Science Plan for AmeriFlux: Long-term flux measurement network of the Americas

Measurements and Modeling Net Ecosystem CO_2 Flux from Major Terrestrial Biomes Using Continuous, Long-Term Flux Measurements at the Ecosystem Scale.

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Executive Summary

Gaps in understanding the global carbon cycle cause significant uncertainty to be attached to predictions of future concentrations of atmospheric CO_2. Significant net uptake of fossil-fuel CO_2 by terrestrial ecosystems has been postulated to account for the observed imbalance between annual increments in atmospheric CO_2 from fossil fuel combustion and deforestation and estimated uptake by the oceans, the so-called "missing carbon". The rate of accumulation of CO_2 in the atmosphere varies significantly on interannual and decadal time scales. We are currently unable to account definitively and quantitatively for these observations; different explanations imply different mechanisms, leading to contrasting predictions for the future uptake or release of CO_2 in the global environment. This uncertainty represents a major impediment to the formulation of wise policies for mitigating the growth of atmospheric levels of CO_2.

The AmeriFlux network will address this concern by:

- contributing critical new information to help define the current global CO_2 budget,
- enabling improved predictions of future concentrations of atmospheric CO_2, and
- enhancing understanding of Net Ecosystem Production (NEP) and carbon sequestration of the terrestrial biosphere.

The resulting information will provide the scientific foundation for a range of CO_2 policy and mitigation actions.

Recent studies have demonstrated that long-term, direct measurements of CO_2 flux using the eddy-covariance method can define the magnitude of CO_2 fluxes and net ecosystem production on time scales ranging from hourly to seasonal, annual, and interannual, for intact forest ecosystems. When associated with measurements of environmental conditions, ecological and physiological studies, and modeling, these observations appear capable of elucidating the relationship between CO_2 sequestration and underlying environmental and ecosystem parameters, on time scales long enough to be highly relevant to climate issues (interannual to decadal). The flux measurements provide, therefore, unique fundamental mechanistic, process, and environmental data for evaluating ecosystem models and for assessing the role of terrestrial ecosystems in the global carbon balance.

AmeriFlux investigators will measure the ***net flux*** of CO_2 to/from major terrestrial ecosystems, with the aim of understanding the factors regulating CO_2 exchange, including soil processes, vegetation structure, physiology, and stage of succession, and to determine principal feedbacks that affect the future, such as response to changes in climate, air pollution, and CO_2 concentrations. Some sites will also measure concentrations of various trace gases in addition to CO_2 to help distinguish between fossil fuel and biotic influences and to elucidate the ecosystem response to pollution and anthropogenic nutrient inputs.

The long-term flux sites potentially have the capability to measure, and thus remove, the effects of nearby sources or sinks, thus providing data ideally suited to define large-scale concentration gradients for CO_2 in continental source regions; in addition, by using measurements of distinctive tracers of combustion in combination with observations of CO_2 and CO_2 flux, the sites provide the capability for distinguishing biotic CO_2 exchange from fossil fuel burning. Models attempting to determine uptake by the terrestrial biosphere typically perform an inverse analysis of observed CO_2 concentrations, focusing on data from remote marine stations to avoid the "local" influence of proximate sources on the land surface. Unfortunately, the marine stations are, by design, insensitive to the very processes under study. AmeriFlux data defining concentration gradients over the continents will provide unique new information for understanding current carbon fluxes on the continental scale, complementing the mechanistic and process data obtained from the measurements of fluxes and ecological parameters.

The science plan envisions a network of sites with long-term flux measurements and associated interdisciplinary studies, incorporating comprehensive trace gas measurements at selected sites. The experimental protocols for AmeriFlux will be carefully coordinated among the sites using intercalibrated instruments; sites will be distributed in key biomes of the Americas. A *network strategy* will enhance data quality assuring meaningful intercomparison of site specific results. This strategy will broaden the data base of monitored variables resulting in wider programs of synthesis and model testing. It will safeguard data and make them conveniently available. The network strategy will also make possible new investigations into the spatial and spatial-temporal patterning of carbon exchange.

The network of long-term, interdisciplinary, flux measurement projects, at widely dispersed sites, requires an organizational framework. This includes a science team for each site, a scientific steering committee, and strong managerial and programmatic guidance from an agency program office. The management teams will ensure traceable measurements at diverse sites that are strictly comparable. Working through the AmeriFlux Science Team, the groups within the network will continually refine science goals, assess progress, and seek participants to develop priority new projects or to fill gaps. Participants will be selected in competitive procedures by program offices at the sponsoring agencies. Inter-site calibration exercises and scientific forums for the network will be implemented by the AmeriFlux project office, with scientific oversight by the Project Scientist and by the team as a whole.

The deliverables from the AmeriFlux network are:

(1) **measurements to help define the magnitude of CO_2 sequestration or release in important biomes,**
(2) **determination of the responses of CO_2 fluxes and NEP to changes in climate and in other environmental parameters, such as air pollution and**
(3) **a data base for CO_2 and associated tracer concentrations over North America.**

The network framework will deliver **better science** through intercalibration and team-wide QA/QC, **new science** by integrating ecosystem measurements across diverse landscapes and biomes, and **more accessible and applicable science** to the wider science community, to the public, and to policymakers.

AmeriFlux Science Plan

Introduction

This document discusses rationales and guidelines for the development of AmeriFlux, a network of CO_2 flux measurement sites throughout North and Central America. The AmeriFlux network is intended to address complex issues relating to the global carbon cycle by contributing to the understanding of factors that regulate rates of uptake and net sequestration of CO_2 by major biomes.

The challenges for AmeriFlux are to; (1) extend surface-atmosphere CO_2 flux studies in the spatial domain, producing a continental-scale data base for evaluating the capacity of the terrestrial biosphere to sequester carbon, (2) understand the analogous phenomena in a broad range of major ecosystem types of potential importance in the global carbon budget, (3) extend studies in the temporal domain to define the impact of climate variation and climate change on carbon exchange between the atmosphere and major biomes at decadal time scales, and, (4) contribute to a global data base needed for global carbon cycle model testing and validation.

Scientific Questions

"*Missing Carbon*"

The CO_2 concentration of the atmosphere has risen from 280 parts per million (ppm), prior to the industrial revolution, to a present value exceeding 360 ppm (Keeling and Whorf, 1994; Conway et al., 1994). The long-term increase in atmospheric CO_2 concentration is expected to continue into the future. The magnitude of growth of future concentrations, and associated effects on climate and vegetation, depend critically on the fate of the carbon released. Only 40 to 60% of the anthropogenically released CO_2 remains in the atmosphere (Tans et al., 1990; Conway et al., 1994). Current estimates of the fraction of the missing half of emitted CO_2 being sequestered in the soils and plant biomass of terrestrial ecosystems are very uncertain, with relatively few constraints based on observations such as are available from measurements of the partial pressure of CO_2 over the world's oceans. We also do not understand the large-scale changes in the global system that modulate the interannual increments of atmospheric CO_2. If a significant part of the missing CO_2 is being sequestered by terrestrial vegetation, as inferred in several analyses of the atmospheric record (e.g. Tans et al., 1990; Ciais et al., 1995), we cannot identify the underlying causes and therefore cannot project whether this uptake will accelerate, decelerate, or even reverse, in the future.

Interannual Variations

Important clues to understanding the sink for the "missing carbon" may be the observed interannual variations of the carbon cycle (Conway et al., 1994). Moreover, if global-scale variations can be disaggregated, such that climatic forcing can be discerned (e.g., on the annual time scale), we stand to gain unique insight into the potential response of terrestrial vegetation to climate change and to define a crucial element in the climate-carbon dioxide feedback. Long-

term measurements of CO_2 net exchange and NEP by eddy-covariance (Goulden et al., 1996 a,b) have shown interannual changes in net uptake by midlatitude deciduous forests analogous to anomalies in the global atmospheric accumulation rate (Keeling et al., 1996), with increased rates of annual uptake associated somewhat unexpectedly with positive temperature anomalies. The response of the forest was shown to be due to the dominant influence of length of the growing season. In boreal evergreen forests the opposite influence of temperature anomalies was observed (Goulden et al., 1997; Grelle, 1997), due to the dominant influence of soil and peat decomposition processes.

These recent papers have demonstrated that long-term eddy-covariance measurements, in concert with carefully focused ecological measurements, can potentially delineate the relevant climatic factors, partition the net flux from the whole ecosystem into contributions from major compartments, and quantify the effects of climatic variations on seasonal and annual net uptake of CO_2 by a forest. Particularly significant is the capability to define the influence of soil processes. In boreal forests (Goulden et al., 1997; Grelle, 1997), tundra (Oechel et al., 1992) and wetlands (Gorham, 1995), enhanced CO_2 production from increases in mineralization rates for soil organic matter overwhelm enhanced CO_2 uptake from increased vegetation growth associated with warming, an interaction very difficult to quantify by other methods.

Effects of Atmospheric Fertilization and Air Pollution at Continental and Global Scales

It is controversial whether or not deposition of fixed nitrogen from the atmosphere is increasing the rates of carbon uptake and net production by the terrestrial biosphere (Kauppi et al., 1992; Melillo et al., 1993; Aber, 1993). The "fertilization" effect (e.g. Keeling et al., 1996) of rising CO_2 is also uncertain. Deleterious effects of ozone have been demonstrated for some agricultural crops, and for trees in severely impacted areas, but in remote environments the influence of small, long-term enhancements of ozone on vegetation is unclear (Ollinger et al., 1996).

Long-term ecosystem-level measurements can, if combined with suitable physiological and ecological studies, provide key data on these important interactions between carbon sequestration and global-scale cycles of nutrients, pollutants, and CO_2. For example, some AmeriFlux sites measure ozone concentrations and deposition fluxes (using eddy-covariance) along with CO_2 and water fluxes. The effects of ozone uptake on photosynthetic efficiency, stomatal conductance, or other parameters can be determined by careful examination of data under a variety of environmental conditions (c.f. Ollinger et al., 1996). Due to the correlations that may exist among temperature, wind direction, ozone, and sunlight, and the possible confounding effects of seasonal or longer-term variations in ecosystem function, very large data sets such as those being developed in AmeriFlux continuous measurement programs are essential for this type of analysis.

Constraining and Testing Global Carbon Models

Progress in testing global models of the carbon cycle is essential if we are to use the models as tools for regional and global assessments of CO_2 budgets. These models consist of interactive sub-models, each a sophisticated computer representation of physical, chemical and biological processes. Atmospheric transport is simulated using winds from a General Circulation Model or

from meteorological data with parameterized subgrid processes. Exchanges of CO_2 with the terrestrial biosphere, soils and oceans are computed as functions of environmental conditions using complex sub-models that require detailed *a priori* specification of vegetation type, successional stage, soil characteristics, etc., and associated model parameters.

It is difficult to devise definitive tests of models as complex as these, and in general global carbon models have had only limited tests comparing simulated and observed carbon balances and atmospheric concentrations at daily, seasonal, and annual time scales (e.g. Janecek et al., 1989; Running and Nemani, 1989; McMurtrie et al., 1992; Potter et al., 1993). More work has been done on model intercomparisons (e.g. Law et al., 1996), which have shown that there are large variations in model treatment of both atmospheric transport and biological processes, with major impact on model predictions and on inverse analyses of the carbon budget (e.g., attribution of particular source or sink strengths to parts of the terrestrial biosphere.) Hence, there is a critical need to develop data sets to test models rigorously and to provide direct confirmation of the accuracy of model representations of important phenomena, such as Net Primary and Ecosystem Productivity (NPP and NEP), and long-term carbon sequestration.

When combined with suitable physiological and ecological studies, *long-term ecosystem-level flux measurements are uniquely suited to developing improved, robust models for the global carbon cycle* by challenging simulations of mean seasonal and annual net exchange, sub-model representations of disaggregated ecosystem production and respiration, and predictions of transient response to perturbations on a range of time scales (e.g. Amthor et al., 1994; Fan et al., 1995; Aber et al., 1996; Williams et al., 1996; Frolking et al., 1996; Denning et al., 1996). Since many global models are intended to simulate a representative year, not a specific year, a statistical ensemble of observations is needed for comparison. Other models (Schimel, 1995) highlight the lags in ecosystem response due to feedbacks between CO_2 exchange, temperature, decomposition and nutrient availability. For assessing both types of models, several years of continuous measurements are required.

An innovative recent study (Denning et al., 1996) used the SiB2 ecosystem model coupled with a GCM to develop new ideas about the relationships between large scale sources and sinks and spatial and seasonal variations of atmospheric CO_2. These authors made extensive use of data from long-term flux sites; one important result indicated that the diurnal and seasonal covariance of atmospheric fluxes of heat and momentum and biotic fluxes of CO_2 can lead to global scale atmospheric gradients ("rectification effects"), introducing potentially serious errors into inverse modeling analyses. They showed that long-term flux and concentration measurements can have enormous utility in testing and refining global models. However, this work also demonstrates that many more comprehensive sets of measurements are needed, and that the analysis must be rigorous and meticulous, with deep understanding of both the experimental framework and of the inner workings of the model.

Recent studies at two of the longer-running sites, Harvard Forest (Wofsy et al., 1997) and the WLEF tower in Wisconsin (Bakwin, 1997) showed that trace gas data from flux sites provide unique information on the concentrations of CO_2 in the continental boundary layer. The simultaneous acquisition of data for CO_2 and momentum fluxes, along with concentrations of CO and halocarbon tracers, allows determination of the influence of local (canopy) exchanges, fossil fuel emissions, and large-scale biotic exchange on ambient concentrations. Model runs

can of course be carried out with each of these influences treated separately, and it appears that powerful new tests of models will develop based on the capability to measure ambient concentration data partitioned amongst these influences.

Models have the capability to interpolate and extrapolate measurements in time and space, providing a mechanism for effectively extending to regional and global scales, the information obtained at particular sites; one important goal of AmeriFlux is to develop data to evaluate critically these extrapolations. Both spatially distributed data and temporal ensembles are needed. An important step is to maximize the geographic distribution and biotic representation of the measurements, implying cooperation and coordination between U.S. government entities to support a range of sites across the US, including those of DOE (NIGEC, TCP & PER), NOAA (ATDD, CMDL, OGP), NSF (TECO, Atmospheric Sciences, Polar Programs), and NASA (Ecological Processes and Modeling Program) as well as international programs (e.g. IGBP activities such as BAHC, GCTE, IGAC/TRAGEX, EUROFLUX). Flux measurements by aircraft (ultra-lites, Twin Otter) add spatial components at scales from 10-100 km, potentially providing tests for the scales represented by tower measurements. Careful coordination with aircraft campaigns should be an important adjunct to the tower observations; in turn, the long-term tower sites of AmeriFlux will provide uniquely valuable temporal context and ground truth for airborne measurements.

Meeting at La Thuile, Italy, on Flux Networks

The AmeriFlux concept emerged from the IGBP workshop in La Thuile, Italy, in March of 1995, summarized by Baldocchi et al. (1996): "There is strong scientific need for long-term measurements of carbon dioxide and water vapor fluxes between terrestrial ecosystems and the atmosphere. Data compiled from a network of long-term measurements of canopy CO_2 exchange can be used to: (1) quantify the seasonal variations of carbon dioxide fluxes due to annual changes in insolation, temperature and canopy structure; (2) understand the biological and climatic processes that control canopy scale CO_2 exchange; (3) test carbon balance models; and improve the ability of models to simulate seasonal dynamics with fidelity (e.g., tune phenological switches that initiate budbreak, grow leaves and initiate leaf senescence); and (4) quantify the spatial and temporal (inter-annual and intra-annual) differences in carbon dioxide exchange rates that may be experienced within and among natural ecosystems." The initiation of the AmeriFlux network of long-term measurement sites followed the recommendations presented by this workshop.

Design of a Long-term Flux Network

It is now well-established (Wofsy et al., 1993) that commercially available sonic anemometers and infrared gas analyzers are sufficiently rugged and reliable to measure fluxes of CO_2 and water vapor over and under forest canopies for long periods, extending the techniques developed in shorter studies (e.g. Baldocchi et al., 1988). Strenuous efforts are required however to reduce or eliminate systematic errors (Goulden et al., 1996) and to insure intercomparability of data. The AmeriFlux project is designed to address these measurement issues through a Science Team that carries out intercomparisons and that develops guidelines for experimental protocols, data

sharing, and site selection and development. The Science Team also provides a forum for discussion of measurement issues and for interaction with modelers.

Time Scales for the Measurements

In designing a flux network, planners should recognize the need to elucidate the processes that control the fluxes of carbon dioxide and water vapor into and out of ecosystems and how they are modeled. These processes operate on time scales of hours, days, seasons, years and decades, with particular time scales appropriate for various parts of the ecosystems. Long time scales apply most clearly to soil carbon and moisture budgets and to tree growth. Appropriate flux, climate, soil and biological measurements must be made that will allow scientists to operate and test a hierarchy of concepts that underlie carbon balance models. The time duration of flux measurements must be sufficient to observe the various time scales that are associated with the processes that control the fluxes of carbon dioxide and water vapor into and out of the systems. Measurements of appropriate flux, climate, soil and biological parameters must be made therefore on time scales from hours to years, with meticulous attention to the procedures for data aggregation to avoid accumulation of error.

For example, many of the processes driving carbon dioxide and water vapor exchange are strongly dependent on seasonal changes in climate and on phenology. Extreme climate events (extreme temperature, winds, drought, fire) and biotic stresses (insect and pathogen infestations) are usually not considered in field experiments or in models, but these events influence the carbon cycle and net production of an ecosystem on both long and short time scales. Mediterranean or boreal ecosystems, for example, operate on 20 to 100 year fire cycles (Bonan and Shugart, 1989). Boreal and tundra systems store vast amounts of carbon in peat, which is very sensitive to long-term temperatures in deep soil strata (Oechel and Billings, 1992; Gorham, 1995; Goulden et al., 1998; Grelle, 1997).

Short-term (hours, days and weeks) flux measurements can miss vital environmental interactions. For example, measurements made during a wetter than normal year would be of little value in characterizing system response to drought. Such short-term measurements would also lead to inaccurate estimates of the carbon sink strength of ecosystems. In boreal systems, for example, the fire regime, successional stages of ecosystem redevelopment, and the ablation of deep peat and soil carbon reservoirs must be understood. Long-term (months, seasons, years) flux measurements increase the likelihood of observing extreme events, while defining the response of longer-lived C reservoirs. Such data provide unique information for testing and improving ecosystem models.

In order to characterize the key factors which modulate C exchange in ecosystems, multi-year investigations, as continuous as possible, are planned. Experience has shown that changes are often required in the experimental design during the first year, adding uncertainty to the comparison with later years, and climate variations such as El Nino often last 2 years. Thus a 5-year data set appears to be needed to obtain first-order information on the response of the system to climate variability. There is no obvious upper limit on the duration of the measurement period beyond which it could be presumed that further observations would not contribute to program goals. Some sort of "sunset" criteria should be developed, and reviewed over time, to ensure that the results from individual sites and from the network justify continuing costs.

Spatial Coverage; Sampling of Biomes

The biosphere consists of numerous and diverse ecosystems. To assess the carbon budget of the biosphere we need to make measurements in a representative selection of ecosystems, with as much replication as feasible. This requirement forces AmeriFlux to focus on dominant ecosystems. Modelers assessing vegetation dynamics and global change do not deal with individual species, but instead adopt the concept of functional types. This approach appears promising for the distribution of AmeriFlux sites.

The number of operational carbon flux measurement sites has increased rapidly in the last several years (Table 1, upper portion) with many more studies planned or having just begun, operations (Table 1, lower portion). The results from the handful of longer running sites have highlighted the value of the eddy-covariance technique, underscored the need for consistency and intercomparability among the sites, and provided a research agenda of questions that must be addressed to refine this approach.

Logistics and practical issues have tended to encourage a placement of flux measurement sites near institutes with competent personnel and reasonable infrastructure. Such placement helps in general to restrain costs and to entrain new talent. Indeed, the availability of highly trained and motivated personnel will almost certainly be a pacing factor in the evolution of the network of long-term flux measurement sites. An examination of Table 1, however, suggests that even with the planned stations there remain gaps in the coverage of North American biomes. These gaps, in arid and early successional systems, may need to be addressed in the future.

Maximizing Intercomparability while Fostering a High Level of Innovation

A fundamental goal of AmeriFlux is to establish and maintain long-term intercomparability of results between the sites. Precise intercomparability is the key to exploiting and using what may be subtle spatial and temporal trends in the data across the sites to answer additional questions about the role of terrestrial systems in the carbon cycle. This intercomparability is one of the essential factors which transform a group of independent sites into a *network* which can address new questions and maximize the scientific return from all of the stations. It is achieved by consistency in technique, strict attention to calibrations (and traceability to standards), and site intercomparisons in, for example, software processing of standardized flux data files and comparison of flux system response to a roving standard.

In order to participate in the flux network, each site must make a commitment to obtain multi-year, continuous measurements of carbon dioxide, water vapor, heat, and momentum fluxes using the eddy-covariance technique. Measurements should also be made of other environmental and ecological variables that are needed to interpret the fluxes (see “Scope of Measurements” below). Each site must participate in network intercalibration and QC activities and is required to submit processed data to the publicly-available central data archive in a timely manner. Each site should maintain copies of all raw flux system data. All sites are also to produce World Wide Web pages describing site characteristics and methods, and summarizing preliminary results.

The measurement and interpretation of surface-atmosphere carbon fluxes is still a developing science. Important questions remain regarding the measurement of nocturnal fluxes, identifying the influence of anthropogenic emissions, the role of atmospheric dynamics, partitioning fluxes into different ecosystem components and many other factors. Different groups are expected to have different objectives and approaches. This is healthy for the overall success of the program and should be encouraged. Thus, another goal of AmeriFlux is to promote a high level of innovation in carbon flux research. This is already being realized in studies of the influence of non-ideal terrain, pollution effects, stable isotope discrimination, and detailed partitioning of CO_2 sources and sinks at various sites. At other sites, research is focused on the influence of planetary boundary layer dynamics, experimental manipulation of the ecosystem, or detailed studies of the flux source ("footprint") regions. A broad range of innovation and investigation will be a strength of the AmeriFlux network by identifying problems and solutions at specific sites that may have applicability at other sites or across the whole network.

Scope of Measurements

An eddy-covariance flux system mounted on a tower measures net carbon dioxide fluxes between the biosphere and atmosphere. To understand the processes that are responsible for this integrated value, it is vitally important to *define the fluxes from the components of the system*, e.g. leaves, boles, roots, and soil. Chamber or eddy-covariance measurements over the soil are a means of assessing respiratory fluxes of carbon from the rhizosphere. Cuvette measurements on leaves can assess photosynthetic and stomatal conductance model parameters and can determine the physiological status of leaves. Periodic and concurrent measurements of soil respiration and leaf physiological function in an ecological context (i.e., species composition, grazing pressure, etc.) are required to complement ecosystem-level observations. Accurate and reliable observations are needed for a wide range of environmental and ecological variables, including air and soil temperature, humidity, soil moisture, incident and reflected solar radiation (PAR, total) and longwave incoming and outgoing radiation, rainfall, and rain composition. Tables 2 and 3 summarize the set of parameters identified as required (core) or desired by Baldocchi et al. (1996) as modified by a subcommittee of the AmeriFlux science team.

A multi-disciplinary, fully-integrated and focused study is needed for each site in order to obtain the full suite of observations and to acquire understanding of the underlying processes. Without definition of the environmental forcings and improved mechanistic understanding, observations at a particular site cannot be extended to assess CO_2 sequestration, or response to climate forcing, on the large spatial scales needed for analysis of global CO_2 concentrations; the full suite of observations is essential for testing and improving models.

Quality Assurance, Quality Control, Site Calibration, and Data Archive

The observational technique is subject to a wide variety of possible systematic errors, some generic and some site-specific. In order for site results to be comparable, and to lessen the cost impact and time delay associated with the significant learning curve for site development, considerable emphasis is being placed on quality assurance, cross-comparisons, and calibrations. A relocatable flux measurement system has been assembled by the AmeriFlux Project Scientist, Dr. David Hollinger, and deployed at several sites. The data will be compared at all levels, from

high-frequency measurements, through the data processing to the production of fluxes and other values. Similarly, maintaining a high degree of accuracy in environmental measurements such as CO_2 concentration and temperature is needed so that subtle variation in the spatial and temporal patterns of these variables can be exploited for the interpretation of flux patterns. Detailed calibration and comparison protocols will be developed by the AmeriFlux Science Team.

A multi-site data archive is being developed that will greatly enhance the scientific value and the policy applications of the network. It will leverage the work done at NIGEC to develop publicly-available data resources at each regional center. The Carbon Dioxide Information Analysis Center (CDIAC) at Oak Ridge in conjunction with the ORNL-DAAC will manage the archive. Investigators will be required to submit fully-documented data sets in a short period after acquisition, allowing for time needed to check and assure data quality. CDIAC has the expertise to help all investigators format and quality assure their data for archiving. They have a superb track record of archiving, quality assuring, and disseminating greenhouse gas data for use by the research community. CDIAC is also maintaining the AmeriFlux web site (http://www.esd.ornl.gov/programs/NIGEC/).

Synthesis/Integration of Network Data

All data will be available to researchers subject to fair-use conditions decided upon by network members in collaboration with the funding agencies. These conditions are published on the AmeriFlux web site. It is expected that teams from each site will analyze and publish data from their own site and that groups of researchers from both inside and outside the network will utilize network data to investigate spatial patterns of NEP, carbon sequestration, and other factors. Since it is a goal of AmeriFlux to obtain data for the purposes of developing, constraining, and testing models, a formal collaboration between the modeling community and AmeriFlux (perhaps similar to VEMAP) should be developed.

National Institute for Global Environmental Change (NIGEC) role in the Network

DOE, through NIGEC and the TCP supports over half of the AmeriFlux researchers in Table 1. NIGEC is organized into regionally-distributed institutes with scientific and programmatic oversight at the national level. Regional directors and management committees have the potential to lead, focus and oversee the scientific effort, and the programs are reviewed thoroughly each year by NIGEC's National Technical Advisory Committee (NTAC) and by the National office. This structure makes the Regional Centers of NIGEC ideally situated for implementing a spatially distributed network using their special knowledge of regional resources and capabilities.

NIGEC has encouraged development of coherent, focused (but not narrow) programs at the regional centers and NIGEC support has been long-term. Thus long-term flux measurement sites with a broad range of associated ecological and atmospheric studies have developed naturally at several locations. The NIGEC framework has provided a strong starting point for developing the coherent network of flux stations envisioned for AmeriFlux.

NIGEC is contributing to this effort by:

(1) developing a strong, coherent component of NIGEC programs across regions to establish and sustain sites making long-term flux measurements and by

(2) forming science teams for the sites, with science and program objectives as described above, analogous for example to the NASA science teams in ER-2 experiments.

The National Director, key Regional Directors, and the DOE program manager are jointly managing the administrative aspects. A senior scientist (currently David Hollinger) serves as Science Team chair, with oversight provided by a science steering committee working with the NIGEC National Technical Advisory Committee, the National Director, and DOE program manager for NIGEC and TCP.

Participation in the science team is decided on a competitive basis with full peer review, in which proposals responding to the NIGEC RFPs or to other programs are judged, in part, by how well they address the goals stated in the science plan for the network.

Value of a Network

It should be clear from the preceding discussion that a properly instituted network will result in *better science*, *more accessible science*, and *new science*. These benefits of the AmeriFlux strategy are summarized below.

Better Science.

The AmeriFlux strategy focuses on insuring precision in the physical measurements via network-wide calibration and QC protocols and uniformity of analysis via software and data intercomparisons. These steps greatly increase the statistical power of comparisons between the sites and through time and thus enhance the scientific understanding of ecosystem carbon exchange that results from these comparisons. Similarly, a network strategy results in the collection of a common set of variables that will likely exceed what most researchers would obtain on their own. This expanded breadth of independent variables will result in the development of a wider program with an integrated database for synthesis and also for testing and developing process-level models. The enhanced communication amongst network members (resulting from AmeriFlux meetings, the web site, a listserver, etc.) improves the science in several ways. First, it facilitates the rapid sharing and development of improved measurement and analysis methodologies and “tricks of the trade”. Secondly, it brings together researchers that work in very different sites with a range of biological and meteorological conditions. This helps researchers separate the complex interactions between site biological and meteorological conditions and the confounding effects of less-than-optimum terrain, leading to improved understanding of the underlying processes. Finally, a network also permits enhanced leverage on members over the distribution and documentation of data so that the site-specific data can more

quickly and clearly reach the user community. This will be especially valuable as synthesis and modeling efforts get under way.

More Accessible Science.

To the scientific community-- The data archiving and support of AmeriFlux by CDIAC in conjunction with the ORNL-DAAC will insure that data from the individual stations is quality controlled and widely available. Specific advantages of this network approach include enhanced user support allowing compatibility across computer platforms, long-term accessibility of data, data backup and security, and an institutional memory of AmeriFlux results.

To the public and policy-makers-- **Results from the network will have greater visibility to the public and to persons in the policy arena than would an equal number of individual sites. Through the *Science Team*, the understanding of policy-relevant questions by participating scientists and the communication of policy-relevant results to society will be enhanced.**

New Science.

The enhanced intercomparability resulting from network protocols and procedures allow network-wide data to be used in a variety of ways. These include spatial comparisons along environmental gradients or among and within biomes. It should also be possible to apply formal geostatistical techniques to the data from networked stations. An additional area for exploration with a network is that of spatial-temporal analysis. There is a large degree of spatial and temporal coherence in the atmosphere which can be exploited in the formulation and testing of hypotheses relating to the processes of ecosystem C exchange. Cold air outbreaks from Canada, for example, occur coherently across large areas of the eastern and midwestern U.S. The degree to which large-scale short-term events (such as cold air leading to early frosts) regulate carbon exchange of large geographical areas can be easily addressed with the current network design. Similarly, it will also be possible to investigate the impact of short-term, high-level pollution events.

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Table 1. List of investigators, conducting or planning long-term studies of carbon exchange over vegetated ecosystems using the eddy-covariance method.

Ongoing studies

PI	*Institution*	*field site*	*vegetation*	*current length*
Wofsy[+o]	Harvard Univ	Harvard Forest, MA	deciduous forest[†]	7
Wofsy	Harvard Univ.	Thompson, MAN	boreal spruce[†]	3
Baldocchi[+o]	NOAA/ATDD	Oak Ridge, TN	deciduous forest[†]	3
Grace	U Edinburgh	Manaus, BRASIL	tropical forest	2
Hollinger[+o]	USDA-FS	Howland, ME	conifer[†]	2
Parker	Smithsonian	Edgewater, MD	deciduous forest[†]	2
Bakwin	NOAA/CMDL	North Wisconsin	mixed forests[†]	1
Black	U B C	Prince Albert, SASK	boreal aspen[†]	1
Desjardins	Ag Canada	Ottawa, ONT	crops SC;	
Gholz [o]	Univ. Fla	Gainesville, FL	slash pine[†]	1
Ham [o]	Kansas State	Konza Prarie, KA	C4 prairie[†]	1
Oechel	San Diego	northern Alaska	tundra[†]	1, 3 (SC)
Oechel	San Diego	southern CA	chaparral[†]	1, 2 (SC)
Unsworth	Oregon State	western Oregon	Ponderosa[†]	1
Verma[+o]	U Nebraska	Shidler, OK	tallgrass prarie[†]	1
Verma[+o]	U Nebraska	Ponca City, OK	wheat[†]	1
Euroflux	15 sites	Europe	various forest	1 – 3

planned studies (see notes)

Investigator	*Institution*	*Site location*	*vegetation*
Black	U B C	Vancouver, B.C.	Douglas fir[†]
Dunin	CSIRO	Wagga Wagga,AUST	crops
Field	Carnegie Inst.	Stanford, CA	grassland[†]
Grimmond [o]	Indiana U	Monroe, IN	decid. forest[†]
Jarvis	U Edinburgh	Prince Albert,SASK	boreal spruce
Katul [o]	Duke Univ.	Durham, NC	loblolly pine[†]
Massman	USDA-FS	Glacier Lakes, WY	sub-alpine fir[†]
Meyers	NOAA	Bondville	crops
Monson	U Colorado	Niwot Ridge, CO	sub-alpine fir[†]
Oberbauer [o]	Florida U	La Selva, Costa Rica	tropical forest[†]
Paw U [o]	UC Davis	Wind River, WA	Douglas fir[†]
Smith [o]	U Wyoming	Wyoming	various[†]
Teeri [o]	U Michigan	UMBS, MI	mixed forest[†]
LBA	many teams	Amazon Basin	forests/pastures

Notes:
† AmeriFlux site
SC denotes (discontinuous) seasonal campaigns.
o NIGEC/DOE supported.

Table 2. Recommended core and desired Meteorological and Flux Measurements to be carried out at each AmeriFlux site.

I. EDDY FLUX DENSITIES

A. CORE MEASUREMENTS

1. sensible heat
2. latent heat (evapotranspiration)
3. CO_2
4. momentum

II. STORAGE FLUXES

A. CORE MEASUREMENTS

1. CO_2 storage in canopy air layer (CO_2 profile)

B. DESIRED MEASUREMENTS

1. heat storage in canopy air (temperature profile)

III. SOIL FLUXES

A. CORE MEASUREMENTS

1. CO_2 flux
2. heat flux

B. DESIRED MEASUREMENTS

1. water vapor flux

IV. METEOROLOGY

A. CORE MEASUREMENTS

1. air temperature (ventilated shielded)
2. net radiation
3. global radiation or photosynthetically active photon flux density (PPFD)
4. RH, or dewpoint temperature or wet bulb temperature
5. precipitation
6. wind speed and direction

B. DESIRED MEASUREMENTS

1. diffuse radiation or PPFD
2. longwave radiation
3. canopy wetness
4. pressure
5. estimated aerodynamic roughness length and zero plane displacement

Table 3. Recommended core and desired environmental, soil and biological measurements for forested ecosystems for data interpretation and model execution and testing and application (adopted by the AmeriFlux Science team on the recommendation of the Ecological Measurements Subcommittee of the Science Team, Oct. 29-30, 1997, St. Louis, MO; contributors to this list were: Jiquan Chen, Ken Clark, Peter Curtis, Henry Gholz, Dave Hollinger, Ray Hunt, Hank Loescher, Ram Oren, and Jess Parker.). A similar list for grassland and crop systems has yet to be finalized although a tentative list is included.

Statement of the Committee: The overall objectives of making these measurements are to facilitate among-site comparisons and to provide biological process-level interpretation to the eddy-covariance flux measurements. Matching ecological measurements with parameterization needs of forest carbon and nutrient flux models is important for both these objectives.

This list is divided into three sections: stand characteristics, stand physiology, and soil characteristics. Within each section we enumerate 'Core' and 'Desired' measurements. Following each measurement is the suggested frequency of collection and occasionally additional notes in brackets. For the most part, no mention is made regarding methods. We have attempted to keep this list as short as possible, recognizing that not all sites are appropriately staffed or funded to carry out extensive ecophysiological studies. However, we feel very strongly that a core set of ecological measurements is critical to the success of the AmeriFlux network.

FORESTED ECOSYSTEMS

I. STAND CHARACTERISTICS

A. CORE MEASUREMENTS

1. Species composition: single
2. Aboveground biomass: single, {basal area, sapwood area, stem density; by species}
3. Root biomass: single, {soil cores}
4. Canopy height: single
5. Maximum leaf area index: annual, {direct - annual litterfall and/or indirect - IPAR}
    a) Seasonal change in canopy LAI: annual
    b) Understory LAI: annual
6. Max IPAR: annual.
7. Seasonal litterfall: annual
8. Site history: single

B. DESIRED MEASUREMENTS

1. LAI profile: single
2. Ground (soil and litter) albedo and canopy albedo: single
3. High resolution, muti-spectral satellite image: annual
4. Atmospheric N deposition: annual

II. STAND PHYSIOLOGY

A. CORE MEASUREMENTS

1. Annual aboveground growth increment: annual
2. Bole temperature: repeated
3. Leaf total nitrogen and carbon content: repeated
    a) Specific leaf area: repeated
    b) Total woody tissue and sapwood nitrogen and carbon content: annual

B. DESIRED MEASUREMENTS

1. Stomatal conductance: repeated {max, leaf water potential or VPD at closure}
    a) Minimum spring leaf water potential
    b) Sap flow: repeated
2. Annual below ground growth increment: repeated {in-growth cores, minirhiz tubes}
3. Leaf photosynthesis: repeated
    a) light response curves: annual {Ic, Amax}
    b) A/C_i curves: annual
4. Foliar and bole respiration: repeated
5. Leaf and woody tissue total non-structural carbohydrate content: repeated
    a) Tissue $^{13}C/^{12}C$ ratio: annual
    b) Atmospheric $^{13}C/^{12}C$ ratio: repeated

III. SOIL CHARACTERISTICS

A. CORE MEASUREMENTS

1. Soil temperature profiles: repeated
2. Soil moisture: repeated {content, capacity}
3. Soil bulk density and porosity: single
    a) soil texture (clay, sand, silt): single
    b) root depth: single
4. litter decomposition rate: annual {bags}

B. DESIRED MEASUREMENTS

1. Litter carbon, nitrogen, lignin: single
2. Soil carbon and nitrogen: single
3. Nitrogen mineralization rate: single
4. Soil thermal and hydraulic conductivities: single
5. Cation exchange capacity: single

GRASSLAND AND CROPS (tentative list)

I. VEGETATION CHARACTERISTICS

A. CORE MEASUREMENTS
1. Species composition: single
2. Aboveground biomass: single
3. LAI
4. Canopy height
5. Site History

B. DESIRED MEASUREMENTS
1. Root biomass
2. Ground (soil and litter) albedo and canopy albedo: single
3. High resolution, muti-spectral satellite image: annual

II. STAND PHYSIOLOGY

A. CORE MEASUREMENTS
1. Annual aboveground growth increment: annual
2. Leaf total nitrogen and carbon content: repeated
    a) Specific leaf area: repeated

B. DESIRED MEASUREMENTS
1. Stomatal conductance: repeated {max, leaf water potential or VPD at closure}
    a) Minimum spring leaf water potential
    b) Sap flow: repeated
2. Annual below ground growth increment: repeated {in-growth cores, minirhiz tubes}
3. Leaf photosynthesis: repeated
    a) light response curves: annual {Ic, Amax}
    b) A/C_i curves: annual
4. Foliar respiration: repeated
5. Leaf total non-structural carbohydrate content: repeated
    a) Tissue $^{13}C/^{12}C$ ratio: annual
    b) Atmospheric $^{13}C/^{12}C$ ratio: repeated

III. SOIL CHARACTERISTICS

A. CORE MEASUREMENTS
1. Soil temperature profiles: repeated
2. Soil moisture: repeated {content, capacity}
3. Soil bulk density and porosity: single
    a) soil texture (clay, sand, silt): single
    b) root depth: single

B. DESIRED MEASUREMENTS
1. Soil carbon and nitrogen: single
2. Nitrogen mineralization rate: single
3. Soil thermal and hydraulic conductivities: single
4. Cation exchange capacity: single