

FLUXNET: A New Tool to Study the Temporal and Spatial Variability of Ecosystem-Scale Carbon Dioxide, Water Vapor and Energy Flux Densities

Dennis Baldocchi^{1,*}, Eva Falge², Lianhong Gu¹, Richard Olson³, David Hollinger⁴, Steve Running⁵, Peter Anthoni⁶, Ch. Bernhofer⁷, Kenneth Davis²¹, Robert Evans⁴, Jose Fuentes⁸, Allen Goldstein¹, Gabriel Katul⁹, Beverly Law⁶, Xuhui Lee¹⁰, Yadvinder Malhi¹¹, Tilden Meyers¹², William Munger¹³, Walt Oechel¹⁴, K.T. Paw U¹⁹, Kim Pilegaard¹⁵, H.P. Schmid²⁰, Riccardo Valentini¹⁶, Shashi Verma¹⁷, Timo Vesala¹⁸, Kell Wilson¹², and Steve Wofsy¹³

April 17, 2001

To, *Bulletin of the American Meteorological Society (revised)*

¹ESPM, University of California, Berkeley, Berkeley, CA 94704, USA

²Pflanzenökologie, Universität Bayreuth, 95440 Bayreuth, Germany

³Environmental Science Division, Oak Ridge National Laboratory, Oak Ridge, TN, USA

⁴USDA Forest Service, 271 Mast Rd, Durham, NH 03824, USA

⁵School of Forestry, University of Montana, Missoula, MT

⁶Richardson Hall, Oregon State University, Corvallis, Oregon 97331-2209, USA

⁷Technische Universität Dresden, IHM Meteorologie, Pienner Str. 9, 01737 Tharandt, Germany

⁸Dept of Environmental Science, University of Virginia, Charlottesville, VA

⁹School of the Environment, Box 90328, Duke University, Durham, NC 27708-0328, USA

¹⁰School of Forestry, Yale University, New Haven, CT

¹¹Institute of Ecology and Resource Management, University of Edinburgh, Edinburgh EH9 3JU, UK

¹²NOAA/ATDD, 456 S. Illinois Avenue, Oak Ridge, TN 37831-2456, USA

¹³Harvard University, Dept. of Earth and Planetary Sciences, 20 Oxford St., Cambridge, MA 02138, USA

¹⁴Dept of Biology, San Diego State University, San Diego, CA

¹⁵Plant Biology and Biogeochemistry Dept, Risoe National Lab, P.O. Box 49, DK-4000 Roskilde, Denmark

¹⁶DISAFRI, Università de Tuscia, Viterbo, Italy

¹⁷School of Natural Resource Sciences, 244 L.W. Chase Hall, PO Box 830728, University of Nebraska-Lincoln, Lincoln, NE 68583-0728, USA

¹⁸Department of Physics, P.O.Box 9, University of Helsinki, FIN-00014 Helsinki, Finland

¹⁹Land, Air and Water Resources, University of California, Davis, CA

²⁰Dept of Geography, Indiana University, Bloomington, IN

²¹Department of Meteorology, Pennsylvania State University, University Park, PA 16877

*Corresponding Author: Department of Environmental Science, Policy and Management, Ecosystems Science Division, 151 Hilgard Hall, University of California, Berkeley, CA 94720; email: Baldocchi@nature.berkeley.edu

ABSTRACT

Baldocchi, DD, Falge, E, Gu, L. et al. 2000. FLUXNET: A New Tool to Study the Temporal and Spatial Variability of Ecosystem-Scale Carbon Dioxide, Water Vapor and Energy Flux Densities *Bulletin of the American Meteorological Society*.

FLUXNET is a global network of micrometeorological flux measurement sites, which measure the exchanges of carbon dioxide, water vapor and energy between the biosphere and atmosphere. At present over 140 sites are operating on a long-term and continuous basis. Vegetation under study includes temperate conifer and broadleaved (deciduous and evergreen) forests, tropical and boreal forests, crops, grasslands, chaparral, wetlands and tundra. Sites exist on five continents and their latitudinal distribution ranges from 70 degrees north to 30 degrees south.

FLUXNET has several primary functions. First, it provides infrastructure for compiling, archiving and distributing carbon, water and energy flux measurement, meteorological, plant and soil data to the science community. Data and site information are available from the FLUXNET website, <http://www-eosdis.ornl.gov/FLUXNET>. Second, the project supports calibration and flux inter-comparison activities. This activity ensures that data from the regional networks are inter-comparable. And thirdly, FLUXNET supports the synthesis, discussion and communication of ideas and data by supporting project scientists, workshops and visiting scientists. The overarching goal is to provide information for validating computations of net primary productivity, evaporation and energy absorption that are being generated by sensors mounted on the NASA TERRA satellite.

Data being compile by FLUXNET are being used to quantify and compare magnitudes and dynamics of annual ecosystem carbon and water balances, to quantify the response of stand-scale carbon dioxide and water vapor flux densities to controlling biotic and abiotic factors, and to validate a hierarchy of soil-plant-atmosphere trace gas exchange models. Findings so far include: 1) net CO₂ exchange of temperate broadleaved forests increases by about 5.7 gC m⁻² day⁻¹ for each additional day that the growing season is extended; 2) the sensitivity of net ecosystem CO₂ exchange to sunlight doubles if the sky is cloudy rather than clear; 3) the spectrum of CO₂ flux density exhibits peaks at time scales of days, weeks and year and a spectral gap at the month time scale; 4) the optimal temperature of net CO₂ exchange varies with mean summer temperature; and 5) stand age affects carbon dioxide and water vapor flux densities.

INTRODUCTION

Large scale, multi-investigator projects have been the keystone of many scientific and technological advances in the twentieth century. Physicists have learned much about the structure of an atom's nucleus with particle accelerators. Astrophysicists now peer deep into space with the Hubble Space Telescope and an array of radio telescopes. Molecular biologists are decoding the structure of our DNA with the Human Genome project.

Ecosystem scientists need a tool that assesses the flows of carbon, water and energy to and from the terrestrial biosphere across the spectrum of time and space scales over which the biosphere operates (see Running et al., 1999; Canadell et al., 2000). Similarly, atmospheric scientists need a tool to quantify surface energy fluxes at the land-atmosphere interface, as these energy fluxes influence weather and climate (Betts et al., 1996; Pielke et al. 1998). In this paper, we report on such a tool. It consists of a global array of micrometeorological towers that are measuring flux densities of carbon dioxide, water vapor and energy between vegetation and the atmosphere on a quasi-continuous and long-term (multi-year) basis. The objectives of this paper are to introduce the FLUXNET project, describe its rationale, goals, measurement methods and geographic distribution. We also present a sampling of new results that are being generated through the project. The intent is to show how information from this network can aid ecologists, meteorologists, hydrologists and biogeochemists to understand temporal and spatial variations that are associated with fluxes of carbon and water between the biosphere and atmosphere.

What is the problem?

Over the past century, the states of the Earth's atmosphere and biosphere have experienced much change. Since the dawn of the industrial revolution, the mean global CO₂ concentration has risen from about 280 ppm to over 368 ppm (Keeling and Whorf, 1996, Conway et al., 1994). The secular rise in atmospheric carbon dioxide concentrations is occurring due to imbalances between the rates that anthropogenic and natural sources emit CO₂ and the rate that biospheric and oceanic sinks remove CO₂ out of the atmosphere. Superimposed on the secular trend of CO₂ is a record of large inter-annual variability in the annual rate of growth of atmospheric CO₂. Typical values of inter-annual variability are on the order of 0.5 to 3 ppm yr⁻¹. On a mass basis, these values correspond with a range between 1 and 5 Gt C yr⁻¹. Potential sources of year-to-year changes in atmospheric CO₂ remain a topic of debate. Studies of atmospheric ¹³C and O₂ distributions imply that the terrestrial biosphere plays an important role in this inter-annual variability (Cias et al., 1995; Keeling et al., 1996). Sources of this variability have been attributed to *El Nino/La Nina* events, which cause regions of droughts or superabundant rainfall (Conway et al., 1994; Keeling et al., 1995), and alterations in the timing and length of the growing season (Myneni et al, 1997; Randerson et al., 1997).

Rising levels of CO₂, and other greenhouse gases, are of concern to scientists and policy makers because they trap infrared radiation that is emitted by the Earth's surface. Potential consequences of elevated CO₂ concentrations include a warming of the Earth's surface (Hansen et al., 1998), melting of polar icecaps and a rising sea level, an alteration of plant and ecosystem physiological functioning and plant composition (Amthor, 1995; Norby et al., 1999).

With regards to plants and ecosystems, short-term experiments with elevated CO₂ increases rates of photosynthesis and plant growth and lowers stomatal conductance (Drake et al., 1996). The long-term sustainability of enhanced rates of growth by plants, however, depends on nutrient and water availability, temperature and light competition (Ceulemans and Mousseau, 1994; Norby et al., 1999). Warmer temperatures, associated with elevated CO₂ promote increased rates of respiration, when soil moisture is ample. But if climate warming is associated with drying, there can be reduced assimilation and lower rates of soil/root respiration in temperate ecosystems. In the tundra and boreal forest, warming and drying can lower water tables, exposing organic peat to air and increasing its rate of respiration (Goulden et al., 1998; Lindroth et al., 1998; Oechel et al., 2000).

How evaporation is impacted by elevated CO₂ depends on the scale of study and concurrent changes in leaf area index, canopy surface conductance and the depth of the planetary boundary layer. Theory indicates that complex feedbacks among stomatal conductance, leaf temperature and the air's vapor pressure deficit cause responses at the leaf scale to differ differently at the canopy scale. For instance, a potential reduction of leaf transpiration, by stomatal closure, is compensated in part by the entrainment of dry air from above the planetary boundary layer and elevated leaf temperatures and humidities (Jacob and deBruin, 1992). Hence, canopy evaporation may not be reduced to the same degree as leaf transpiration in an elevated CO₂ world.

In the meantime, the composition of the land surface has changed dramatically to meet the needs of the growing human population. Many agricultural lands have transformed into suburban and urban landscapes, wetlands have been drained and many

tropical forests have been logged, burnt and converted to pasture. In contrast, abandoned farmland in the northeast United States and Europe is returning to forest as those societies become more urban. Changes in land use alter the Earth's radiation balance by changing its albedo, Bowen ratio (the ratio between the flux densities of sensible and latent heat exchange), leaf area index and physiological capacity to assimilate carbon and evaporate water (Betts et al., 1996; Pielke et al., 1998). Changing a landscape from forest to agricultural crops, for instance, increases the surface's albedo and decreases the Bowen ratio (Betts et al., 1996); forests have a lower physiological capacity to assimilate carbon and a lower ability to transpire water, as compared to crops (Kelliher et al., 1995; Baldocchi and Meyers, 1998). A change in the age structure of forests due to direct (deforestation) or indirect (climate-induced fires) disturbance alters its ability to acquire carbon and transpire water (Amiro et al., 1999; Schulze et al. 1999).

The issues identified above all require information on fluxes of carbon, water and energy at the Earth's surface and how these fluxes interact with the physical climate and physiological functioning of plants and ecosystems. In the next section we identify, numerous ways to obtain this information and illustrate how a network of long flux measurement sites can provide particularly useful information to study these complex problems.

How to Study Biosphere CO₂ Exchange?

Study of the Earth's biogeochemistry and hydrology involves quantifying the flows of matter in and out of the atmosphere. Numerous techniques exist for studying biosphere-atmosphere CO₂ exchange, each with distinct advantages and disadvantages. At the continental and global scales, scientists assess carbon dioxide sources and sinks

using atmospheric inversion models, that ingest information on fields of CO₂, ¹³C and O₂ concentration and wind (Tans et al., 1990; Ciais et al., 1995; Denning et al., 1996; Fan et al., 1998). This approach is subject to errors due to the sparseness of the trace gas measurement network, their biased placement in the marine boundary layer and the accuracy of the atmospheric transport models (Tans et al., 1990; Denning et al., 1996; Fan et al., 1998).

Instruments mounted on satellites platforms, view the Earth in total. Consequently, satellite-based instruments offer the potential to evaluate surface carbon fluxes on the basis of algorithms that can be driven by reflected and emitted radiation measurements (Running et al. 1999; Cramer et al., 1999). This approach, however, is inferential, so it is dependent on the accuracy of the model algorithms, the frequency of satellite images and the spectral information contained in the images.

At the landscape to regional scale we can use instruments mounted on aircraft (Crawford et al., 1996; Desjardins et al., 1984, 1997) or boundary layer budget methods (Denmead et al., 1996; Levy et al., 1999; Yi et al., 2000) to assess carbon and water fluxes. Aircraft-based eddy-covariance flux density measurements give good information on spatial patterns of carbon and water fluxes across transects of 10's to 100's of kilometers. However, they do not provide information that is continuous in time, nor do they provide insights on the physiological mechanisms that govern carbon and water fluxes. Boundary layer budget methods can be implemented using tall towers, tethered balloons or small aircraft. This method provides information on spatially integrated fluxes of tens to hundreds of square kilometers, but it can be applied only during ideal

meteorological conditions (Denmead et al., 1996). Routine application of this method is hampered by a lack of data on entrainment and horizontal advection.

One measure of carbon flux ‘ground truth’ can be provided by biomass surveys (Kauppi et al., 1992; Gower et al., 1999). However, biomass surveys provide information on multi-year to decadal time scales, so they do not provide information on shorter-term physiological forcings and mechanisms. Furthermore, forest inventory studies are labor intensive and inferential estimates of net carbon exchange. Such studies rarely measure growth of small trees and below-ground allocation of carbon. Instead biomass surveys commonly assume a certain portion of carbon is allocated below ground (Gower et al., 1999). Soil carbon surveys can be conducted too, but like biomass surveys, they require long intervals to resolve detectable differences in net carbon uptake or loss (Amundson et al., 1998).

The eddy covariance method, a micrometeorological technique, provides a direct measure of net carbon and water fluxes between vegetated canopies and the atmosphere (Baldocchi et al., 1988; Foken and Wichura, 1996; Aubinet et al. 2000). With current technology, the eddy covariance method is able to measure mass and energy fluxes over short and long time scales (hour, days, seasons and years) with minimal disturbance to the underlying vegetation. Another attribute of the eddy covariance method is its ability to sample a relatively large area of land. Typical footprints have longitudinal length scales of 100 to 2000 m (Schmid, 1994). If deployed as a coordinated network of measurements sites, the eddy covariance method has the potential of quantifying how whole ecosystems respond to a spectrum of climate regimes, thereby expanding the spatial scope of this method.

The eddy covariance method is not without weaknesses. Its application is generally restricted to periods when atmospheric conditions are steady and to locations with relatively flat terrain and vegetation that extends horizontally about one hundred times the sampling height. Consequently, the method is not suitable for measuring fluxes in rough mountainous terrain or near distinct landscape transitions such as lakes.

Nevertheless, the strengths of the eddy covariance method far outweigh its weaknesses, as it can provide information that can aid inferential carbon fluxes being determined by the global inversion model community, remote sensing scientists and forest ecologists. For example, data from an eddy covariance measurement site has the potential to complement the global flask sampling network in a very direct way. Historically, the global flask sampling network has been concentration at marine locations (Tans et al., 1990). Recent studies using tall-towers show that there are times during the day, when either local surface fluxes are small or convective mixing is vigorous, that CO₂ concentrations measured in the atmospheric surface layer are very close to the mean boundary layer concentration (Bakwin et al., 1998; Potosnak et al., 1999). High precision CO₂ concentration measurements and surface carbon flux measurements, made at eddy covariance measurement sites, have the potential to expand the density of the existing flask network. Data from a network of eddy covariance measurement sites can also be used to improve and validate the algorithms being used by remote sensing scientists and ecosystem modelers. And finally, such data can aid forest ecologists in their interpretation of forest biomass inventories, by providing information on fluxes from carbon pools and how these fluxes vary on a seasonal and interannual basis.

History: What Has Been Done?

Micrometeorologists have been making measurements of CO₂ and water vapor exchange between vegetation and the atmosphere since the late 1950's and early 1960's. Yet, only been recently have we had the technology available that enables us to make continuous flux measurements at numerous sites.

The earliest reported micrometeorological measurements of CO₂ exchange were conducted by Inoue (1957), Lemon (1960), Monteith and Sziecz (1960), and Denmead (1969). These studies employed the flux-gradient method over agricultural crops during the growing season. By the late 1960s and early 1970s, a few scientists started applying flux gradient method over natural landscapes. Several flux-gradient studies of CO₂ exchange were conducted over forests (Denmead, 1969; Baumgartner, 1969; Jarvis et al., 1976). And one team ventured to assess the annual carbon balance of a salt marsh (Houghton and Woodwell, 1980).

As more data were collected it became evident that the flux-gradient method was suffering from major deficiencies, when applied over tall forests. One flaw arose from large-scale transport in the roughness sublayer, which caused local eddy exchange coefficients to be enhanced relative to estimations based on Monin-Obukhov scaling theory (Raupach and Legg, 1984; Kaimal and Finnigan, 1992). The flux-gradient method also failed to provide reliable means of evaluating eddy exchange coefficients at night.

Routine application of the eddy covariance method was delayed until the 1980's, when technological advances in sonic anemometry, infrared spectrometry, and digital computers were made. Initial studies were conducted over crops (Anderson et al., 1984; Desjardins et al. 1984; Ohtaki, 1984), forests (Verma et al., 1986) and native grasslands

(Verma et al, 1989) for short intense periods during the peak of the growing season. By the late 1980s and early 1990s, the further technological developments, such as larger data storage capacity and linear and non-drifting instruments, enabled scientists to make defensible measurements of eddy fluxes for extended periods. Wofsy et al. (1993), at Harvard Forest, and Vermetten et al. (1993), in the Netherlands, were among the first investigators to measure carbon dioxide and water vapor fluxes continuously over a forest over the course of a year with the eddy covariance method. Spurred by these two pioneering studies, a handful of other towers were soon established and operating by 1993 in North America (Oak Ridge, TN, Greco and Baldocchi, 1996; Prince Albert, Saskatchewan, Canada, Black et al., 1996) and Japan (Yamamoto et al., 1999) and in Europe by 1994 (Valentini et al., 1996). This era also heralded the start of longer, quasi-continuous multi-investigator experiments. Noted examples include the BOREAS (Sellers et al., 1997) and NOPEX (Halldin et al., 1999) experiments.

The next natural step in the evolutionary development of this field was to establish a global network of research sites. The concept of a global network of long-term flux measurement sites had a genesis as early as the 1993, as noted in the Science Plan of the IGBP/BAHC (International Geosphere-Biosphere Program/Biospheric Aspects of the Hydrological Cycle). Formal discussion of the concept among the international science community occurred at the 1995 La Thuile workshop (Baldocchi et al., 1996). At this meeting, the flux measurement community discussed the possibility, problems and pitfalls associated with making long-term flux measurements (e.g Goulden et al., 1996; Moncreiff et al., 1996). After the La Thuile meeting there was acceleration in the establishment of flux tower sites and regional flux measurement networks. The

EuroFlux project started in 1996 (Aubinet et al., 2000; Valentini et al., 2000). The AmeriFlux project was conceived in 1997, subsuming the several on-going tower studies and initiating many new studies. With the success of the European and American regional networks and anticipation of the Earth Observation Satellite (EOS/TERRA), NASA decided, in 1998, to fund the global-scale FLUXNET project, as a means of validating EOS products.

What is being done?

The FLUXNET project serves as a mechanism for uniting the activities of several regional and continental networks into an integrated global network. At present over one hundred and forty flux tower sites are registered on the FLUXNET data archive.

Research sites are operating across the globe (Figure 1) in North, Central and South America, Europe, Scandinavia, Siberia, Asia, and Africa. The regional networks include AmeriFlux (which includes LBA sites in Brazil), CarboEuroFlux (which has subsumed EuroFlux and Medeflu), AsiaFlux, OzFlux (Australia, New Zealand). There are also disparate sites in Botswana and South Africa.

The global nature of FLUXNET extends the diversity of biomes, climate regions and methods that are associated with the regional networks. For example, sites in the original EuroFlux network consisted of conifer and deciduous forests and Mediterranean shrubland. The European networks also used a standard methodology, based on closed path infrared spectrometers (Aubinet et al., 2000; Valentini et al., 2000). By contrast, the American network, AmeriFlux, has more diversity in terms the number of biomes and climates studied and methods used. The American regional network includes sites in temperate conifer and deciduous forests, tundra, cropland, grassland, chaparral, boreal

forests and tropical forests. Regarding methodology, open and closed path infrared spectrometers are used to measure CO₂ and water vapor fluctuations. Another unique dimension of AmeriFlux is its inclusion of a tall (400 m) tower (Bakwin et al., 1998; Yi et al., 2000) for study of CO₂ flux and concentration profiles and boundary layer evolution.

The placement of field sites in FLUXNET has been *ad hoc*, due to limited funding and investigator capabilities, rather than following a pre-determined geostatistical design. So with the current network configuration, we are not capable of, nor intend to, measure fluxes from every patch on Earth. On the other hand, this coordinated network of sites is able to deduce certain information on spatial patterns of fluxes by placing research sites across a spectrum of climate and plant functional regions (Running et al., 1999). Spatially integrated fluxes of carbon and water can only be constructed by combining eddy flux measurements with ecosystem and biophysical models and satellite-measurements to perform the spatial integration (Running et al., 1999).

The scientific goals of FLUXNET are to:

- 1) quantify the spatial differences in carbon dioxide and water vapor exchange rates that may be experienced within and across natural ecosystems and climatic gradients;
- 2) quantify temporal dynamics and variability (seasonal, inter-annual) of carbon, water and energy flux densities; such data allows us to examine the influences of phenology, droughts, heat spells, *El Nino*, length of growing season and presence or absence of snow on canopy-scale fluxes; and
- 3) quantify the variations of carbon dioxide and water vapor fluxes due to changes in insolation, temperature, soil moisture, photosynthetic capacity, nutrition, canopy structure and ecosystem functional type.

FLUXNET has two operational components, a project office and a data archive office. The project office houses the principal investigator and a postdoctoral scientist.

Specific duties of the FLUXNET office include:

- 1) communicating with participants to ensure the timely submission of data and documentation to the data archive
- 2) constructing and analyzing integrated data sets for synthesis of field data and the for the development and testing of Soil-Atmosphere-Vegetation-Transfer models.
- 2) organizing workshops for data synthesis and model testing activities.
- 3) preparing peer-reviewed research papers and reports on FLUXNET activities and analyzes.
- 4) funding the execution and analysis of site inter-comparison studies.
- 5) providing scientific guidance to the FLUXNET Data and Information System (DIS).

The data archive office is responsible for:

- 1) compiling and documenting data in consistent formats
- 2) developing data guidelines and coordinating development of the FLUXNET Data and Information system (FLUXNET DIS),
- 3) scrutinizing data sets with standard quality control and assurance procedures.
- 4) maintaining the FLUXNET Web page for communications and data exchange (<http://www-eosdis.ornl.gov/FLUXNET/>), and
- 5) transferring FLUXNET data and metadata to a long-term archive, currently designated as the Oak Ridge National Laboratory Distributed Active Archive Center.

Back up of data and long-term accessibility of the data, provided by FLUXNET DIS, ensures the protection and extended use of the data by project scientists, as well as students and citizens, well into the future.

FLUXNET does not fund tower sites directly, but depends upon institutional support associated with the funding of the AmeriFlux, CarboEuroFlux, AsiaFlux and OzFlux networks (see Acknowledgments).

Methodology

The eddy covariance method is used to assess trace gas fluxes between the biosphere and atmosphere at each site within the FLUXNET community (Aubinet et al., 2000; Valentini et al., 2000). Vertical flux densities of CO₂ (F_c), latent (λE) and sensible heat (H) between vegetation and the atmosphere are proportional to the mean covariance between vertical velocity (w') and the respective scalar (c') fluctuations (e.g., CO₂, water vapor, and temperature). Positive flux densities represent mass and energy transfer into the atmosphere and away from the surface and negative values denote the reverse; ecologists use an opposite sign convention where the uptake of carbon by the biosphere is positive. Turbulent fluctuations were computed as the difference between instantaneous and mean scalar quantities.

Our community is interested in assessing the net uptake of carbon dioxide by the biosphere, not the flux across some arbitrary horizontal plane. When the thermal stratification of the atmosphere is stable or turbulent mixing is weak, material diffusing from leaves and the soil may not reach the reference height z_r in a time that is small compared to the averaging time T , thereby violating the assumption of steady state conditions and a constant flux layer. Under such conditions the storage term becomes non-zero, so it must be added to the eddy covariance measurement to represent the balance of material flowing into and out of the soil and vegetation (Wofsy et al., 1993; Moncrieff et al., 1996). With respect to CO₂, the storage term is small over short crops

and is an important quantity over taller forests. The storage term value is greatest around sunrise and sunset when there is a transition between respiration and photosynthesis and between the stable nocturnal boundary layer and daytime convective turbulence (Aubinet et al., 2000; Yi et al., 1999). Summed over 24 hours, the storage term is null (Baldocchi et al., 2000).

Horizontal advection is possible when vegetation is patchy or is on level terrain (Lee, 1998, Finnigan, 1999). At present, routine corrections for advection may require a three-dimensional array of towers (Finnigan, 1999), rather than the application of a vertical velocity advection correction (see Lee, 1998; Baldocchi et al., 2000).

Instrumentation, Data Acquisition and Processing

Typical instrumentation at FLUXNET field sites includes a three-dimensional sonic anemometer, to measure wind velocities and virtual temperature, and a fast responding sensor to measure CO₂ and water vapor. Scalar concentration fluctuations are measured with open and closed path infrared gas analyzers. Standardized data processing routines are used to compute flux covariances (Foken and Wichura, 1995; Moncrieff et al., 1996; Aubinet et al., 2000).

Application of the eddy covariance methods involves issues relating to site selection, instrument placement, sampling duration and frequency, calibration and post-processing (Moore, 1986; Baldocchi et al., 1988; Foken and Wichura, 1995; Moncrieff et al., 1996; Aubinet et al., 2000). Ideally the field site should be flat, with an extensive fetch of uniform vegetation. In practice many of the FLUXNET sites are on undulating or gently sloping terrain, as this is where native vegetation exists. Sites on extreme terrain, which may force flow separation and advection, are excluded. The degree of

uniformity of the underlying vegetation varies across the network, too. Some sites consist of monospecific vegetation, others contain a mixture of species and a third grouping possesses different plant functional types in different wind quadrants. All sites have sufficient fetch to generate an internal boundary layer where fluxes are constant with height (Kaimal and Finnigan, 1994).

Agricultural scientists mount their sensors on small poles, while forest scientists use either walk-up scaffolding or low-profile radio towers. The height of the sensors depends on the height of the vegetation, the extent of fetch, the range of wind velocity and the frequency response of the instruments. To minimize tower interference on scaffold towers, investigators place their instruments booms that point several meters up wind or at the tower of the tower. Spatial separation between anemometry and gas analyzers depend on whether one uses a closed or open path gas sensor. With the closed path systems, the intake is often near or within the volume of the sonic anemometers. A delay occurs as air flows through the tubing to the sensor, which is compensated with software during post-processing. Some investigators place their gas transducer on the tower in a constant environment box to minimize the lag time from the sample port and the sensor. Others draw air down long tubes to instruments housed in an air-conditioned hut below the tower. In either circumstance, flow rates are high (6 liter per minute) to insure turbulent flow and minimize the diffusive smearing of eddies (Aubinet et al., 2000). Open path gas sensors are typically placed within a 0.5 m of a sonic anemometer, a distance that minimizes flow distortion and lag effects (Baldocchi et al., 2000; Meyers, 2001).

Sampling rates between 10 and 20 Hz ensure complete sampling of the high frequency portion of the flux co-spectrum (Anderson et al., 1984). The sampling duration must be long enough to capture low frequency contributions to flux covariances, but not too long to be affected by diurnal changes in temperature, humidity and CO₂. Adequate sampling duration and averaging period vary between 30 and 60 minutes for most teams (Aubinet et al., 2000). Coordinate rotation calculations of the orthogonal wind vectors (w,u,v) are performed to correct for instrument misalignment and non-level terrain. The vertical velocity, w, is rotated to zero, allowing flux covariances to be computed orthogonal to the mean streamlines.

Calibration frequencies of gas instruments vary from team to team. With closed path sensors, investigators are able to calibrate frequently and automatically, such as hourly or once a day. Teams with open path sensors calibrate less frequently, e.g. every few weeks. However, a body of accumulating data indicates that calibration coefficients of contemporary instruments remain steady within that duration (+/- 5%, Meyers, 2001). Scientists using open path sensors also compare their instrument responses to an independent measure of CO₂ concentration and humidity. Members of this network do not use a uniform standard for calibrating CO₂, yet. But many of us use CO₂ gas standards that are traceable to the standards at the Climate Monitoring and Diagnostics Laboratory of the National Oceanic and Atmospheric Administration, the standards of the global flask network.

To ensure network intercomparability, the AmeriFlux project circulates a set of reference sensors to members in the network and the FLUXNET project sponsors the circulation of this set of instruments to sites in Europe, Asia and Australia. Figure 2

shows a typical comparison between the roving set of reference instrumentation and data from one research group. CO₂ flux densities measured by the two systems agree within 5% of one another on an hour-by-hour basis. A similar level of agreement has been found by comparing open and closed path CO₂ sensors. Side-by-side comparisons between open and closed path water vapor sensors, on the other hand, are not as good. The absorption and desorption of water vapor on tubing walls can cause water uptake to be underestimated by 20%.

Gap Filling:

Most clients of eddy flux data, e.g. modelers, require uninterrupted time series. It is the intent of the micrometeorological community to collect eddy covariance data 24 hours a day and 365 days a year. However, missing data in the archived records is a common feature. Gaps in the data record are attributed to system or sensor breakdown, periods when instruments are off-scale, when the wind is blowing through a tower, when spikes occur in the raw data, if the vertical angle of attack by the wind vector is too severe and when data are missing because of calibration and maintenance. Other sources of missing data arise from farming operations and other management activities (e.g., prescribed burn of grasslands). Rejection criteria applied to the data vary among the flux tower groups. Data might be rejected, when stationarity tests or integral turbulence characteristics fail (Kaimal and Finnigan, 1994; Foken and Wichura, 1995), when precipitation limits the performance of open path sensors, during sensor calibration, or when spikes occur in instrument readings. Other criteria used to reject data include applications of biological or physical constraints (lack of energy balance closure; Aubinet et al., 2000) and a meandering flux-footprint source area (e.g. Schmid, 1994). If the wind

is coming from a non-preferred direction as may occur over mixed stands, a certain portion of the data will need to be screened. In addition, rejection probability for some sites is higher during nighttime because of calm wind conditions.

The average data coverage during a year is between 65 % and 75% due to system failures or data rejection (Falge et al., 2001). Tests show that this observed level of data acceptance provides a statistically robust and over-sampled estimate of the ensemble mean. So the filling of missing data does not provide a significant source of bias error.

Accuracy Assessment

Errors associated with the application of the eddy covariance method can be random or biased (Moncrieff et al., 1996). Random errors arise from sensor noise and the random nature of atmospheric turbulence. Fully systematic bias errors arise from errors due to sensor drift, limited spectral response of instruments, limited sampling duration and frequency and calibration errors. Selectively systematic bias errors arise from mis-application of the eddy covariance method, as when advection or storage occur. Formal discussions on errors associated with long-term flux measurements were reported in previous papers by our colleagues (e.g. Goulden et al. 1996a; Moncrieff et al. 1996; Aubinet et al, 2000). For clarification, we provide a summary of their findings.

Moncrieff et al. (1996) demonstrate how random sampling errors diminish greatly as the number of samples increase. The overall random error using a data set of 44 days is about $0.4 \text{ } \mu\text{mol m}^{-2} \text{ s}^{-1}$. This figure of merit is close to the 'flux detection' level that many of us see with our field measurements. Accumulated over a year, this random error is plus/minus $53 \text{ gC m}^{-2} \text{ y}^{-1}$, a value that agrees with a formal error analysis by Goulden et al. (1996).

Fully systematic bias errors associated with imperfect sensor response, sensor orientation, sampling frequency and duration are typically compensated by applying spectral transfer functions to the flux covariance calculations (Moore, 1986; Massman, 2000). Depending on instrument configuration, wind speed and thermal stratification, corrections can range from a few to fifty percent.

Selectively systematic bias errors are more difficult to assess. A cohort of carbon flux researchers suspect that they may be under-evaluating the nighttime measure of CO₂ fluxes, despite attempts to measure the storage term (Black et al., 1996; Goulden et al., 1996a; Baldocchi et al., 2000; Aubinet et al., 2000). Potential explanations include insufficient turbulent mixing, incorrect measurement of the storage term of CO₂ in the air space and soil and the drainage of CO₂ out of the canopy volume at night. At present, several teams of investigators are applying an empirical correction to compensate for the underestimate of nighttime carbon flux measurements. This correction is based on CO₂ flux density measurements obtained during windy periods or by replacing data with a temperature-dependent respiration function (Black et al., 1996; Goulden et al., 1996a, b; Lindroth et al., 1998). Most researchers presume that data from windy periods represent conditions when the storage and drainage of CO₂ is minimal (Aubinet et al., 2000).

When using FLUXNET data, the user should recognize that some sites are more suitable for constructing annual sums than others. Yet good science can be produced from the non-ideal sites, too. They can provide information on physiological functioning, temporal dynamics and response to the environment during the day. We also note that the factors that cause large bias errors associated with nocturnal CO₂ fluxes may not cause significant errors to water vapor fluxes, since evaporative fluxes are near zero during the

night. Consequently, studies comparing integrated annual measurements of evaporation with lysimeters and watersheds show good agreement (Barr et al., 2000; Wilson et al., 2001). On the other hand, tests of surface energy balance closure suggest that turbulent fluxes at some sites are systematically 10% to 30% too small to close the energy budget, raising the possibility that CO₂ fluxes are similarly underestimated (Aubinet et al., 2000). The solution to this problem remains unresolved at the time of this writing.

RECENT FINDINGS

As we write this report, 69 site-years of carbon dioxide and water vapor flux data have been published in the literature. Table 1 presents a survey of the annual sums of net carbon dioxide exchange. Most sites are net sinks of CO₂ on an annual basis.

Magnitudes of net carbon uptake by whole ecosystems range from near zero to up to 700 gC m⁻² year⁻¹. Largest values of carbon uptake are associated with temperate forests (conifer and deciduous) growing near the southern edge of that climate range. The substantial rates of net carbon uptake by tropical and temperate forests sites, under study, is an indicator that these sites have experienced substantial amounts of disturbances in the relatively near past (50 to 100 years) and have not reached long-term steady state.

On close inspection of Table 1, we note that several sites are sources of CO₂. Sites losing carbon dioxide include boreal forests and tundra, which are experiencing disturbance of long-term carbon storage pools (Goulden et al., 1998; Lindroth et al., 1998; Oechel et al., 2000), and grasslands, that were burnt (Sukyer and Verma, 2000) or were suffering from drought (Meyers, 2001). The maximum carbon lost by these sites on an annual basis does not exceed 100 g C m⁻².

With the plethora of long-term carbon flux data available, we can quantify seasonal patterns of carbon fluxes across a variety of climates, biomes and plant functional groups. Figure 3 shows the annual pattern of daily CO₂ exchange for several temperate broadleaved deciduous forests. Broadleaved forests lose carbon during the winter, when they are leafless and dormant, and gain carbon during the summer growing season. What differs most among broadleaved forest sites is the timing of the transition between gaining and losing carbon. The site in the southeastern United States is the first to experience spring growth and photosynthesis, followed by the site in Denmark and one in the northeast United States. The Harvard Forest in Massachusetts is on eastern side of the North American continent. It experiences a later spring than the more northerly Danish site because the climate of Denmark is moderated by the Gulf Stream. During the peak of the growing season, these three sites, separated by several thousand kilometers, experience similar daily sums of carbon uptake (around days 160-170). And the two North American sites, separated by over a 1000 km, experience similar daily sums of net CO₂ exchange from about day 160 to 250. In the autumn, the Danish site is first to drop leaves and respire and the most southern site is last. Another feature to be gathered from this figure how ideal and non-ideal sites affect the measurement of respiration. During the winter the Tennessee site experience extremely low rates of respiration. This site is situated on rolling terrain and near several power plants. Cold air drainage causes CO₂ to drain out from under the flux tower and plume impaction causes downward carbon fluxes that counter the upward respiratory flux.

Based on data in Figure 3, one may suspect that phenological timing of spring and autumn would be a major factor causing site variability among net carbon exchange of

temperate deciduous forests. We quantify this effect in Figure 4 by plotting annual net ecosystem CO₂ exchange versus length of growing season; for convenience, we define the growing season as the period over which mean daily CO₂ exchange is negative, due to net uptake by the biosphere. We observe that net ecosystem CO₂ exchange increases 5.8 gC m⁻² for each day that the length of the growing season increases. The predictive power of this result is very robust as variations in the length of the growing season account for 83% of the variance of CO₂ exchange that is observed. The coherent response of net ecosystem CO₂ exchange of the deciduous forest biome reflects their broadly similar growing season climate, age and disturbance history. It also gives us confidence about the accuracy of independent research sites across the network. On the basis of this figure, one may conclude that site-to-site measurement errors and biases may be relatively small compared to variance caused by ecological and meteorological factors.

In Figure 4, we also added a data point from a tropical forest, which experiences a year round growing season. On the basis of data from the tropics we expect the regression curve to reach an asymptote as the growing extends beyond 220 days. Consequently, one should not extrapolate the regression line out to 365 days. Nor, do we advocate using this plot for estimating year-to-year variability in net ecosystem CO₂ exchange at a site. To illustrate this point we show an example of year-to-year variation of the annual cycle of CO₂ exchange at Harvard forest (Figure 5), the site with the world's longest measurement record. Other factors, such as the presence or absence of snow cover, degree of cloudiness (Goulden et al., 1996b; Lee et al., 1999) and drought (Wilson and Baldocchi, 2000) impose variance on the annual carbon budget, too.

The seasonal trend of CO₂ exchange experienced by conifer forests is affected by latitudinal differences, that shorten or lengthen the growing season, and by continental position, which forces conifer ecosystems to experience oceanic, Mediterranean or continental climates. To illustrate these points we present data on seasonal patterns of net CO₂ exchange from three contrasting conifer forest systems (Figure 6). The Duke site is at a temperate and humid locale in the southeastern United States. There, the canopy is able to take up carbon all year. The Oregon site experiences cool wet winters and dry, warm summers. It assimilates carbon during the late winter, spring and autumn, but experiences large reductions in carbon dioxide uptake during the dry summer growing season (there are instances when it loses carbon, too). The Finnish site is in the boreal zone. The trees are dormant during the cold winter, but the forest stand loses carbon due to soil and microbial respiration under the snow pack. In the spring, the onset of photosynthesis is much delayed, compared to the more southerly temperate sites, and its conclusion is sooner in the autumn.

With longer data sets, alternative analytical methods can be used to interpret them. Application of Fourier transforms to year-long and multi-year flux measurement records provides a means of quantifying the time scales of flux variance (Baldocchi et al., 2001). Figure 7 shows the power spectra of CO₂ fluxes over a variety of field sites. The dominant time periods over which carbon dioxide fluxes vary have periods of days, weeks, seasons and years. On the daily time scale, variations in CO₂ and water vapor exchange are forced by daily rhythms in solar radiation, air and soil temperature, humidity, CO₂, stomatal aperture, photosynthesis and respiration. Weekly-scale fluctuations in CO₂ and water vapor exchange are induced at mid-latitude sites from

synoptic weather changes that are associated with the passage of high and low-pressure systems and fronts. Weather events cause distinct periods of clear skies, overcast, and partly cloudy conditions, which alter the amount of available light to an ecosystem, how light is transmitted through a plant canopy and the efficiency by which it is used to assimilate carbon (Gu et al., 1999). The passing of weather fronts also changes air temperature, humidity deficits, and pressure. On seasonal times scales, changes in the sun's position alters the amount of sunlight received, the air, soil and surface temperature of the ecosystem and its water balance. Superimposed upon these meteorological factors is a variance caused by phenology and seasonal changes in photosynthetic capacity (Wilson et al., 2000). The timing and occurrence of leaf expansion, senescence, and leaf fall, fine root growth and turnover, and seasonal changes in photosynthetic capacity and leaf area index are examples of phenological factors affecting low frequency fluctuations in canopy CO₂ exchange. Prolonged wet and dry spells are other factors that exert variance on the spectral record.

Canopy-scale quantum yield represents the initial slope of the relation between net ecosystem CO₂ exchange and the photosynthetic photon flux density. Canopy-scale quantum yield is of particular interest, as it is a parameter used by many biogeochemical carbon cycling models to translate remotely sensed radiation measurements to an area-wide estimate of carbon uptake (Ruimy et al., 1995; Cramer et al., 1999). Figure 8 shows that the canopy-scale quantum yield depends on the sky conditions, as well as temperature. The canopy-scale quantum yield is nearly double under diffuse radiation, as compared to direct radiation.

Combining data from the North American and European networks gives us wider breadth of information on how CO₂ flux densities respond to temperature. The temperate zone of Europe is displaced northward, as compared to North America, due to the presence of the Gulf Stream. Summer temperatures in Europe are on the order of 15 to 20 C, while in North America summer temperatures are in the range of 20 to 30 C. Figure 9 indicates that the temperature at which peak gross CO₂ exchange occurs is several degrees lower for many European sites than for their North American counterparts. These data suggest that global carbon flux models will need to vary CO₂ flux-temperature response curves for North America and Europe, in support of findings by Niinemets et al. (1999).

With regards to meteorology, the FLUXNET network can provide new information on how the biosphere affects the partitioning of net radiation into sensible and latent heat exchange, as quantified by the Bowen ratio. Figure 10 shows the yearly course in Bowen ratio for several selected sites. During the winter Bowen ratio is variable, and in many instances large, with H being up to 6 times greater than λE . Occurrences of negative Bowen ratios are recorded as well and are attributed to radiative cooling and the presence of water on the surface. In both instances, stable thermal stratification is associated with the downward transfer of sensible heat. The timing of leaf out in the temperate broadleaved forest and grassland biomes affects the Bowen ratio markedly. The presence of leaves causes Bowen ratios to drop in magnitude, compared to their leafless states, and range between 0 and one. The timing of leaf-out also has a distinct impact on the humidity and temperature of the planetary boundary layer

(Schwartz, 1996) and the seasonal pattern of its maximum height (Wilson and Baldocchi, 2000; Yi et al., 2000).

There is a growing trend towards using coupled carbon-water flux models in global climate and forecasting models (Foley et al., 1998). The trend is warranted because information on photosynthesis constrains the information on stomatal conductance, a variable needed to compute sensible and latent heat exchange. Figure 11 shows how well carbon and water fluxes are coupled for two functional groups. Water use efficiency can be defined as the regression slope between F_c and λE . We observe that broadleaved forests use water more efficiently than conifer forests, by a factor of almost 1.5. Furthermore, variations in latent heat flux explain more of the variance in CO₂ exchange of broadleaved forests than it does for conifer forests; the coefficients of variation were 0.77 and 0.42, respectively. Another conclusion that can be drawn from this information relates to carbon sequestration and carbon storage. Greater carbon uptake cannot be achieved without the availability and use of water. Ecosystems with high rates of carbon uptake use more water.

The EUROFLUX community published results showing that gross primary productivity is relatively constant (Valentini et al., 2000). These data, however, come from a relatively narrow range of plant architectural and functional types (closed conifer and deciduous forests) and climate conditions, so one can question how applicable the results may be across a wider range of conditions. Using a biophysical model (Baldocchi and Meyers, 1998), we predict that gross primary productivity is an asymptotic function of leaf area index, leaf nitrogen and the fraction of photosynthetically active radiation that the canopy intercepts. Theoretical calculations also support the idea that gross primary

productivity is relatively constant for the range site characteristics studied by the EUROFLUX network (Figure 12).

There is a growing body of literature that is attempting to understand the impact of stand age on carbon and water fluxes (Amiro et al., 1999; Schulze et al., 1999; Law et al., in review; Paw U et al., in review), as productivity is assumed to diminish with age and disturbance affects the relative ratio between canopy carbon uptake and soil respiration and the ratio between canopy transpiration and soil evaporation. An attribute of a global network, such as FLUXNET, is the occurrence of sites with similar species and functionality, but different ages. Based on the data surveyed in Table 1d, we can draw the conclusion that the net carbon exchange of old growth conifer forests is not carbon neutral (eg. Paw U et al., in review). A direct comparison of flux densities of carbon dioxide and water vapor that were measured over an old age Ponderosa pine stand in Oregon and a young stand in northern California are shown in Figure 13. Peak rates of evaporation are almost triple for the young stand, as compared to the old stand. Net daytime carbon assimilation fluxes of the young and old stand are out of phase during the summer growing season. The old stand is most productive during the spring and autumn periods, while soil water deficits restrict summer time rates of CO₂ uptake. The young stand experiences greatest rates of uptake during the summer and peak rates can exceed peak rates of the old stand by 14% (-140 vs -120 gC m⁻² month⁻¹). Simulation modeling, which includes the effects of tree age, suggested that the milder winters and ample annual rainfall in the young stand allow it to have a higher leaf area than the old forest, allowing more carbon uptake through the year (Law et al. 2000). Site management also has a

substantial impact on carbon and water fluxes at the young site. The removal of understory shrubs in 1999 reduced both CO₂ uptake and evaporation.

CONCLUSIONS

A global network of long term measurement sites has been established and is producing new information on how CO₂ and water vapor between the terrestrial biosphere and atmosphere vary across a broad spectrum of biomes, climates and time scales. The science generated so far indicates that rates of net carbon uptake by tropical and temperate forests are substantial and exceed estimates previously generated with biospheric modeling systems. Gross primary productivity of forest ecosystems may not be constant, but may depend on plant architecture (e.g., on leaf area), foliage photosynthetic capacity and the amount of sunlight absorbed.

Carbon net ecosystem exchange of broad-leaved deciduous forests strongly depends on length of growing season, but are sensitive to perturbations such as droughts, clouds, winter snow cover and early thawing, too. Concerning conifer forests, the conclusions are not as unifying. Seasonal and annual sums of net carbon exchange by boreal, semi-arid, temperate and humid conifers differ among one another and for different physiological reasons.

The response of canopy-scale CO₂ exchange to sunlight varies with cloud cover as clouds alter the direction of incoming sunlight and how it penetrates into a canopy. The response of canopy-scale CO₂ exchange to temperature is sensitive to the local climate. The temperature optima for canopy photosynthesis are different for similar functional forest types in Europe and North America.

Future plans

The presence of sites on less than ideal terrain affords the micrometeorological community to take the challenge and assess the impact of advection on the measurement of long-term fluxes. Given the current tower site distribution, there is a need to develop transect studies at anchor sites, so we can study spatial patterns in greater detail and better assess the impact of forest stand age, biodiversity and land disturbances. Aircraft flux studies can be used to augment and extrapolate tower information in the spatial domain. More physiological and stand structure studies will be needed to aid in the interpretation of tower measurements and to provide contextual information to test ecophysiological models.

As data accumulate, new questions are arising about how to interpret fluxes made over mixed stands. Frontal passages cause the annual sums of ecosystem CO₂ exchange to be biased, as associated changes in wind direction and speed cause a tower site to view a different flux footprint (Amiro, 1998) or expose the ecosystem to different temperature and humidity regimes. Over sites with inadequate fetch or mixed vegetation in the flux footprint, flux densities that are measured will vary with wind direction. As knowledge evolves we may have to evaluate annual sums by weighting field measurements on the basis of wind direction and the appropriate flux footprint probability density functions (Schmid, 1994). On the flip side, we can use information from different wind directions to address questions relating to the role of biodiversity on mass and energy exchange of ecosystems.

ACKNOWLEDGEMENTS

The FLUXNET project office and Data Archive is sponsored by NASA's EOS Validation Program. The component regional networks and individual field sites are sponsored by an array of government agencies. The Americas network, AmeriFlux is sponsored by the United States Departments of Energy (Terrestrial Carbon Program, National Institutes of Global Environmental Change, NIGEC), Commerce (NOAA), Agriculture (USDA/Forest Service), NASA, the National Science Foundation and the Smithsonian Institution. These federal agencies sponsor the Global Change Research Program (USGCRP) to promote cooperation with each other, academia, and the international community in order to make it as easy as possible for researchers and others to access and use global change data and information.

European sites in the EUROFLUX and MEDEFU projects are supported by the European Commission Directorate General XII Environment and Climate Program. Canadian collaborators are sponsored by the Natural Sciences and Engineering Research Council of Canada (NSERC). Japanese and Asian sites are supported by the Ministry of Agriculture, Forest and Fisheries (MAFF), the Ministry of Industrial Trade and Industry, (MITI), and Ministry of Education, Science, Sports and Culture (MESSC).

We thank the numerous scientists, students and technicians responsible with the day to day gathering of the flux data and the agency representatives who fund the respective projects. Without the dedicated efforts of so many individuals, this global network would not function or exist. Special appreciation is extended to Drs. Roger Dahlman, Diane Wickland Ruth Reck, and David Starr, who have provided funds that supported initial planning workshops and that support many of the operating science teams.

REFERENCES

- Amiro, BD, MacPherson, JI and Desjardins, RL. 1999. BOREAS flight measurements of forest-fire effects on carbon dioxide and energy fluxes. *Agricultural and Forest Meteorology*. 96, 199-208.
- Amundson, R., L. Stern, T. Raisden and Y. Wang. 1998. The isotopic composition of soil and soil-respired CO₂. *Geoderma*. 82, 83-114.
- Amthor, J.S. 1995. Terrestrial higher-plant response to increasing atmospheric [CO₂] in relation to the global carbon cycle. *Global Change Biology* 1,243-274.
- Anderson, DE, Verma, S.B., Rosenberg, NJ. 1984. Eddy correlation measurements of CO₂, latent heat and sensible heat fluxes over a crop surface. *Boundary Layer Meteorology*. 29, 167-183.
- Anthoni PM, Law BE, Unsworth MH. 1999. Carbon and water vapor exchange of an open-canopied ponderosa pine ecosystem. *Agricultural and Forest Meteorology*, 95, 115-168
- Aubinet, M., A. Grelle, A. Ibrom, U. Rannik, J. Moncrieff, T. Foken, A. Kowalski, P. Martin, P. Berbigier, Ch. Bernhofer, R. Clement, J. Elbers, A. Granier, T. Grunwald, K. Morgenster, K. Pilegaard, C. Rebmann, W. Snijders, R. Valentini and T. Vesala. 2000. Estimates of the annual net carbon and water exchange of European forests: the EUROFLUX methodology, *Advances of Ecological Research*. 30, 113-175.
- BAHC Core Project Office (eds). 1993. Report No. 27. Biospheric Aspects of the Hydrological Cycle. The Operational Plan. Stockholm: IGBP, 103 p.
- Baldocchi, D.D and Meyers, T.P. 1998. On using eco-physiological, micrometeorological and biogeochemical theory to evaluate carbon dioxide, water vapor and gaseous deposition fluxes over vegetation. *Agricultural and Forest Meteorology* 90: 1-26.
- Baldocchi, D.D., Hicks, B.B. and Meyers, T.P. 1988. Measuring biosphere-atmosphere exchanges of biologically related gases with micrometeorological methods. *Ecology*. 69:1331-1340.
- Baldocchi, D.D., R.Valentini, S.R. Running, W. Oechel and R. Dahlman. 1996. Strategies for measuring and modeling CO₂ and water vapor fluxes over terrestrial ecosystems. *Global Change Biology*.2: 159-168.
- Baldocchi, D.D., J.J. Finnigan, K.W. Wilson, K.T. Paw U, and E. Falge. 2000. On measuring net ecosystem carbon exchange in complex terrain over tall vegetation. *Boundary Layer Meteorology*. 96: 257-291.

- Baldocchi, D.D., E. Falge and K. Wilson. 2001. A spectral analysis of biosphere-atmosphere trace gas flux densities and meteorological variables across hour to multi-year time scales. *Agricultural and Forest Meteorology*. 107, 1-27.
- Barr, A.G, G van der Kamp, R. Schmidt and T. A.Black. 2000 Monitoring the moisture balance of a boreal aspen forest using a deep groundwater piezometer, *Agricultural and Forest Meteorology*, 102, 13-24.
- Bakwin PS, Tans PP, Hurst DF, *et al.* 1998. Measurements of carbon dioxide on very tall towers: results of the NOAA/CMDL program. *Tellus B* 50: 401-415
- Baumgartner, A. 1969. Meteorological approach to the exchange of CO₂ between atmosphere and vegetation, particularly forests stands. *Photosynthetica* 3: 127-149.
- Betts, A.K., J.H. Ball, A.C. Beljaars, M.J.Miller, and P.A. Viterbo. 1996. The land surface-atmosphere interaction: a review based on observational and global modeling perspectives. *Journal of Geophysical Research*. 101 : 7209-7225.
- Black, T.A., G. den Hartog, H. Neumann, P. Blanken, P. Yang, Z. Nesic, S. Chen, C. Russel, P. Voroney and R. Staebler. 1996. Annual cycles of CO₂ and water vapor fluxes above and within a Boreal aspen stand, *Global Change Biology*. 2:219-230.
- Buchmann N, Schulze ED 1999. Net CO₂ and H₂O fluxes of terrestrial ecosystems. *Global Biogeochemical Cycles*. 3:751-760.
- Canadell, J., H. Mooney, D. Baldocchi, J. Berry, J. Ehleringer, C.B. Field, T. Gower, D. Hollinger, J. Hunt, R. Jackson, S. Running, G. Shaver, S. Trumbore, R. Valentini and B. Yoder. 2000. Carbon metabolism of the terrestrial biosphere. *Ecosystems* 3, 115-130.
- Ceulemans, R. and Mousseau, M. 1994. Tansley Review No. 71. Effects of elevated atmospheric CO₂ on woody plants. *New Phytologist*. 127, 425-446.
- Ciais, P., Tans, P.P., Trolier, M., White, JWC, Francy, RJ. 1995. A large North Hemisphere terrestrial CO₂ sink indicated by the ¹³C/¹²C ratio of atmospheric CO₂. *Science*. 269, 1098-1102.
- Conway, T.J., P.P. Tans, L.S. Waterman, K.W. Thoning, D.R. Kitzis, K. Masarie and N. Zhang. 1994. Evidence for interannual variability of the carbon cycle from NOAA/CMDL global sampling network. *Journal of Geophysical Research*. 99, 22831-22855.
- Cramer, W.J., D.W. Kicklighter, A. Bondeau et al., 1999. Comparing global models of terrestrial primary productivity (NPP): overview and key results. *Global Change Biology*. 5, 1-15.
- Crawford, T.L., Dobosy, R.J., McMillen, R.T., Vogel, C.A., and Hicks, B.B., 1996. Air-surface exchange measurement in heterogeneous regions: Extending tower

- observations with spatial structure observed from small aircraft. *Global Change Biology*, 2:275-285.
- Denmead, O.T. 1969. Comparative micrometeorology of a wheat field and a forest of *Pinus radiata* *Agricultural and Forest Meteorology* 6: 357-
- Denmead, O.T., Raupach, M.R., Dunin, F.X., Cleugh, H.A. and Leuning, R. 1996. Boundary layer budgets for regional estimates of scalar fluxes. *Global Change Biology*. 2, 255-264.
- Denning, A. S., J. G. Collatz, C. Zhang, D. A. Randall, J. A. Berry, P. J. Sellers, G. D. Colello, and D. A. Dazlich, 1996: Simulations of terrestrial carbon metabolism and atmospheric CO₂ in a general circulation model. Part 1: Surface carbon fluxes. *Tellus*, 48B, 521-542.
- Desjardins, R.L., D.J. Buckley and G. St.Amour. 1984. Eddy flux measurements of CO₂ above corn using a microcomputer system.. 32, 257-265.
- Desjardins, R.L., J.I. MacPherson, L. Mahrt, P. Schuepp, E. Pattey, H. Neumann, D. Baldocchi, S. Wofsy, D. Fitzjarrald and H. McCaughey. 1997. Scaling up flux measurements for the boreal forest using aircraft-tower combinations. *Journal of Geophysical Research* 102: 29125-29134.
- Drake, B.G., Gonzalez-Meler, M.A. and Long, S.P. 1996. More efficient plants: a consequence of rising atmospheric CO₂? *Annual Review of Plant Physiology and Plant Molecular Biology*. 48, 609-639.
- Falge, E., D. Baldocchi, R. Olson, P. *et al.* 2001. Gap filling strategies for defensible annual sums of net ecosystem exchange. *Agricultural and Forest Meteorology* 107, 43-69.
- Fan, S.M., M.Gloor, J. Mahlman, S. Pacala, J. Sarmiento, T. Takahashi and P. Tans. 1998. 'A large terrestrial carbon sink in North America implied by atmospheric and oceanic carbon dioxide data and models', *Science*. **282**, 442-446.
- Field, C.B., Randerson, J.T., and Malmstrom, C.M., 1995. Global net primary production: combining ecology and remote sensing. *Remote Sensing of the Environment*, 51: 74-88.
- Finnigan J.J. 1999 A comment on the paper by Lee (1998): "On micrometeorological observations of surface-air exchange over tall vegetation", *Agricultural and Forest Meteorology* 97: 55-64
- Foken, Th. and B. Wichura. 1995. 'Tools for quality assessment of surface-based flux measurements', *Agricultural and Forest Meteorology* , **78**, 83-105.

- Foley, J.A., S. Levis, I.C. Prentice, D. Pollard and S.L. Thompson. 1998. Coupling dynamic models of climate and vegetation. *Global Change Biology*. 4, 561-580.
- Gower, S.T., CJ Kucharik and JM Norman. 1999. Direct and indirect estimation of leaf area index, fpar and net primary production of terrestrial ecosystems. *Remote Sensing of the Environment*. 70, 29-51
- Goldstein, AH, NE Hultman, JM Fracheboud, MR Bauer, JA Panek, M Xu, Y Qi, AB Guenther, W Baugh, 2000. Effects of climate variability on the carbon dioxide, water, and sensible heat fluxes above a ponderosa pine plantation in the Sierra Nevada (CA). *Agricultural and Forest Meteorology*, 101, 113-129.
- Goulden, M.L., Munger, J.W., Fan, S.M. Daube, B.C., and Wofsy, S.C. 1996a. Measurement of carbon storage by long-term eddy correlation: Methods and a critical assessment of accuracy, *Global Change Biology*, 2, 169-182.
- Goulden, M.L., J.W. Munger, S.-M. Fan, B.C. Daube and S.C. Wofsy. 1996b. Exchange of carbon dioxide by a deciduous forest: Response to interannual climate variability. *Science*, 271, 1576-1578.
- Goulden, M.L., S.C. Wofsy, J.W. harden, S.E. Trumbore, P.M. Crill, S.T. Gower, T. Fires, B.C. Daube, S.M. Fan, D.J. Sutton, A. Bazzaz, and J.W. Munger. 1998. Sensitivity of boreal forest carbon balance to soil thaw. *Science*. 279, 214-217.
- Granier, A. E. Ceschia, C. Damesin, et al. 2000. The carbon balance of a young beech forest. *Functional Ecology*. 14, 312-325.
- Greco, S. and D.D. Baldocchi. 1996. Seasonal variations of CO₂ and water vapor exchange rates over a temperate deciduous forest. *Global Change Biology*. 2: 183-198.
- Gu, L., J.D. Fuentes, H.H. Shugart, R.M. Staebler and T.A. Black. 1999. Responses of net ecosystem exchanges of carbon dioxide to changes in cloudiness: results form two North American deciduous forests. *Journal of Geophysical Research* 104: 31421-31434.
- Halldin S, Gryning SE, Gottschalk L, et al. 1999. Energy, water and carbon exchange in a boreal forest landscape - NOPEX experiences *Agricultural and Forest Meteorology* 98-9: 5-29
- Hanson, J.E., M. Sato, A.Lacis, R. Ruedy, I. Tegen and E. Matthews. 1998. Climate forcings in the Industrial era. *Proceedings of the National Academy of Science, USA*. 95, 12753-12758.

- Houghton, R.A. and G. Woodwell. 1980. The flax pond ecosystem study: exchanges of CO₂ between a salt marsh and the atmosphere. *Ecology*. 61, 1434-1445.
- Inoue, I. 1958. An aerodynamic measurement of photosynthesis over a paddy field. *Proc. 7th Japan National Congress of Applied Mechanics*. pp. 211-214.
- Jarvis, P.G., G.B. James and J.J. Landsberg. 1976. Coniferous forest. In: **Vegetation and the Atmosphere, vol 2**. ed. J.L. Monteith. Academic Press. London. pp. 171-240.
- Jacobs, C.M.J., De Bruin, H.A.R., 1992. The sensitivity of transpiration to land-surface characteristics: Significance of feedback. *Journal of Climate*, 5, 683-698.
- Kaimal, J.C. and J.J. Finnigan. 1994. *Atmospheric Boundary Layer Flows: Their Structure and Measurement*. Oxford University Press, Oxford, UK. 289 pp.
- Kauppi, P.E., K. Mielikainen and K. Kuuseia. (1992). Biomass and carbon budget of European forests, 1971 to 1990. *Science*, 256: 70-74.
- Keeling, C.D. and T.P. Whorf. (1994). Atmospheric CO₂ records from sites in the SIO air sampling network. pp 16-26. In: *Trends '93: A compendium of Data on Global Change*. ORNL/CDIAC-65. Oak Ridge, TN
- Keeling, C.D., Whorf, T.P., Wahlen, M., and v.d. Plicht, J., 1995. Interannual extremes in the rate of rise of atmospheric carbon dioxide since 1980. *Nature*, 375: 666-670.
- Keeling, R.F., S.C. Piper and M. Heimann. 1996. Global and hemispheric CO₂ sinks deduced from changes in atmospheric O₂ concentration. *Nature*. 381, 218-221.
- Kelliher, F.M., R. Leuning, M.R. Raupach, and E.D. Schulze. 1995. Maximum conductances for evaporation from global vegetation types. *Agricultural and Forest Meteorology*. 73: 1-16.
- Law, B.E., A.H. Goldstein, P.M. Anthoni, J.A. Panek, M.H. Unsworth, M.R. Bauer, J.M. Fracheboud, N. Hultman. 2000. CO₂ and water vapor exchange by young and old ponderosa pine ecosystems during a dry summer. *Tree Physiology*. (in press).
- Law, B.E., P. Thornton, J. Irvine, P. Anthoni, S. Van Tuyl. 2000. Carbon storage and fluxes in ponderosa pine forests at different developmental stages. *Global Change Biology* (submitted).
- Lee, X. 1998. On micrometeorological observations of surface-air exchange over tall vegetation, *Agricultural and Forest Meteorology*, **91**, 39-50.

- Lee, X., Fuentes, J.D., Staebler, R.M. and Neumann, H.H. 1999. Long-term observation of the atmospheric exchange of CO₂ with a temperate deciduous forest in southern Ontario, Canada. *Journal of Geophysical Research*. 104, 15975-15984.
- Lemon, E.R. 1960. Photosynthesis under field conditions. II. An aerodynamic method for determining the turbulent carbon dioxide exchange between the atmosphere and a corn field. *Agronomy Journal*. 52: 697-703.
- Levy, P.E., A. Grelle, a. Lindroth, M. Molder, P.G. Jarvis, B. Kruijt and J. B. Moncrieff. 1999. Regional scale CO₂ fluxes over central Sweden by a boundary layer budget method. *Agricultural and Forest Meteorology*. 98-99, 169-180.
- Lindroth, A., A. Grelle, A.S. Moren. 1998. Long-term measurements of boreal forest carbon balance reveal large temperature sensitivity, *Global Change Biology*, **4**, 443-450.
- Mahli, Y, Nobre, A.D., Grace, J., Kruijt, B., Pereira, M. Culf, A., Scott, S. 1998. Carbon dioxide transfer over a central Amazonian rain forest. *Journal of Geophysical Research*. 31, 593-612.
- Markkanen, T., U. Rannik, P. Keronen, T. Suni and T. Vesala. 2001. Eddy covariance fluxes over a boreal Scots pine forest. *Boreal Environment Research*. In press
- Massman, W.J. 2000. A simple method for estimating frequency response corrections for eddy covariance systems. *Agricultural and Forest Meteorology*. 104, 185-198.
- Meyers, T.P. 2001. A comparison of summertime water and CO₂ fluxes over rangeland for well-watered and drought conditions. *Agricultural and Forest Meteorology*. 106, 205-214.
- Moncrieff, J.B., Y. Mahli and R. Leuning. 1996. The propagation of errors in long term measurements of land atmosphere fluxes of carbon and water, *Global Change Biology*, **2**, 231-240.
- Monteith, J.L. and G. Szeicz. 1960. The CO₂ flux over a field of sugar beets. *Quarterly Journal of the Royal Meteorological Society*. 86: 205-214.
- Moore, C.J. 1986. Frequency response corrections for eddy covariance systems. *Boundary Layer Meteorology*. 37, 17-35.
- Myneni, R.B., C.D. Keeling, C.J. Tucker, G. Asrar and R.R. Nemani. 1997. Increased plant growth in the northern high latitudes from 1981-1991. *Nature*. 386, 698-702.

- Myneni, R.B., Nemani, R.R., and Running, S.W., 1997b. Estimation of global leaf area index and absorbed par using radiative transfer models. *IEEE Transactions on Geoscience and Remote Sensing*, 35(6): 1380-1393.
- Niinemets U, Oja V, Kull O. 1999. Shape of leaf photosynthetic electron transport versus temperature response curve is not constant along canopy light gradients in temperate deciduous trees. *Plant Cell Environ.* 22: 1497-1513.
- Norby, R.J., S.D. Wullschleger, C.A. Gunderson, D.W. Johnson, and R. Ceulemans. 1999. Tree responses to rising CO₂ in field experiments: implication for the future forest. *Plant, Cell and Environment* 22, 683-714.
- Oechel WC, Vourlitis GL, Hastings SJ, Zulueta RC, Hinzman L, Kane D. 2000. Acclimation of ecosystem CO₂ exchange in the Alaskan Arctic in response to decadal climate warming. *Nature* 406: 978-981.
- Ohtaki, E. 1984. Application of an infrared carbon dioxide and humidity instrument to studies of turbulent transport. *Boundary-Layer Meteorology*. 29, 85-107.
- Paw U, K.T., M.B. Falk, T.H. Suchanek, S.L. Ustin, J. Chen, Y. Park, W.E. Winner, S.C. Thomas, T.C. Hsiao, R.H. Shaw, T.S. King, R.D. Pyles and A.A. Matista. 2000. Carbon dioxide exchange between old growth forest and the atmosphere. *Ecosystems*. To be submitted.
- Pielke, R.A., R. Avissar, M. Raupach, A.J. Dolman, X. Zeng and A.S. Denning. 1998. Interactions between the atmosphere and terrestrial ecosystems: influence on weather and climate. *Global Change Biology*. 4, 61-476.
- Pilegaard, K., Hunnelshøj, P., Jensen, N.O. and Chen, Z. 2001. Two years of continuous CO₂ eddy-flux measurements over a Danish beech forest. *Agricultural and Forest Meteorology* 107, 29-41.
- Postonak, M.J., S.C. Wofsy, A.S. Denning, T.J. Conway, J.W. Munger and D.H. Barnes. 1999. Influence of biotic exchange and combustion sources on atmospheric CO₂ concentrations in New England from observations at a forest flux tower. *Journal of Geophysical Research*. 104, 9561-9569.
- Randerson, J.T., Thompson, M.V., Conway, T.J., Fung, I.Y., and Field, C.B., 1997. The contribution of terrestrial sources and sinks to trends in the seasonal cycle of atmospheric carbon dioxide. *Global Biogeochemical Cycles*, 11: 535-560.
- Raupach, M.R. and B.J. Legg. 1984. The uses and limitations of flux-gradient relationships in micrometeorology. *Agricultural Water Management*. 8, 119-131
- Running, S.W., D.D. Baldocchi, D. Turner S.T. Gower, P. Bakwin and K. Hibbard. 1999. A global terrestrial monitoring network, scaling tower fluxes with ecosystem

- modeling and EOS satellite data. *Remote Sensing of the Environment*. 70, 108-127.
- Ruimy, A., Jarvis, P.G., Baldocchi, D.D. and Saugier, B. 1995. CO₂ fluxes over plant canopies and solar radiation: a review. *Advances in Ecological Research*. 26, 1-53.
- Schmid, H.P. 1994. Source areas for scalars and scalar fluxes. *Boundary Layer Meteorology* 67: 293-318.
- Schmid, HP, C.S. Grimmond, F. Cropley, B. Offerle and H-B. Su. 2000. Measurements of CO₂ and energy fluxes over a mixed hardwood forest in the mid-western United States. *Agricultural and Forest Meteorology*. 103, 357-374.
- Schwartz, M.D., 1996. Examining the spring discontinuity in daily temperature ranges. *Journal of Climate*, 9, 803-808.
- Schulze ED, Lloyd J, Kelliher FM, et al. 1999. Productivity of forests in the Eurosiberian boreal region and their potential to act as a carbon sink - a synthesis *Global Change Biology* 5:703-722.
- Sellers, P.J., F.G. Hall, R.D.Kelly, A.Black, D. Baldocchi, J.Berry, H. Margolis, M.Ryan, J. Ranson, P.Crill, D. Lettenmaier, J Cihlar, J Newcomer, D Halliwell, D. Fitzjarrald, P. Jarvis, S. Gower, D. Williams, B. Goodison, D. Wickland and F. Guertin. 1997. BOREAS in 1997: Scientific results, experimental overview and future directions. *Journal of Geophysical Research*. 102: 28731- 28770.
- Steffen, W., I. Noble, J. Canadell, M. Apps, E.D. Schulze, P. Jarvis, D. Baldocchi, P. Ciais, W. Cramer, J. Ehleringer, G. Farquhar, C. Field, A. Ghazi, R. Gifford, M. Heimann, R. Houghton, P. Kabat, C. Korner, E. Lambin, S. Linder, J. Lloyd, H. Mooney, D. Murdiyarso, W. Post, C. Prentice, M. Raupach, D. Schimel, A. Shvidenko, R. Valentini. 1998. The terrestrial carbon cycle: implications for the Kyoto protocol. *Science*. 280: 1393-1394
- Suyker, A.E. and S.B. Verma. 2000. Year-round observations of the net ecosystem exchange of carbon dioxide in a native tall grass prairie. *Global Change Biology*. (in press).
- Tans, P.P., Fung, I.Y., and Takahashi, T., 1990. Observational constraints on the global atmospheric CO₂ budget. *Science*, 247: 1431-1438.
- Wilson, K.B. and Baldocchi, D.D. 2000. Estimating annual net ecosystem exchange of carbon over five years at a deciduous forest in the southern United States. *Agricultural and Forest Meteorology*. 100, 1-18.

- Wilson, K.B., Baldocchi, D.D. and Hanson, P.J. 2000. Spatial and seasonal variability of photosynthesis parameters and their relationship to leaf nitrogen in a deciduous forest. *Tree Physiology* 20, 787-797.
- Wofsy, S.C, M.L. Goulden, J.W. Munger, S.M. Fan, P.S. Bakwin, B.C. Daube, S.L. Bassow and F.A. Bazzaz. 1993. 'Net exchange of CO₂ in a mid-latitude forest', *Science*. **260**, 1314-1317.
- Valentini, R. P. de Angelis, G. Matteucci, R. Monaco, S. Dore, and G.E. Scarascia-Mugnozza. 1996. Seasonal net carbon dioxide exchange of a beech forest with the atmosphere. *Global Change Biology*. 2: 199-208.
- Valentini, R. G. Matteucci, A.J. Dolman, et al. Respiration as the main determinant of carbon balance in European forests. *Nature*. 2000. 404, 861-864.
- Verma, S.B., D.D. Baldocchi, D.E. Anderson, D.R. Matt and R.E. Clement. 1986. Eddy fluxes of CO₂, water vapor, and sensible heat over a deciduous forest. *Boundary Layer Meteorology*. 36: 71-91.
- Verma, S.B., J. Kim and R.J. Clement. 1989. Carbon dioxide, water vapor and sensible heat fluxes over a tall grass prairie. *Boundary Layer Meteorology* 46, 53-67.
- Vermetten, A.W.M., L. Ganzeveld, A. Jeuken, P. Hofschreuder and G.M.J. Mohren. 1994. CO₂ uptake by a stand of Douglas fir: flux measurements compared with model calculations', *Agricultural and Forest Meteorology*, 72, 57-80.
- Yamamoto, S., S. Murayama, N. Saigusa and H. Kondo. 1999. Tellus. Seasonal and interannual variation of CO₂ flux between a temperate forest and the atmosphere in Japan. *Tellus*. 51B 402-413.
- Yi, C., K.J. Davis, P.S. Bakwin, B.W. Berger and L.C. Marr. 2000. Influence of advection on measurements of the net ecosystem-atmosphere exchange of CO₂ from a very tall tower. *Journal of Geophysical Research*. 105, 9991-9999.

List of Figures

Figure 1 Global map of FLUXNET field sites.

Figure 2. A comparison of CO₂ flux densities between the FLUXNET reference set of instruments and instruments at the Italian CarboEuroFlux site.

Figure 3 Annual course of net ecosystem CO₂ exchange for three temperate deciduous forests, one in Oak Ridge, TN, Petersham, MA and Denmark

Figure 4 Impact of length of growing season on temperate broadleaved forests and one tropical forest. B₀ is the zero intercept and B₁ is the slope. R² is the coefficient of determination.

Figure 5. Year to year variation in the annual cycle of CO₂ exchange at Harvard Forest, a broad-leaved deciduous forest (adapted from Goulden et al., 1996).

Figure 6 Seasonal course of net CO₂ exchange over contrasting conifer forests during 1997.

Figure 7 Power spectrum of CO₂ flux over the course of a year at sites of contrasting climate, functionality and structure. The power spectrum for the deciduous forest was computed from a three-year time series. Power spectra for the other sites were derived from time series one year in duration. The power spectra on the y axis are multiplied by natural frequency (n) and are normalized by variance.

Figure 8 Seasonal variation of initial quantum yield of a Scots pine forest in Finland. Quantum yield is the initial slope of the response between canopy CO₂ exchange and photosynthetic photon flux density.

Figure 9 The relation between the optimum temperature for canopy-scale gross primary productivity versus maximum mean monthly air temperature as a function of plant functional type. These data show how photosynthesis adapts to climate.

Figure 10 Seasonality of Bowen ratio, the ratio between sensible and latent heat flux densities at representative deciduous and conifer forest, crop and grassland sites.

Figure 11 The linkage between carbon and water fluxes for conifer and temperate forests. B₀ is the zero intercept and B₁ is the slope. R² is the coefficient of determination

Figure 12 Synthesis of gross primary productivity using field data and a biophysical model.

Figure 13 The impact of stand age on daytime CO₂ exchange and latent heat exchange. The data are from a young (< 10 years) and old (> 200 years) ponderosa pine forest (see Law et al., 2000).

Table 1

List of published year-long studies of net biosphere-atmosphere CO₂ exchange, N_e. Negative signs represent a loss of carbon from the atmosphere and a net gain by the ecosystem

Table 1a. Temperate Broadleaved Deciduous Forests

Site	Vegetation	N _e	obs year	PI	Citation
		gC m ⁻² yr ⁻¹			
Italy	Beech, <i>Fagus</i>	-470	1994	R. Valentini	Valentini et al 1996
France	Beech, <i>Fagus</i>	-218	1996	A. Granier	Granier et al. 2000
		-257	1997		
Denmark	Beech, <i>Fagus</i>	-169	1997	N.O. Jensen	Pilegaard et al. in press
		-124	1998		Pilegaard et al in press
Iceland	Poplar	-100	1997	H. Thoreirsson	Valentini et al
Saskatchewan, Canada	Aspen	-160	1994	T.A. Black	Black et al 1996
		-144	1994		Black et al 2000
		-80	1996		
		-116	1997		
		-290	1998		
Oak Ridge, TN	<i>Quercus</i> , <i>Acer</i>	-525	1994	D. Baldocchi	Greco +Baldocchi 1996
		-610	1995		Wilson + Baldocchi, 2000
		-597	1996		
		-652	1997		
		-656	1998		
		-739	1999		
Petersham, MA	<i>Acer</i> , <i>Quercus</i>	-280	1991	S. Wofsy	Wofsy et al., 1993
		-220	1992		
		-140	1993		Goulden et al 1996
		-210	1994		

		-270	1995		
Borden, Ontario	Maple, <i>Acer</i>	-80	1996	X. Lee/J. Fuentes	Lee et al, 1999
		-270	1997		
		-200	1998		
Indiana	deciduous forest	-240	1998	H.P. Schmid	Schmid et al 2000
Takayama, Japan	broadleaf deciduous	-120	1994		Yamamoto et al. 1999
		-70	1995		
		-140	1996		
		-150	1997		
		-140	1998		

Table 1b. Mixed deciduous and evergreen forests, Temperate and Mediterranean

Site	Vegetation	N _e	obs year	PI	Citation
Belgium	conifer+ broadleaf	-430	1997	M. Aubinet	Valentini et al. 2000
Belgium	conifer+ broadleaf	-157	1997	R. Ceulemans	Valentini et al. 2000

Table 1c Tropical Forests

Site	Vegetation	N _e gC m ⁻² yr ⁻¹	obs year	PI	Citation
Amazon	Tropical Forest	-590	1995-96	Y. Malhi	Malhi et al., 1998

Table 1d Needle-leaf, evergreen, conifer forests

Site	Vegetation	N _e gC m ⁻² yr ⁻¹	obs year	PI	Citation
Sweden	<i>Pinus sylvestris</i>	90	1995	A. Lindroth	Lindroth et al. 1998
		-5	1996		
		80	1997		
	<i>Picea abies</i>	-190	1997		

Italy	<i>Picea abies</i>	-450	1998	R. Valentini	Valentini et al 2000
France	<i>Pinus pinaster</i>	-430	1997	P. Berbiger	Valentini et al 2000
Germany	<i>Picea abies</i>	-77	1997		Valentini et al
Germany	<i>Picea abies</i>	-330	1996	Ch. Bernhofer	Valentini et al 2000
		-480	1997		
		-45	1998		
Germany	Conifer	-310	1996	A. Ibrom	Valentini et al. 2000
		-490	1997		
Germany	<i>Picea abies</i>	-77	1997	E-D Schulze	Valentini et al. 2000
Netherlands	<i>Pinus sylvestris</i>	-210	1997	H. Dolman	Valentini et al
United Kingdom	<i>Picea sitchensis</i>	-670	1997	J. Moncrieff	Valentini et al
		-570	1998		Valentini et al
Finland	<i>Pinus sylvestris</i>	-230	1997	T. Vesala	Valentini et al
		-260	1998		Markkanen et al. 2000
		-190	1999		
Howland, ME	Conifer	-210	1996	D. Hollinger	Hollinger et al 1999
Florida	slash pine	-740	1996	H. Gholz	Clarke et al. 1999
		-610	1997		
Florida	Cypress	-84	1996	H. Gholz	Clarke et al. 1999
		-37	1997		
Manitoba, Canada	<i>Picea mariana</i>	70	1995		Goulden et al. 1998
		20	1996		
		-10	1997		
Metolius, OR	<i>Pinus ponderosa</i>	-320	1996	B. Law	Anthoni et al 1999
		-270	1997		
Wind River, WA	<i>Pseudotsuga</i>	-167 to	1998	K.T. Paw U	Paw U et al. 2000

	<i>menziei</i>	-220			
Prince Albert, Saskatchewan	<i>Picea mariana</i>	-68	1995	P. Jarvis	Mahli et al, 1999

Table 1e Broadleaved Evergreen, Mediterranean Forests

Site	Vegetation	N _e	obs year	PI	Citation
Italy	<i>Quercus ilex</i>	-660	1997	R. Valentini	Valentini et al 2000

Table 1f Grassland

Site	Vegetation	N _e	obs year	PI	Citation
Ponca, OK	Tall-grass prairie	0	1997	S.B. Verma	Suyker and Verma, in press
Little Washita, OK	Grazed grassland	41	1997		Meyers, 2001

Table 1g Tundra

Site	Vegetation	N _e	obs year	PI	Citation
Alaska	tundra	40		W. Oechel	Oechel et al. 2000

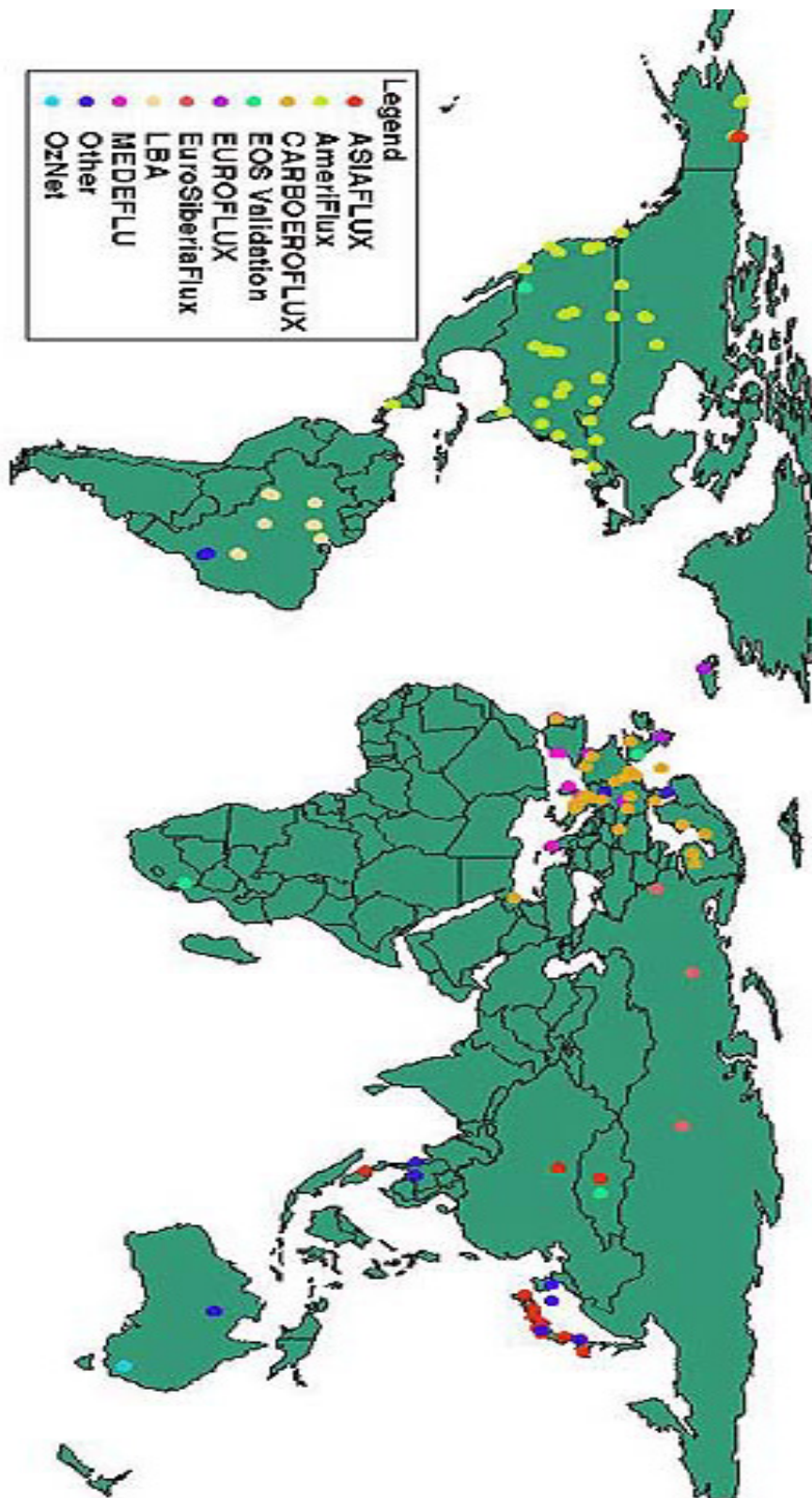


Figure 1 Global map of FLUXNET field sites

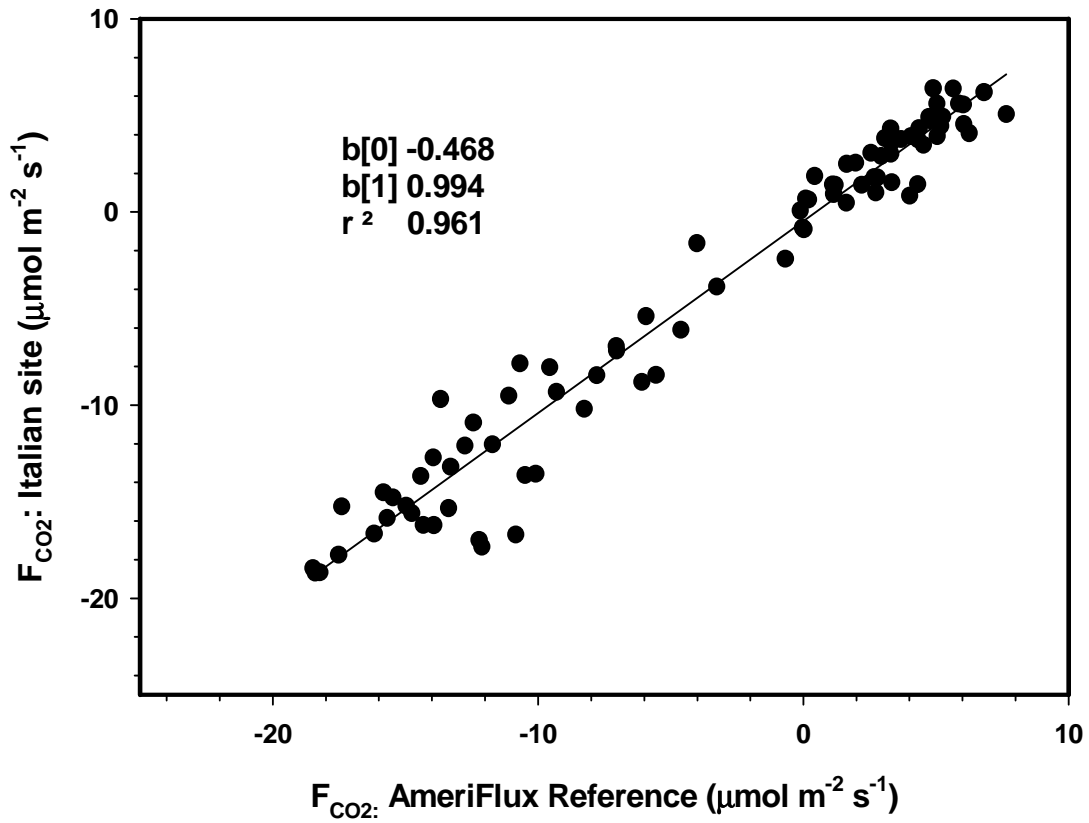


Figure 2

Comparison between CO_2 flux densities measured at the Italian CarboEuroFlux site. The locally measured fluxes are compared with those produced by the roving AmeriFlux reference system.

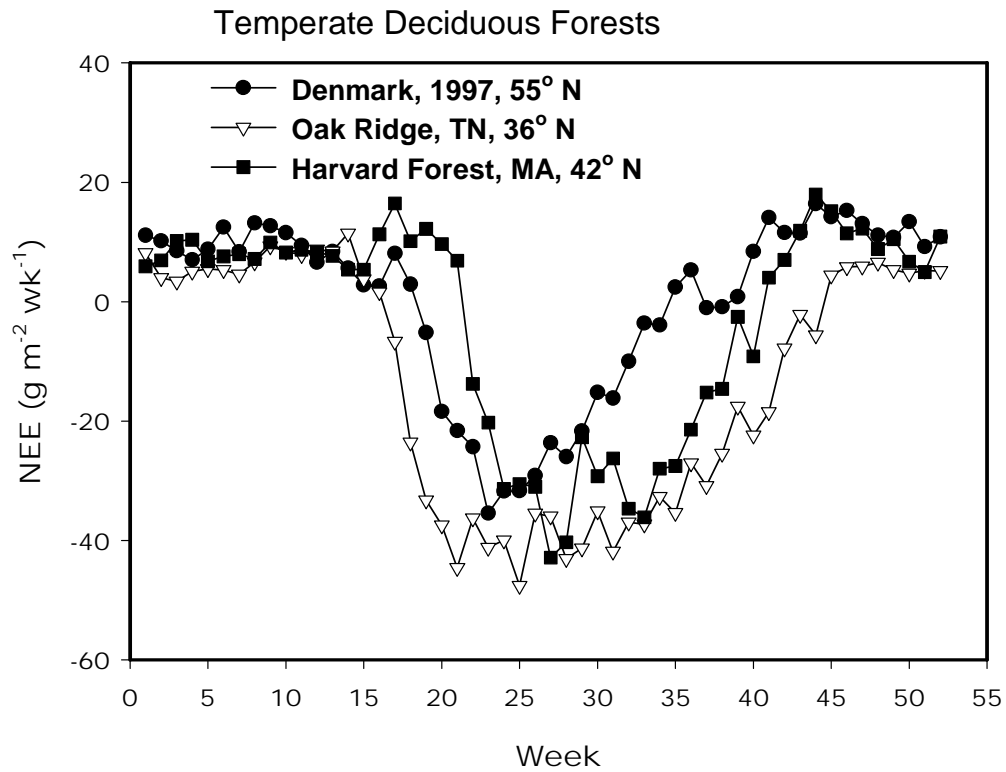
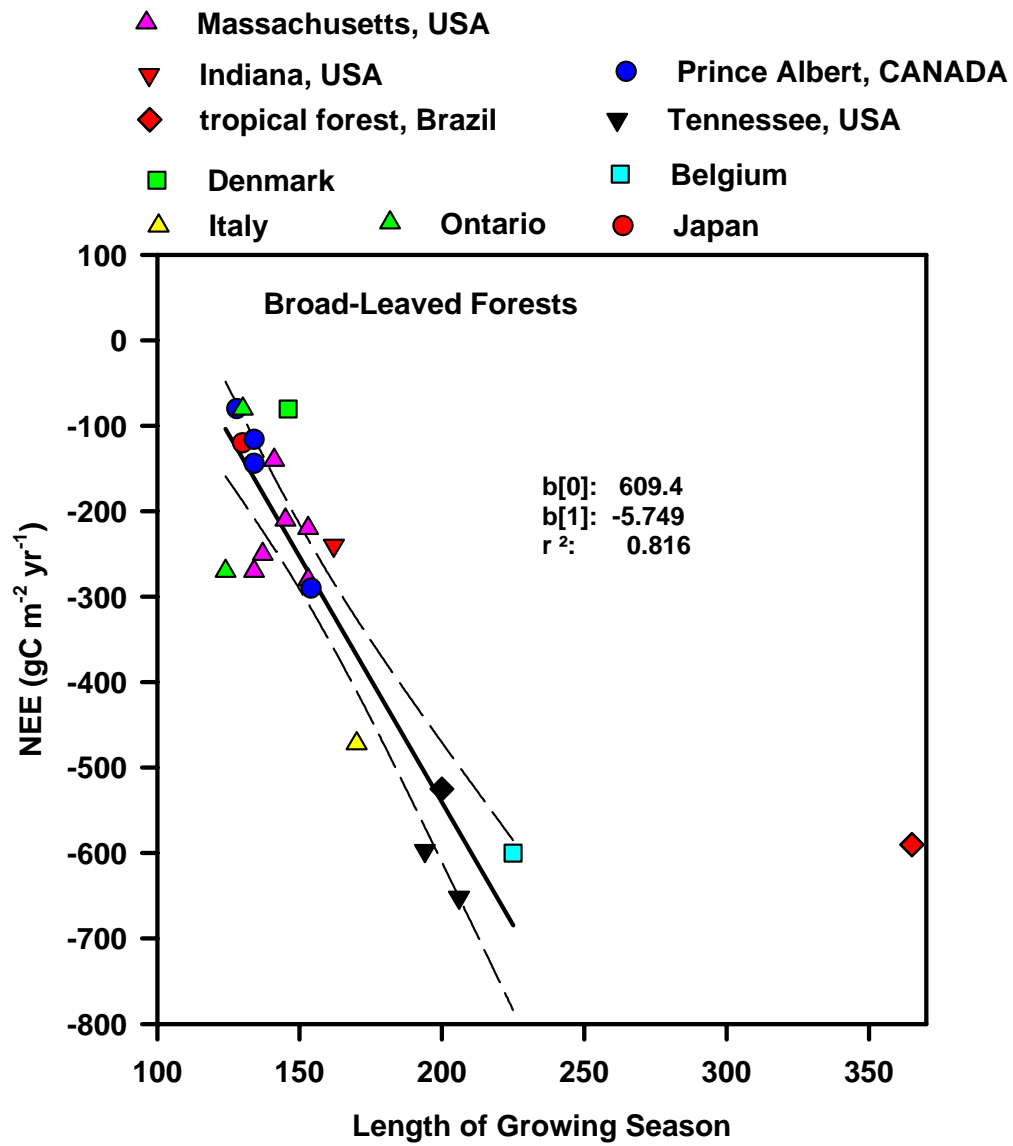


Figure 3 Annual course of daily-integrated net ecosystem CO₂ exchange for three temperate deciduous forests. The sites are near Oak Ridge, TN, Petersham, MA and Soroe, Denmark.



neebrdlf.spw
10/12/2000

Figure 4 Impact of length of growing season on the annual sum of net ecosystem CO₂ exchange of temperate broadleaved forests. Also plotted is data from a tropical forest.

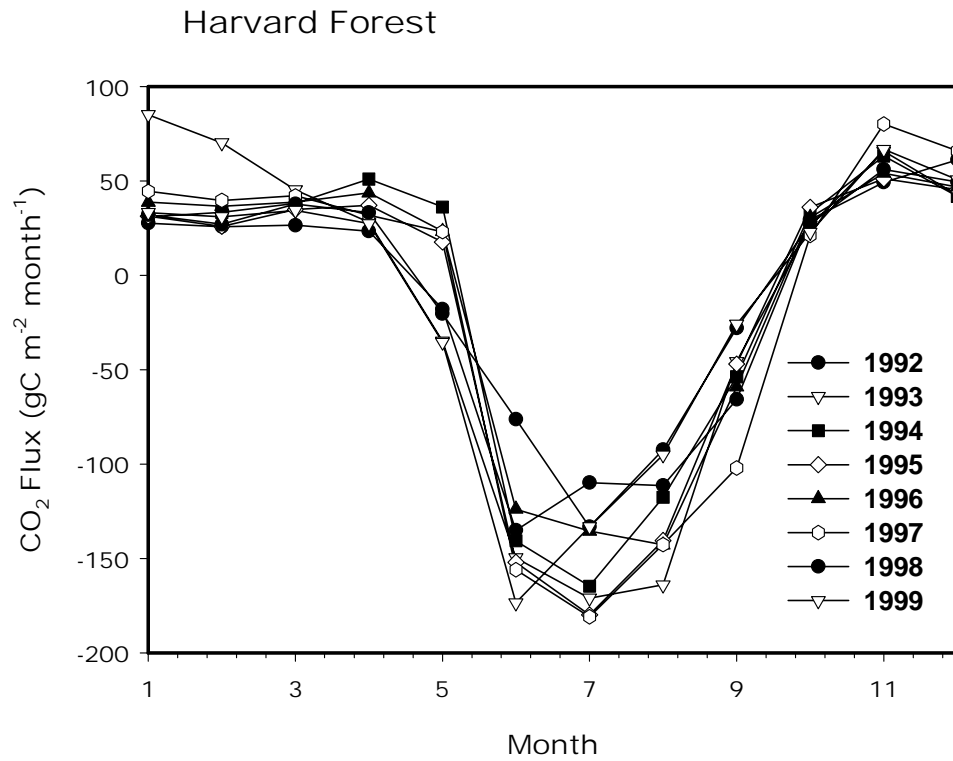
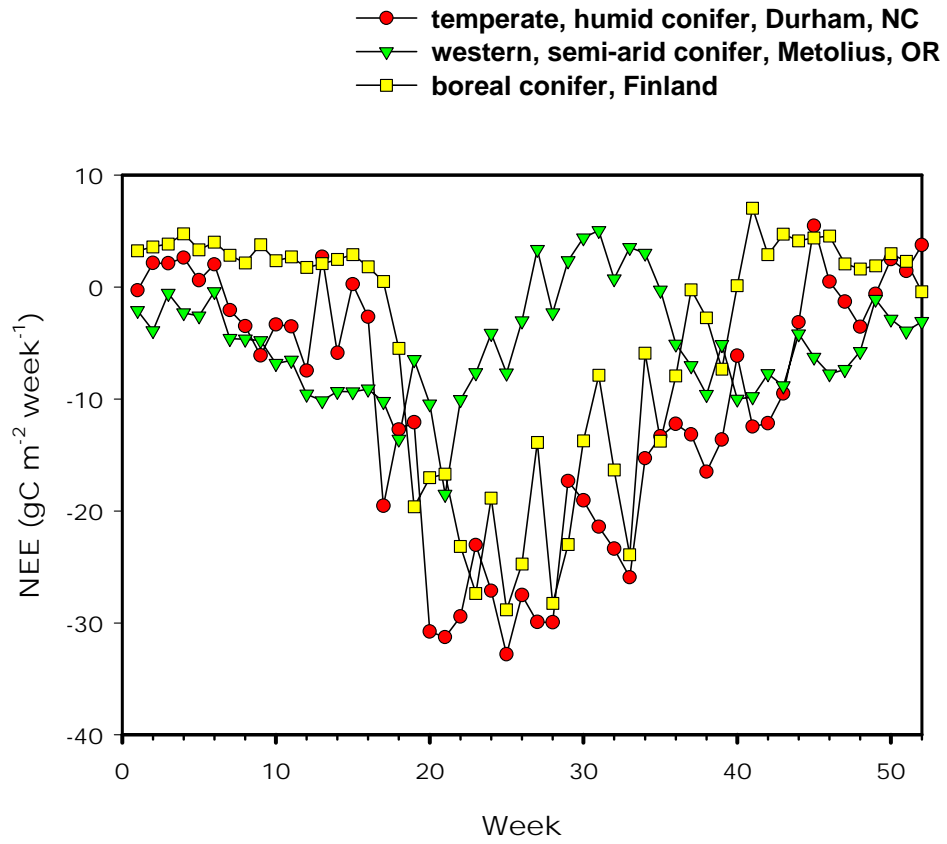


Figure 5 Year to year variation in the annual cycle of CO₂ exchange at a temperate broadleaved forest, near Petersham, MA.



5/27/2000

Figure 6 Seasonal course of net CO₂ exchange over contrasting conifer forests. The data are integrated over week durations.

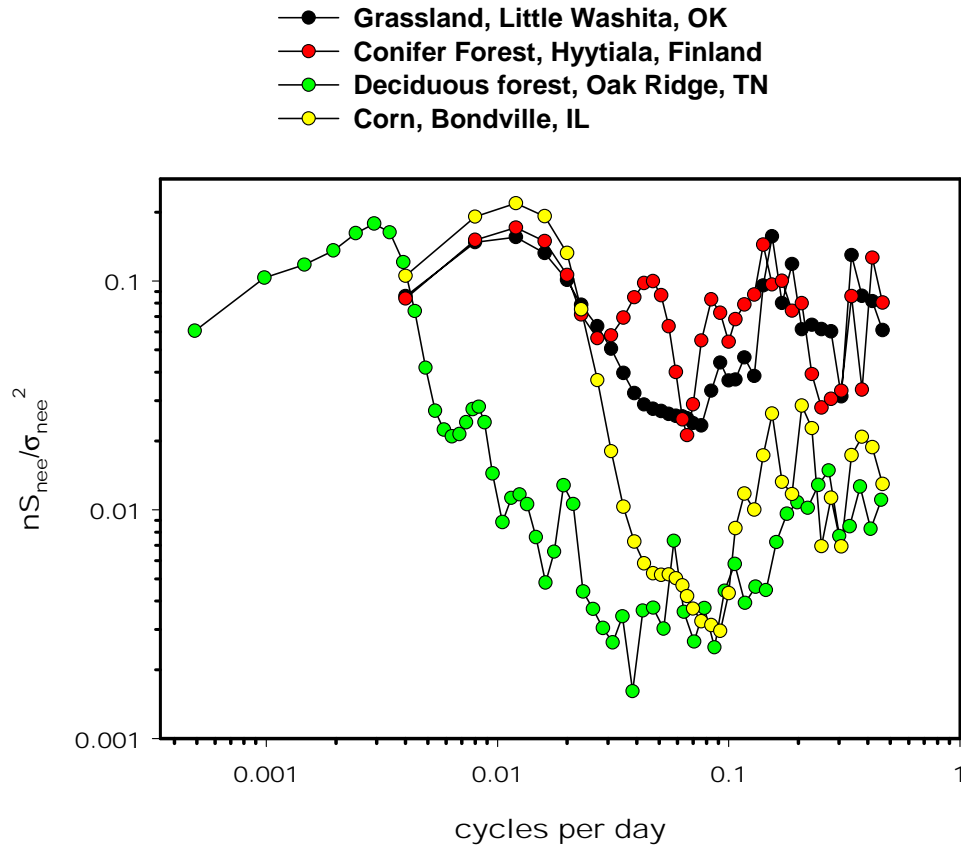


Figure 7 Normalized power spectra of CO₂ flux densities over the course of a year at sites of contrasting climate, functionality and structure. The power spectrum for the deciduous forest was computed from a three-year time series. Power spectra for the other sites were derived from time series one year in duration.

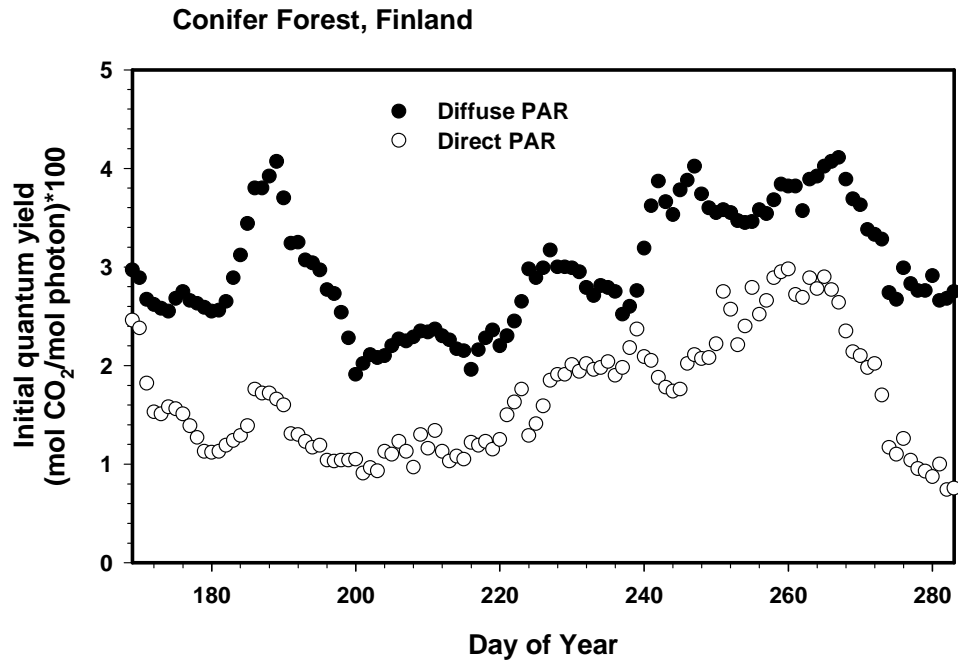


Figure 8 Seasonal variation of initial quantum yield of a Scots pine forest in Finland as a function of direct and diffuse solar radiation in the visible waveband.

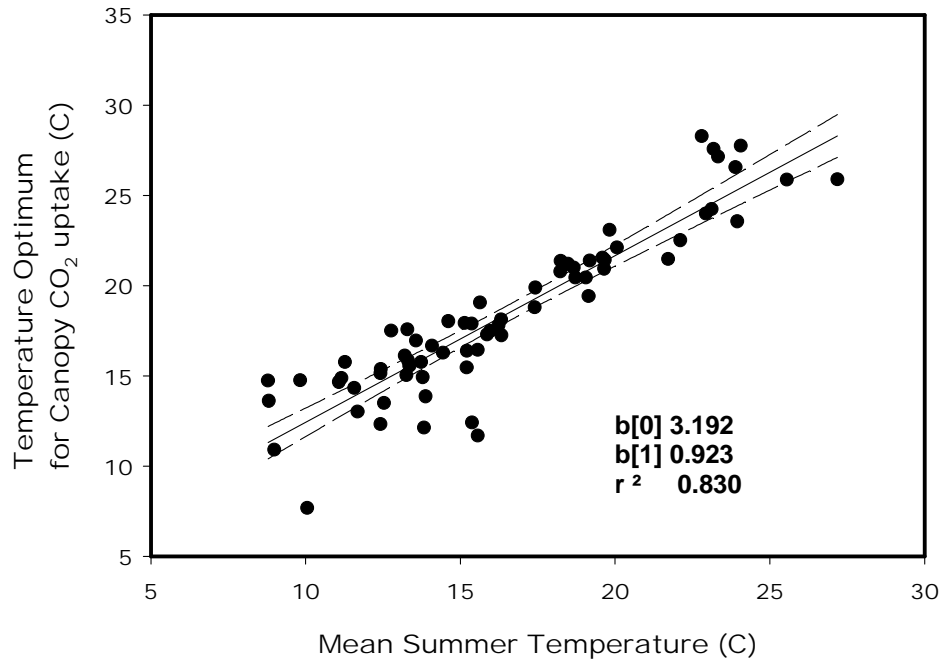


Figure 9 The relation between the optimum temperature for canopy-scale gross primary productivity versus mean monthly air temperature during the summer growing season. These data show how canopy-scale photosynthesis adapts to climate.

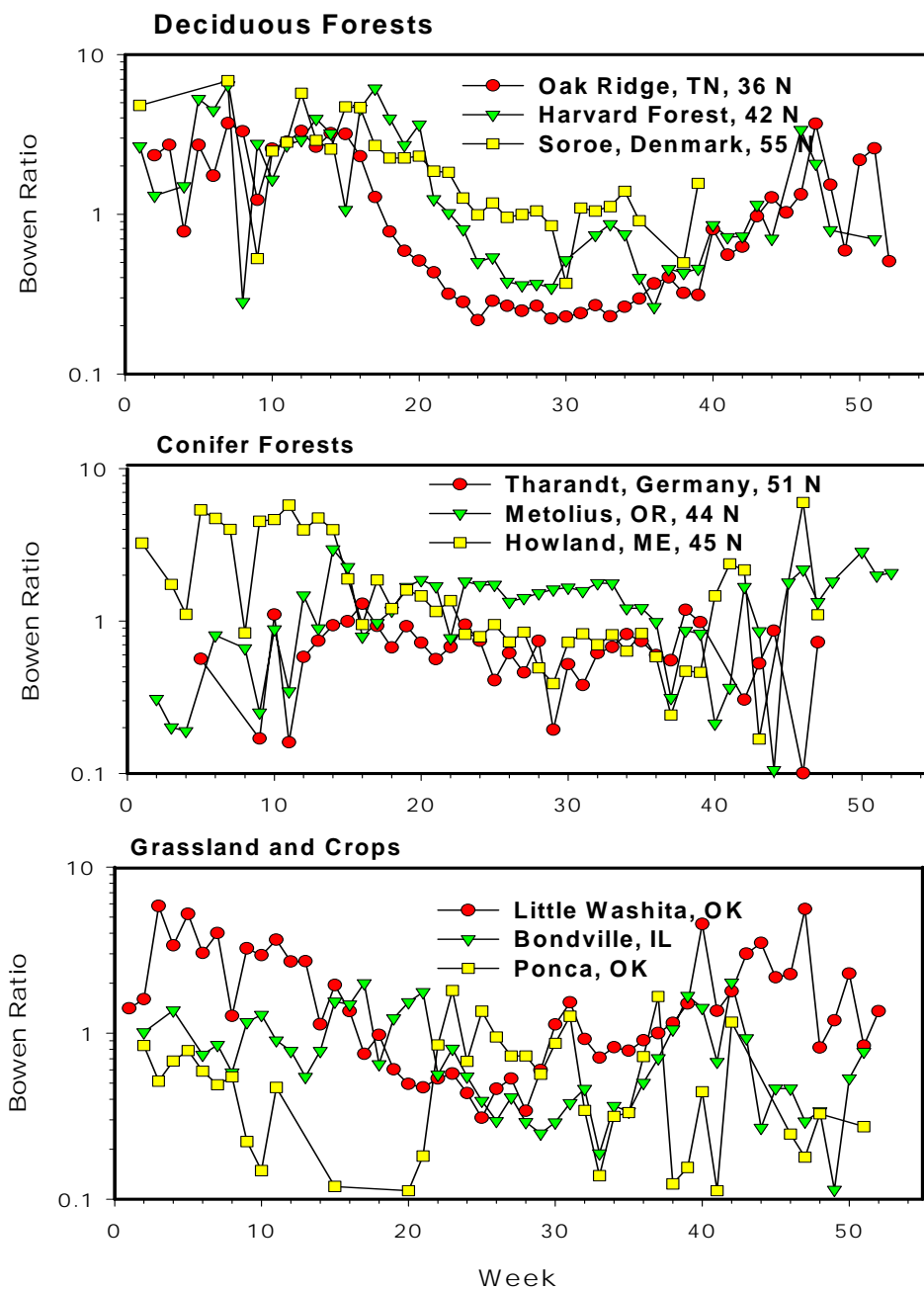


Figure 10 Seasonality of Bowen ratio, the ratio between sensible and latent heat flux densities at representative deciduous and conifer forest, crop and grassland sites. The data were averaged over a week-long periods.

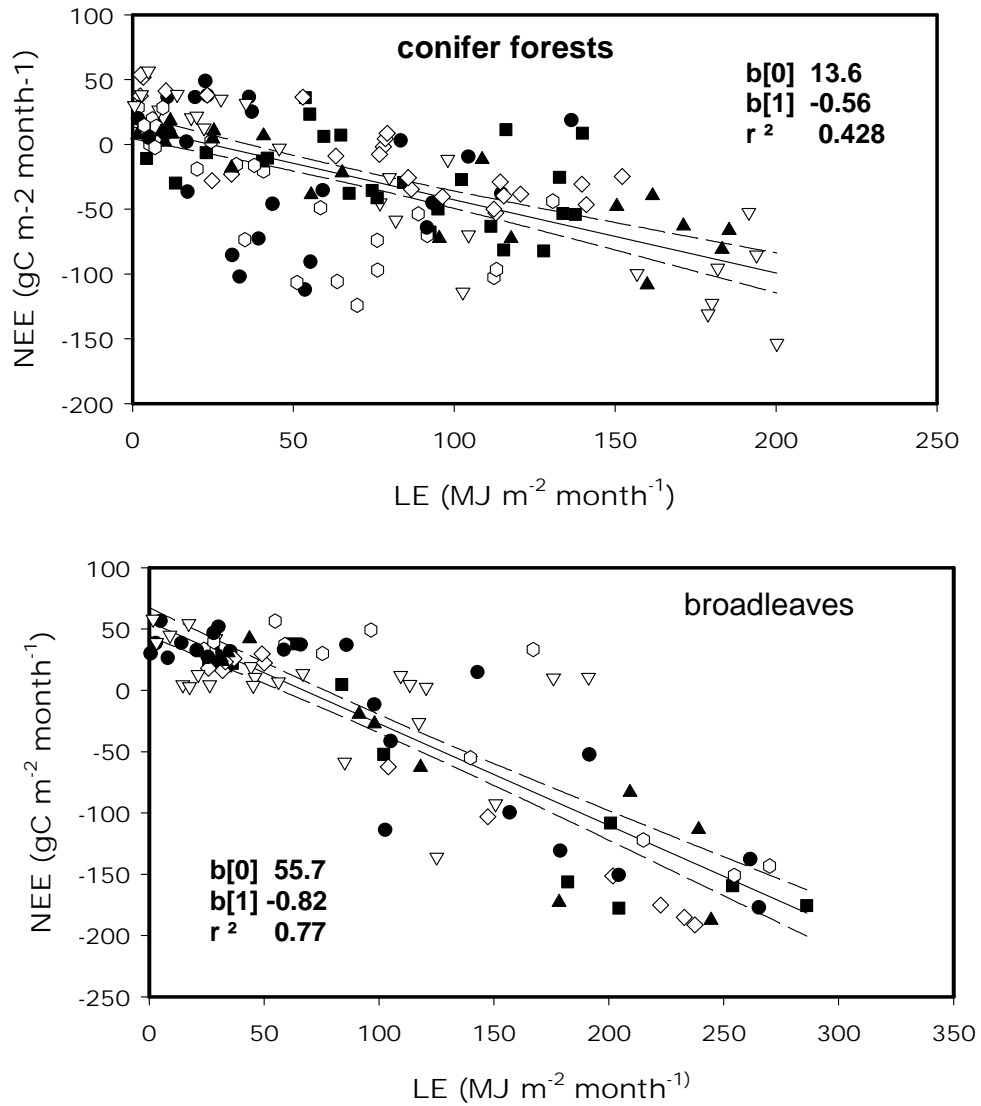


Figure 11 The linkage between carbon and water fluxes for conifer and temperate forests, a measure of water use efficiency. The coefficients $b(0)$ and $b(1)$ refer to the intercept and slope of linear regression. R^2 is the coefficient of determination.

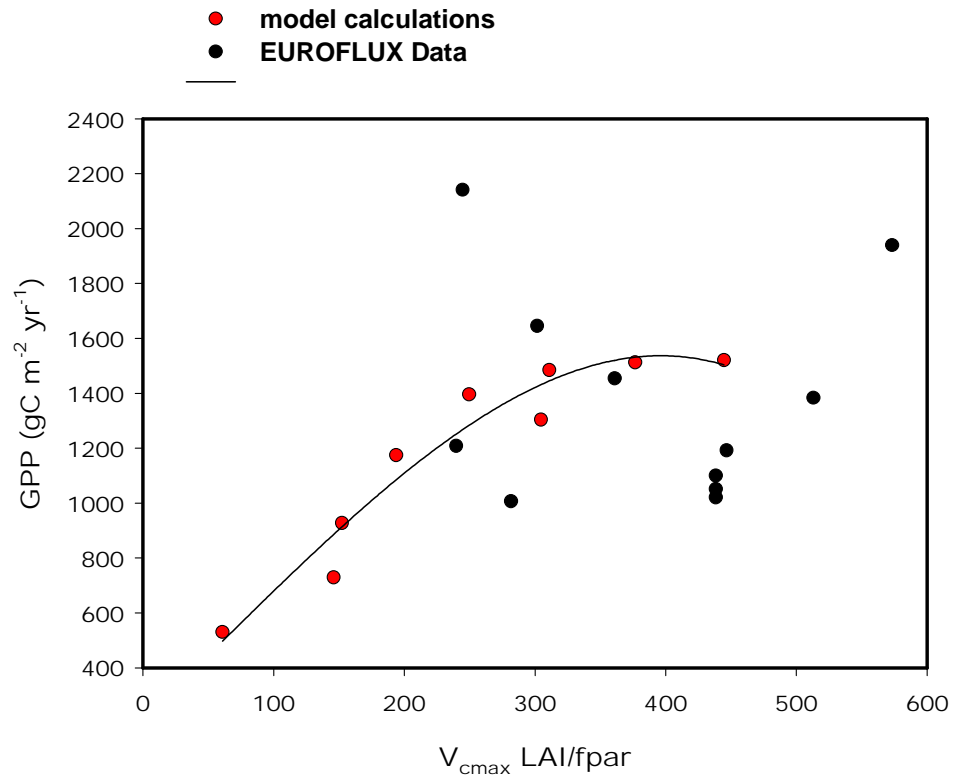


Figure 12 The relation between gross primary productivity and plant physiological capacity using field data and a biophysical model. The index of plant physiological capacity is a function of the maximum carboxylation velocity of photosynthesis (V_{cmax}), leaf are index (LAI) and the fraction of absorbed visible sunlight (fpar). The EUROFLUX field data are reported in Valentini et al. (2000).

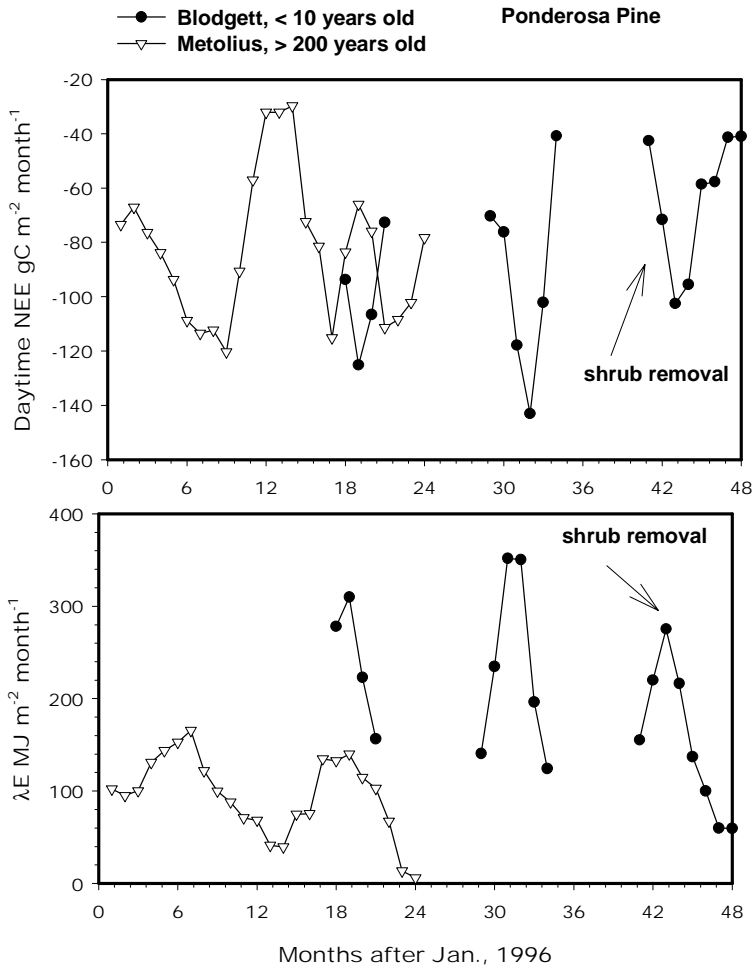


Figure 13 The impact of stand age on daytime CO₂ exchange and latent heat exchange. The data are from a young (< 10 years) and old (> 200 years) ponderosa pine forest (see Law et al., 2000).