). In this section, we discuss these challenges in more detail and highlight ways they could be addressed through cross-network synergies that would benefit all relevant networks, allowing them to fully capitalize on the potential of network-enabled ecosystem science to generate scalable, generalizable information for mitigating and managing environmental change.

***Table 3**: Strengths and weaknesses of AmeriFlux's bottom-up approach*

Feature of Approach	**Associated Strengths**	**Associated Weaknesses**
Voluntary, PI-driven research; inclusive approach to network participation	Diverse research questions; interdisciplinarity; strong sense of community	Lack of incentives for data sharing. Insecurity of funding for many sites.
	Good spatial and temporal representativeness of many biome types.	Underrepresentation of some biomes.
Lack of standardization of instrumentation and processing	Flexibility in methodological approach can advance observation theory.	Biases related to instrument design and processing can challenge cross-site syntheses.
"collaborative' data policy	Promotes cross-disciplinary perspectives; strengthens interpersonal connections within the network; promotes incentive for PIs to submit data	Large, multi-author papers are sometimes challenging to write, presenting a disincentive for network end-users.
Network oriented around a relatively few core observations (i.e. fluxes and meteorological drivers)	Few required variables makes it easier for sites to join the network	Inconsistent submission of non-biometeorological data across sites, which when present provides important ecological context for the fluxes, and guides model development.

5.1: Cross-site syntheses of non-standardized data . Integrating and synthesizing non-standardized data represents a challenge for many environmental fields that are adopting network-enabled approaches (Peters et al., 2014). In the case of AmeriFlux, and perhaps because eddy covariance methodology evolved in concert with the use of eddy covariance data in a network setting, methodological biases in flux observations have been exceptionally well studied. As discussed in subsection 3.5, these biases have many sources, including the instruments, post-processing of high-frequency data, and the approach for detecting and gapfilling half-hourly observations collected during periods of low turbulence when turbulent fluxes are not representative of ecosystem fluxes. Efforts to partition measured NEE into its principal components – GPP and ecosystem respiration – are further sensitive to the choice of partitioning approach (Lasslop et al., 2010; Reichstein et al., 2005; van Gorsel et al., 2009).

Fortunately, observations from the AmeriFlux PECS have revealed that biases due to site-level instrumentation and flux processing decisions tend to be small (on the order of ~8% for CO_2 fluxes, 5% for H_2O fluxes, and 2% for sensible heat fluxes, Schmidt et al., 2012). Similarly, biases due to the choice of gapfilling and partitioning approaches are also on the order of 5 to 10% (Desai et al., 2008b). Moreover, biases due to instrumentation or processing choice are usually not in the same direction and may be partially cancelled through cross-site syntheses. Furthermore, post-processing approaches to gapfilling and partitioning are becoming increasingly standardized, due to the recent release of the FLUXNET2015 data product (Pastorello et al. 2017), and available to the community as R-codes or online tools (e.g. Reddyproc, Reichstein and Moffat, 2014). A particularly important feature of the FLUXNET2015 product is its focus on quantifying the uncertainty in flux estimates linked to the choice of gapfilling and partitioning. Moving forward, calculating these uncertainties will become the purview of regional networks like AmeriFlux; access to these post-processing results should motivate sites to join, or continue submitting data to, AmeriFlux, and offer expanded opportunities for cross-network integration.

Despite challenges to cross-site syntheses and inter-site comparisons, the flexible, non-standardized measurement approaches adopted by AmeriFlux and LTER permits PIs to choose the instruments that are best suited for conditions at their site. Open-path gas analyzers, for example, may be a good choice for solar-powered installations because they use less power than closed-path analyzers, but would be a poor choice in humid or polluted environments where fog or dust frequently cloud the optical path. Similarly, post-processing approaches designed to minimize the contribution of advection to the flux records (e.g. van Gorsel et al. 2009) may be a particularly good choice in areas of complex terrain, where advection from cold-air drainage frequently dominates nocturnal flux regimes (Novick et al. 2016b). Thus, networks relying on a highly standardized approach to observation and processing are also exposed to measurement bias, with a greater likelihood that the bias errors will be in the same direction.

. . Ample opportunities also exist to coordinate standardization of flux data processing across networks, with many efforts already well underway. NEON is already generating a new level of harmonization and standardization of flux tower methodology which will be of significant benefit to AmeriFlux scientists. For example, open-source eddy covariance codes are being developed by NEON for broad application (Metzger et al., in press). At the same time, continued efforts to evaluate uncertainty in flux records linked to the choice of instrumentation and data processing will be difficult using NEONs centralized design, but should continue to be a hallmark of AmeriFlux's PI-driven approach. Indeed, AmeriFlux scientists have been at the forefront of reviewing NEON sensor design and protocols through leadership in NEON's Technical Working Groups (TWGs) and Science, Technology, & Educational Advisory Committee (STEAC).

5.2: Rewards and incentives for voluntary data sharing . Much of the science conducted by AmeriFlux investigators occurs in the so-called "long tail of science" (Heidorn, 2008, Figure 1), where projects are relatively small in size and scope, and are funded through diverse mechanisms. With the exception of AmeriFlux Core Sites, which are contractually obligated to supply data to the network in a timely fashion, most AmeriFlux sites have no data sharing mandate. Undoubtedly, many AmeriFlux scientists shared data altruistically. In addition, the benefits of AmeriFlux's collaborative approach to data sharing and community building, addressed in detail in subsection 3.6, have also historically served as important incentives for data sharing. Nonetheless, nearly 90 projects registered as AmeriFlux sites have yet to upload flux data records (Table 1), Furthermore, the number of sites contributing data to the network appears to have decreased in recent years (Figure 5), even as the number of sites has continued to grow. Curators of the FLUXNET2015 data product have noted difficulty in encouraging scientists to submit data of the necessary quality (Chu et al., 2017).

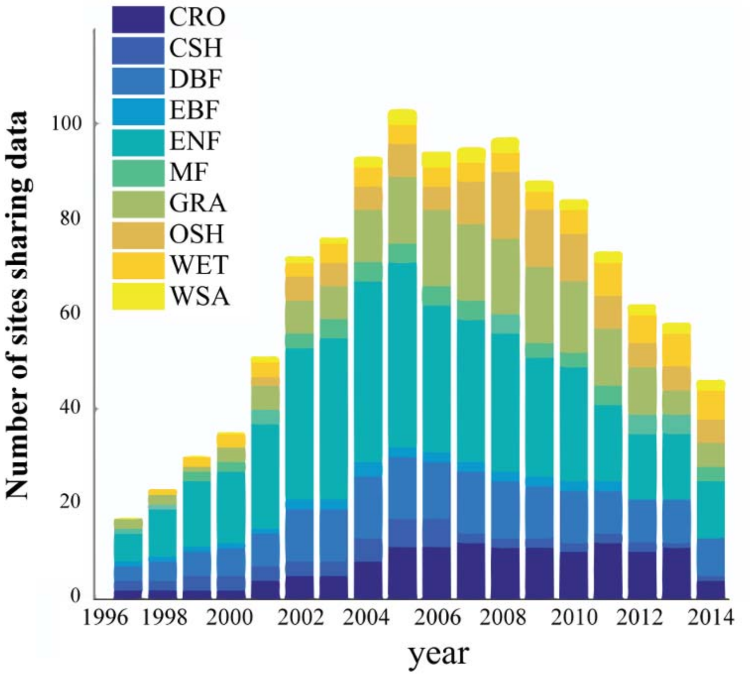


Figure 5: *AmeriFlux data availability, organized by plant functional type and year of collection. Abbreviations are: CRO = cropland, CSH = closed shrubland, DBH = deciduous broadleaf forest, EBF = evergreen broadleaf forest, ENF = evergreen needleleaf forest, MF = mixed forest, GRA = grassland, OSH = open shrubland, WET = wetland, WSA = woody savannah.*

The difficulty of extracting data from the long-tail of science -- generated by multiple projects run by individual PIs – challenges network-enabled approaches across many fields of environmental science and ecology (Goring et al., 2014; Hampton et al., 2013; Reichman et al., 2011). However, in the case of AmeriFlux, which relies on voluntary participation, the problem is a particularly important one to solve. Many obstacles to data sharing are not technological but rather sociological (Reichman et al., 2011), and include: (1) fear of losing “rights” to one’s data, (2) concerns that others will misinterpret observations, and (3) a dearth of metrics in formal evaluations of scientific success that reflect the time required to prepare and curate shared datasets (Goring et al. 2014; Hampton et al., 2013; Reichman et al., 2011). Strategies to overcome these obstacles include institutionalizing evaluation metrics that better reward data sharing and team-based collaboration (Goring et al., 2014), and the publication of peer-reviewed datasets with digital object identifier (DOI) numbers (Reichman et al., 2011), which AmeriFlux has recently adopted. Putting recommendations like these into practice would be to the benefit of all the networks discussed here, and represents a significant synergistic opportunity.

5.3: Flux towers as integrated ecosystem research sites . As we move past AmeriFlux's 20-year milestone, we have the opportunity to consider the controls of carbon, water and energy balance over decades with more data – and more rigor. The genesis of the eddy covariance technique is in biometeorology, and much of the question-oriented research emerging from the network has focused on linking patterns in whole ecosystem fluxes to meteorological conditions at seasonal and interannual timescales (as reviewed in Baldocchi et al. 2008). These studies are useful for diagnosing sensitivities of land-atmosphere exchanges to ongoing climate and land use change and are requisite, but not sufficient, for constructing a mechanistic understanding of the processes that control ecosystem energy, carbon, and water cycling.

These processes are driven by ecosystem components operating at scales much smaller than a tower footprint. For example, GPP integrates a cellular level processes (photosynthesis) that typically occurs across multiple species and/or canopy layers, and is linked to whole-plant hydraulic function. Similarly, ecosystem respiration reflects both autotrophic and heterotrophic contributions occurring through multiple layers of the vegetative canopy and the soil. Because these individual components may respond differently to climate change and other biophysical forcings, understanding the relative contribution of each component to the stand-level fluxes is necessary to understand how ecosystems will respond to environmental change.

Experiments and non-biometeorological measurements can be leveraged to fill in gaps in our mechanistic understanding of ecosystem fluxes. For example, soil and tissue respiration measurements can help to constraint estimates of the differential contribution of autotrophic and heterotrophic respiration to ecosystem respiration (Zobitz et al., 2008; Maurer et al., 2016; Phillips et al. 2017, Ryan et al., 1997; Zha et al., 2007), particularly when they are conducted within experimental root exculsions or other manipulations. Similarly, leaf- and tree-level eco-physiological measurements, including observations of leaf gas exchange, sap flux, and xylem vulnerability, can be leveraged to understand how carbon uptake and water loss differ between species, in different canopy positions, or for plants of different age and height (Roman et al. 2015, Oishi et al. 2008, Fisher et al. 2007, Irvine et al. 2004). Eddy covariance records can be augmented and extended at even longer timescales by repeated censuses of forest ecosystems and metrics of inter-annual variability in growth derived from tree rings (Babst et al., 2014, Dye et al. 2016, Montane et al., in press). Linking fluxes to the canopy composition, age, and structure is particularly important for understanding flux sensitivity to processes like succession, disturbance recovery, and management regimes shifts, which can drive large changes in species composition and stand structure over timescales much longer than the lifespan of a typical flux tower.

Process-level studies at AmeriFlux sites, where results can be upscaled and compared to the whole-ecosystem exchange of carbon, water and energy, provides an advantage for those seeking to improve terrestrial ecosystem models or use these models as integrating tools (Wang et al. 2017). Non-biometeorological observations can be integrated with tower fluxes through “data assimilation,” which refers to the process of directly informing model states or parameters with observations (Zobitz et al., 2011). Virtually all recent advances in weather forecasting have been driven by improved assimilation of observations in meteorological models (Kalnay, 2003), and a similar revolution is underway in ecosystem modeling (Braswell et al 2005; Moorcroft, 2006: Moore et al 2008; Dietze et al., 2014; Dietze, 2017). Model-data fusion techniques can be used to compare the information contained in measurements collected at different spatial scales, including eddy covariance, soil respiration, leaf area index, litterfall, and woody biomass data (Richardson et al., 2010, Keenan et al. 2013). Data assimilation is also useful for testing mechanistic hypotheses by altering the model structure (Sacks et al., 2006; Zobitz et al., 2008), illustrating one pathway by which network-supported observations datasets can be used to answer hypothesis-oriented research questions which have historically dominated ecological fields of inquiry.

5.4: Education and training . As the number of AmeriFlux sites has grown, the community of AmeriFlux data end users has also expanded from a relative small group of specialists to a broad group of scientists including biometeorologists, ecosystem scientists, hydrologists, microbial ecologists, soil scientists, remote sensing scientists and Earth system modelers. Many current users of the data have not visited an AmeriFlux site in person, and may be unfamiliar with the sources of uncertainty and bias in flux records that are well known to scientists who collect the data firsthand. This gap in expertise between data providers and data users, which will also likely challenge NEON, represents an additional constraint on the utility of cross-site syntheses; for example, it is not uncommon to see tower-derived estimates of GPP referred to as ‘observations’ in the literature, even though they are largely modeled products.

To help bridge this gap, the AmeriFlux community has invested in educational workshops and training opportunities focused on core principles of flux tower data generation and end use. Chief among these is “Flux Course”, described in subsection 3.6, which should be viewed as a useful training resource for scientists using flux observations from all the networks. NEON is also beginning to sponsor workshops to provide scientists with the skills needed to conduct cross-site syntheses, including events focused on data from their airborne platform. Similarly, LTER’s All-Scientists Meeting, held every 2 to 3 years, features many community-driven working groups focused on within- and cross-network synergies that should be of utility and interest to AmeriFlux scientists.

Figure 6 *Flux Course students engage in peer-learning about the basics of eddy covariance instrumentation. Photo by Edward Swiatek.*

Section 6: Conclusion. AmeriFlux scientists were early adopters of a network-enabled approach to studying land-atmosphere interactions, and have a 20-year history of leveraging biosphere-atmosphere flux observations to understand the mechanistic controls on local- to continental-scale carbon and water cycling. More recently, flux tower observations have become an important component of NEON, CZO and LTER network activities; in this paper, we assessed past and future research activities which are particularly well suited for AmeriFlux's unique approach to network science. The length of AmeriFlux records make them especially useful for investigating the causes of interannual flux variability and for fingerprinting the effects of extreme events. The spatial representativeness of AmeriFlux sites, including the existence of many co-located "site-clusters," should motivate continued efforts to use AmeriFlux data to disentangle climate versus vegetative controls on ecosystem function, and to benchmark ESMs. AmeriFlux's bottom-up operational approach positions AmeriFlux scientists to continue to lead the development of novel methodologies, and merge flux tower and biometric data at the site level to investigate a host of multi-disciplinary research questions. Challenges for AmeriFlux related to data standardization, data sharing, and the merging of ecosystem-scale flux observations with leaf-, tree- and plot-scale biometric data persist. Ample opportunities exist to address these challenge via cross-network synergies that would benefit of all networks supporting flux tower observations to inform understanding of, and solutions for, environmental challenges at policy- and management-relevant scales.

Acknowledgements: The authors would like to thank the AmeriFlux PIs for sharing their data to the network, noting that most do so voluntarily. The authors acknowledge support from the AmeriFlux Management Project, administered by Lawrence Berkeley National Laboratory through the US Department of Energy, Office of Science, under contract number DE-AC02-05CH11231. K. Novick acknowledges support from the NSF Division of Environmental Biology (through grant DEB 1552747). A. Desai acknowledges support from NSF Division of Biological Infrastructure Advances in Biological Informatics (through grant DBI-1457897 and DBI-1062204), and thanks Elisabeth Andrews for editing a previous draft of the manuscript.

Bibliography

Alley, W.M., 1984. The Palmer drought severity index: limitations and assumptions. Journal of Climate and Applied Meteorology, 23:1100-1109.

Amiro, B. Barr, A.G., Black, T.A., Iwashita, H., Kljun, N., McCaughey, J.H., Morgenstern, K., Murayama, S., Nesic, Z., Orchansky, A.L., and Saigusa, N., 2006. Carbon, energy and water fluxes at mature and disturbed forest sites, Saskatchewan, Canada. Agricultural and Forest Meteorology, 136: 237-251.

Amiro, B.D., Barr, A.G., Barr, J.G., Black, T.A., Bracho, R., Brown, M., Chen, J., Clark, K.L, Davis, K.J., Desai, A.R., Dore, S., Engel, V., Fuentes, J.D., Goldstein, A.H., Goulden, M.L., Kolb, T.E., Lavigne, M.B., Law, B.E., Margolis, H.A., Martin, T., McCaughey, J.H., Misson, L., Montes-Helu, M., Noormets, A., Randerson, J.T., Starr, G., and Xiao, J., 2010. Ecosystem carbon dioxide fluxes after disturbance in forests of North America. Journal of Geophysical Research-Biogeosciences, 115: G00K02, doi:10.1029/2010JG001390.

Anderegg, W.R., Schwalm, C., Biondi, F., Camarero, J.J., Koch, G., Litvak, M., Ogle, K., Shaw, J.D., Shevliakova, E., Williams, A.P., Wolf, A., Ziaco, E., and Pacala, S., 2015. Pervasive drought legacies in forest ecosystems and their implications for carbon cycle models. Science, 349: 528-532.

Anderson-Teixeira, K.J., Delong, J.P., Fox, A.M., Brese, D.A. and Litvak, M.E., 2011. Differential responses of production and respiration to temperature and moisture drive the carbon balance across a climatic gradient in New Mexico. Global Change Biology, 17: 410-424.

Asaf, D., Rotenber, E., Tatarinov, F., Dicken, U., Montzka, S.A., and Yakir, D., 2013. Ecosystem photosynthesis inferred from measurements of carbonyl sulphide flux. Nature Geoscience, 6: 186-190.

Aubinet, M., Grelle, A., Ibrom, A., Rannik, Ü., Moncrieff, J., Foken, T., Kowalski, A.S., Martin, P.H., Berbigier, P., Bernhofer, C., Clement, R., Elber, J., Granier, A., Grünwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R., and Vesala, T., 1999. Estimates of the annual net carbon and water exchange of forests: the EUROFLUX methodology. Advances in Ecological Research, 30: 113-175.

Babst, F., Alexander, M.R., Szejner, P., Bouriaud, O., Klesse, S., Roden, J., Ciais, P., Poulter, B., Frank, D., Moore, D.J. and Trouet, V., 2014. A tree-ring perspective on the terrestrial carbon cycle. Oecologia, 176: 307-322.

Baker, J. and Griffis, T., 2005. Examining strategies to improve the carbon balance of corn/soybean agriculture using eddy covariance and mass balance techniques. Agricultural and Forest Meteorology, 128: 163-177.

Baldocchi, D., 2008. Breathing of the terrestrial biosphere: lessons learned from a global network of carbon dioxide flux measurement systems. Australian Journal of Botany, 56: 1-26.

Baldocchi, D., Falge, E., Gu, L., Olson, R., Hollinger, D., Running, S., Anthoni, P., Bernhofer, C., Davis, K., Evans, R. Fuentes, J., Goldstein, A., Katul, G., Law, B.E., Lee, X., Malhi, Y., Meyers, T.P., Munge,r W., Oechel, W., Paw U., K.T., Pilegaard, K., Schmid, H.P., Valentini, R., Verma, S., Vesala, T., Wilson, K., and Wofsy, S., 2001. FLUXNET: A new tool to study the temporal and spatial variability of ecosystem–scale carbon dioxide, water vapor, and energy flux densities. Bulletin of the American Meteorological Society, 82: 2415-2434.

Baldocchi, D. and Ma, S.Y., 2013. How will land use affect air temperature in the surface boundary layer? Lessons learned from a comparative study on the energy balance of an oak savanna and annual grassland in California, USA. Tellus Series B-Chemical and Physical Meteorology, 65: 19994.

Baldocchi, D.D., 2003. Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. Global Change Biology, 9: 479-492.

Baldocchi, D.D. and Vogel, C.A., 1996. Energy and CO~ 2 flux densities above and below a temperate broad-leaved forest and a boreal pine forest. Tree Physiology, 16: 5-16.

Barry, R., 1970. A framework for climatological research with particular reference to scale concepts. Transactions of the Institute of British Geographers, 49: 61-70.

Beringer, J., Hutley, L.B., McHugh, I., Arndt, S.K., Campbell, D., Cleugh, H.A., Cleverly, J., Resco de Dios, V., Eamus, D., Evans, B., Ewenz, C., Grace, P., Griebel, A., Haverd, V., Hinko-Najera, N., Huete, A., Isaac, P., Kanniah, K., Leuning, R., Liddell, M.J., Macfarlane, C., Meyer, W., Moore, C., Pendall, E., Phillips, A., Phillips, R.L., Prober, S.M., Restrepo-Coupe, N., Rutledge, S., Schroder, I., Silberstein, R., Southall, R., Yee, M.S., van Gorsel, E., Vote, C., Walker, J., and Wardlaw, T., 2016. An introduction to the Australian and New Zealand flux tower network– OzFlux. Biogeosciences, 13: 5895-5916.

Biederman, J.A., Scott, R.L., Goulden, M.L., Vargas, R., Litvak, M.E., Kolb, T.E., Yepez, E.A., Oechel, W.C., Blanken, P.D., Bell, T.W., Garatuza-Payan, J., Mauerer, G.E., Dore, S., and Burns, S.P., 2016. Terrestrial carbon balance in a drier world: the effects of water availability in southwestern North America. Global Change Biology, 22: 1867-1879.

Billesbach, D.P., Berry, J.A., Seibt, U., Maseyk, K., Torn, M.S., Fischer, M.L., Abu-Naser, M. and Campbell, J.E., 2014. Growing season eddy covariance measurements of carbonyl sulfide and CO_2 fluxes: COS and CO_2 relationships in Southern Great Plains winter wheat. Agricultural and Forest Meteorology, 184: 48-55.

Billesbach, D., Fischer, M., Torn, M. and Berry, J., 2004. A portable eddy covariance system for the measurement of ecosystem–atmosphere exchange of CO2, water vapor, and energy. Journal of Atmospheric and Oceanic Technology, 21: 639-650.

Boden, T.A., Krassovski, M. and Yang, B., 2013. The AmeriFlux data activity and data system: an evolving collection of data management techniques, tools, products and services. Geoscientific Instrumentation, Methods and Data Systems, 2: 165-176.

Bohrer, G., Gu., L., Gurney, K., Law, B., McFadden, J., Noormets, A., Pardyjak, E., Poindexter, C., Stoll, R., and Torn, M.S., 2015. An AmeriFlux network perspective on urban and managed systems, AmeriFlux Management Project, U.S. DOE BERAC Workshop on the potential Integrated Field Laboratory (IFL). Available online at: http://ameriflux.lbl.gov/resources/reports/

Booth, B.B., Jones, C.D., Collins, M., Totterdell, I.J., Cox, P.M., Sitch, S., Huntingford, C., Betts, R.A., Harris, G.R. and Lloyd, J., 2012. High sensitivity of future global warming to land carbon cycle processes. Environmental Research Letters., 7: 024002.

Braswell, B. H., Sacks, W. J., Linder, E., and Schimel, D. S., 2005. Estimating diurnal to annual ecosystem parameters by synthesis of a carbon flux model with eddy covariance net ecosystem exchange observations. Global Change Biology, 11: 335-355.

Brown, T.B., Hultine, K.R., Steltzer, H., Denny, E.G., Denslow, M.W., Granados, J., Henderson, S., Moore, D., Nagai, S., SanClements, M. and Sánchez-Azofeifa, A., 2016. Using phenocams to monitor our changing Earth: toward a global phenocam network. Frontiers in Ecology and the Environment, 14: 84-93.

Brzostek, E.R., Dragoni, D., Schmid, H.P., Rahman, A.F., Sims, D., Wayson, C.A., Johnson, D.J. and Phillips, R.P., 2014. Chronic water stress reduces tree growth and the carbon sink of deciduous hardwood forests. Global Change Biology, 20: 2531-2539.

Burba, G.G., McDermitt, D.K., Anderson, D.J., Furtaw, M.D. and Eckles, R.D., 2011. Novel design of an enclosed CO(2)/H(2)O gas analyser for eddy covariance flux measurements. Tellus Series B-Chemical and Physical Meteorology, 62: 743-748.

Burba, G.G., McDermitt, D.K., Grelle, A., Anderson, D.J. and Xu, L.K., 2008. Addressing the influence of instrument surface heat exchange on the measurements of CO(2) flux from open-path gas analyzers. Global Change Biology, 14: 1854-1876.

Campbell, J.E., Whelan, M.E., Seibt, U., Smith, S.J., Berry, J.A. and Hilton, T.W., 2015. Atmospheric carbonyl sulfide sources from anthropogenic activity: Implications for carbon cycle constraints. Geophysical Research Letters, 42: 3004-3010.

Carpenter, S. R., & Turner, M. G., 2000. Hares and tortoises: interactions of fast and slow variables in ecosystems. Ecosystems, 3: 495-497.

Chen, H., Tian, H., Liu, M. and Melillo, J., 2006. Effect of land-cover change on terrestrial carbon dynamics in the southern United States. Journal of Environmental Quality, 35: 1533-1547.

Chorover, J., Scatena, F.N., White, T., Anderson, S., Aufdenkampe, A.K., Bales, R.C., Brantley, S.L., and Tucker, G., 2012. Common Critical Zone Observatory (CZO) Infrastructure and Measurements. A Guide Prepared by CZO PIs. Avilable online at http://criticalzone.org/christina/publications/report-proposal/.

Chu, H., Baldocchi, D.D., John, R., Wolf, S. and Reichstein, M., 2017. Fluxes all of the time? A primer on the temporal representativeness of FLUXNET. Journal of Geophysical Research: Biogeosciences, 122: 289-307.

Clark, K.L., Gholz, H.L. and Castro, M.S., 2004. Carbon dynamics along a chronosequence of slash pine plantations in north Florida. Ecological Applications, 14: 1154-1171.

Decker, M., Brunke, M.A., Wang, Z., Sakaguchi, K., Zeng, X. and Bosilovich, M.G., 2012. Evaluation of the reanalysis products from GSFC, NCEP, and ECMWF using flux tower observations. Journal of Climate, 25: 1916-1944.

Desai, A.R., 2010. Climatic and phenological controls on coherent regional interannual variability of carbon dioxide flux in a heterogeneous landscape. Journal of Geophysical Research: Biogeosciences, 115: G00J02.

Desai, A.R., Noormets, A.N., Bolstad, P.V., Chen, J., Cook, B.D., Davis, K.J., Euskirchen, E.S., Gough, C.M., Martin, J.G., Ricciuto, D.M., Schmid, H.P., Tang, J.W. and Wang, W., 2008a. Influence of vegetation and seasonal forcing on carbon dioxide fluxes across the Upper Midwest, USA: Implications for regional scaling. Agricultural and Forest Meteorology, 148: 288-308.

Desai, A.R., Richardson, A.D., Moffat, A.M., Kattge, J., Hollinger, D.Y., Barr, A., Falge, E., Noormets, A., Papale, D., Reichstein, M. and Stauch, V.J., 2008b. Cross-site evaluation of eddy covariance GPP and RE decomposition techniques. Agricultural and Forest Meteorology, 148: 821-838.

Detto, M., Verfaillie, J., Anderson, F., Xu, L. and Baldocchi, D., 2011. Comparing laser-based open-and closed-path gas analyzers to measure methane fluxes using the eddy covariance method. Agricultural and Forest Meteorology, 151: 1312-1324.

Dietze, M., 2017. Ecological Forecasting. Princeton University Press, Princeton, NJ, 288 pp.

Dietze, M.C., Serbin, S.P., Davidson, C., Desai, A.R., Feng, X., Kelly, R., Kooper, R., LeBauer, D., Mantooth, J., McHenry, K. and Wang, D., 2014. A quantitative assessment of a terrestrial biosphere model's data needs across North American biomes. Journal of Geophysical Research: Biogeosciences, 119: 286-300.

Dragoni, D., Schmid, H.P., Wayson, C.A., Potter, H., Grimmond, C.S.B. and Randolph, J.C., 2011. Evidence of increased net ecosystem productivity associated with a longer vegetated season in a deciduous forest in south-central Indiana, USA. Global Change Biology, 17: 886-897.

Dye, A., Barker Plotkin, A., Bishop, D., Pederson, N., Poulter, B. and Hessl, A., 2016. Comparing tree-ring and permanent plot estimates of aboveground net primary production in three eastern US forests. Ecosphere, 7: e01454.

Ellison, D., Morris, C.E., Locatelli, B., Sheil, D., Cohen, J., Murdiyarso, D., Gutierrez, V., Van Noordwijk, M., Creed, I.F., Pokorny, J., Gaveau, D., Spracklen, D.V., Tobella, A.B., Ilstedt, U., Teuling, A.J., Gebrehiwot, S.G., Sands, D.C., Muys, B., Verbist, B., Springgay, E., Sugandi, Y., and Sullivan, C.A., 2017. Trees, forests and water: Cool insights for a hot world. Global Environmental Change, 43: 51-61.

Fisher, J.B., Melton, F., Middleton, E., Hain, C., Anderson, M., Allen, R., McCabe, M.F., Hook, S., Baldocchi, D., Townsend, P.A. Kilic, A., Tu, K., Miralles, D.D., Perret, J., Lagouarde, J.-P., Waliser, D., Purdy, A.J., French, A., Schimel, D., Famigliette, J.S., Stephens, G., and Wood, E.F., 2017. The Future of Evapotranspiration: Global requirements for ecosystem functioning, carbon and climate feedbacks, agricultural management, and water resources. Water Resources Research, 53, doi:10.1002/2016WR020175.

Foken, T., 2008. The energy balance closure problem: An overview. Ecological Applications, 18: 1351-1367.

Frank, J.M., Massman, W.J., Swiatek, E., Zimmerman, H.A. and Ewers, B.E., 2016. All sonic anemometers need to correct for transducer and structural shadowing in their velocity measurements. Journal of Atmospheric and Oceanic Technology, 33: 149-167.

Frankenberg, C., O'Dell, C., Berry, J., Guanter, L., Joiner, J., Köhler, P., Pollock, R. and Taylor, T.E., 2014. Prospects for chlorophyll fluorescence remote sensing from the Orbiting Carbon Observatory-2. Remote Sensing of Environment, 147: 1-12.

Franklin, J.F., Bledsoe, C.S. and Callahan, J.T., 1990. Contributions of the long-term ecological research program. BioScience, 40: 509-523.

Friedlingstein, P., Meinshausen, M., Arora, V.K., Jones, C.D., Anav, A., Liddicoat, S.K. and Knutti, R., 2014. Uncertainties in CMIP5 climate projections due to carbon cycle feedbacks. Journal of Climate, 27: 511-526.

Goring, S.J., Weathers, K.C., Dodds, W.K., Soranno, P.A., Sweet, L.C., Cheruvelil, K.S., Kominoski, J.S., Rüegg, J., Thorn, A.M. and Utz, R.M., 2014. Improving the culture of interdisciplinary collaboration in ecology by expanding measures of success. Frontiers in Ecology and the Environment, 12: 39-47.

Gough, C.M., Hardiman, B.S., Nave, L.E., Bohrer, G., Maurer, K.D., Vogel, C.S., Nadelhoffer, K.J. and Curtis, P.S., 2013. Sustained carbon uptake and storage following moderate disturbance in a Great Lakes forest. Ecological Applications, 23: 1202-1215.

Goulden, M.L., Munger, J.W., Fan, S.M., Daube, B.C. and Wofsy, S.C., 1996. Measurements of carbon sequestration by long-term eddy covariance: Methods and a critical evaluation of accuracy. Global Change Biology, 2: 169-182.

Hampton, S.E., Strasser, C.A., Tewksbury, J.J., Gram, W.K., Budden, A.E., Batcheller, A.L., Duke, C.S. and Porter, J.H., 2013. Big data and the future of ecology. Frontiers in Ecology and the Environment, 11: 156-162.

Hara, N., Solomon, P., Kim, S.L. and Sonnenwald, D.H., 2003. An emerging view of scientific collaboration: Scientists' perspectives on collaboration and factors that impact collaboration. Journal of the American Society for Information Science and Technology, 54: 952-965.

Heidorn, P.B., 2008. Shedding light on the dark data in the long tail of science. Library Trends, 57: 280-299.

Hill, T., Chocholek, M. and Clement, R., 2017. The case for increasing the statistical power of eddy covariance ecosystem studies: why, where and how? Global Change Biology, 23: 2154–2165.

Hobbie, J.E., Carpenter, S.R., Grimm, N.B., Gosz, J.R. and Seastedt, T.R., 2003. The US long term ecological research program. BioScience, 53: 21-32.

Hollinger, D.Y., Aber, J., Dail, B., Davidson, E.A., Goltz, S.M., Hughes, H., Leclerc, M.Y., Lee, J.T., Richardson, A.D., Rodrigues, C., Scott, N.A., Achuatavarier, D., and Walsh, J., 2004. Spatial and temporal variability in forest-atmosphere CO2 exchange. Global Change Biology, 10: 1689-1706.

Hollinger, D.Y., Goltz, S.M., Davidson, E.A., Lee, J.T., Tu, K. and Valentine, H.T., 1999. Seasonal patterns and environmental control of carbon dioxide and water vapour exchange in an ecotonal boreal forest. Global Change Biology, 5: 891-902.

Hui, D., Luo, Y. and Katul, G., 2003. Partitioning interannual variability in net ecosystem exchange between climatic variability and functional change. Tree physiology, 23: 433-442.

Huntzinger, D.N., Post, W.M., Wei, Y., Michalak, A.M., West, T.O., Jacobson, A.R., Baker, I.T., Chen, J.M., Davis, K.J., Hayes, D.J., Hoffman, F.M., Jain, A.K., Liu, S., McGuire, A.D., Neilson, R.P., Potter, C., Poulter, B., Prince, D., Raczka, B.M., Tian, H.Q., Thornton, P., Tomelleri, E., Viovy, N., Xiao, J., Yuan, W., Zeng, N., Zhao, M., and Cook, R., 2012. North American Carbon Program (NACP) regional interim synthesis: Terrestrial biospheric model intercomparison. Ecological Modelling, 232: 144-157.

Jones, K.B., Bogena, H., Vereecken, H. and Weltzin, J.F., 2010. Design and importance of multi-tiered ecological monitoring networks, Long-Term Ecological Research. Springer, pp. 355-374.

Jones, L., Kimball, J.S., Reichle, R.H., Madani, N., Glassy, J., Ardizzone, J., Colliander, A., Cleverly, J., Desai, A.R., Eamus, D., Euskirchen, E., Hutley, L., MacFarlane , C., and Scott, R., 2017. The SMAP Level 4 Carbon Product for Monitoring Ecosystem Land-Atmosphere CO2 Exchange. IEEE Transactions on Geoscience and Remote Sensing, #TGRS-2016-01206, *in press*. DOI: 10.1109/TGRS.2017.2729343.

Juang, J.Y., Katul, G., Siqueira, M., Stoy, P. and Novick, K., 2007. Separating the effects of albedo from eco-physiological changes on surface temperature along a successional chronosequence in the southeastern United States. Geophysical Research Letters, 34: L21408.

Jung, M., Reichstein, M., Ciais, P., Seneviratne, S.I., Sheffield, J., Goulden, M.L., Bonan, G., Cescatti, A., Chen, J., De Jeu, R., Dolman, A.J., Eugster, W., Gerten, D., Gianelle, D., Gobron, N., Heinke, J., Kimball, J., Law, B.E., Montagnani, L., Mu, Q., Mueller, B., Oleson, K., Papale, D., Richardson, A.D., Roupsard, O., Running, S., Tomelleri, E., Viovy, N., Weber, U., Williams, C., Wood, E., Zaehle, S., and Zhang, K., 2010. Recent decline in the global land evapotranspiration trend due to limited moisture supply. Nature, 467: 951-954.

Kalnay, E., 2003. Atmospheric modeling, data assimilation and predictability. Cambridge University Press.

Keenan, T. F., Davidson, E. A., Munger, J. W. and Richardson, A. D., 2013. Rate my data: quantifying the value of ecological data for the development of models of the terrestrial carbon cycle. Ecological Applications, 23: 273–286.

Keller, M., Schimel, D.S., Hargrove, W.W. and Hoffman, F.M., 2008. A continental strategy for the National Ecological Observatory Network. Frontiers in Ecology and the Environment, 6: 282-284.

Knapp, A.K., Smith, M.D., Hobbie, S.E., Collins, S.L., Fahey, T.J., Hansen, G.J., Landis, D.A., La Pierre, K.J., Melillo, J.M., Seastedt, T.R., Shaver, G.R., and Webster, J., 2012. Past, present, and future roles of long-term experiments in the LTER network. BioScience, 62: 377-389.

Lasslop, G., Reichstein, M., Papale, D., Richardson, A.D., Arneth, A., Barr, A., Stoy, P. and Wohlfahrt, G., 2010. Separation of net ecosystem exchange into assimilation and respiration using a light response curve approach: critical issues and global evaluation. Global Change Biology, 16: 187-208.

Law, B., 2005. Carbon dynamics in response to climate and disturbance: recent progress from multi-scale measurements and modeling in AmeriFlux, Plant Responses to Air Pollution and Global Change. Springer, pp. 205-213.

Law, B.E., Sun, O., Campbell, J., Van Tuyl, S. and Thornton, P., 2003. Changes in carbon storage and fluxes in a chronosequence of ponderosa pine. Global Change Biology, 9: 510-524.

Law, B.E., Turner, D., Campbell, J., Sun, O.J., Van Tuyl, S., Ritts, W.D. and Cohen, W.B., 2004. Disturbance and climate effects on carbon stocks and fluxes across Western Oregon USA. Global Change Biology, 10(9): 1429-1444.

Lee, X., Finnigan, J. and Paw U, K., 2005. Coordinate systems and flux bias error. Handbook of Micrometeorology 29: 33-66.

Lee, X., Goulden, M.L., Hollinger, D.Y., Barr, A., Black, T.A., Bohrer, G., Bracho, R., Drake, B., Goldstein, A., Gu, L. Katul, G., Kolb, T., Law, B.E., Margolis, H., Meyers, T., Monson, R., Munger, W., Oren, R., Paw U, K.T., Richardson, A., Schimd, H.P., Staebler, R., Wofsy, S., and Zhao, L., 2011. Observed increase in local cooling effect of deforestation at higher latitudes. Nature, 479: 384-387.

Levis, S., Bonan, G.B., Kluzek, E., Thornton, P.E., Jones, A., Sacks, W.J. and Kucharik, C.J., 2012. Interactive crop management in the Community Earth System Model (CESM1): Seasonal influences on land–atmosphere fluxes. Journal of Climate, 25: 4839-4859.

Lewis, J.M., Ross, S. and Holden, T., 2012. The how and why of academic collaboration: disciplinary differences and policy implications. Higher Education, 64: 693-708.

Luo, Y.Q., Randerson, J.T., Abramowitz, G., Bacour, C., Blyth, E., Carvalhais, N., Ciais, P., Dalmonech, D., Fisher, J.B., Fisher, R., Friedlingstein, P., Hibbard, K., Hoffman, F., Huntzinger, D., Jones, C.D., Koven, C., Lawrence, D., Li, D.J., Mahecha, M., Niu, S.L., Norby, R., Piao, S.L., Qi, X., Peylin, P., Prentice, I.C., Riley, W., Reichstein, M., Schwalm, C., Wang, Y.P., Xia, J.Y., Zaehle, S., and Zhoe, X.H., 2012**.** A framework for benchmarking land models. Biogeosciences, 9: 3857-3874.

Mammarella, I., Werle, P., Pihlatie, M., Eugster, W., Haapanala, S., Kiese, R., Markkanen, T., Rannik, U. and Vesala, T., 2010. A case study of eddy covariance flux of N 2 O measured within forest ecosystems: quality control and flux error analysis. Biogeosciences, 7: 427-440.

Massman, W.J., 2000. A simple method for estimating frequency response corrections for eddy covariance systems. Agricultural and Forest Meteorology, 104: 185-198.

Massman, W.J., 2001. Reply to comment by Rannik on "A simple method for estimating frequency response corrections for eddy covariance systems". Agricultural and Forest Meteorology, 107: 247-251.

Maurer, G.E., Chan, A.M., Trahan, N.A., Moore, D.J. and Bowling, D.R., 2016. Carbon isotopic composition of forest soil respiration in the decade following bark beetle and stem girdling disturbances in the Rocky Mountains. Plant, Cell & Environment, 39: 1513-1523.

McDermitt, D., Burba, G., Xu, L., Anderson, T., Komissarov, A., Riensche, B., Schedlbauer, J., Starr, G., Zona, D., Oechel, W., Oberbauer, S., and Hastings, S., 2011. A new low-power, open-path instrument for measuring methane flux by eddy covariance. Applied Physics B: Lasers and Optics, 102: 391-405.

Metzger, S., Durden, D., Sturtevant, C., Luo, H., Pingintha-Durden, N., Sachs, T., Serafimovich, A., Hartmann, J., Li, J., Xu, K., Desai, A.R., 2017. eddy4R: A community-extensible processing, analysis and modeling framework for eddy-covariance data based on R, Git, Docker and HDF5. Geoscientific Model Development Discuss., 10, 3189–3206.

Mizoguchi, Y., Miyata, A., Ohtani, Y., Hirata, R. and Yuta, S., 2009. A review of tower flux observation sites in Asia. Journal of Forest Research, 14: 1-9.

Moncrieff, J., Clement, R., Finnigan, J. and Meyers, T., 2005. Averaging, detrending, and filtering of eddy covariance time series. Handbook of Micrometeorology, 29: 297-31.

Montané, F., Fox, A. M., Arellano, A. F., MacBean, N., Alexander, M. R., Dye, A., Bishop, D. A., Trouet, V., Babst, F., Hessl, A. E., Pederson, N., Blanken, P. D., Bohrer, G., Gough, C. M., Litvak, M. E., Novick, K. A., Phillips, R. P., Wood, J. D., and Moore, D. J. P.:,2017. Evaluating the effect of alternative carbon allocation schemes in a land surface model (CLM4.5) on carbon fluxes, pools and turnover in temperate forests, Geosci. Model Dev. Discuss., doi:10.5194/gmd-2017-74, *in press*. DOI: doi:10.5194/gmd-2017-74.

Moorcroft, P.R., 2006. How close are we to a predictive science of the biosphere? Trends in Ecology & Evolution, 21: 400-407.

Moore, D.J., Hu, J., Sacks, W.J., Schimel, D.S. and Monson, R.K., 2008. Estimating transpiration and the sensitivity of carbon uptake to water availability in a subalpine forest using a simple ecosystem process model informed by measured net CO_2 and H_2O fluxes. Agricultural and Forest Meteorology, 148: 1467-1477.

Moore, D.J., Trahan, N.A., Wilkes, P., Quaife, T., Stephens, B.B., Elder, K., Desai, A.R., Negron, J. and Monson, R.K., 2013. Persistent reduced ecosystem respiration after insect disturbance in high elevation forests. Ecology Letters 16: 731-737.

Nippert, J.B., Ocheltree, T.W., Skibbe, A.M., Kangas, L.C., Ham, J.M., Arnold, K.B.S. and Brunsell, N.A., 2011. Linking plant growth responses across topographic gradients in tallgrass prairie. Oecologia, 166: 1131-1142.

Nishida, K., Nemani, R.R., Running, S.W. and Glassy, J.M., 2003. An operational remote sensing algorithm of land surface evaporation. Journal of Geophysical Research: Atmospheres, 108: 4270.

Novick, K.A., Ficklin, D.L., Stoy, P.C., Williams, C.A., Bohrer, G., Oishi, A.C., Papuga, S.A., Blanken, P.D., Noormets, A., Sulman, B.N., Scott, R.L., Wang, L, and Phillips, R.P., 2016a. The increasing importance of atmospheric demand for ecosystem water and carbon fluxes. Nature Climate Change, 6: 1023-1027.

Novick, K.A., Oishi, A.C., and Miniat, C.F., 2016b. Cold air drainage flows subsidize montane valley ecosystem productivity. Global Change Biology, 22: 4014-4027.

Novick, K.A., Oishi, A.C., Ward, E.J., Siqueira, M., Juang, J.Y. and Stoy, P.C., 2015. On the difference in the net ecosystem exchange of CO2 between deciduous and evergreen forests in the southeastern U.S. Global Change Biology, 21: 827-842. .

Novick, K.A., Walker, J.T., Chan, W.S., Sobek, C.M. and Vose, J.M., 2013. Eddy covariance measurements with a new fast-response, closed-path analyzer: spectral characteristics and cross-system comparisions. Agricultural and Forest Meteorology, 181: 17-32.

Pastorello, G., Papale, D., Chu, H., Trotta, C., Agarwal, D., Canfora, E., Baldocchi, D. and Torn, M., 2017. A New Data Set to Keep a Sharper Eye on Land-Air Exchanges. *EOS 98,* https://doi.org/10.1029/2017EO071597. Published on 17 April 2017.

Peters, D.P., Groffman, P.M., Nadelhoffer, K.J., Grimm, N.B., Collins, S.L., Michener, W.K. and Huston, M.A., 2008. Living in an increasingly connected world: a framework for continental-scale environmental science. Frontiers in Ecology and the Environment, 6: 229-237.

Peters, D.P., Havstad, K.M., Cushing, J., Tweedie, C., Fuentes, O. and Villanueva-Rosales, N., 2014. Harnessing the power of big data: infusing the scientific method with machine learning to transform ecology. Ecosphere, 5: 1-15.

Phillips, C.L., Bond-Lamberty, B., Desai, A.R., Lavoie, M., Risk, D., Tang, J., Todd-Brown, K. and Vargas, R., 2017. The value of soil respiration measurements for interpreting and modeling terrestrial carbon cycling. Plant and Soil, 413: 1-25.

Reichman, O.J., Jones, M.B. and Schildhauer, M.P., 2011. Challenges and opportunities of open data in Ecology. Science, 331: 703-705.

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A. and Grünwald, T., Havránková, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F., Ourcival, J.-M., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D., Valentinie, R., 2005. On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. Global Change Biology, 11: 1424-1439.

Reichstein, M. and Moffat, A., 2014. REddyProc: Data processing and plotting utilities of (half-) hourly eddy-covariance measurements. R package version 0.6-0/r9. https://rdrr.io/rforge/REddyProc/

Richardson, A.D., Anderson, R.S., Arain, M.A., Barr, A.G., Bohrer, G., Chen, G., Chen, J.M., Ciais, P., Davis, K.J., Desai, A.R., Dietze, M.C., Dragoni, D., Garrity, S.R., Gough, C.M., Grant, R., Hollinger, D.Y., Margolis, H.A., McCaughey, H., Migliavacca, M., Monson, R.K., Munger, J.W., Poulter, B., Raczka, B.M., Ricciuto, D.M., Sahoo, A.K., Schaefer, K., Tian, H., Vargas, R., Verbeeck, H., Xiao, J., and Xue, Y., 2012. Terrestrial biosphere models need better representation of vegetation phenology: results from the North American Carbon Program Site Synthesis. Global Change Biology, 18: 566-584.

Richardson, A.D., Williams, M., Hollinger, D.Y., Moore, D.J., Dail, D.B., Davidson, E.A., Scott, N.A., Evans, R.S., Hughes, H., Lee, J.T., Rodrigues, C., and Savage, K., 2010. Estimating parameters of a forest ecosystem C model with measurements of stocks and fluxes as joint constraints. Oecologia, 164: 25-40.

Richardson, A.D., Hollinger, D.Y., Aber, J.D., Ollinger, S.V. and Braswell, B.H., 2007. Environmental variation is directly responsible for short- but not long-term variation in forest-atmosphere carbon exchange. Global Change Biology, 13: 788-803.

Richardson, A.D., Hollinger, D.Y., Burba, G.G., Davis, K.J., Flanagan, L.B., Katul, G.G., Munger, J.W., Ricciuto, D.M., Stoy, P.C., Suyker, A.E., Verma, S.B., and Wofsy, S.C., 2006. A multi-site analysis of random error in tower-based measurements of carbon and energy fluxes. Clo, 136: 1-18.

Richter, D. and Billings, S.A., 2015. 'One physical system': Tansley's ecosystem as Earth's critical zone. New Phytologist, 206(3): 900-912.

Rigden, A.J. and Salvucci, G.D., 2017. Stomatal response to humidity and CO2 implicated in recent decline in US evaporation. Global Change Biology, 23: 1140-1151.

Roman, D.T., Novick, K.A., Brzostek, E.R., Dragoni, D., Rahman, F. and Phillips, R.P., 2015. The role of isohydric and anisohydric species in determining ecosystem-scale response to severe drought. Oecologia, 179: 641-654.

Rundel, P.W., Graham, E.A., Allen, M.F., Fisher, J.C. and Harmon, T.C., 2009. Environmental sensor networks in ecological research. New Phytologist, 182: 589-607.

Runkle, B.R., Rigby, J.R., Reba, M.L., Anapalli, S.S., Bhattacharjee, J., Krauss, K.W., Liang, L., Locke, M.A., Novick, K.A., Sui, R. Suvočarev, K., and White, P.M., 2017. Delta-Flux: An Eddy Covariance Network for a Climate-Smart Lower Mississippi Basin. Agricultural & Environmental Letters, 2: 170003.

Running, S.W., Nemani, R.R., Heinsch, F.A., Zhao, M., Reeves, M. and Hashimoto, H., 2004. A continuous satellite-derived measure of global terrestrial primary production. Bioscience, 54: 547-560.

Ryan, M.G., Lavigne, M.B. and Gower, S.T., 1997. Annual carbon cost of autotrophic respiration in boreal forest ecosystems in relation to species and climate. Journal of Geophysical Research, 103: 28871-28883.

Sacks, W.J., Schimel, D.S., Monson, R.K. and Braswell, B.H., 2006. Model-data synthesis of diurnal and seasonal CO2 fluxes at Niwot Ridge, Colorado. Global Change Biology, 12: 240-259.

Schimel, D., 2011. The era of continental-scale ecology. Frontiers in Ecology and the Environment, 9(6): 311-311.

Schimel, D., Hargrove, W., Hoffman, F. and MacMahon, J., 2007. NEON: A hierarchically designed national ecological network. Frontiers in Ecology and the Environment, 5: 59-59.

Schmidt, A., Hanson, C., Chan, W.S. and Law, B.E., 2012. Empirical assessment of uncertainties of meteorological parameters and turbulent fluxes in the AmeriFlux network. Journal of Geophysical Research: Biogeosciences, 117: G04014.

Schwalm, C.R., Williams, C.A., Schaefer, K., Arneth, A., Bonal, D., Buchmann, N., Chen, J., Law, B.E., Lindroth, A., Luyssaert, S., Reichstein, M., and Richardson, A.D., 2010. Assimilation exceeds respiration sensitivity to drought: A FLUXNET synthesis. Global Change Biology, 16: 657-670.

Schwalm, C.R., Williams, C.A., Schaefer, K., Baldocchi, D., Black, T.A., Goldstein, A.H., Law, B.E., Oechel, W.C., Paw U., K.T., and Scott, R.L., 2012. Reduction in carbon uptake during turn of the century drought in western North America. Nature Geoscience, 5: 551-556.

Scott, R.L., Biederman, J.A., Hamerlynck, E.P. and Barron-Gafford, G.A., 2015. The carbon balance pivot point of southwestern US semiarid ecosystems: Insights from the 21st century drought. Journal of Geophysical Research: Biogeosciences, 120: 2612-2624.

Scott, R.L., Hamerlynck, E.P., Jenerette, G.D., Moran, M.S. and Barron-Gafford, G.A., 2010. Carbon dioxide exchange in a semidesert grassland through drought-induced vegetation change. Journal of Geophysical Research-Biogeosciences, 115: G03026.

Seibt, U., Kesselmeier, J., Sandoval-Soto, L., Kuhn, U. and Berry, J., 2010. A kinetic analysis of leaf uptake of COS and its relation to transpiration, photosynthesis and carbon isotope fractionation. Biogeosciences, 7: 333-341.

Serbin, S.P., Singh, A., Desai, A.R., Dubois, S.G., Jablonski, A.D., Kingdon, C.C., Kruger, E.L. and Townsend, P.A., 2015. Remotely estimating photosynthetic capacity, and its response to temperature, in vegetation canopies using imaging spectroscopy. Remote Sensing of Environment, 167: 78-87.

Shen, W., Jenerette, G., Hui, D. and Scott, R., 2016. Precipitation legacy effects on dryland ecosystem carbon fluxes: direction, magnitude and biogeochemical carryovers. Biogeosciences, 13: 425-439.

Stöckli, R., Lawrence, D.M., Niu, G.Y., Oleson, K.W., Thornton, P.E., Yang, Z.L., Bonan, G.B., Denning, A.S. and Running, S.W., 2008. Use of FLUXNET in the Community Land Model development. Journal of Geophysical Research: Biogeosciences, 113: G01025.

Stoy, P.C., Katul, G., Siqueira, M., Juang, J.-Y., Novick, K.A., McCarthy, H.R., Oishi, A.C., Oren, R., 2008. Role of vegetation in determining carbon sequestration along ecological succession in the southeastern United States. Global Change Biology, 14: 1409-1427.

Stoy, P.C., Mauder, M., Foken, T., Marcolla, B., Boegh, E., Ibrom, A., Arain, M.A., Arneth, A., Aurela, M., Bernhofer, C. and Cescatti, A., 2013. A data-driven analysis of energy balance closure across FLUXNET research sites: The role of landscape scale heterogeneity. Agricultural and Forest Meteorology, 171: 137-152.

Su, H.B., Schmid, H.P., Grimmond, C.S.B., Vogel, C.S. and Oliphant, A.J., 2004. Spectral characteristics and correction of long-term eddy-covariance measurements over two mixed hardwood forests in non-flat terrain. Boundary-Layer Meteorology, 110: 213-253.

van der Tol, C., Berry, J., Campbell, P. and Rascher, U., 2014. Models of fluorescence and photosynthesis for interpreting measurements of solar-induced chlorophyll fluorescence. Journal of Geophysical Research: Biogeosciences, 119: 2312-2327.

Turnipseed, A.A., Blanken, P.D., Anderson, D.E. and Monson, R.K., 2002. Energy budget above a high-elevation subalpine forest in complex topography. Agricultural and Forest Meteorology, 110: 177-201.

Van der Molen, M., Gash, J. and Elbers, J., 2004. Sonic anemometer (co) sine response and flux measurement: II. The effect of introducing an angle of attack dependent calibration. Agricultural and Forest Meteorology, 122: 95-109.

Van Gorsel, E., Delpierre, N., Leuning, R., Black, A., Munger, J.W., Wofsy, S., Aubinet, M., Feigenwinter, C., Beringer, J., Bonal, D. and Chen, B., Chen, J., Clement, R., Davis, K.J., Desai, A.R., Dragoni, D., Etzold, S., Grünwald, T., Gu, L., Heinesch, B., Hutyar, L.R., Jans, W.W.P., Werner, K., Law, B.E., Leclerc, M.Y., Mammarella, I., Montagnani, L., Noormets, A., Rebmann, C., Wharton, S., 2009. Estimating nocturnal ecosystem respiration from the vertical turbulent flux and change in storage of CO2. Agricultural and Forest Meteorology, 149: 1919-1930.

Verma, M., Schimel, D., Evans, B., Frankenberg, C., Beringer, J., Drewry, D.T., Magney, T., Marang, I., Hutley, L., Moore, C., Eldering, A., 2017. Effect of environmental conditions on the relationship between solar induced fluorescence and gross primary productivity at an OzFlux grassland site. Journal of Geophysical Research: Biogeosciences 122: 716-733.

Verma, S.B., Dobermann, A., Cassman, K.G., Walters, D.T., Knops, J.M., Arkebauer, T.J., Suyker, A.E., Burba, G.G., Amos, B., Yang, H., Ginting, D., Hubbard, K.G., Gitelson, A.A., Walter-Shea, E.A., 2005. Annual carbon dioxide exchange in irrigated and rainfed maize-based agroecosystems. Agricultural and Forest Meteorology, 131: 77-96.

Vuichard, N. and Papale, D., 2015. Filling the gaps in meteorological continuous data measured at FLUXNET sites with ERA-Interim reanalysis. Earth System Science Data, 7(2): 157.

Walbridge, M.R. and Shafer, S.R., 2011. A long-term agro-ecosystem research (LTAR) network for agriculture, Proceedings of the Fourth Interagency Conference in the Watersheds: Observing, Studying, and Managing Change, pp. 26-30.

Wang, H., Prentice, I.C., Keenan, T.F., Davis, T.W., Wright, I.J., Cornwell, W.K., Evans, B.J., and Peng, C. Towards a universal model for carbon dioxide uptake by plants. Nature Plants, 3: 734-741.

Wehr, R., Commane, R., Munger, J.W., McManus, J.B., Nelson, D.D., Zahniser, M.S., Saleska, S.R. and Wofsy, S.C., 2017. Dynamics of canopy stomatal conductance, transpiration, and evaporation in a temperate deciduous forest, validated by carbonyl sulfide uptake. Biogeosciences, 14: 389.

White, T., Brantley, S., Banwart, S., Chorover, J., Dietrich, W., Derry, L., Lohse, K., Anderson, S., Aufdendkampe, A., Bales, R. and Kumar, P., Richter, D., McDowell, B., 2015. The role of critical zone observatories in critical zone science. Developments in Earth Surface Processes, 19: 15-78.

Wilczak, J.M., Oncley, S.P. and Stage, S.A., 2001. Sonic anemometer tilt correction algorithms. Boundary-Layer Meteorology, 99: 127-150.

Wilson, K., Goldstein, A., Falge, E., Aubinet, M., Baldocchi, D., Berbigier, P., Bernhofer, C., Ceulemans, R., Dolman, H., Field, C. and Grelle, A., Ibrom, A., Law, B.E., Kowalski, A., Meyers, T., Moncrieff, J., Monson, R., Oechel, W., Tenhunen, J., Valentini, R., Verma, S., 2002. Energy balance closure at FLUXNET sites. Agricultural and Forest Meteorology, 113: 223-243.

Wolf, S., Keenan, T.F., Fisher, J.B., Baldocchi, D.D., Desai, A.R., Richardson, A.D., Scott, R.L., Law, B.E., Litvak, M.E., Brunsell, N.A. and Peters, W., van der Laan-Luijkx, I.T., 2016. Warm spring reduced carbon cycle impact of the 2012 US summer drought. Proceedings of the National Academy of Sciences: 201519620.

Xiao, J., Zhuang, Q., Baldocchi, D., Law, B.E., Richardson, A.D., Chen, J., Oren, R., Starr, G., Noormets, A., Ma, S., Verma, S.B., Wharton, S., Wofsy, S.C., Bolstad, P.V., Burns, S.P., Cook, D.R., Curtis, P.S., Drake, B.G., Falk, M., Fischer, M.L, Foster, D.R., Gu, L, Hadley, J.L., Hollinger, D.Y., Katul, G.G., Litvak, M., Martin, T.A., Matamala, R., McNulty, S., Meyers, T.P., Monson, R.K., Munger, J.W., Oechel, W.C., Paw U, K.T., Schmid, H.P., Scott, R.L., Sun, G., Suyker, A.E., Torn, M.S., 2008. Estimation of net ecosystem carbon exchange for the conterminous United States by combining MODIS and AmeriFlux data. Agricultural and Forest Meteorology, 148: 1827-1847.

Xiao, J.F., Zhuang, Q., Law, B.E., Baldocchi, D.D., Chen, J., Richardson, A.D., Melillo, J.M., Davis, K.J., Hollinger, D.Y., Wharton, S., Oren, R., Noormets, A., Fischer, M.L., Verma, S.B., Cook, D.R., Sun, G., McNulty, S., Wofsy, S.C., Bolstad, P.V., Burns, S.P., Curtis, P.S., Drake, B.G., Falk, M., Foster, D.R., Gu, L., Hadley, J.L., Katul, G.G., Litvak, M., Ma, S., Martin, T.A., Matamala, R., Meyers, T.P., Monson, R.K., Munger, J.W., Oechel, W.C., Paw U., K.T., Schimd, H.P., Scott, R.L., Starr, G., Suyker, A.E., Torn, M.S., 2011. Assessing net ecosystem carbon exchange of U.S. terrestrial ecosystems by integrating eddy covariance flux measurements and satellite observations. Agricultural and Forest Meteorology, 151: 60-69.

Xu, K., Metzger, S. and Desai, A.R., 2017. Upscaling tower-observed turbulent exchange at fine spatio-temporal resolution using environmental response functions. Agricultural and Forest Meteorology, 232: 10-22.

Yang, X., Tang, J., Mustard, J.F., Lee, J.E., Rossini, M., Joiner, J., Munger, J.W., Kornfeld, A. and Richardson, A.D. 2015. Solar-induced chlorophyll fluorescence that correlates with canopy photosynthesis on diurnal and seasonal scales in a temperate deciduous forest. Geophysical Research Letters, 42: 2977-2987.

Yuan, W., Luo, Y., Richardson, A.D., Oren, R.A.M., Luyssaert, S., Janssens, I.A., Ceulemans, R., Zhou, X., Grünwald, T., Aubinet, M. and Berhofer, C., Baldocchi, D.D., Grünwald, T., Aubinet, M., Berhofer, C., Baldocchi, D.D., Chen, J., Dunn, A., Deforest, J.L., Dragoni, D., Goldstein, A.H., Moors, E., Munger, J.W., Monson, R.K., Suyker, A.E., Starr, G., Scott, R.L., Tenhunen, J., Verma, S.B., Vesala, T., Wofsy, S.C., 2009. Latitudinal patterns of magnitude and interannual variability in net ecosystem exchange regulated by biological and environmental variables. Global Change Biology, 15: 2905-2920.

Zha, T., Xing, Z., Wang, K.-Y., Kellomäki, S. and Barr, A.G., 2007. Total and component carbon fluxes of a Scots pine ecosystem from chamber measurements and eddy covariance. Annals of Botany, 99: 345-353.

Zobitz, J., Desai, A., Moore, D. and Chadwick, M., 2011. A primer for data assimilation with ecological models using Markov Chain Monte Carlo (MCMC). Oecologia, 167: 599.

Zobitz, J.M., Moore, D.J.P., Sacks, W.J., Monson, R.K., Bowling, D.R. and Schimel, D.S., 2008. Integration of process-based soil respiration models with whole-ecosystem CO2 measurements. Ecosystems, 11: 250-269.

Zreda, M., Shuttleworth, W.J., Zeng, X., Zweck, C., Desilets, D., Franz, T. and Rosolem, R., 2012. COSMOS: the cosmic-ray soil moisture observing system. Hydrology and Earth System Sciences, 16: 4079-4099.

Zscheischler, J., Fatichi, S., Wolf, S., Blanken, P.D., Bohrer, G., Clark, K., Desai, A.R., Hollinger, D., Keenan, T., Novick, K.A. and Seneviratne, S.I., 2016. Short-term favorable weather conditions are an important control of interannual variability in carbon and water fluxes. Journal of Geophysical Research: Biogeosciences, 121: 2186-2198.