Recommendations for Belowground Carbon Data and Measurements for the AmeriFlux Network

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Introduction

The terrestrial carbon (C) sink offset about 25% of global anthropogenic CO_2 emissions over the past decade (Global Carbon Project, 2013 and the references therein). However, uncertainty regarding the continued function of the terrestrial biosphere as a sink for atmospheric C inhibits our ability to confidently predict future climate. In this context, developing a predictive understanding of belowground C pools and fluxes is especially urgent. Soil contains more than twice as much C as the atmospheric and plant pools combined (CCSP, 2007 updated with values from Tarnocai et al., 2009). Soil fluxes into the atmosphere are more than 20 times the net terrestrial C sink (Schlesinger, 1997), and are sensitive to climate (Schuur et al., 2013; Bond-Lamberty and Thomson, 2010). Therefore, in addition to playing a major role in the overall C cycle of terrestrial ecosystems, belowground C has important feedbacks to the rate of continued climate change. In particular, climate change may accelerate the rate of decomposition and result in a positive feedback to climate change (Davidson and Janssens 2006). An improved understanding of the distribution, cycling, dynamics, and vulnerability of belowground C pools at multiple spatial scales is needed to model and predict responses and feedbacks of terrestrial ecosystems to climate and other aspects of global change.

The AmeriFlux network has made critical contributions to quantifying and explaining the C balance of terrestrial ecosystems through eddy covariance measurements, plot-based data collection, and data synthesis projects (*e.g.*, Curtis et al., 2002; Amiro et al., 2010; Gough et al., 2008). These efforts have provided invaluable insight into patterns of and processes controlling inter-annual variations in the terrestrial C sink, its response to disturbance, and the potential for sustained C sequestration. Eddy covariance fluxes, however, provide few meaningful constraints on the processes controlling some of the largest pools and fluxes of C in terrestrial ecosystems, which are found belowground. Integrating measurements of eddy covariance fluxes with belowground C will yield substantial improvements to process-level representations of the C cycle in ecosystem and Earth system models. Measuring the quantity, distribution and turnover of C belowground is fundamental to achieving AmeriFlux strategic goals that cannot be completed by eddy covariance flux measurements alone.

Currently, 160 tower sites have membership in AmeriFlux, though not all are actively collecting or reporting data. The network provides opportunities to improve mechanistic understanding of the whole-ecosystem C cycle by coupling eddy-covariance measurements with research on the belowground pools and fluxes of C at AmeriFlux sites. Presently, the AmeriFlux network does not require measurements of belowground C pools, fluxes, or soil ancillary data, except for Core Sites (long term sites that are supported to produce comprehensive data sets). Compounding the lack of belowground data in the AmeriFlux archives, there is also a lack of accessible data from other sources that could be used at eddy covariance sites. Given that soil respiration is the second highest ecosystem C flux after gross primary production, it is critical to measure and understand the processes controlling belowground C fluxes; this will facilitate process-level representation of C fluxes in land models.

Allocating greater effort to collecting, publishing and, in particular, sharing data on belowground C pools and fluxes from AmeriFlux would:

1. Benefit the scientific community by making available coordinated, belowground C cycle measurements across a network that comprises sites varying in climate, landform, soil properties, vegetation, management and disturbance history and coupling these measurements to existing data on ecosystem-scale fluxes of C and water.
2. Enhance the potential for this network to meet its goals of quantifying and explaining the C balance of terrestrial ecosystems, and
3. Allow the DOE-Terrestrial Ecosystem Science program to better achieve its goal of understanding the sources and sinks for atmospheric CO_2 and their change over time in response to climatic and atmospheric change.

In this white paper, we define important belowground C cycling parameters and summarize datasets currently available for belowground C storage and cycling research within the AmeriFlux network. We also identify crucial gaps in these datasets and recommend approaches for increasing the availability of high quality, quantitative belowground C datasets. Collectively, this white paper and the recommendations herein establish a plan for advancing network and DOE program goals to improve our understanding and modeling of C at ecosystem, regional, and global scales, through a focus on belowground C.

Important Belowground Carbon Cycle Parameters

Belowground measurements at AmeriFlux sites are motivated by the need to (1) accurately partition NEE into its component fluxes through careful partitioning of ecosystem respiration (Re) into aboveground and belowground components (e.g., Giasson et al. 2013), (2) close C budgets, and (3) conduct temporal analysis of belowground C storage and turnover across the United States (e.g., Gaudinski et al. 2000). In order to ask informed questions about C cycling within and between belowground pools, it is first necessary to define and quantify the amount of C in those pools and their dynamic changes. We recommend consideration of the following belowground parameters:

1. Bulk Soil and Fraction Carbon Stocks

An inventory of the amount and distribution of bulk soil (all soil that passes a 2 mm sieve) C stocks provides the foundation for understanding the belowground components of the C cycle. The amount and distribution of bulk soil C reflect the net balance of C input, output, transfer and transformation fluxes, each of which vary over space and time. Because spatial (and to some degree, temporal) variability in the amount and distribution of soil C are to be expected in disturbed and undisturbed ecosystems, understanding these components of the belowground C cycle requires spatial and temporal replication of measurements with coincident measurement of the factors potentially responsible for this variability. Measurements of bulk soil C pools are strengthened by additional measurements of C in physical fractions that differ in their source, location within the soil matrix, and apparent stability or vulnerability. This information is particularly useful for inferring the vulnerability of soil C pools to future change. Detailed information on soil C stocks, their distribution within ecosystems, soil profiles, horizons, and physical fractions will provide a baseline for assessment of future change in ecosystem C storage and allow for cross-site synthesis activities.

2. Soil Respiration

Soil respiration (R_s) accounts for a substantial fraction of ecosystem respiration (R_e). Soil respiration changes in response to temperature and moisture variations at diurnal to inter-annual time scales (Rustad et al. 2001, Suseela et al., 2012) and its measurement is a key constraint for models of the terrestrial C cycle (Keenan et al. 2013). In many respects Rs can be considered a "barometer" of the belowground C cycle in terrestrial ecosystems. Current technology, including automated chamber measurements, enables cost effective measurements of Rs with moderate to high temporal resolution. These measurements, taken at multiple sites across the AmeriFlux network would allow for investigation into the relative importance of factors controlling soil respiration (i.e., soil temperature, moisture, C inputs, etc.). Continuous measurement of soil respiration measured with a coordinated protocol across the the AmeriFlux network would provide unprecedented datasets for modeling development, cross-site synthesis to identify universal drivers of soil respiration, validate eddy flux data (e.g. night flux data), and decrease uncertainty in estimating global CO_2 fluxes from soils.

3. Litterfall and Estimates of Total Belowground Carbon Flux

In combination with measurements of CO_2 efflux, measurement of the annual rate of aboveground litterfall enables a first-order estimate of the total belowground C flux (TBCF). This can be calculated as the difference between annual soil respiration and the sum of annual litterfall, hydrological losses DOC, and annual change in root and soil C stocks (all in g C m^{-2} yr^{-1}, see Davidson et al. 2000). While all terms are theoretically needed to estimate TBCF, it is reasonable to assume that annual changes in root and soil C stocks as well as DOC losses are small on an annual basis and minor terms in the overall equation. Estimates of TBCF on seasonal to annual time scales not only measure the flux of C belowground but also enable estimation of partitioning coefficients for GPP above vs. belowground (i.e., TBCF / GPP), one of the least constrained parameters in ecosystem models.

4. Root Biomass and Dynamics

Roots are the major conduit for C entering the subsurface and the largest contributor of C to storage pools in mineral soil horizons (Drake et al. 2011, Schmidt et al. 2011). At the annual time scale, changes in root biomass may be small but this masks large belowground C fluxes associated with root production, maintenance respiration, and turnover, in addition to exudation and allocation to mycorrhizal fungi (Vargas and Allen 2008). Such inputs of C also influence microbial activity, the decomposition of soil organic C pools, and nutrient supply to support primary production. As such, root production and associated fluxes are necessary information for estimation of site-level C budgets. We recognize, however, the difficulty in measuring C fluxes in root exudation and support of mycorrhizal fungi, but also note that in combination with estimates of TBCF it is possible to infer what these fluxes may be (Drake et al. 2011).

5. Bulk Soil and Fraction Radiocarbon Measurements

Radiocarbon measurements of bulk soil and soil fractions enable estimation of the turnover time of these pools, particularly those cycling at century to millennial timescales. In addition to providing valuable information for parameterizing C cycle models (e.g., Frank et al. 2002), these data enable among-site comparisons of the turnover time of different belowground C pools (e.g., Trumbore, 1993; McFarlane et al., 2013) and their dependence on climate and the physical properties of soil (e.g., Torn et al., 1997). Turnover times (or the inverse, decay rate) can be used to calculate or model C-input rates for specific soil depths or fractions (e.g., Frank et al., 2012). Changes in ^{14}C signatures over time can indicate the gain or loss of soil C over years or decades in response to disturbance, land-use change, etc. (Wang et al., 1999; Marín-Spiotta et al., 2008; Heckman, et al., 2013; O'Brien et al., 2013). Furthermore, these measurements allow for parameterization and improvement of site-specific C cycle models and provide data and process-level knowledge necessary for the improvement of regional and global scale C cycle models.

6. Microbial Biomass and Community Composition

Microbial biomass is a small C pool in terrestrial ecosystems but soil microbes exert major control over the C cycle at micrometer to global scales. Analysis of the composition, biomass and function of microbes using modern techniques is complicated, requires substantial infrastructure, and may be beyond the scope of what could be easily accomplished by the AmeriFlux community. There are, however, relatively simple assays that measure major features of the microbial community including biomass and the activity of the extracellular enzymes produced by microbes that decompose soil organic matter pools of different C chemistry.

7. Other Ecosystem and Belowground Parameters

Sections 1-6 primarily describe measurements of direct value in quantifying belowground components of the broader C cycle. However, these are more powerful with the accompanying measurement of explanatory or predictor variables such as climate, soil texture and taxonomy, and plant community. Some of these variables, especially those related to climate, vegetation, and aboveground processes, are already customarily measured at AmeriFlux sites. A comprehensive inventory of all the possible descriptor variables that would further belowground C measurements is beyond the scope of this document; the essential point here is that in order to extract the highest benefit from belowground C datasets, it is necessary to integrate them with measurements of the variables needed for predictive modeling capacity.

Available Resources

In June 2013, the AmeriFlux Data and Support Team at Lawrence Berkeley National Lab produced a report from the Biological, Ancillary, Disturbances, Management (BADM) templates to allow assessment of currently available data on belowground pools and fluxes of C within the AmeriFlux network (herein referred to as the “AmeriFlux Report”). We also searched AmeriFlux data pages and other multi-site data repositories (FLUXNET, LTER, ISCN) for additional datasets on belowground C pools, fluxes, and dynamics not captured by the AmeriFlux Report, but that are available to the community. At the time the report was produced, 62 of the 160 AmeriFlux sites provided data on belowground C (Table 1).

As the majority of these data are available through the AmeriFlux BADM, it is worth noting that there are several important limitations to the utility of these data. First, there is a lack of coordination among the belowground C variables, their units, descriptions, and methods of collection as reported by individual sites. Important information about these details, methods of sampling, and measures of variability are often missing despite the ability of the BADM template to accept such information. This inconsistency hinders cross-site data synthesis efforts for these variables.

Additionally, several of the variables described in Section 2 (above) have not been included in the standard AmeriFlux data files, although efforts are already underway to improve the BADM. Furthermore, additional datasets, published and unpublished, have been collected that are not available to the community. Some of these may be too recent while others are too old to have been included in these datafiles. While standardization has not been a requisite for participation in AmeriFlux, coordination is a strength of the network. Coordination of future data collection efforts, perhaps supported by topical working groups, is needed to ensure cross-compatibility of datasets from different sites for the sake of synthesis.

4. Recommendations

Based on available resources we propose a set of recommendations for belowground C cycle science at Ameriflux sites that fall under two main categories: 1) Improved management of existing belowground data and 2) New measurements of belowground variables.

First, belowground C datasets previously collected from each site should be uploaded to the AmeriFlux database, provided these datasets meet consensus standards of quality and provenance. To meet this end, ancillary data files, metadata files, site webpages, and site bibliographies should be updated annually (this includes uploading of new data, the retroactive addition of older datasets, and publication information). It is recommended that rigorous review of data uploading be required for continued funding of AmeriFlux Core Sites, and strongly encouraged for all sites. At a minimum, BADM templates should be revised to include the belowground C parameters described above. Partnership with other data repositories (*e.g.*, ISCN) regarding how these data can be best managed for ease of upload and use should be considered. For example, because the ISCN and AmeriFlux Databases exist on shared infrastructure and are interoperable, reporting soil C stock data to either database will be sufficient. Likewise, because the ISCN Database has a flexible system for reporting soil fraction data, we recommend that this existing system be used to report this type of belowground C dataset; AmeriFlux Database users can then access soil fraction data through the ISCN using shared login information. This would allow the AmeriFlux network to avoid inclusion of soil fraction data into the BADM, provided there is a mechansim for referring users to the ISCN. While it is undeniably a significant commitment of effort to undertake retroactive data synthesis, full participation in data sharing is necessary for successful cross-site synthesis, meta-analyses, and modeling efforts, and integration of these existing databases ensures that data contributions need not be duplicated.

Second, there is a significant need for new data collection on belowground C pools and fluxes. These measurements should be required of the AmeriFlux Core Sites that do not already collect this information and encouraged for all network sites. To the extent possible, the sites should collect data using coordinated protocols and instrumentation to facilitate cross-site modeling and synthesis. We recommend the following measurements and methodologies in order of priority:

1. <u>Bulk soil C stocks</u>. Bulk soil C should be measured from the surface of the organic horizon (if present) to the parent material by soil horizon [preferred] or depth increment. If sampling by horizon, descriptions and thicknesses of horizons should be reported. If sampling by depth increment, increments should be reported and justified. Estimates of bulk soil C stocks should be measured with some spatial replication in biometry plots in tower footprint areas, and repeatedly over time if management- or disturbance-induced variability is suspected. Soil nitrogen content should also be determined from the same samples and reported. Lastly, and perhaps greatest in importance,

care must be given to measuring and reporting soil bulk density if it is used in the estimation of soil C or N stocks.

2. Annual rates of soil respiration and litterfall. The preferred technique for Rs is the automated chamber method. If not possible, manual chamber measurements of R_s should be made biweekly throughout the growing season and, if practicable, biweekly or monthly during the non-growing season. Chamber measurements could, where available, be supported by solid-state sensor measurements of soil pCO_2 (Tang et al. 2003). Measurements of annual aboveground litterfall should accompany those of R_s to enable estimation of TBCF. If possible but of lower priority due to limitation in methodology, partitioning of soil respiration into microbial and root respiration via the trenching technique is recommended.
3. Root biomass and production. Root biomass should be quantified from soil cores or quantitative pits using the same horizon/depth increment approached used in point #1 (above), including organic and mineral soils. Root biomass should be quantified on an annual basis to a minimum of 45 cm (or to bedrock in the case of soils shallower than 45 cm). Ideally, root biomass should be measured to a sufficient depth to catch 90% of root biomass across the vertical profile if this depth is determined from sampling to at least 1 m depth. Roots should be sorted by diameter into two fractions: > 2mm and ≤ 2mm. Of slightly less importance, root production and mortality should be quantified, ideally using minirhizotrons installed to 45 cm depth or the depth that catches 90% of root biomass if it has been determined. Minirhizotrons should be sampled bi-weekly to monthly throughout the growing season.
4. Radiocarbon Content of Soil Organic Matter. Radiocarbon measurements to determine turnover times for soil C pools should be made on bulk soils from the same horizon/depth increment used in #1 (above), including organic and mineral soils. Ideally, ^{14}C measurements should also be made for all physical soil fractions resulting from soil fractionation. These measurements should be prioritized starting with the core sites and expanding to sites selected to encompass the range in biomes, climates, and soil types found within the network.
5. Soil C fractions. Soil fractionation should be performed on mineral soils from the same horizon/depth increment used in #1 (above), or a subset of these that include surface and deep soil layers. Soil fraction C, N, and ^{14}C content should be measured for all physical fractions. A comprehensive discussion of possible fractionation methods is beyond the scope of this document. However, we do recommend coordination across the network to ensure these data are as useful as possible for synthesis and modeling activities.
6. Microbial Biomass and Activity: Microbial biomass should be measured using the chloroform fumigation-extraction procedure bimonthly throughout the growing season (Murage and Voroney 2007). The activity of the C degrading microbial exoenzymes beta-glucosidase, cellobiohydrolase, N-

acetylglucosaminidase and phenol oxidase should be measure using a microplate technique (Finzi et al. 2006). It is recommended that microbial biomass be measured in the organic horizon, if present, and in the surface mineral soil horizon/depth increment bimonthly throughout the growing season.

4. Conclusions

The lack of community-accessible belowground C datasets for the majority of sites within AmeriFlux hinders development of broader insights into basic and complex questions from how belowground C stocks vary across the network to how these stocks and their associated fluxes will respond to future change. We need accessible quantifications of soil C stocks and turnover, continuous soil respiration, and root biomass and production to compliment the expansive and ongoing datasets for ecosystem-level C exchange available through the AmeriFlux network. The recommendations outlined in this white paper would allow for aggregation of new and existing site-level data resources at a community level to the benefit of the research community as a whole. The availability and accessibility of high quality data for these important parameters would foster the advancement of terrestrial C cycle science by facilitating cross-site comparisons and synthesis, providing more complete ecosystem-level C budgets, and providing the basic information on soil C cycling required to begin answering the set of complex questions challenging our ability to predict the response of these terrestrial ecosystems to future change.

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Table 1. Summary of Belowground Carbon Data for Selected Variables Currently Available through AmeriFlux's BADM Database (June 2013 AmeriFLUX Report and manual survey)

Type	**Parameter**	**# of Sites Reporting***	**Site ID's of Sites Reporting***	**Note**
Soil	Soil_C	49 (4)	CA-NS1, CA-NS2, CA-NS3, CA-NS5, CA-NS6, CA-NS7, CR-Lse, US-ARb, US-Arc, US-ARM, US-Atq, US-Bar, US-Brw, US-Dk3, US-Fmf, US-FR2, US-Fuf, US-Fwf, US-Ha1, US-Ha2, US-Ho1, US-Ho2, US-Ho3, US-IB1, US-IB2, US-KS2, US-Los, US-LPH, US-Me1, US-Me2, US-Me3, US-Me4, US-Me5, US-MMS, US-Ne1, US-Ne2, US-Ne3, US-NR1, US-PFa, US-Slt, US-SP2, US-SP3, US-SRM, US-Syv, US-Ton, US-UMB, US-WBW, US-Wkg, US-Wrc, (US-Bn1, US-Dk1, US-Dk2, US-Seg)	C stock, total or by depth, data for soil fractions not accessible through AmeriFLUX
	Rs, mean[+]	18 (3)	US-Bar, US-Dk2, US-Dk3, US-Me1, US-Me2, US-Me3, US-Me4, US-Me5, US-MMS, US-Ne1, US-Ne2, US-Ne3, US-NR1, US-SP1, US-SP2, US-SP3, US-Ton, US-WCr, (US-Bn1, US-Ha1, US-UMB)	Variable timescale
	^{14}C[§]	0	Measurements have been made at 9 sites, but are not currently available to community	Bulk soil or soil fractions
Root	FR_ biomass	18 (4)	US-Bar, US-Dk3, US-Fmf, US-Fuf, US-Fwf, US-Ha1, US-IB2, US-Me1, US-Me2, US-Me3, US-Me4, US-Me5, US-MMS, US-PFa, US-Slt, US-Syv, US-UMB, US-WCr, (US-Bn1, US-Cop, US-Kon, US-Wrc)	Total or by depth
	FR_prod	13 (1)	US-Dk3, US-Fmf, US-Fuf, US-Fwf, US-Me1, US-Me2, US-Me3, US-Me4, US-Me5, US-MMS, US-UMB, US-WCr, (US-NR1)	Total or by depth
	Root_C	10	US-Dk2, US-Dk3, US-IB2, US-MMS, US-PFa, US-SO2, US-SO3, US-SO4, US-UMB, US-WCr	Con-centration
	Root_N	9	US-Dk2, US-Dk3, US-IB2, US-PFa, US-SO2, US-SO3, US-SO4, US-UMB, US-WCr	Con-centration
	Root Phen-ology***	0		Assessed with minirhizotrons
Litter	LIT_Mass	19	US-Bar, US-Dk2, US-Dk3, US-Ha1, US-IB2, US-Me1, US-Me2, US-Me3, US-Me5, US-Me5, US-MMS, US-MOz, US-NR1, US-Slt, US-SP1, US-SP2, US-SP3, US-UMB, US-WCr	
	LIT_PROD	21	US-Dk3, US-Fmf, US-Fuf, US-Ha1, US-Ho1, US-Ho2, US-Los, US-Me2, US-Me3, US-Me4, US-Me5, US-MOz, US-NR1, US-PFa, US-Slt, US-SP1, US-SP2, US-SP3, US-Ton, US-UMB, US-WCR	Various methods
Mi-crobes	Biomass***	0		

*Not all sites reflected in AmeriFlux Report. The number or Site ID's of additional sites with data available in other repositories are in parentheses.

[+] Flux-met variable, not BADM variable. Data is available for US-MOz, US-MRf, and US-Me1.

[§] Variable not included in AmeriFLUX datafiles.