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Strategies for measuring and modelling carbon dioxide and water vapour fluxes over terrestrial ecosystems

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Abstract

Continuous and direct measurements of ecosystem carbon dioxide and water vapour fluxes can improve our ability to close regional and global carbon and hydrological budgets. On this behalf, an international and multidisciplinary group of scientists (micrometeorologists, ecophysiologists and biogeochemists) assembled at La Thuile, Italy to convene a workshop on 'Strategies for Monitoring and Modelling CO_2 and Water Vapour Fluxes over Terrestrial Ecosystems'. Over the course of the week talks and discussions focused on: (i) the results from recent field studies on the annual cycle of carbon dioxide and water vapour fluxes over terrestrial ecosystems; (ii) the problems and pitfalls associated with making long-term flux measurements; (iii) alternative methods for assessing ecosystem carbon dioxide and water vapour fluxes; (iv) how direct and continuous carbon dioxide and water vapour flux measurements could be used by the ecological and biogeochemical modelling communities; and (v) if, how and where to proceed with establishing a network of long-term flux measurement sites. This report discusses the purpose of the meeting and summarizes the conclusions drawn from the discussions by the attending scientists.

There was a consensus that recent advances in instrumentation and software make possible long-term measurements of carbon dioxide and water vapour fluxes over terrestrial ecosystems. At this writing, eight research teams have conducted long-term carbon dioxide and water vapour flux experiments and more long-term studies are anticipated. The participants advocated an experimental design that would make long-term flux measurement valuable to a wider community of modelers, biogeochemists and ecologists. A network of carbon dioxide and water vapour flux measurement stations should include ancillary measurements of meteorological, ecological and biological variables. To assess spatial representativeness of the long term and tower-based flux measurements, periodic aircraft-based flux experiments and satellite-based assessments of land cover were recommended. Occasional cuvette-based measurements of leaf-level carbon dioxide and water vapour fluxes were endorsed to provide information on the biological control of surface fluxes. They can also provide data to parameterize ecophysiological models. Flask sampling of stable carbon isotopes was advocated to extend the flux measurements to the global scale.

Keywords: biogeochemistry, carbon balance, carbon dioxide, CO_2 flux monitoring network, eddy covariance

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1 Introduction

Carbon dioxide and water vapour play important roles in the functioning of our earth's climate and biology. Regarding climate, carbon dioxide and water vapour are strong absorbers of infrared energy. Their presence in the atmosphere causes the mean surface temperature of the earth to be warmer than the radiative temperature that would otherwise occur due to the balance between absorbed solar and outgoing terrestrial radiation. Without the biogeochemical cycling of carbon dioxide and water vapour between atmospheric, terrestrial and oceanic reservoirs, life, as we know it, would be unsustainable. The fixation of CO_2 by photosynthesis converts solar energy to forms of chemical energy that are used for the growth and maintenance of plants and the sustenance of trophic communities. Water, being a universal solvent, is the key medium for the solution, transport and uptake of important nutrients by plants and microbes.

Major changes are occurring in the chemical composition of our atmosphere. The secular increase in carbon dioxide concentration is the most widely known change. Since the industrial revolution, the CO_2 concentration of the atmosphere has risen from 280 ppm to near 360 ppm (Keeling and Whorf, 1994; Conway *et al.*, 1994). Year to year changes in atmospheric carbon dioxide concentrations are due to imbalances between the rate that sources emit and sinks remove CO_2 into and out of the atmosphere (fossil fuel and biomass combustion and plant and microbial respiration release CO_2 into the atmosphere and carbon chemistry of the oceans and plant photosynthesis remove it). Possible adverse effects of elevated levels of atmospheric CO_2 include global warming and perturbations of regional precipitation and soil moisture patterns (Manabe and Stouffer, 1994). Potential benefits of rising CO_2 concentrations include stimulation of photosynthesis, crop growth and water use efficiency (Eamus and Jarvis, 1989; Mussleman and Fox, 1991). On the other hand, improved biomass production may not be experienced by all natural ecosystems. Limitations of soil nitrogen and increases in soil respiration may offset or restrict biomass gains stimulated by additional carbon dioxide (McMurtrie *et al.*, 1992; Melillo *et al.*, 1993).

A full understanding of the global carbon cycle is needed to understand how it will respond to possible perturbations in climate and ecology. Knowledge about the carbon cycle is also critical for developing societal policies on future energy use. Yet, for many reasons our understanding of the global carbon budget is incomplete. At present, 40–60% of the anthropogenically-released CO_2 remains in the atmosphere (Tans *et al.* 1990; Conway *et al.*, 1994). We do not know, with confidence, whether the missing half of emitted CO_2 is being sequestered in the deep oceans, in soils or in plant biomass. Uncertainties about flows of carbon into and out of major reservoirs also result in an inability to simulate year to year variations of the annual increment of CO_2, its latitudinal variation across the globe and seasonal variations of its amplitude (Tans *et al.*, 1990; Conway *et al.*, 1994).

Carbon balance models, despite their flaws, provide us with the capacity to interpolate and extrapolate measurements in time and space. Hence, they are and will be a key tool for making regional and global assessments of the carbon balance. Mechanistic carbon balance models also have the potential for predicting how ecosystems will respond to changes in atmospheric CO_2, temperature, nitrogen loading and precipitation. Yet, many important and widely used carbon balance models have not been satisfactorily validated (i.e. Janecek *et al.*, 1989; Running and Nemani, 1989g; McMurtrie *et al.*, 1992; Potter *et al.*, 1993).

Most data for testing ecosystem, regional and global carbon models stems from long-term monitoring of carbon dioxide concentrations (Keeling and Whorf, 1994; Conway *et al.*, 1994) and biomass inventories (i.e. Kauppi *et al.*, 1992; Houghton, 1993). Monitoring CO_2 concentration and biomass changes, alone, are insufficient to gain a thorough understanding of local, regional and global carbon budgets since they are indirect measures of net ecosystem carbon dioxide exchange. There is strong scientific need for direct and long-term measurements of carbon dioxide and water vapour fluxes between terrestrial ecosystems and the atmosphere. Data compiled from long-term measurements of canopy CO_2 and water vapour exchange can be used to:

1 quantify the seasonal variations of carbon dioxide and water vapour fluxes due to annual changes in insolation, temperature and canopy structure;
2 understand the biological and climatic processes that control canopy scale CO_2 and water vapour exchange;
3 test carbon balance and hydrological models;
4 improve the ability of models to simulate seasonal dynamics (e.g. tune phenological switches that initiate budbreak, grow leaves and initiate leaf senescence);
5 quantify the spatial and temporal (inter-annual and intra-annual) differences in carbon dioxide and water vapour exchange rates that may be experienced within and among natural ecosystems.

Recognizing a need for more long-term measurements, we recently convened a workshop on 'Strategies for Long-term Studies of CO_2 and Water Vapour Fluxes over Terrestrial Ecosystem'. The explicit goals of the workshop were to assess the state-of-art of making long-term flux measurements and to obtain advice and consensus on the direction of future long-term flux research. The main objectives of this paper are to summarize some of the findings that were reported at the workshop and to transmit some of the discussions that transpired. An implicit aim of this paper is to encourage cooperation, participation and standardization among current and future practitioners. In the following sections we evaluate the available measurement methods and present a conceptual plan for implementing a network of flux measurement sites.

2 What and how?

There is a dearth of long-term and direct measurements of whole ecosystem CO_2 exchange in the literature. Most published reports on net carbon exchange over vegetation are derived from studies made during two to three week periods of the growing season (Verma *et al.*, 1986; Valentini *et al.*, 1991; Baldocchi and Harley, 1995). Only a few teams have ventured to measure and publish annual-scale flux measurements of CO_2 over whole ecosystems (Wofsy *et al.* 1993; Vermetten *et al.*, 1994).

Although more long-term carbon dioxide and water vapour flux measurements are desirable, long-term measurements at individual site are inadequate by themselves. A network of flux measurement stations, sited across a spectrum of ecosystems, would provide a better insight on how, how much and when terrestrial ecosystems inhale and exhale carbon dioxide and transpire water vapour.

One conclusion drawn at the workshop is that it is technically feasible to establish a network of long-term CO_2 and water vapour flux measurement. Rugged, stable and waterproof sonic anemometers and infrared gas analysers are now available for measuring wind velocity, CO_2 and water vapour fluctuations. And advances in software and personal computers facilitate the real-time acquisition of eddy covariance data.

In designing of a flux network, planners should be cognizant of the time and space scales at which the ecosystems operate. They also need to consider the physical and biological processes of that control the fluxes of carbon dioxide and water vapour into and out of the system. Regarding time scales, short-term measurements (hourly to daily time scales) are needed to assess the roles that certain environmental (light, temperature, humidity deficits) and physiological (stomatal conductance) variables have on canopy-scale fluxes of carbon dioxide and water vapour. An ensemble of daily fluxes, over the course of a year, are needed to provide information on how mass and energy fluxes respond to seasonal changes in climate and phenology.

Extreme climate events (extreme temperature, winds, drought, fire) and biotic stresses (insect and pathogen infestations) are not considered in most field experiments, but these events can influence the carbon cycle of an ecosystem on an interannual time scale. Multi-year flux measurements would allow the investigator to observe the impact of extreme events and would provide unique data for testing and improving ecosystem models (Goulden *et al.*, p. 169, this issue). Co-locating flux measurement sites near deposition monitoring stations would allow investigators to examine whether or not the long term deposition of acidic compounds is affecting the carbon and water exchange of intact ecosystems (Kauppi *et al.* 1994).

To assess the biosphere component of the global carbon dioxide cycle, it will also be necessary to translate point measurements (the canopy scale) to areas (the landscape, regional and global scales). Hence, planners should recognize that long-term flux measurements at a specific site may not represent an entire landscape. Mediterranean or boreal ecosystems, for example, operate on 30- to 100-year fire cycles (Bonan and Shugart, 1989). These landscapes consist of a mosaic of sites that are burned, regenerating and mature. In hilly and mountainous terrain, local variations in soil, climate, water availability and vegetation will affect the representativeness of fluxes measured at a given tower site (Running *et al.*, 1989).

Ancillary measurements of a suite of climate, soil and biological variables musts be made to enable scientists to interpret the flux measurements and to parameterize and test a hierarchy of carbon balance and hydrological models. A favoured approach towards assessing carbon dioxide and water vapour fluxes of ecosystems involves a combination of measurement and modelling techniques. As expected, tower-based flux measurements can only provide information on hourly, daily, seasonal and annual fluxes of carbon and water. Periodic field measurements of soil and vegetation properties and spatial representativeness will be needed to make the tower data applicable to the scientific community at-large. Surveys of soil thermal and hydraulic properties and vegetation classes and architectural characteristics can be attained through field transect measurements. More frequent studies on leaf physiology are needed to parameterize leaf photosynthesis and stomatal conductance models and to provide information on how leaves acclimate to changes in climate as the growing season proceeds. To extend tower-based data to the landscape scale, periodic field campaigns, using aircraft-mounted flux and remote sensing instruments, will be needed. Finally, leaf-to-canopy integration models and satellite-driven scaling models of CO_2 and water vapour exchange are required to extend empirical measurements to mechanistic and global ecosystem and biogeochemical cycling models (i.e. Melillo *et al.*, 1993; Potter *et al.*, 1993). Close interaction with models will also provide testable hypotheses, that in turn will drive the experimental measurement programmes.

3 Measurement methods and uncertainties

Various methods of assessing carbon and water fluxes were discussed at the workshop. Tower and aircraft-mounted micrometeorological, chamber and sap flow techniques and isotope budgets received attention. Each method, that was discussed, had positive and negative attributes. Next, we highlight particular strengths and weaknesses of the key measurement methods.

3.1 Eddy covariance method

At the local scale, the eddy covariance method is a tried and true method for measuring trace gas flux densities between the biosphere and atmosphere (e.g. Baldocchi *et al.*, 1988; Lenschow, 1995; Moncrieff *et al.*, p. 231, this issue); vertical flux densities of CO_2 and water vapour between the biosphere and the atmosphere are proportional to the mean covariance between vertical velocity (w') and scalar (c') fluctuations. While the method has many strengths – it is the only direct method of measuring trace gas fluxes between the biosphere and atmosphere – it is not without limits. Random, fully systematic and selective errors are associated with eddy covariance flux measurements.

The noted errors have atmospheric, surface and instrumental origins. Most random errors are associated with violations of atmospheric stationarity and the consequences of intermittent turbulence. When the atmosphere is unstable, vertical and horizontal motions have length scales that are comparable with the height of the planetary boundary layer. The infrequent passage of large scale eddies is one cause of run to run variability of surface fluxes. The intermittent nature of this turbulence causes the temporal sampling error to be at least 10%, on an hourly time scale. Greater sampling errors will occur when the thermal stratification of the atmosphere is stable, when the sky is partly cloudy and over inhomogeneous terrain. When the atmosphere is stable, turbulence is suppressed. Chaotic instabilities, associated with the non-linear properties of turbulence cause turbulent fluxes to be highly variable in time. Under a partly cloudy sky, the land surface is a mosaic of sunlit and shaded patches. This effect causes the fluxes of mass and energy to be highly variable in space. Other errors associated with the composition of the underlying surface arise from the effects of complex terrain and the heterogeneity of surface features on wind flow, turbulence and source-sink strengths. Such surface-induced errors tend to be selective in nature and can be minimized through proper site selection.

Instrument errors are systematic. They arise from a sensor's insufficient time response, the spatial separation between a sensor and an anemometer, digital filtering of the time signal, aerodynamic flow distortion from support towers, calibration drift, loss of frequency via sampling over a finite space and sensor noise (Moore, 1986; Moncrieff *et al.*, p. 231, this issue). These errors can be minimized through sensor and experiment design.

Two instrument configurations are used when applying the eddy covariance method to measure CO_2 and water vapour fluxes (Leuning *et al.*, p. 241, this issue). One approach uses an open path infrared gas analyser (e.g. Auble and Meyers, 1992). This configuration introduces minimal distortion to wind flow and does not introduce a lag between the sensing of wind velocity and scalar fluctuations. Unfortunately, a commercial version is not widely available. The physical principle on which the instrument is based causes it to measure CO_2 density, not the preferred quantity, mixing ratio. Consequently, CO_2 density fluctuations need simultaneous measurements of temperature and humidity fluctuations to assess fluctuations of CO_2 mixing ratio (Webb *et al.*, 1980).

The other approach draws air through a tube and senses CO_2 concentrations with a closed-path infrared absorption analyser. Numerous brands of closed-path CO_2 sensors are available commercially. One advantage of using the closed-path method is the ability to house the sensor away from extremes in temperature and humidity. Another advantage is a capacity to introduce calibration and zero gases into the sensor, automatically and at regular intervals, for quality assurance and control. The effect of temperature fluctuations on the assessment of CO_2 mixing ratio is minimized because temperature fluctuations are dampened by heat transfer through the sampling tube.

The closed-path method can suffer from an attenuation of concentration fluctuations as air is sampled through a sampling tube. Typically, this error is less than 10% (Leuning and Moncrieff, 1990), but it is a function of tube diameter, tube length and flow rate. Sampling air through a tube also requires frequent assessment of the time it takes parcels of air to travel from the tube intake, near the anemometer, to the transducer. The time response due to internal electronics and residence time in the sample chamber place physical limits on the application of closed-path sensors. They should not be used in conditions where they severely attenuate the contribution of small scale eddies (which possess high frequencies) to the turbulent flux. Furthermore, pumping requirements may sometimes restrict the closed-path method to locales where electrical power is plentiful.

Limitations in our ability to interpret flux measurements were also discussed at the workshop. Short-term flux densities measured across a horizontal plane may not be equal to the net ecosystem flux at night and during the sunrise and sunset transition periods. Under stable stratification, for example, CO_2 respired by the canopy accumulates under the measurement level. The storage of CO_2 in the air layer under a flux measuring device (at height, z_r) equals the integration with respect to height of the time rate of change of the CO_2 concentration profile:

$$F_{storage} = \int_0^{z_r} \frac{\partial c(z)}{\partial t} \, dz. \quad (1)$$

When the storage flux is significant, the net ecosysten CO_2 exchange should be evaluated as the sum of the turbulent and storage fluxes. On the other hand, new data show that the storage of CO_2 under an eddy flux system averages to near zero over 24 hours (Greco and Baldocchi, p. 183, this issue). Daily-averaged fluxes also reduce the sampling errors associated with fluxes measured over 30–60 minutes intervals (Moncrieff *et al.*, p. 231, this issue). Hence, daily integrals of net carbon flux can be accepted with a reasonable degree of confidence. Goulden *et al.* (p. 169, this issue) conclude that the long term precision of eddy covariance flux measurements is ± 5% and the confidence interval about an annual estimate of net canopy CO2 exchange is ± 30 g C m^{-2} y^{-1}.

3.2 *Alternative methods*

While tower-mounted flux instruments provide a very good means for measuring temporal trends of carbon and water fluxes, the area sampled by the method is limited. As a rule of thumb, the flux footprint extends about 100 m for every meter measured above the zero plane displacement of the vegetation, yielding a spatial scale of the order of 100–1000 m. Aircraft-mounted eddy flux systems are a complementary means of assessing spatial patterns of carbon fluxes (Crawford *et al.*, p. 275, this issue). Aircraft-mounted flux systems can sample carbon dioxide and water vapour fluxes across entire landscapes and examine the horizontal heterogeneity of fluxes. Participants also advocated the use of aircraft as a platform to obtain remotely-sensed information of surface properties.

While eddy flux measurements from an aircraft is strongly suited for assessing spatial variations, it is a poor method for addressing temporal trends. Repeated runs close to the surface and across landscapes are needed to obtained statistically reliable data. Biophysical information must also be obtained along the flight-line to interpret the flux measurements. Key variables include land surface position, photosynthetic photon- and net radiation flux densities, normalized difference vegetation index (NDVI), vegetation type, surface elevation, soil type and depth, and organic matter content.

In the past, aircraft-mounted flux measurement systems have been very expensive and complex to implement routinely. It was encouraging to hear reports that a new generation of small and cheap experimental aircraft and ultra-lights are available for field application. Advances in global positioning systems (GPS) also make small aircraft more useful for addressing landscape scale patterns of surface fluxes.

An eddy flux system mounted on a tower or an aircraft only measures net carbon dioxide fluxes between the biosphere and atmosphere. It is also important to understand fluxes from the components of the system, e.g. leaves, boles and soil. Chamber-based measurements over the soil provide a means of assessing respiratory fluxes of carbon dioxide from the rhizosphere. Chambers are a cheap and simple method. However, care must be exercised not to perturb the efflux of carbon dioxide from the soil. Different bias errors can arise depending on whether air is pushed or pulled through a chamber. If a closed chamber is used, a large build-up of CO_2 in the chamber can also restrict carbon loss from the soil or may cause gas to flow around the chamber (a detailed discussion on chamber methodology is presented by Hutchinson and Livingston, 1993).

Cuvette measurements on leaves provide data to assess photosynthetic and stomatal conductance model parameters. Periodic and concurrent measurement of leaf-level carbon dioxide and water vapour fluxes were strongly encouraged to interpret the canopy-scale flux data.

Sap flow methods measure whole-tree transpiration. This method is attractive because it is cheap, simple and can be implemented in non-ideal terrain (Granier *et al.*, p. 265, this issue). They can also be made continuously and provide information on physiological control of whole tree (versus stand level) transpiration.

Molecular diffusion into leaves and carboxylation of CO_2 within leaves discriminate against the heavier isotope, ^{13}C over its lighter cousin ^{12}C. There was strong advocacy for occasional measurements of carbon isotope concentrations. Global scale measurements of carbon isotope ratios would help to discriminate whether the biosphere or ocean is a dominant sink or source of CO_2 over particular regions of the globe (Lloyd and Farquhar, 1994). They can also be used to estimate water use efficiency and gross primary productivity. It was recommended that flask samples be taken over a 24-h period once a month and analysed for $^{13}CO_2$ and $^{18}O_2$ content. For the sake of intercomparability, it was recommended that the flask samples be sent to a common laboratory for analysis.

Under certain conditions, the convective boundary layer is analogous to a box with an adjustable lid. Fluxes of material into or out of the 'box' can be estimating by knowing the rate at which the convective boundary layer is grows and by knowing the temporal rate by which CO_2 in the mixed layer changes (Denmead *et al.*, p. 255, this issue). Evaluating the convective boundary layer

(CBL) budget has the potential to estimate surface fluxes over wide areas (kilometres). While appealing, the CBL budget method is applicable only over flat terrain. It also requires information of variables that are not commonly measured; the rate of growth of the convective boundary layer and the evolution of CO_2 concentration in the mixed layer of the planetary boundary layer. Periodic use of this method, however, would help determine the spatial representativeness of tower-based flux measurements.

Geographical information systems (GIS) and satellite-derived indices of vegetation extent, type and physiological status were not discussed much at the workshop. Yet, it was widely recognized that these products will play a key role in extrapolating point-derived measurement and model information to landscape, regional and global scales. Empirical evidence already exists showing that canopy-scale carbon fluxes are correlated with the normalized difference vegetation index (Desjardins *et al.*, 1992). Wide application of this method must be used with caution over ecosystems whose carbon fluxes are also modulated by variations in temperature and humidity and soil moisture deficits (Waring *et al.*, 1995).

4 Where?

The biosphere consists of numerous and diverse ecosystems. A key question, therefore, arises: to assess the carbon budget of the biosphere do we need to make measurements over each ecosystem, and each sub-unit, or can we focus on making measurements over a limited number of dominant functional vegetation types?

Modelers assessing vegetation dynamics and global change do not deal with individual species, but instead adopt the concept of functional types (de Fries *et al.* 1995). There is some rationale to this logic with regards to mass and energy transfer. Evaporation, for example, is controlled by available energy, stomatal conductance and the atmospheric humidity deficit. For many cases, evaporation is independent of surface conductance, so the contribution of individual species can be ignored (see Jarvis and McNaughton, 1986). Since photosynthesis scales with transpiration, it may be valid to focus on dominant functional types when establishing the first set of flux measurement sites. Consequently, there was no conclusion was reached about where to place flux measurement sites.

Logistical and practical problems tend to encourage the placement of flux measurement sites near institutes with competent personnel. Table 1 lists a small, widely-spread and uncoordinated network of long-term CO_2 and water vapour flux measurement that exists or is planned for the near future. Teams are actively measuring carbon dioxide and water vapour fluxes over boreal, temperate, Mediterranean and tropical forests, crops, grasslands and wetlands at sites on four continents (North and South America, Europe and Australia). Obviously more sites are needed. However, a simple and modest goal of this workshop seems to have been met—to show the scientific community that it is possible to make long-term flux measurements and to identify measurement and data gaps.

5 Implementation and operation plans

Equipment and infra-structure resources and the availability of trained scientists and technicians are key components for the successful operation of any flux measurement site. Considerable attention was focused on the necessary and desired measurements that should be made at each flux measurement site. A plethora of flux, meteorology, soil physics, biological and canopy architectural variables were identified that would allow proper interpretation and use of the data.. These variables are summarized in Table 2. A typical cost for purchasing instruments to make core measurements is on the order of US$40,000 to $50,000. The cost of site infrastructure is extra. It will vary according to the remoteness of the site (the need for a road and line-power), the height of the vegetation (whether or not a tall tower must be built) and the existence of other facilities. The cost of a small mast over a pasture and an insulated container to house computers may be less than US$500. The typical cost of a 30 m walk-up scaffold tower for forest meteorology research is on the order of US$20,000 to $40,000.

Recent advances in remote power generation may minimize the need and cost of bring line power to a remote site. Many colleagues are successfully running eddy flux instruments on a system which combines batteries, solar panels and wind generators (Tilden Meyers, personal communication). Advances in cellular telephone technology also allow an investigator to access and query a remote field station from home or the office.

The requirement for personnel is diminishing as flux systems become more reliable and automated. At minimum, a team of two individuals would be required to operate a flux system. A technician or student can handle the day-to-day chores of calibration, instrument and computer maintenance, data archiving and periodic site characterization (e.g. soil moisture and leaf area measurements). Typical duties of a principal investigator include data processing, interpretation and analysis, report writing, project management and occasional fieldwork. Additional personnel would be needed for intensive studies that may be carried out periodically.

Calibration is one of the most important activities of science. Attention to common calibration standards must be made. Several sources of standard CO_2 gases exist. Examples include Scripps Institute of Oceanography, the

Table 1a List of investigators conducting long-term studies of carbon and water vapour exchange over vegetated ecosystems using the eddy covariance method. + denotes ongoing operation.

PI	Institute	Field site	Vegetation	Duration of operation
Wofsy	Harvard Univ	Harvard Forest, MA	temperate deciduous forest	4 y+
Wofsy	Harvard Univ.	Thompson, Manitoba	boreal spruce forest	1 y+
Jensen	RISO	Rosskilde, Denmark	crops	5 y+
Valentini	Univ. Tuscia	Appenines, Italy	beech forest	2 y+
Baldocchi	NOAA/ATDD	Oak Ridge, TN	temperate deciduous forest	2 y+
Verma	Univ. Nebraska	Valentine, NE	wetlands	1 y+
Hollinger	USFS	Howland, ME	conifer	9 mo+
Meyers	NOAA/ATDD	Little Washita, OK	rangeland	6 mo+
Black	Univ. British Columbia	Prince Albert, Sask	boreal aspen	1 y

Table 1b List of investigators soon to be conducting long-term studies of carbon and water vapour exchange over vegetated ecosystems using the eddy covariance method. Seasonal LTP denotes long-term study is planned.; SC denotes campaigns

PI	Institute	Field site	Vegetation
Grace	Univ. Edinburgh	Manaus, BRASIL	tropical forest
Black	Univ. British Columbia	Prince Albert, SASK	boreal aspen
Black	Univ. British Columbia	Vancouver, B.C.	Douglas fir
den Hartog	Atmos. Environ. Service	Borden, ONT.	temperate deciduous forest
Field	Carnegie Inst. Wash	Stanford, CA	grassland
Dunin	CSIRO	Wagga Wagga, Australia	crops
Desjardins	Agric. Canada	Ottawa, ONT	crops
Anderson	USGS	Trout Lake, WI	mixed forests
Bakwin	NOAA/CMDL	North Wisconsin	mixed forests
Jarvis	Univ. Edinburgh	Prince Albert, SASK	boreal spruce
Oechel	San Diego State Univ.	northern Alaska	tundra
Gholz	Univ. Fla	Florida	slash pine
Miranda		Brazil	cerrado
Kelliher	Landcare	southern New Zealand	Pinus radiata
Ham	Kansas State Univ.	Manhattan, KS	Konza prairie
Valentini *et al.*	EUROFLUX project	15 sites in Europe	conifer and broadleaf forests
Baldocchi	NOAA/ATDD	western Oregon	Ponderosa pine

National Bureau of Standards, and the World Meteorological Organization. Temperature, wind and radiation sensors must also be calibrated periodically and referenced to common sources.

Sites in an organized global flux network can also expect to attract additional science activities. There would be a potential for synergism between these flux and meteorological measurements and an array of other terrestrial science projects, as mentioned in the introduction. Terrestrial bioclimatology, productivity, water resource and nutritional biogeochemistry studies are examples of science that may be attracted to the flux network sites.

6 Data archiving and network oversight

Agreeing to archive the flux and meteorological data and to provide documentation of the experimental protocol at a network datacentre would be required of groups wanting to participate in a flux network; an excellent working protocol has been established during the BOREAS project, which could be a model for this effort.

The Data Archive Centre (DAAC) at the Oak Ridge Laboratory in Tennessee is an example of a data centre. It currently archives and disseminates datasets to the scientific community on terrestrial biogeochemistry. It's personnel have the expertise to archive and disseminate for data from a flux network, providing that operational funds are provided. Unfortunately, data archiving is not free and independent funds must be acquired to maintain a facility of this type.

We invision that data from each site would be transmitted in a standardized format to the archive centre via Internet ftp file transmission. A full year's data could be transmitted at the end of each year, or more regularly, at

Table 2 Recommended core and desired environmental, soil and biological measurements for data interpretation and model execution and testing and application.

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1 Eddy Flux Densities
(a) core measurements
carbon dioxide, sensible heat, latent heat (water vapour), momentum (friction velocity) flux densities.

2 Storage Fluxes
(a) core measurements
canopy heat (requiring bole temperature), CO_2 storage in canopy air layer (requiring CO_2 concentration profiles)
(b) desired
water vapour and heat storage in canopy air layer

3 Soil Fluxes
(a) core
soil heat flux density
(b) desired
carbon dioxide and water vapour flux densities.

4 Meteorology
(a) core
global radiation, wind speed, wind direction, air temperature, relative humidity, precipitaition.
(b) desired
net radiation, photon flux density (direct and diffuse), absorbed photon flux density, longwave radiation, canopy wetness, pressure, carbon isotope descrimination (δ_{13}), snow depth and snow water equivalent, canopy radiative temperature, bole temperature, height of planetary boundary layer.

5 Biology
(i) canopy structure
(a) core
leaf area index, canopy height, biomass, species composition, seasonal change in leaf area.
(b) desired
leaf area index profile, leaf inclination angle distribution, clumping index, aerodynamic roughness length and zero plane displacement, site history, leaf optical properties (reflectance and transmission).
(ii) photosynthetic capacity
(a) core
leaf nitrogen content
(b) desired
leaf nutrition (P and K content), maximum rate of carboxylation, stomatal conductance.

6 Soil Physics
(a) core
Soil temperature profiles, soil moisture profile
(b) desired
soil bulk density, porosity, thermal and hydraulic conductivities, soil chemistry, biomass (root and litter), litter and soil carbon content, cation exchange capacity.

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the discretion of the principal scientist. Clearly, the site scientist needs time for quality control and error checking, and must be allowed first opportunity for publication of these data.

Mutually beneficial arrangements must be planned for scientific credit when data are used by the external scientific community. Initially, the annual network dataset would be available to all network members via Internet. It may be appropriate for network members to have one-half year privileged access to the data before access is opened to the broader scientific community. Accumulated annual network datasets may also be distributed by CD-ROM for wider dissemination to scientists without high-speed computer linkages.

As a primary BAHC Focus 1 science activity of the BAHC/IGBP (Biospheric Aspects of the Hydrologic Cycle/International Geosphere-Biosphere Program/) project, BAHC would have a primary role in publicizing the flux network to the scientific community. We also recommend that BAHC/IGBP establish and sponsor a Steering Committee to provide quality control of choosing potential sites, and make procedural decisions on network data access and other details of operation. Essential activities of this Steering Committee may be (i) designing an instrument intercalibration plan, (ii) standardizing units, (iii) choosing and recommending site locations, (iv) surveying and recommending software for raw data processing, (v) advising on procedures for filling missing data, and other actions to assure comparable high data quality from all flux network sites and (vi) organizing workshops and commissioning special publications for the dissemination of the data and information.

7 Overview and recommendations

Direct measurements of canopy CO_2 exchange on daily and annual scales are useful for improving our understanding of the carbon dioxide budget of ecosystems and for providing data sets for the testing and parameterization of carbon balance models. But such measurements will only be successful and utilized if micrometeorologists, ecophysiologists, biogeochemists, modellers and experimentalists work together and design useful and multidisciplinary protocols.

Direct and long-term measurement of ecosystem CO_2 exchange is now possible with modern micrometeorological equipment. Many teams are operating and others are becoming operational. As documented in Table 1, a nascent network of long-term carbon flux measurement sites exists. What is missing is coordination and communication among sites, a central data archive and funding and prioritization for the establishment of future and additional sites.

For practical purposes there is a desire to keep equipment costs and personnel requirements of a site low, encouraging as many sites globally as possible and to encourage participation by researchers in developing countries. Advanced micrometeorological research sites may provide the testbed for instrumentation advances, intercalibrations, and personnel training for the standard sites. It is also hoped that recognized field sites would attract collaborators, who will augment the breadth and power of the available data

The establishment of a network of long-term flux measurement sites would fulfil needs being echoed by the broader, international scientific community. Three international bodies of scientists, under the auspices of the International Geosphere-Biosphere Programme (IGBP), call for long-term measurements of water and carbon fluxes over terrestrial ecosystems. These IGBP projects include the Global Change and Terrestrial Ecosystems (GCTE), Biospheric Aspects of the Hydrological Cycle (BAHC), and International Global Atmospheric Chemistry (IGAC). The GCTE project also advocates continued work on process-based whole ecosystem carbon balance modelling. Long-term measurements of CO_2 would also contribute to international efforts to monitor pollutant deposition and climate flux variables (Global Atmospheric Watch, GAW, and the Global Climate Observing System, GCOS) since the water, carbon and nutrient cycles are linked and must be evaluated in concert (see McMurtrie *et al.*, 1992).

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