ELSEVIER

A Global Terrestrial Monitoring Network Integrating Tower Fluxes, Flask Sampling, Ecosystem Modeling and EOS Satellite Data

S. W. Running, D. D. Baldocchi,† D. P. Turner,‡ S. T. Gower,§ P. S. Bakwin,‖ and K. A. Hibbard¶*

Accurate monitoring of global scale changes in the terrestrial biosphere has become acutely important as the scope of human impacts on biological systems and atmospheric chemistry grows. For example, the Kyoto Protocol of 1997 signals some of the dramatic socioeconomic and political decisions that may lie ahead concerning CO_2 *emissions and global carbon cycle impacts. These decisions will rely heavily on accurate measures of global biospheric changes (Schimel, 1998; IGBP TCWG, 1998). An array of national and international programs have inaugurated global satellite observations, critical field measurements of carbon and water fluxes, and global model development for the purposes of beginning to monitor the biosphere. The detection by these programs of interannual variability of ecosystem fluxes and of longer term trends will permit early indication of fundamental biospheric changes which might otherwise go undetected until major biome conversion begins. This article describes a blueprint for more comprehensive coordination of the various flux measurement and modeling activities into a global terrestrial monitoring network that will have direct relevance to the political decision making of global change.* ©Elsevier Science Inc., 1999

* Numerical Terradynamic Simulation Group, School of Forestry, University of Montana, Missoula
† ATDD, Oak Ridge National Laboratory, Oak Ridge, Tennessee
‡ Forest Science Department, Oregon State University, Corvallis
§ Department of Forestry, University of Wisconsin, Madison
‖ NOAA/CMDL, Boulder, Colorado
¶ Climate Change Research Center, University of New Hampshire, Durham

Address correspondence to S. W. Running, Numerical Terradynamic Simulation Group, School of Forestry, University of Montana, Missoula, MT 59812. E-mail: swr@ntsg.umt.edu
Received 10 August 1998; revised 15 April 1999.

OVERVIEW OF GLOBAL TERRESTRIAL MONITORING AND VALIDATION

The dynamics of the terrestrial biosphere are an integral part of global change. Society needs to know particularly if the "human habitability" of the biosphere is decreasing, especially because more humans are inhabiting the land each year. One direct way of quantifying human habitability is by evaluation of the vegetation cover and the primary productivity that provides food, fiber, and fuel for human endeavors. The distribution, health, and productivity of global vegetation is typically evaluated in the context of the global carbon budget. Much of what is known about the contemporary global carbon budget has been learned from careful observations of atmospheric CO_2 concentration trends and $^{13}C/^{12}C$ isotope ratios ($d^{13}C$), interpreted with global circulation models. From these studies we have learned the following important things about the global carbon cycle:

1. On average over the last 40 years roughly half of the annual anthropogenic input of CO_2 to the atmosphere is taken up by the oceans and the terrestrial biosphere (Keeling et al., 1989).
2. Interpretation of the latitudinal gradient of atmospheric CO_2, using transport models indicates that a significant portion of the net uptake of CO_2 occurs at midlatitudes of the Northern Hemisphere (Tans et al., 1990; Ciais et al., 1995; Denning et al., 1995).
3. There are large year-to-year changes in the net uptake of CO_2 by the terrestrial biosphere. These changes are associated with climate anomalies such as ENSO (Conway et al., 1994; Keeling et al., 1995; Keeling et al., 1996).
4. The seasonality of terrestrial biosphere carbon

REMOTE SENS. ENVIRON. 70:108–127 (1999)

655 Avenue of the Americas, New York, NY 10010
0034-4257/99/$–see front matter
PII S0034-4257(99)00061-9

flux appears to be changing as indicated by shifts in the timing and amplitude of the seasonal cycle of atmospheric CO_2 measured at many "background" sites. In particular, it appears that spring is beginning earlier and fall arriving later (Randerson et al., 1997; Field et al., 1998). This result is supported by satellite phenology observations (Myneni et al., 1997a).

These indications of biospheric changes point to the need to 1) better understand and monitor the processes that regulate uptake and release of CO_2 by terrestrial ecosystems, 2) provide verification from more direct ground-based measurements, and 3) employ satellite observations to clarify spatial patterns in ecosystem function. There is also new interest in computing sources and sinks of carbon for individual nations that will challenge current data availability. This article suggests how a number of current international research activities can be integrated into a biospheric monitoring program that efficiently collects and disseminates key data and analyses for evaluation of global change in terrestrial ecosystems (Running, 1998).

Necessary Components of a Biospheric Monitoring System

Accurate quantification of the trajectory of change and potential degradation of the terrestrial biosphere is essential because this understanding will influence many socioeconomic decisions concerning resource consumption and conservation. Global estimates of biospheric processes will require a permanent network of ground monitoring and model validation points, much like the surface weather station network, to quantify seasonal and interannual dynamics of ecosystem activity, that is, to cover the *Time* domain. Remote sensing must be used to quantify the heterogeneity of the biosphere, the *Space* domain. Finally, because these Time and Space measurement regimes cannot provide a complete view of biospheric biogeochemical activity, modeling is required to isolate unmeasured ecosystem processes, and to provide predictive capacity. In this article, we outline a nested terrestrial measurement network, a regular remote sensing product stream, and an integrating modeling framework to continuously monitor and validate large scale estimates of key variables in terrestrial carbon and water budgets.

Temporal Monitoring—Carbon, Water and Energy Fluxes

Eddy-covariance flux towers serve as the core infrastructure for three reasons. First, they measure carbon and water fluxes and the surface energy budget, processes directly related to ecosystem function, continuously and semiautomatically, representing an area of approximately 1–3 km^2. Second, a global representation of over 80 stations already exists. The current eddy flux network of sites is growing rapidly and becoming increasingly organized. Third, the flux towers provide a critical infrastructure of organized personnel and equipment for other comprehensive measurements, including ecophysiology, structure and biomass of the vegetation, fluxes of other greenhouse gases, and micrometeorology.

Monitoring of the spatial and temporal patterns in the concentration of CO_2, O_2, and their isotopic variants can provide the basis for estimates of carbon cycle fluxes at large scales (Tans et al., 1996). The remarkable achievements from the geochemistry approach, beginning with the observations at Mona Loa, which first detected the upward trend in the global atmospheric CO_2 concentration, establish its importance for biospheric monitoring. The limitations in the geochemistry approach for terrestrial monitoring are that it is not spatially explicit, and generally indicates the net effect of multiple, potentially opposing, processes.

Spatial Monitoring—Terrestrial Vegetation Products from EOS

After launch in mid-1999, the EOS (Earth Observing System) will inaugurate the first *regular, global* terrestrial vegetation products, including land cover, spectral vegetation indices (SVI), leaf area index LAI, fraction absorbed photosynthetic active radiation (FPAR), and net primary production (NPP) (Fig. 1; Running et al., 1994; Justice et al., 1998). Many labs now calculate global net primary production (NPP), evapotranspiration (ET), and/or precursor variables like leaf area index (LAI) or fraction absorbed PAR (FPAR) (Melillo et al., 1993; Ruimy et al., 1994; Field et al., 1995; Hunt et al., 1996; Prince and Goward, 1995; Randerson et al., 1997; Foley et al., 1996; Myneni et al., 1997b). Because these EOS variables provide the basis for spatial scaling of all relevant ground-based measurements, their validation is essential. The following web site has summaries and links to important EOS Land validation activities: http://www-eosdis.ornl.gov/eos_land_val/valid.html.

The field measurements required for this EOS land validation are primarily multitemporal sequences of vegetation structure and biomass accumulation and turnover, accurately georeferenced to provide spatial fractions of vegetation structure across the landscape. LAI and NPP, the most directly measured vegetation structural and functional variables, respectively, range by 2 orders of magnitude among the diverse terrestrial biomes and change seasonally with annual plant growth cycles. Spectral vegetation indices such as the well known NDVI and FPAR are radiometric products that can only be measured instantaneously but can be inferred by vegetation structural measurements, most commonly by LAI. The plans discussed below will measure LAI to provide inferred validation of VI and FPAR, and will measure fractional vegetation cover of regional study areas.

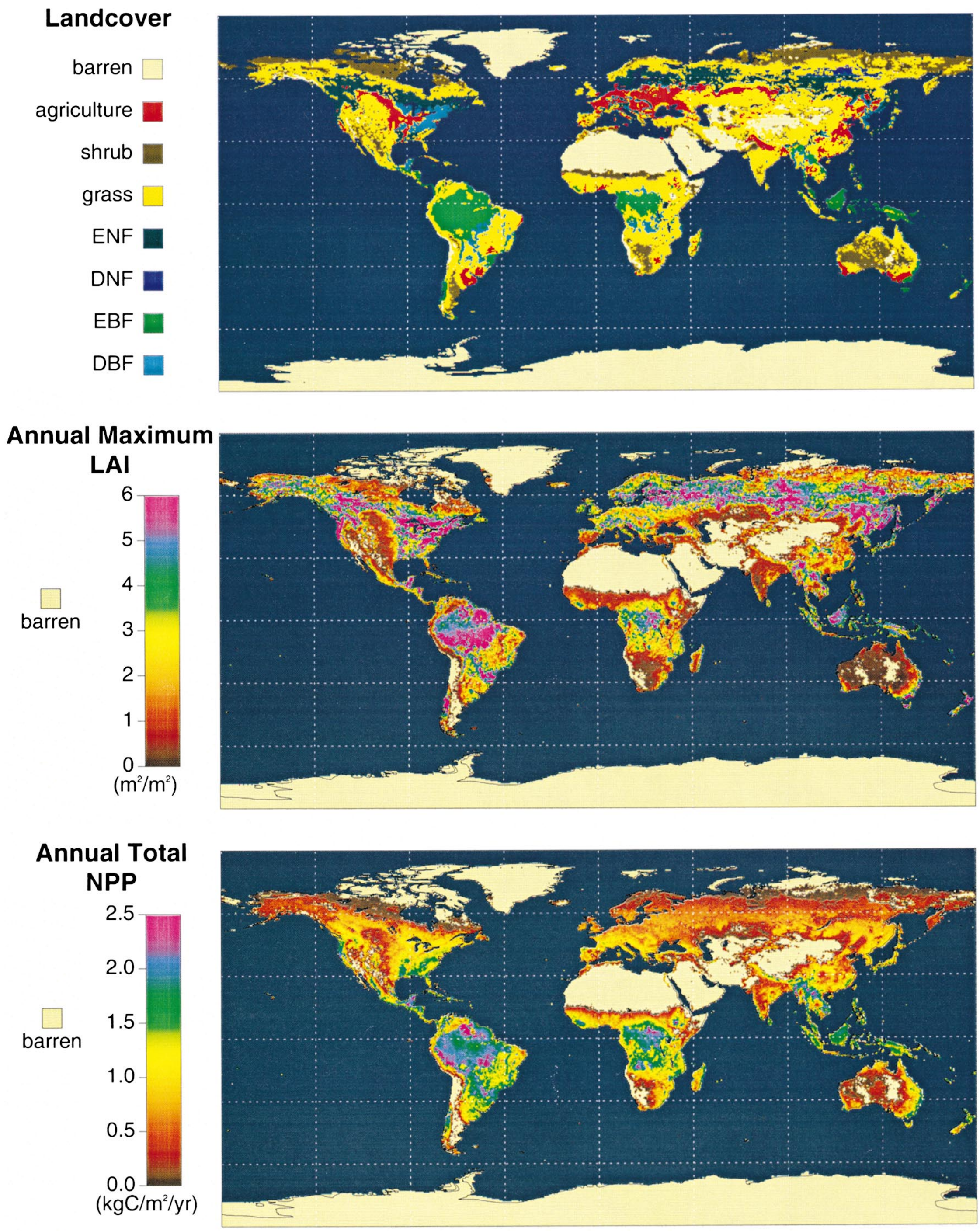

Figure 1. An example of global land cover (LC), leaf area index (LAI), and net primary production (NPP) terrestrial variables that will be produced from the Earth Observing System (EOS) every 8 days at 1 km. These data will be invaluable for scaling of ecological research and land management, but first need global field validation [see Running et al. (1994) and Justice et al. (1998) for details].

System Processes and Integration—Ecological Modeling
The eddy fluxes and ecophysiological measurements provide process level understanding of ecosystem function that can be incorporated into ecosystem models. However, there will never be sufficient eddy flux towers or field measures to adequately characterize all terrestrial ecosystems under all conditions. Models must then be used to interpolate and extrapolate flux measurements in time and space. Hence, models are and will be a key tool for making regional and global assessments (Waring and Running, 1998). Mechanistic ecosystem models also have the potential for *predicting* how ecosystems will respond

to future changes in atmospheric CO_2, temperature, land use change, nitrogen loading, and precipitation.

Critical Variables in a Global Terrestrial Monitoring System

We initially focus on one key variable each of the carbon and water cycles: net primary production (NPP) and evapotranspiration (ET). The carbon budget consists of several major processes that describe the exchange of carbon dioxide between terrestrial ecosystems and the atmosphere. Gross primary production (GPP) is the total carbon assimilated by vegetation. A fraction of GPP is lost back to the atmosphere as the result of autotrophic respiration (R_A). Net primary production (NPP), the balance between GPP and autotrophic respiration, is allocated to wood, foliage, roots, reproductive tissues, storage, etc. NPP, the direct measure of vegetation productivity, has been measured from field biomass surveys for decades and has the largest historical database. NPP relates directly to forest, range, and crop productivity, and so also has high socioeconomic value. NEE, the net exchange of CO_2 between terrestrial ecosystems and the atmosphere, is measured by flux towers. NEE has high scientific relevance for terrestrial carbon budgets and greenhouse gas production, but less direct socioeconomic significance.

Under optimal conditions, NEE is measured continuously and calculated on a half-hourly or hourly basis, whereas the field-based NPP is measured periodically and calculated on an annual basis. The two fluxes are related in that if NEE is summed over a year, the sum should be the difference between NPP and heterotrophic respiration (R_H) summed over the year. Thus

$$\mathrm{NEE}_{\mathrm{annual}}=\mathrm{NPP}_{\mathrm{annual}}-R_{H\,\mathrm{annual}}\,. \tag{1}$$

Note that on a daily time step NEE is related to GPP and R_A in Eq. (2):

$$\mathrm{NEE}_{\mathrm{daily}}=\mathrm{GPP}_{\mathrm{daily}}-(R_H+R_A)_{\mathrm{daily}}\,. \tag{2}$$

NPP and NEE are related theoretically, but the two carbon fluxes are measured at very different temporal and spatial scales, necessitating an integrated approach to provide global coverage for rapid validation and monitoring opportunities. The ultimate goal is to validate global measures of NEE *and* NPP.

The other primary variable, evapotranspiration (ET), is a component of the surface hydrologic balance and an integral part of surface energy partitioning. ET is also measured continuously by a flux tower, providing a high temporal resolution measurement of the partitioning of precipitation (PPT) in the hydrological budget of an ecosystem. However, much like with NPP and NEP, the variable of the hydrologic cycle with the longest history and widest distributed data is watershed discharge Q. These variables are generally related as in Eq. (3):

$$Q=\mathrm{PPT}-\mathrm{ET} \tag{3}$$

when soil moisture changes and groundwater losses are ignored. Also, both of these historical ecosystem measures, NPP and Q, are typically measured on a weekly-to-monthly basis, so are temporally inconsistent with the continuous flux tower measures of NEE and ET. Additionally, there are spatial scale mismatches. The tower fluxes represent a footprint of roughly 1–3 km^2, while NPP is typically measured on ≃0.1 ha plot, and watersheds can drain many hundreds of square kilometers. Process-based terrestrial ecosystem models, driven by spatially represented climate and satellite derived vegetation parameters, are essential for integrating the suite of field-based measurements of inconsistent temporal and spatial scale to provide a complete and consistent view of global biospheric function.

We now visit each of four components critical to a comprehensive monitoring scheme and identify associated on-going research activities. In the temporal dimension, it is a global flux tower network and a global flask sampling network that are essential. For the spatial dimension, we discuss the EOS products. SVAT modeling is then examined as a means of scaling carbon and water flux over space and time. Subsequently, we consider the nature of the required information flow among these components and identify international programs concerned with integration.

GLOBAL FLUX TOWER NETWORK (FLUXNET)

The cornerstone of this global terrestrial vegetation monitoring is the tower flux network, FLUXNET. This global array of tower sites is currently comprised of regional networks in Europe (EUROFLUX), North America (AmeriFlux), Asia (JapanNet, OzFlux), and Latin America (LBA). The towers provide a continuous and representative measure of terrestrial carbon cycle dynamics, and an important ancillary suite of measurements of energy and water fluxes for interpreting carbon fluxes (Fig. 2). The role of FLUXNET includes coordinating the regional networks so that information can be attained at a global scale, ensuring site to site intercomparability, coordinating enhancements to current network plans and operation of a global archive and distribution center at the Oak Ridge DAAC. The FLUXNET project web address is http://daacl.ESD.ORNL.Gov/FLUXNET/. The web sites contain measurement protocols for consistency, and data on site, vegetation, climate, and soil characteristics. It provides a route for users to gain access of hourly meteorological and flux measurements and proper documentation.

The FLUXNET concept originated at a workshop on "Strategies for Long Term Studies of CO_2 and Water Vapor Fluxes over Terrestrial Ecosystems" held in March 1995 in La Thuile, Italy (Baldocchi et al., 1996). The first organized flux tower network was EUROFLUX, which now involves long-term flux measurements of carbon di-

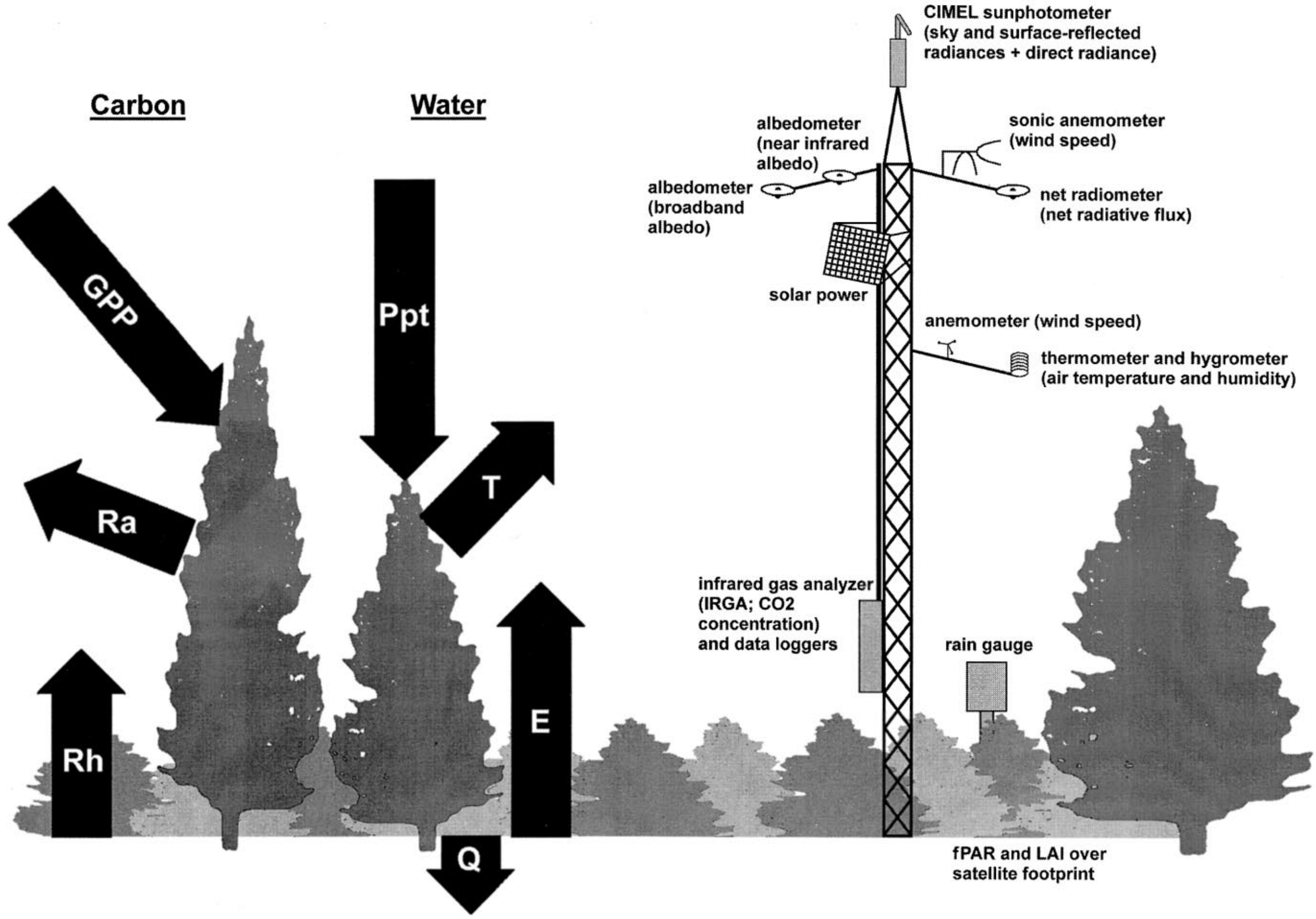

Figure 2. A generalized FLUXNET tower configuration diagram, showing instrument deployment and key carbon and water fluxes measured. Atmospheric optical measurements, automated surface spectral measurements, physiological process studies, flask sampling, and stable isotope sampling are all additions that can be accommodated into this framework to provide a more versatile monitoring system.

oxide and water vapor over 15 forest sites in the United Kingdom, France, Italy, Belgium, Germany, Sweden, Finland, Denmark, The Netherlands, and Iceland. A website is located at http://www.unitus.it/eflux/euro.html. In 1996, AmeriFlux was formed under the aegis of the DOE, NIGEC program, with additional support by NASA, and NOAA. The website is http://www.esd.ornl.gov/programs/NIGEC.

Eddy Covariance Principles

The eddy covariance method is a well-developed method for measuring trace gas flux densities between the biosphere and atmosphere (Baldocchi et al., 1988; Lenschow, 1995; Moncrieff et al., 1996). This method is derived from the conservation of mass and is most applicable for steady-state conditions over flat terrain with an extended tract of uniform vegetation. If these conditions are met, eddy covariance measurements made from a tower can be considered to be within the constant flux layer, and flux density measured several meters over the vegetation canopy is equal to the net amount of material entering and leaving the vegetation. Vertical flux densities of CO_2 and water vapor between the biosphere and the atmosphere are proportional to the mean covariance between vertical velocity and scalar fluctuations. This dependency requires the implementation of sensitive, accurate, and fast-responding anemometry, hygrometery, thermometry, and infrared spectrometry to measure the vertical and horizontal wind velocity, humidity, temperature, and CO_2 concentration.

Errors arise from atmospheric, surface, and instrumental origins, and they may be random, fully systematic and/or selective (Goulden et al., 1996). Most random errors are associated with violations of atmospheric stationarity and the consequences of intermittent turbulence. Instrument errors are systematic, caused by insufficient time response of a sensor, the spatial separation between a sensor and an anemometer, digital filtering of the time signal, aerodynamic flow distortion, calibration drift, loss of frequency via sampling over a finite space, and sensor noise (Moore, 1986; Moncrieff et al., 1996). The AmeriFlux, Euroflux, and FLUXNET programs are attempting to identify and minimize instrumental errors by circulating a set of reference instruments, to which all sites can be compared. Daily-averaged fluxes reduce the sampling errors associated with fluxes measured over 30–60 min intervals. Hence, daily integrals of net carbon flux can be accepted with a reasonable degree of confidence. Goulden et al. (1996) conclude that the long term precision of eddy covariance flux measurements is ±5–10% and the confidence interval about an annual estimate of net canopy CO_2 exchange is ±30 g C m^{-2} y^{-1}.

Implementation and Operation

A typical cost for purchasing instruments to make core measurements is on the order of $40–to $50k (US); this cost can double if spare sensors, data telemetry, and data archiving hardware are purchased. The cost of site infrastructure is extra and 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. Recent advances in remote power generation and storage minimize the need and cost of bringing line power to a remote site. Advances in cellular telephone technology also allow access and query of a remote field station from home or the office. The requirement for on-site personnel is diminishing, as flux systems become more reliable and automated. At minimum, a team of two individuals are required to operate a flux system, and 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).

Sites in an organized global flux network can also expect to attract additional activities. A synergism between flux and meteorological measurements and an array of other terrestrial science projects is likely. Terrestrial bioclimatology, remote sensing, atmospheric optical characterization, water resource, and nutritional biogeochemistry studies are examples of science that are being attracted to the flux network sites (Fig. 2).

Climate and Biome Distribution Requirements

Ideally, global terrestrial monitoring/validation sites should encompass the complete range of climate and biome type combinations. The current global array of flux towers is shown in Figure 3, mapped over the annual temperature/precipitation climate space of current global vegetation (Churkina and Running, 1998). It is clear that large regions, including several important biomes, remain underrepresented including hot desert and cold tundras, which is inevitable with an ad hoc volunteer global network (Table 1). Also, the correspondence between flux tower locations and permanent ecological field sites is low, illustrating the key role for modeling to spatially extrapolate results amongst sites. More sites are needed over intensive agricultural areas. Future planning should identify the climate/biome combinations of highest priority to improve global representativeness.

THE ATMOSPHERIC CO_2 FLASK NETWORK

Inverse Modeling of Carbon Sources and Sinks

The eddy flux tower studies are designed to aid understanding of processes that drive NEE at the ecosystem level, and for evaluation of ecosystem models used for regional and global integration. However, a top-down approach is also needed to test and validate the results of the model extrapolations to global and regional scales. Data from the global CO_2 mixing ratio and isotope ratio measurement network (NOAA/CMDL/Cooperative Air Sampling Network, website at http://www.cmdl.noaa.gov/ccg/), when interpreted within general circulation models, can provide constraints at least at this scale. The basic procedure in this approach is referred to as inverse modeling. It involves simulating the global 3-D atmospheric transport using a general circulation model and tracking the movement and interaction of air parcels having different CO_2 concentrations. Information on the spatial and temporal patterns in measured atmospheric CO_2 concentrations derived from flask samples is incorporated such that sources and sinks of carbon from the Earth's surface can be inferred.

Initially, flask sampling was primarily in well-mixed marine areas. Expansion of the monitoring networks over the last decade has improved the spatial resolution with which annual fluxes can be determined, so that currently fluxes are being estimated at continental scales (Fan et al., 1998). Sampling at continental sites reveals regional contrasts in seasonality of flux dynamics, and sampling at various heights on tall towers (500 m) identifies gradients of CO_2 in the boundary layer dynamics (Fig. 4; Bakwin et al., 1998). As sampling density is increased, it will be possible to use higher resolution transport models, such as mesoscale models, to deduce surface fluxes at finer spatial scales. Additional work is needed to develop and refine the transport models, and particular attention is required to develop parametrizations for simulation of the dynamics of the planetary boundary layer. It is important that the resulting estimates of NEE are entirely independent of the flux tower measurements, and nearly independent of the satellite data (satellite data define surface parameters used in the transport models).

Isotopic Sampling

The state of development of isotopic measurements (particularly in combination with CO_2 flux tower measurements), for better understanding the carbon cycle on local, regional, and global scales, was the topic of a workshop titled Biosphere–Atmosphere Stable Isotope Network (BASIN, Snowbird, Utah, 7–10 December 1997). A sum-

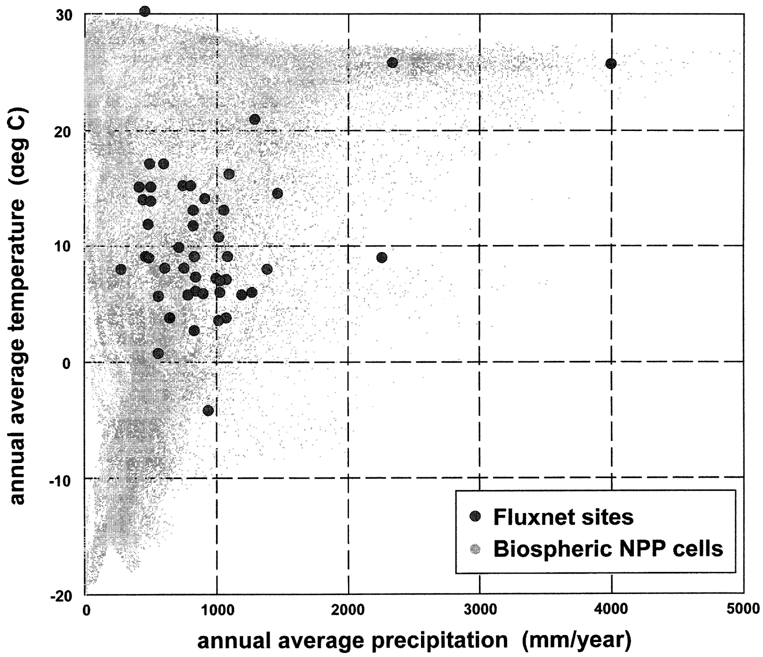

Figure 3. A two-dimensional climate diagram of the distribution of 1° global vegetation cells related to annual precipitation and temperature, suggesting the preferred climatic distribution of sites for complete biome sampling [regraphed from data in Churkina and Running (1998)]. The climates of the current FLUXNET sites as of early 1999 are superimposed.

mary can be found on the Web at http://gcte.org/basin.html. Isotopic data can be used to disaggregate component fluxes (e.g., photosynthesis and respiration, transpiration, and evaporation), and for regional and global scaling. Measurements of $d^{13}C$ in CO_2 can be used to partition net uptake between the oceans and the terrestrial biosphere, or, on a smaller spatial scale, between C_3 and C_4 vegetation. Recent advances in understanding the influence of vegetation (Farquhar et al., 1993) and soils (Tans, 1998) on the $^{18}O/^{16}O$ ratio of CO_2 have opened the possibility to use measurements of $d^{18}O$ to distinguish between photosynthetic and respiratory fluxes. Also, measurements of $^{18}O/^{16}O$ in H_2O could be used to distinguish between transpiration and evaporation from the soil. Recent work by Potosnak et al. (1998) indicates that it may be possible to use the flux tower measurements to assess the influence of local surface exchange, and hence compute regionally representative CO_2 mixing ratios from careful surface layer measurements. This is an exciting result because flux towers are located in continental areas currently underrepresented by the network for monitoring CO_2 mixing ratios, and could improve the accuracy of CO_2 mixing ratio measurements at the flux towers on the order of 0.2 ppm.

Table 1. Current Biome Distribution of the 80 Established FLUXNET Sites

Functional Type	*Percent*
Temperate conifer forest	22
Temperate broad-leaved forest	21
Semiarid woodland	16
Boreal conifer	7
Grassland	7
Crop	6
Alpine	6
Arctic	4
Tropical forest	3
Mixed forest	3
Boreal broad-leaved forest	1
Wetland	1

An alternative for regional flux scaling with good future potential is aircraft based mobile flux platforms (Crawford et al., 1996; Oechel et al., 1998). These light aircraft fly very close to the vegetated surface, often only 5–20 m above the ground, and ingest air samples that flow into a fast response infrared gas analyzer through a special nosecone sampler. Onboard aircraft velocity and micrometerological data are combined to compute fluxes of CO_2 and H_20 with about a 3 km^2 spatial resolution integrated across a multiple kilometer flight path.

VALIDATION OF EOS TERRESTRIAL VEGETATION PRODUCTS

Vegetation Measurements in the EOS/MODIS Grid

EOS will produce regular global vegetation products primarily from the MODIS sensor (Moderate Resolution Imaging Spectroradiometer) (Running et al., 1994; Justice et al., 1998). MODIS satellite products will be in a regular grid of square, 1 km^2 cells that do not exactly overlay a tower "footprint." The tower footprints vary in size (up to several km^2), shape, and orientation, depending on location, height above canopy, wind speed, and direction (Hollinger et al., 1994; Waring et al., 1995). In order to permit comparisons of tower-based NEE estimates and the satellite-based NPP estimates

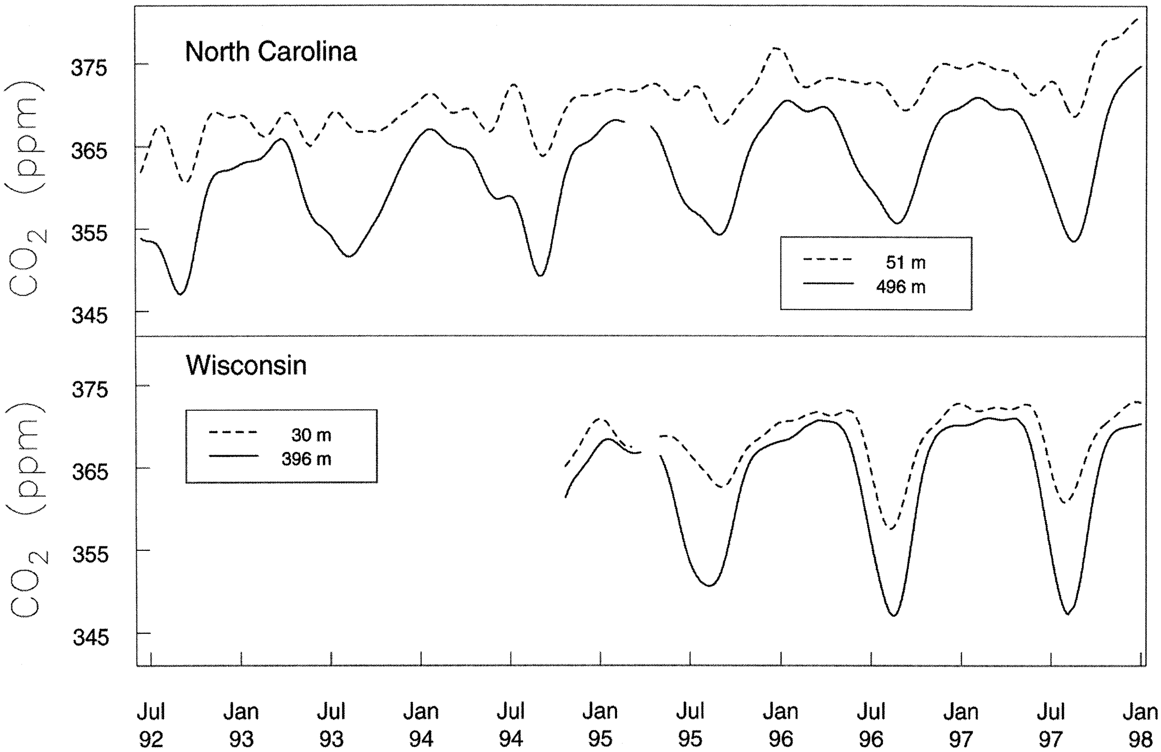

Figure 4. Multiyear trends in monthly atmospheric CO_2 measurements for two tall towers in contrasting climates of North Carolina and Wisconsin from the NOAA/CMDL flask monitoring network. Note the differential activity of CO_2 within the forest canopies at 30–50 m height dominated by biological dynamics compared to the midplanetary boundary layer at 400–500 m where atmospheric transport dominates. When coupled with atmospheric transport models, these data can be used to estimate CO_2 fluxes at regional scales as a "top-down" constraint on fluxtower data (Bakwin et al., 1998).

from the MODIS grid, certain transformations are needed (Fig. 5). A SVAT model that resolves component carbon balance processes of Eq. (1), and validated by local flux tower measurements over a grid of 10–100 km^2 around the tower, provides this scale transformation.

The most direct measurement of NPP for validation involves harvesting and weighing biomass production in a time sequence. The plot size here is considerably smaller than a tower footprint, for example, 1 m^2 for clipping in a grassland or 1 ha plots for tree coring and litterfall traps in forests. Multiple NPP measurements made in the 100 km^2 area surrounding a tower serves to extend the model validation over the local environmental gradients and variation in land use.

Quantifying Land Surface Heterogeneity for EOS Validation—BigFoot

Over a site consisting of homogenous vegetation cover and small environmental gradients, the scale inconsistencies between EOS/MODIS NPP estimates and ground-based validation measurements may be minimal. However, many important ecosystems are fairly complex in structure and topography, even over the relatively small area represented by a MODIS cell or a tower footprint. For example, much of the U.S. Pacific Northwest region is characterized by patches associated with forest clearcuts that are generally much smaller than 1 km on a side (Cohen et al., 1998). In the Lake States the choice of grain size up to 1 km greatly affects estimates of land surface occupied by aquatic versus terrestrial systems (Benson and MacKenzie, 1995). The tendency for the scale of human influence on ecosystem carbon flux to fall below the 1 km resolution was recognized during the design phase of the MODIS instrument (Townshend and Justice, 1988), and accounted in part for including channels at 250 m and 500 m in the visible and near-IR wavelengths.

The BigFoot project makes the link between purely satellite-based C flux estimates, tower fluxes and direct field measurements. The BigFoot website is at http://www.fsl.orst.edu/larse/bigfoot/. The goal is to develop three fine-grained surfaces (25 km^2) using a combination of Landsat Enhanced Thematic Mapper (ETM+), SVAT models, and field observations. These surfaces include the standard EOS products of land cover class, leaf area index (LAI), and NPP. BigFoot currently consists of a set of four sites (all are FLUXNET sites) spanning the climatic gradient from boreal to warm temperate, en-

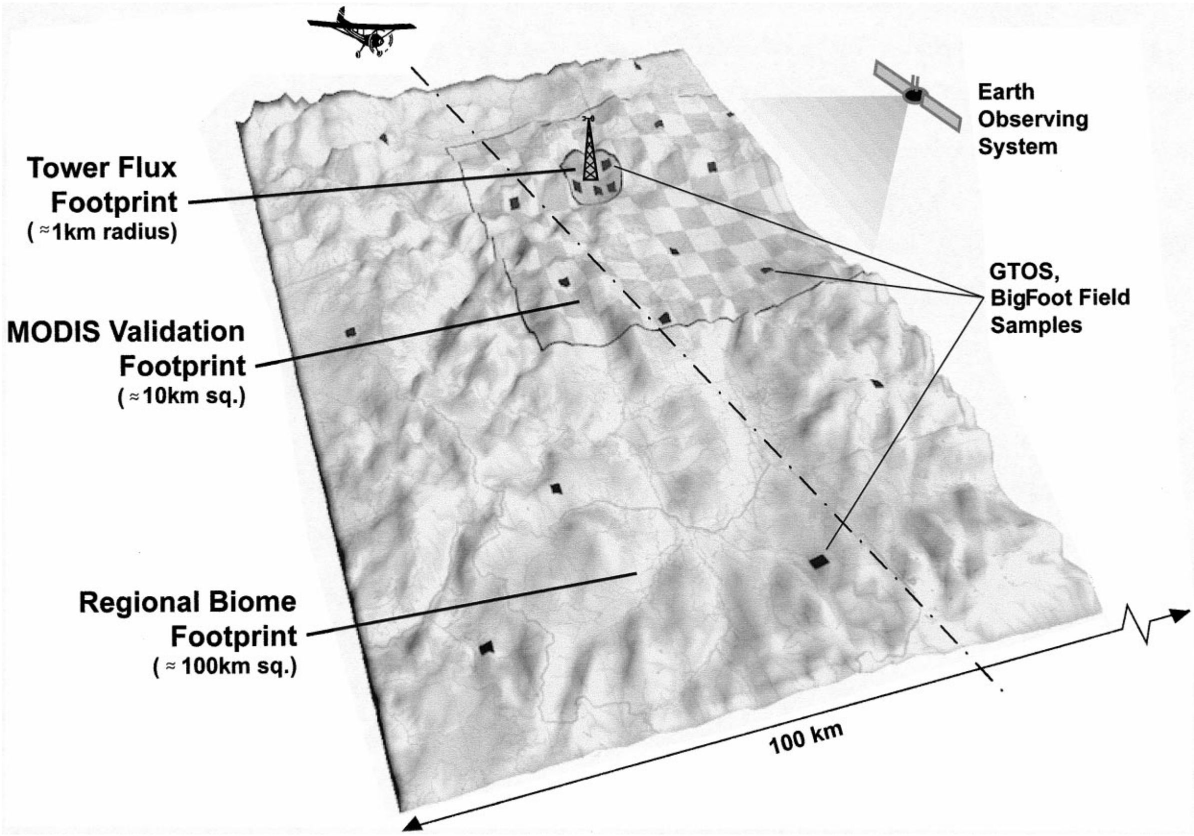

Figure 5. Illustration of the three spatial scales that must be considered for ecological scaling and validation. Measures of vegetation parameters (see Table 2) in the atmospheric footprint of the FLUXNET towers are required for SVAT models to simulate the NEE measured by the towers. Second, a larger area of minimum 3 km×3 km must be sampled to provide ground truth of MODIS LAI and NPP vegetation products. Third, the representativeness of the FLUXNET tower and MODIS sampling site to the larger biome/climate complex must be evaluated by cross biome sampling. Aircraft flux transects and atmospheric flask measurements can provide independent validation of regional flux calculations. Only after all of these scales of measurement are covalidated can comprehensive synthesis of ground data, ecosystem models, and satellite data be accomplished.

compassing several important biomes, and including a variety of land-use patterns. Additional sites will be added in the future, with highest priority being tropical forests, deserts, and arctic tundra, and this protocol is being adopted by the GTOS-NPP project (discussed in a later section) globally.

Land cover is an important variable for the purposes of the BigFoot scaling effort because physiological characteristics that influence carbon, nitrogen, and water vapor exchange between terrestrial ecosystems and the atmosphere differ among vegetation cover types (Landsberg and Gower, 1997). In addition, Thematic Mapper-based classifications are often able to resolve specific stages in local successional sequences (e.g., Cohen et al., 1995) and thus may indicate information about levels of coarse woody debris, an important input to SVAT models simulating heterotrophic respiration. Thus, SVAT models use land-cover type as a stratification factor (Reich et al., 1999, this issue). In BigFoot, land-cover classification will be accomplished using methods described by Thomlinson et al. (1999, this issue). Most importantly, these maps will consist of site-specific cover classes that are locally meaningful for ecological function and model parametrization.

LAI has also proved valuable in scaling efforts, and is an input to most existing SVAT models. LAI surfaces will be based on ETM+ imagery combined with field sampling (Gower et al., 1999, this issue) and will be developed using methods that minimize errors associated with the asymptotic relationship of commonly used spectral vegetation indices and LAI (Turner et al., 1999, this issue). Errors in the land cover and LAI data layers will be evaluated with independent field-collected data using the sampling protocols discussed by Thomlinson et al. (1999, this issue).

Following development of land cover and LAI surfaces, NPP grids will be developed for each BigFoot site using SVAT models (see the next section). These grids will be developed using the models in 2-dimensional mode in conjunction with the site-specific driver surfaces, land cover and LAI, and spatially distributed climatic drivers based on extrapolations from flux tower meteorological observations. Beside the daily time step validation of GPP and ET at BigFoot sites with flux towers, the BigFoot NPP surfaces will be carefully evaluated for error by reference to a gridded network of ground measurements of NPP, collected according to methods described by Gower et al. (1999, this issue). Assuming the errors in these NPP surfaces are acceptable, the fine-grained gridded surface over a 25 km^2 area can then be directly compared to NPP estimates derived from MODIS data over the same area. If the MODIS-based estimates do not satisfactorily agree with the BigFoot estimates, it will be critical to identify causal factors.

BigFoot will isolate and test three key factors—spatial resolution, land cover classification scheme, and light use efficiency factors—that may contribute to differences between EOS-based and BigFoot NPP estimates. To evaluate the role of spatial resolution, the BigFoot 25 m grids for input variables will be aggregated to resolutions of 250 m, 500 m, and 1000 m using a variety of standard and experimental algorithms. Model runs will then be made at each spatial resolution and comparisons of simulated NPP at the different resolutions (including 25 m) will be made with each other and with the EOS/MODIS 1 km NPP products. Results of these scaling exercises over the range of biomes and land use patterns included in BigFoot will test both SVAT models and satellite-based NPP algorithms.

SYSTEM INTEGRATION AND SCALING WITH MODELS

To transform basic tower flux and flask data and global remote sensing into an effective biospheric monitoring program, three steps are now required. *First*, SVAT models must be used at each tower site to compute the important system processes that cannot be directly measured, such as the component carbon fluxes of NEE. In order to operate the SVAT model, certain key site and vegetation characteristics must be measured to parametrize the model for the tower area (Table 2). *Second*, to provide a spatial frame of reference for the tower site, satellite-derived characterization of the surrounding vegetation is needed. The EOS/MODIS standard spatial resolution is 1 km, so as to provide adequate sample size, approximately a 10 m×10 km area needs to be efficiently sampled. *Third*, with validated MODIS vegetation products of landcover, LAI, and NPP, a larger region can now be evaluated to understand how the flux tower data represents the broader biome and region. This three-step scaling process, evaluating the tower footprint of (1 km^2, then the EOS/MODIS footprint of ≃100 km^2, and finally the regional biome footprint of thousands of square kilometers provide the scaling logic for global monitoring (Fig. 5).

SVAT Model Requirements for 1-D Flux Modeling

SVAT models have been designed with a wide array of system complexities (Fig. 6). For example, some models define each age class and branch whorl of leaves, while others use only simple LAI. Time resolutions of various models range from 1 h to monthly. The land surface models such as BATS and SiB in GCMs are effectively SVAT models despite being used at very coarse spatial grids (Dickinson, 1995). SVAT models of highest relevance to FLUXNET have time resolutions in the hourly–daily domain, treat canopy structure fairly explicitly, and resolve components of the carbon balance (photosynthesis, heterotrophic and autotrophic respiration, and allocation). Likewise, stand water balance components, (canopy interception, snowpack, soil water storage, evaporation, and transpiration) must be explicitly computed. All of the leading SVAT models incorporate some treatment of nutrient biogeochemistry interactions with carbon and water processes. However, given these requirements, there are still many available and appropriate SVAT models [see recent books by Landsberg and Gower (1997) and Waring and Running (1998)]. What is needed for a coordinated global program are some common protocols, of variables, units, timesteps, etc. that would allow cooperation and intercomparisons among groups using different SVAT models in their space/time scaling. The 1-D SVAT models require meteorological driving variables measured at the tower, the initializing biomass components of the vegetation, and certain soil physical and chemical properties. All SVAT models have somewhat different specific requirements, but the general list of inputs found in Table 2 covers most of them.

Relating NEE and NPP in the Flux Tower Footprint

Flux towers measure the net gain or loss of carbon over hourly to daily time scales (Fan et al., 1995; Baldocchi et al., 1996; Goulden et al., 1996; Frolking et al., 1996). Because SVAT models estimate photosynthesis, autotrophic, and heterotrophic respiration separately, they generate separate estimates of NEE and NPP. Besides comparisons of measured and modeled NEE and NPP, one specific output of these models is daily GPP (gross primary production or net photosynthesis). This modeled GPP can be compared directly to an estimate of GPP derived from tower data (daytime NEE minus estimated daytime ecosystem respiration) (Fig. 7). Diurnal evapotranspiration (ET) can also be directly compared to ET measured at the tower. Once a SVAT model is parametrized and validated over a daily time step at a tower site, it can be run to simulate NPP and ET for a full year. Using direct field measurements of NPP made at the tower sites, model estimates of annual NPP can also be validated. The SVAT models thus provide an essential link between NEE measurements by the tower, and

Table 2. The Suite of Measurements Collected at FLUXNET Sites and Needed for SVAT Modeling Activity

Variable	*Symbol*	*Unit*	*Frequency*	*Criticality*
Mass and energy flux densities				
CO_2	F_c	μmol m^{-2} s^{-1}	1–2 h^{-1}	Core
CO_2 storage		μmol m^{-2} s^{-1}	1–2 h^{-1}	Core
Latent heat (water vapor)	λE	W m^{-2}	1–2 h^{-1}	Core
Sensible heat	H	W m^{-2}	1–2 h^{-1}	Core
Soil heat conduction	G	W m^{-2}	1–2 h^{-1}	Core
Canopy heat storage	S	W m^{-2}	1–2 h^{-1}	Core
Momentum		kg m^{-1} s^{-2}	1–2 h^{-1}	Core
Dry deposition of N		kg ha^{-1} y^{-1}	Annual	Desired
Meteorology				
Global radiation	R_g	W m^{-2}	1–2 h^{-1}	Core
Net radiation	R_n	W m^{-2}	1–2 h^{-1}	Core
Photosynthetic photon flux density	Q_p	μmol m^{-2} s^{-1}	1–2 h^{-1}	Core
Diffuse radiation		μmol m^{-2} s^{-1} or W m^{-2}	1–2 h^{-1}	Desired
Air temperature	T_a	°C	1–2 h^{-1}	Core
Humidity			1–2 h^{-1}	Core
CO_2 concentration	[CO_2]	μmol mol^{-1}	1–2 h^{-1}	Core
Wind speed	U	m s^{-1}	1–2 h^{-1}	Core
Wind direction		deg	1–2 h^{-1}	Core
Precipitation			Daily	Core
Pressure	P	kPa	Hourly to daily	Desired
Canopy wetness			Hourly	Desired
Pollution (O_3, NO_2, NO, SO_2)		ppb	Hourly	Desired
Bole temperature	T_b	°C	1–2 h^{-1}	Core
Light transmission		μmol m^{-2} s^{-1}	1–2 h^{-1}	Desired
Soil characteristics				
Soil temperature profiles	T_s	°C	1–2 h^{-1}	Core
Soil moisture			Daily to weekly	Core
Bulk density			Once	Core
Soil texture			Once	Core
Root depth			Once	Core
CO_2 efflux		μmol m^{-2} s^{-1}	Hourly to seasonally	Core/desired
Litter decomposition			Annually	Core/desired
Litter chemistry (C, N, Lignin)			Annual	Desired
Soil (C, N)			Annual	Desired
Soil thermal conductivity			Once	Desired
Soil hydraulic conductivity			Once	Desired
Cation exchange capacity			Once	Desired
Vegetation characteristics				
Species composition			Once	Core
Above-ground biomass			Once	Core
Leaf area index			Seasonal to annual	Core
Canopy height	H	m	Seasonal to annual	Core
Albedo				
Aerodynamic roughness length	z_0	m	Once	Desired
Zero plane displacement	D	m	Once	Desired
Multispectral image			Annual	Desired
Above-ground growth increment			Annual	Core
Leaf N and C			Seasonal	Core
Specific leaf weight			Seasonal	Core
Ecophysiology				
Photosynthetic capacity	V_{cmax}, J_{max}	μmol m^{-2} s^{-1}	Weekly to seasonally	Desired
Tissue dark respiration		μmol m^{-2} s^{-1}	Weekly to seasonally	Desired
Predawn water potential	ψ	MPa	Weekly to seasonally	Desired
Stomatal conductance	g_s	mol m^{-2} s^{-1}	Weekly to seasonally	Desired
Tissue $^{13}C/^{12}C$				
Atmospheric $^{13}C/^{12}C$				
Sap flow		mol m^{-2} s^{-1}	Hourly	Desired

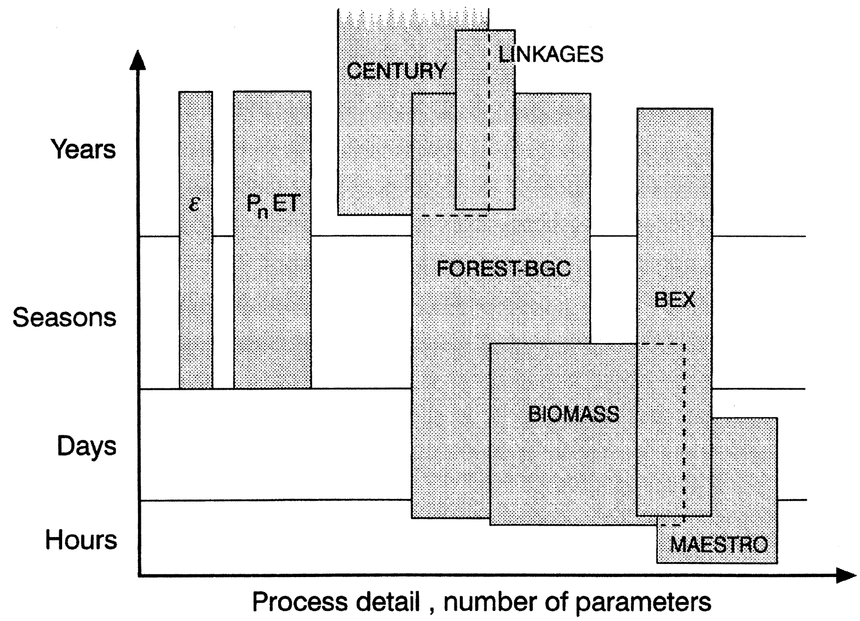

Figure 6. A general evaluation of the varying time scales and mechanistic complexity inherent in various current soil–vegetation–atmosphere–transfer (SVAT) models. The MODIS global NPP estimate is represented by the ε, a model of minimum process complexity. Models of higher process detail are required to validate and interpret the ε models, but cannot be run globally because of lack of data and computing limitations [redrawn from Landsberg and Gower (1997)].

NPP, the C-flux variable most relevant to the standard EOS NPP product.

Scaling to Regional Ecosystem Processes

In a large flat agricultural region with homogeneous topography, microclimate, soils, and crops, the tower footprint fluxes of NEE and ET may directly represent the entire regional flux activity. However, variable topography propagates variation in microclimate and soils, and human land use activity typically precludes homogeneity of land cover over hundreds of kilometers. Consequently, the ecosystem processes computed by a SVAT model with the local tower flux data must be put in the context of the region to be a meaningful biospheric monitor. Effectively this means extending the satellite-based analysis of the landscape planned by BigFoot methodology to an even broader region, and entails limited additional field sampling for validation of vegetation variables (Fig. 5). Mapping ecosystem process rates across thousands of square kilometers is then possible by executing the flux tower validated SVAT model across the landscape with satellite and ancillary data providing georeferenced representation of the landscape heterogeneity (Fig. 8).

Direct measurement of regional heterogeneity can now be accomplished with aircraft flux sampling. Oechel et al. (1998) measured a range of CO_2 flux of 0.1mg m^{-2} s^{-1}, and a range of latent energy flux of 100 W m^2 when flying a 100 km long transect of Alaskan tundra. Aircraft measured fluxes averaged 0.02 mg CO_2 m^{-2} s^{-1} less than tower-based fluxes; however, their measurement scales are different. Aircraft-based measurements will provide fluxes independent of SVAT model extrapolations, thus offering an important alternative for regional model validations.

Regional-scale validation may also be directly accomplished hydrologically. A SVAT model implemented regionally, and incorporating hydrologic flow routing, can reproduce stream discharge records. Accurate simulation of stream discharge tests the SVAT model calculations of snowmelt dynamics, soil water flow, and evapotranspiration (White et al., 1998).

Scaling Carbon and Water Fluxes to the Continental and Global Scales

Continental- to global-scale modeling of carbon and water fluxes has been limited to gridded surfaces of relatively coarse grain sizes. For example, Hunt et al. (1996) used grid cells of nearly 10^4 km^2 to simulate the influence of terrestrial sources and sinks of carbon on the seasonal oscillation in the atmospheric CO_2 concentration. Prince and Goward (1995) used a cell size of 64 km^2 in another global scale estimate of NPP. Field et al. (1998) used 1°×1° data for simulating terrestrial NPP using satellite data. Unfortunately, in areas with topographic and land-use heterogeneity, these resolutions can lead to significant errors associated with a loss of fine-scale vegetation patterns (Pierce and Running, 1995; VEMAP, 1995; Turner et al., 1996). Typically there has not been an effort to validate the global NPP estimates with a sample of site-level data, in part because of the mismatch in scales between model outputs and on-site measurements. The availability of MODIS satellite data will provide a strong impetus towards improved global NPP modeling.

Satellite remote sensing can be used to estimate NPP (see Fig. 1), but is not capable of validating model-generated surfaces for heterotrophic respiration (R_h) and hence NEE. In addition, process-based modeling of R_h

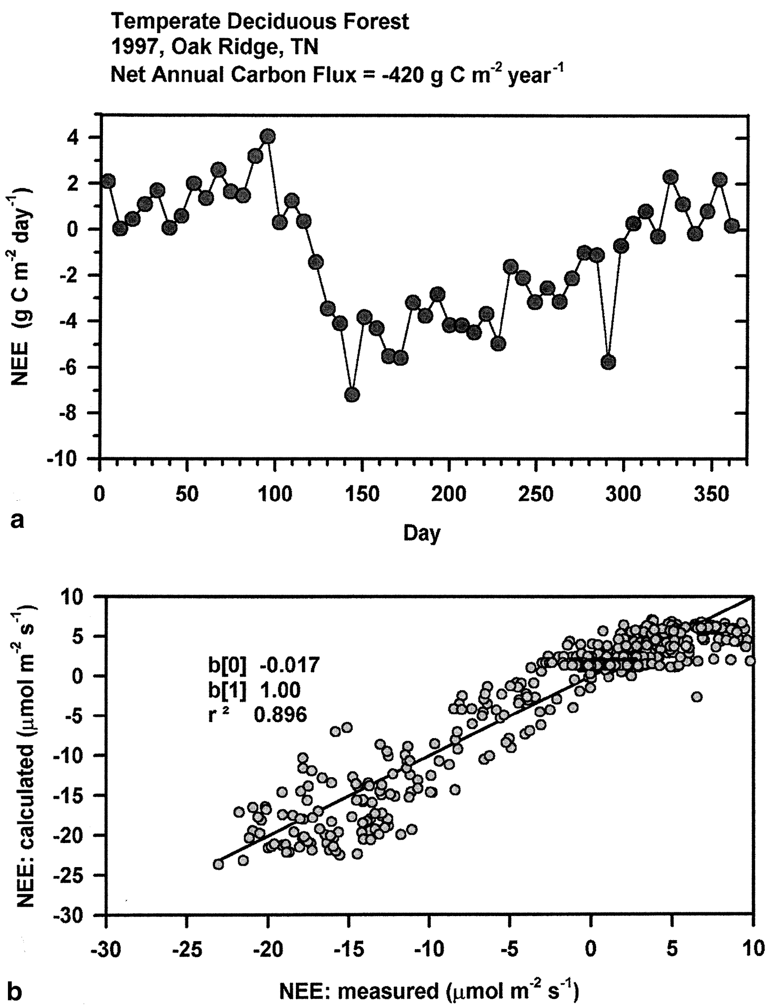

Figure 7. a) An example of FLUXNET carbon balance data, weekly net ecosystem exchange (NEE) for 1997 measured by an eddy covariance fluxtower for a temperate deciduous forest. b) The comparison of SVAT model simulation of NEE to observed NEE in 7a (Baldocchi, unpublished).

generally requires information on the size of the soil carbon pools. Global scale R_h algorithms often assume an equilibrium between R_h and NPP within a grid cell, and base estimated R_h on only the soil temperature and moisture status (e.g., Denning et al., 1996). However, sensitivity analyses have suggested that accounting for litter, soil organic matter, and coarse woody debris pool sizes will improve simulations of the seasonality of terrestrial C flux, and will be needed to capture the influence of interannual variability in climate on global R_h. Approaches to generating these important input surfaces for R_h models have included "spinning up" a carbon cycle model over a several thousand year period to establish pool sizes which are in rough equilibrium with the local climate and soil texture (VEMAP, see below), and recourse to maps of soil taxonomic units and related pedon databases (e.g., Kern et al., 1998). Flux tower sites, where SVAT model development includes the isolation of R_h from GPP and R_a, will provide an opportunity for validating the estimated pool sizes as well as the R_h flux. However, the next level of constraint on R_h flux estimates is apparently at the hemispheric or global scale, where inverse modeling based on spatial and temporal patterns in the atmospheric CO_2, O_2 and various isotopic variants indicate terrestrial sources and sinks of C (Tans et al., 1990; Keeling and Shertz, 1992).

GPPDI (web site at http://www-eosdis.ornl.gov/npp/npp_igbp.html) was launched following a meeting of ecosystem modelers organized under the IGBP-DIS (Data and Information System) at the Potsdam Institute for Climate Impact Research (PIK) in July 1994 (Prince et al., 1995). The Global Primary Production Data Initiative (GPPDI) is intended to provide quality data sets for validating global NPP models by identifying existing field data sets of primary production and associated environmental data. The program is using data sets for representative sites, and extrapolating or regionalizing the better data sets to grid cells sizes of up to 0.5°×0.5° with intelligent scaling logic similar to BigFoot. Emphasis is on variables needed to parameterize primary production models, including above and below ground NPP, standing crop, LAI, climate data, site data, and landscape variability. As of early 1999, over 900 published NPP data sets worldwide have been compiled, and 47 intensive sites

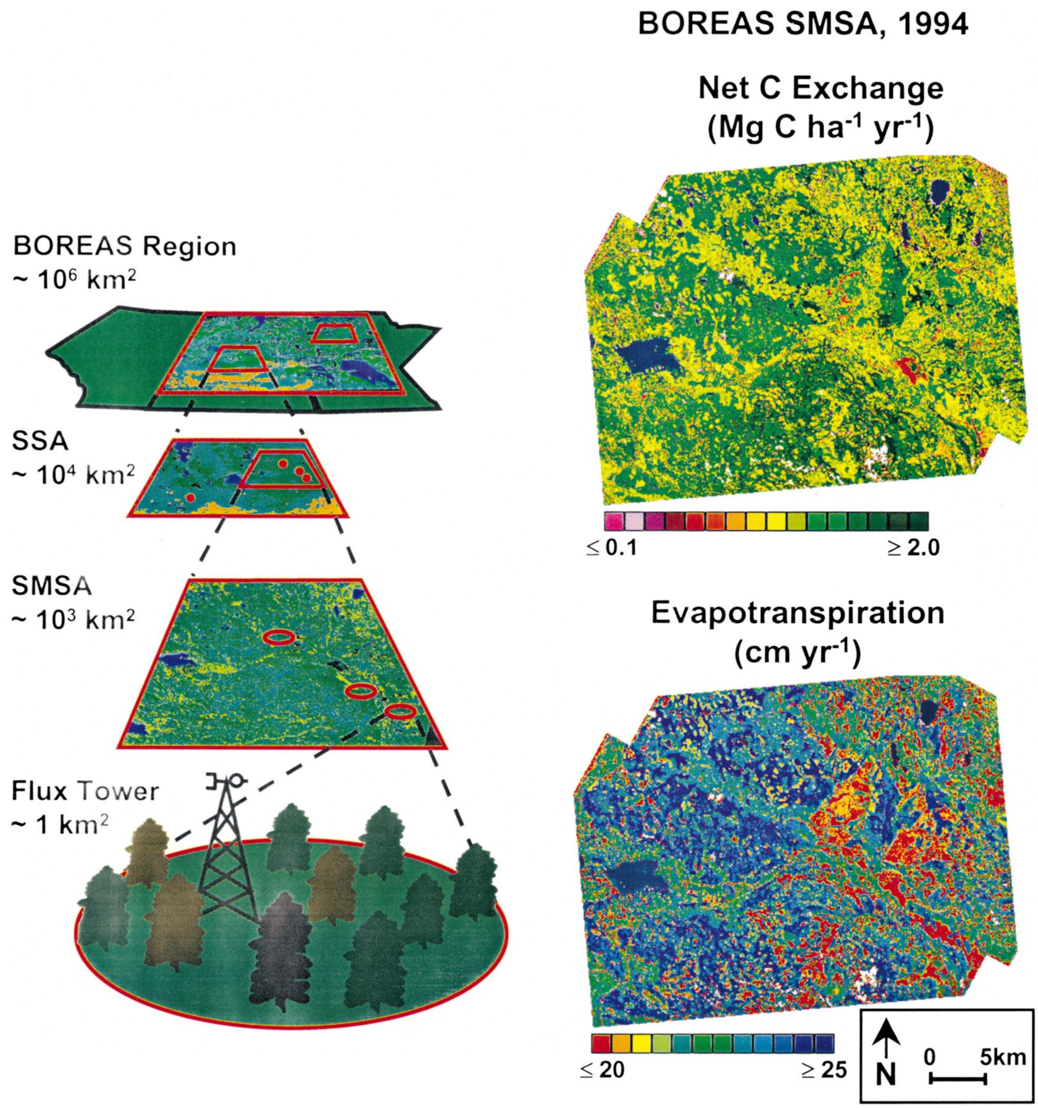

Figure 8. Ecosystem fluxes represented at regional scales by extrapolating FLUXNET data from three flux towers in the BOREAS project (Baldocchi et al., 1997; Black et al., 1996; Jarvis et al., 1997) with a SVAT model. These simulations for the BOREAS Southern Modeling Sub-area (SMSA) of 2000 km^2 used the BIOME-BGC SVAT model, spatially defined stand parameters with satellite data, integrated topography, soils, and microclimate data (Kimball et al., 1999). BIOME-BGC simulations were first validated with FLUXNET data from the three flux towers (Kimball et al., 1997a,b).

have been located to develop data sets with comprehensive ancillary data in this ongoing effort.

General circulation models also incorporate SVAT models such as BATS and SiB that represent the same canopy process dynamics as ecological SVAT models, but generalized to ≃1–2° grid cells. Thus, the climate modeling community faces many of the same validation issues as the ecological SVAT modelers (Pielke et al., 1993; Dickinson, 1995), notably the gap between the ET estimate from a climate model grid cell (≃10^4 km^2) and flux tower estimates of ET over the tower footprint. Methodologies such as the BigFoot project will be able to provide estimates of regional ET based on a SVAT model validated by flux tower ET measurements and extrapolated by EOS vegetation measurements.

Biospheric Model Intercomparisons

Another approach to assess accuracy of biospheric models when direct measurements are not possible is by global model intercomparisons. Major discrepancies in results among models draw attention to potential problem areas and data sets or weak process understanding. Two international biospheric model intercomparison activities are currently underway.

The ongoing IGBP sponsored 1995 Potsdam (PIK)-NPP model intercomparison can use FLUXNET derived

NPP estimates to test global NPP model estimates at locations sampled by the network. The website is at http://gaim.unh.edu/. The 1995 Potsdam NPP model intercomparison project was an international collaboration that produced single-year global NPP simulations (Cramer et al., 1999). There were large discrepancies amongst models of NPP in northern boreal forests and seasonally dry tropics. Over much of the global land surface, water availability most strongly influenced estimates of NPP; however, the interaction of water with other multiple limiting resources influenced simulated NPP in a non-predictable fashion (Churkina and Running, 1998).

VEMAP (http://www.cgd.ucar.edu:80/vemap/) is an ongoing multi-institutional, international effort addressing the response of terrestrial biogeography and biogeochemistry to environmental variability in climate and other drivers in both space and time domains. The objectives of VEMAP are the intercomparison of biogeochemistry models and vegetation distribution models (biogeography models) and determination of their sensitivity to changing climate, elevated atmospheric carbon dioxide concentrations, and other sources of altered forcing. The completed Phase 1 of the project was structured as a sensitivity analysis, with factorial combinations of climate (current and projected under doubled CO_2), atmospheric CO_2, and mapped and model-generated vegetation distributions. Maps of climate, climate change scenarios, soil properties, and potential natural vegetation were prepared as common boundary conditions and driving variables for the models (Kittel et al., 1995). As a consequence, differences in model results arose only from differences among model algorithms and their implementation rather than from differences in inputs (VEMAP, 1995). VEMAP is currently in the second phase of model intercomparison and analysis. The objectives of Phase 2 are to compare time-dependent ecological responses of biogeochemical and coupled biogeochemical–biogeographical models to historical and projected transient forcings across the conterminous United States. Because the VEMAP project has no validation component, interaction with FLUXNET and EOS can provide direct model validations. (Schimel et al., 1997)

INTERNATIONAL COORDINATION AND IMPLEMENTATION

Global validation and monitoring cannot be done without international cooperation that transcends any national

Figure 9. Potential synergism of international programs for validating terrestrial ecosystem variables at different space/time scales. Sites contributing to multiple programs have the highest synergism and efficiency. The programs depicted are: GPPDI=Global Primary Production Data Initiative, FLUXNET=the global network of eddy covariance flux towers, Atm FLASK=the global network of atmospheric flask sampling of NOAA/CMDL and C.D. Keeling and others, GTOS-NPP=a special project of the Global Terrestrial Observing System to measure net primary production of field sites worldwide, BigFoot=a study to establish scaling principles for sampling vegetation over large areas, EOS-MODIS=the Moderate Resolution Imaging Spectroradiometer on the Earth Observing System, the primary terrestrial observation sensor, VEMAP=the Vegetation/Ecosystem Modeling and Analysis Project, GAIM-NPP=the International Geosphere–Biosphere project in Global Analysis Integration and Modeling study of global NPP. See text for details of these projects.

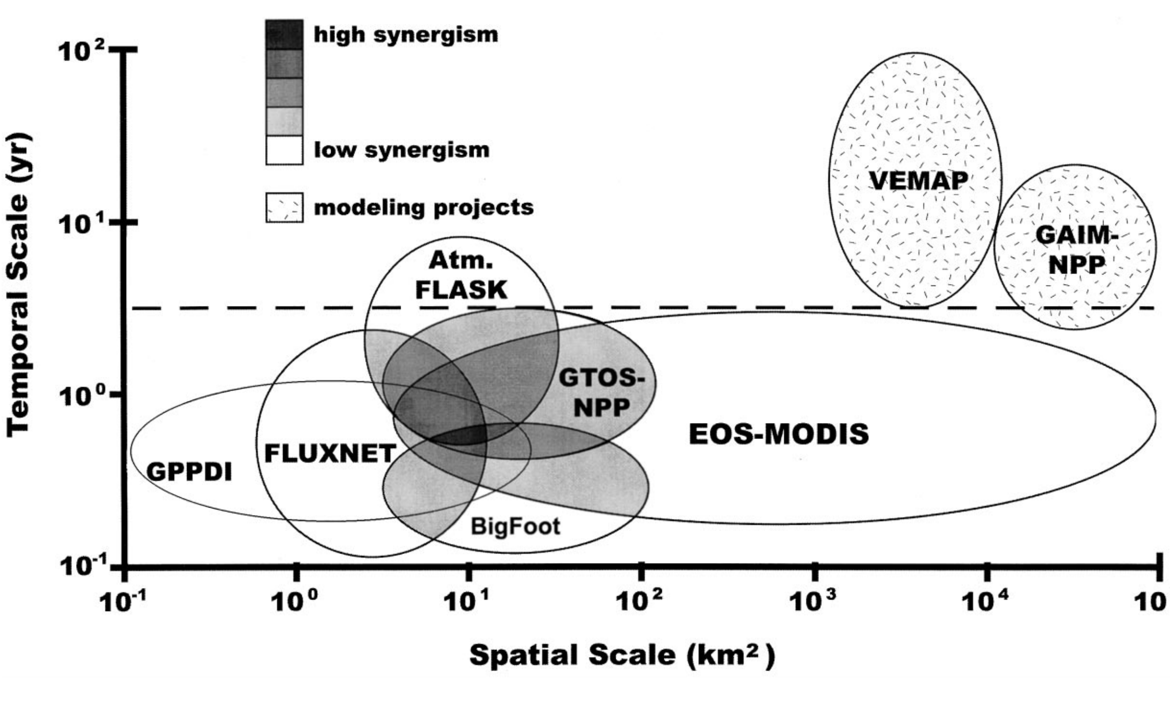

Table 3. The IGBP Terrestrial Transects Currently Identified

Region	*Contributing Transects in Initial Set*
Humid tropics	Tropical forest and its agricultural derivatives
	Amazon Basin/Mexico
	Central Africa/Miombo
	Southeast Asia/Thailand
Semiarid tropics	Forest–woodland–shrubland (the savannas)
	Savannas in the long term (West Africa)
	Kalahari (Southern Africa)
	Northern Australia Tropical Transect
Midlatitude semiarid	Forest–grassland–shrubland
	Great Plains (USA)
	Argentina
	North East China Transect
High latitudes	Boreal forest–tundra
	Alaska
	Boreal Forest Transect (Canada)
	Scandinavia
	Siberia

agency (Fig. 9). When planning global networks, it is essential to recognize that not all facilities have equal levels of scientific activity; however, all are needed to provide adequate global sampling. The Global Terrestrial Observing System (GTOS) and terrestrial components of the Global Climate Observing System GCOS have led in designing consistent international measurements for validation and monitoring work (GCOS, 1997). The strategy for implementing the plan is being developed in conjunction with the World Meteorological Organization (WMO) and the International GeosphereBiosphere Programme (IGBP). The plan will provide the necessary climate requirements for GTOS and the terrestrial requirements for GCOS. See http://www.wmo.ch/web/gcos/gcoshome.html.

Two core projects of IGBP have been instrumental in developing coordinated terrestrial systems. BAHC is the original project to suggest FLUXNET, and GCTE has led in designing the IGBP Terrestrial Transects. Both GAIM and IGAC now are supporting the continuing development of a global validation and monitoring system. Two internationally coordinated activities appear ready to implement FLUXNET and biospheric monitoring activities, the IGBP Transects, and the GTOS-NPP project.

The IGBP Terrestrial Transects, website at: http://gcte.org/LEMA-IGBP/LEMA-IGBP.html, are a set of integrated global change projects consisting of distributed observational studies and manipulative experiments, coupled with modeling and synthesis activities organized along existing gradients of underlying global change parameters, such as temperature, precipitation, and land use. The IGBP Terrestrial Transects consist of a set of study sites arranged along an underlying climatic gradient; of order 1000 km in length and wide enough to encompass the dimensions of remote sensing images. The initial set of IGBP Terrestrial Transects are located in four key regions, with three or four existing, planned or proposed transects contributing to the set in each region (Table 3).

The GTOS-NPP project (website at http://www.fao.org/GTOS/Home.htm) is being coordinated through the international U.S. Long Term Ecological Network (LTER) office, http://lternet.edu/ilter/. The goal of the GTOS-NPP project is to distribute the 1km EOS NPP and LAI products every 8 days to regional networks for evaluation, and after validation, translation of these standard products to regionally specific crop, range, and forest yield maps for land management applications. The project will also provide global validation points for land paramatrization in climate and carbon cycle models.

Databases and Archiving

Establishing data archiving centers is also important for international distribution and long-term availability of data. Several long-term databases are currently being compiled at the Oak Ridge, Tennessee, USA, DAAC facility. This data archive facility is home for data from FLUXNET, BigFoot, and GPPDI projects, all that have been summarized here (Olson et al., 1999, this issue). A centralized permanently funded data center such as the Oak Ridge DAAC insures continuity, consistency, and availability of data. However, the proliferation of Internet makes a more distributed array of data archive facilities equally useful if permanent commitments of support are made.

CONCLUSIONS

Each of the four monitoring scheme components described here—flux towers, flask sampling, ecosystem modeling, and EOS satellite data—are a source of consistency checks and validation to the other components. For example, if [as suggested in Fan et al. (1998)] the inverse modeling from the flask network suggested a C sink on the order of 1–2 Pg C y^{-1} in temperate North America, then results from a sample of flux tower sites in that region could confirm that specific sites were large carbon sinks, and results from a continental SVAT model initialized and driven by satellite data would support the presence of the carbon sink. The achievement of consistent agreement between the annual global NEE estimate from the flask network, and from a budget based on a spatially distributed SVAT model driven by satellite data, a spatially distributed model of marine sources and sinks driven by satellite data, and an inventory of anthropogenic sources, will be an important cross-check.

Accurate monitoring of global scale changes in the terrestrial biosphere are more critical than ever before. The Kyoto Protocol signals some of the huge socioeconomic and political decisions that lie ahead, and that will rely heavily on quantitatively accurate measures of global biospheric changes. The development of daily satellite earth observations, automated field measurement devices such as fluxtowers, powerful ecosystem models summarizing process interactions and high-speed computer networking makes a coordinated global biospheric monitoring program more attainable than ever before. All components of the program outlined in this article currently exist, and primarily need better coordination to become a global monitoring program. This article is designed to accelerate that coordination.

The primary sponsors of this work have been the U.S. Department of Energy, National Aeronautics and Space Administration Earth Science Enterprise, National Oceanic and Atmospheric Administration, and the National Science Foundation. International scientific organizations that have sponsored the evolution of this program include the International Geosphere–Biosphere Program, and the Global Climate and Terrestrial Observing Systems programs of the World Climate Research Program. An early version of this article was presented at the international FLUXNET meeting in Polson, Montana, USA on 3–5 June 1998.

REFERENCES

Bakwin, P. S., Tans, P. P., Hurst, D. F., and Zhao, C. (1998), Measurements of carbon dioxide on very tall towers: Results of the NOAA/CMDL program. *Tellus* 50B:401–415.

Baldocchi, 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., Valentini, R., Running, S., Oechel, W., and Dahlman, R. (1996), Strategies for measuring and modeling carbon dioxide and water vapour fluxes over terrestrial ecosystems. *Global Change Biol.* 2:159–168.

Baldocchi, D. D., Vogel, C. A., and Hall, B. (1997), Seasonal variation in carbon dioxide exchange rates above and below a boreal jack pine forest. *Agric. Forest Meteorol.* 83:147–170.

Benson, B. J., and MacKenzie, M. D. (1995), Effects of sensor spatial resolution on landscape structure parameters. *Landscape Ecol.* 10:113–120.

Black, T. A., den Hartog, G., Neumann, H. H., et al. (1996), Annual cycles of water vapor and carbon dioxide fluxes in and above a boreal aspen forest. *Global Change Biol.* 2:219–229.

Churkina, G., and Running, S. W. (1998), Contrasting climate controls on the estimated productivity of global terrestrial biomes. *Ecosystems* 1:206–215.

Ciais, P., Tans, P. P., Trolier, M., White, J. W. C., and Francey, R. J. (1995), A large northern hemisphere terrestrial CO_2 sink indicated by $^{13}C/^{12}C$ of atmospheric CO_2. *Science* 269: 1098–1102.

Cohen, W. B., Fiorella, M., Gray, J., Helmer, E., and Anderson, K. (1998), An efficient and accurate method for mapping forest clearcuts in the Pacific Northwest using Landsat imagery. *Photogramm. Eng. Remote Sens.* 64:293–300.

Cohen, W. B., Spies, T. A., and Fiorella, M. (1995), Estimating the age and structure of forests in a multi-ownership landscape of western Oregon, U.S.A. *Int. J. Remote Sens.* 16: 721–746.

Conway, T. J., Tans, P. P., Waterman, L. S., et al. (1994), Evidence for interannual variability of the carbon cycle from the National Oceanic and Atmospheric Administration/Climate Monitoring and Diagnostics Laboratory global air sampling network. *J. Geophys. Res.* 99:22,831–22,856.

Cramer, W., Kicklighter, D. W., Boned, A., et al., and Potsdam 95 (1999), Comparing global models of terrestrial net primary productivity (NPP): overview and key results. *Global Change Biol.* 5(Suppl. 1):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 Biol.* 2:275–285.

Denning, A. S., Fung, I. Y., and Randall, D. (1995), Latitudinal gradient of atmospheric CO_2 due to seasonal exchange with land biota. *Nature* 376:240–243.

Dickinson, R. E. (1995), Land processes in climate models. *Remote Sensing Environ.* 51:27–38.

Denning, A. S., Collatz, G. J., Zhang, C., et al. (1996), Simulations of terrestrial carbon metabolism and atmospheric CO_2 in a general circulation model. Part 1: Surface carbon fluxes. *Tellus* 48B:521–542.

Fan, S.-M., Goulden, M., Munger, J., et al. (1995), Environmental controls on the photosynthesis and respiration of a boreal lichen woodland: a growing season of whole-ecosystem exchange measurements by eddy correlation. *Oecologia* 102:443–452.

Fan, S.-M., Gloor, M., Mahlman, J., et al. (1998), A large terrestrial carbon sink in North America implied by atmospheric and oceanic CO_2 data and models. *Science* 282: 442–446.

Farquhar, G. D., Lloyd, J., Taylor, J. A., et al. (1993), Vegetation effects on the isotope composition of oxygen in atmospheric CO_2. *Nature* 363:439–443.

Field, C. B., Behrenfield, M. J., Randerson, J. T., and Falkowski, P. (1998), Primary production of the biosphere: Integrating terrestrial and oceanic components. *Science* 281: 237–240.

Field, C. B., Randerson, J. T., and Malmstrom, C. M. (1995), Global net primary production: combining ecology and remote sensing. *Remote Sens. Environ.* 51:74–88.

Foley, J. A., Prentice, C., Namankutty, N., et al. (1996), An integrated biosphere model of land surface processes, terrestrial carbon balance and vegetation dynamics. *Global Biogeochem. Cycles* 10:603–628.

Frolking, S., Goulden, M. L., Wofsy, S. C., et al. (1996), Modeling temporal variability in the carbon balance of a spruce/moss boreal forest. *Global Change Biol.* 2:343–366.

Global Climate Observing System (GCOS) (1997), *GCOS/GTOS Plan for Terrestrial Climate-Related Observations, Version 2.0* GCOS-32, QMO/TD-No. 796, World Meteorological Organization, Geneva, Switzerland, 130 pp.

Goulden, M. L., Munger, J. W., Fan, S.-M., Daube, B. C., and Wofsy, S. C. (1996), Exchange of carbon dioxide by a deciduous forest: response to interannual climate variability. *Science* 271:1576–1578.

Gower, S. T., Kucharik, C. J., and Norman, J. M. (1999), Direct and indirect estimation of leaf area index, FAPAR and net primary production of terrestrial ecosystems. *Remote Sens. Environ.* 70:29–51.

Hollinger, D. Y., Kelliher, F. M., Byers, J. N., Hunt, J. E., McSeveny, T. M., and Weir, P. (1994), Carbon dioxide exchange between an undisturbed old-growth temperate forest and the atmosphere. *Ecology* 75:134–150.

Hunt, E. R., Jr., Piper, S. C., Nemani, R., Keeling, C. D., Otto, R. D., and Running, S. W. (1996), Global net carbon exchange and intra-annual atmospheric CO_2 concentrations predicted by an ecosystem process model and three-dimensional atmospheric transport model. *Global Biogeochem. Cycles* 10:431–456.

IGBP Terrestrial Carbon Working Group (1998), The terrestrial carbon cycle: implications for the Kyoto Protocol. *Science* 280:1393–1394.

Jarvis, P. G., Massheder, J. M., Hale, S. E., Moncreif, J. B., Payment, R., and Scott, S. L. (1997), Seasonal variation of carbon dioxide, water vapor and energy exchanges of a boreal black spruce forest. *J. Geophys. Res.* 102(D24) 28,953–28,966.

Justice, C. O., Vermote E., Townshend, J. R. G., et al. (1998), The Moderate Resolution Imaging Spectroradiometer (MODIS): land remote sensing for global change research. *IEEE Trans. Geosci. Remote Sens.* 36:1228–1249.

Keeling, C. D., Bacastow, R. B., Carter, A. F., et al. (1989), A three-dimensional model of atmospheric CO_2 transport based on observed winds, 1. Analysis of observational data. In *Aspects of Climate Variability in the Pacific and the Western Americas* (D. H. Peterson, Ed.), Geophys. Monogr., 55, American Geophysical Union, Washington, DC, 363 pp.

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., Piper, S. C., and Heimann, M. (1996), Global and hemispheric CO_2 sinks deduced from changes in atmospheric O_2 concentration. *Nature* 381:218–221.

Keeling, R. F., and Shertz, S. R. (1992), Seasonal and interannual variations in atmospheric oxygen and implications for the global carbon cycle. *Nature* 358:723–727.

Kern, J. S., Turner, D. P. and Dodson, R. F. (1998), Spatial patterns in soil organic carbon pool size in the Northwestern United States. In *Soil Processes and the Carbon Cycle* (R. Lal, J. M. Kimball, R. Follett, and B. A. Stewart, Eds.), CRC Press, Boca Raton, FL, pp 29–43.

Kimball, J. S., Thornton, P. E., White, M. A., and Running, S. W. (1997a), Simulating forest productivity and surface–atmosphere carbon exchange in the BOREAS study region. *Tree Physiol.* 17:589–599.

Kimball, J. S., White, M. A., and Running, S. W. (1997b), BIOME-BGC simulations of stand hydrologic processes for BOREAS. *J. Geophys. Res.* 102(D24):29,043–29,051.

Kimball, J. S. Running, S. W., and Saatchi, S. S. (1999), Sensitivity of boreal forest regional water flux and net primary production simulations to sub–grid scale landcover complexity. *J. Geophys. Res.*, in press.

Kittel, T. G. F, Rosenbloom, N. A., Painter, T. H., Schimel, D. S., and VEMAP Modeling Participants (1995), The VEMAP integrated database for modeling United States ecosystem/vegetation sensitivity to climate change. *J. Biogeogr.* 22 (4–5):857–862.

Landsberg, J. J., and Gower, S. T. (1997), *Applications of Physiological Ecology to Forest Management*, Physiological Ecology Series, Academic, San Diego, CA.

Lenschow, D. H. (1995), Micrometeorological techniques for measuring biosphere–atmosphere trace gas exchange. In *Trace Gases in Ecology* (P. Matson and B. Harris, Eds.) Blackwell Science Ltd., Oxford, pp. 126–163.

Melillo, J. M., McGuire, A. D., Kicklighter, A. D., Moore, B., III, Vorosmarty, C. J., and Schloss, A. L. (1993), Global climate change and terrestrial net primary production. *Nature* 363:234–240.

Moncrieff, J. B., Malhi, Y., and Leuning, R. (1996), The propagation of errors in long-term measurements of land–atmosphere fluxes of carbon and water. *Global Change Biol.* 2:231–240.

Moore, C. J. (1986), Frequency response corrections for eddy correlation systems. *Boundary Layer Meteorol.* 37:17–35.

Myneni, R. B., Keeling, C. D., Tucker, C. J., Asrar, G., and Nemani, R. R. (1997a), 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 Trans. Geosci. Remote Sens.* 35:1380–1393.

Oechel, W. C., Vourlitis, G. L., Brooks, S., Crawford, T. L., and Dumas, E. (1998), Intercomparison among chamber, tower, and aircraft net CO_2 and energy fluxes measured during the Arctic System Science Land–atmosphere–Ice Interactions (ARCSS-LAII) flux study. *J. Geophys. Res.* 103 (D22) 28,993–29,003.

Olson, R. J., Biggs, J. M., Porter, J. H., Mah, G. R., and Stafford, S. G. (1999), Managing data from multiple disciplines, scales and sites to support synthesis and modeling. *Remote Sens. Environ.* 70:99–107.

Pielke, R. A., Schimel, D. S., Lee, T. J., Kittel, T. G. F., and Zeng, X. (1993), Atmosphere–terrestrial ecosystem interactions: implications for coupled modeling. *Ecol. Model.* 67: 5–18.

Pierce, L. L., and Running, S. W. (1995), The effects of aggregating sub-grid land surface variation on large-scale estimates of net primary production. *Landscape Ecol.* 10: 239–253.

Potosnak, M. J., Wofsy, S. C., Denning, A. S., Conway, T. J., Novelli, P. C., and Barnes, D. H. (1998), Influence of biotic exchange and combustion sources on atmospheric CO_2 concentrations in New England from observations at a forest flux tower. *J. Geophys. Res.*, in press.

Prince, S. D. and Goward, S. T. (1995), Global primary production: a remote sensing approach. *J. Biogeogr.* 22: 815–835.

Prince, S. D., Olson, R. J., Dedieu, G., Esser, G., and Cramer, W. (1995), Global Primary Production Data Initiative Project description, IGBP-DIS Working Article No. 12, IGBP-DIS, Toulouse, France.

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 Biogeochem. Cycles* 11: 535–560.

Reich, P. B., Turner, D., and Bolstad, P. (1999), An approach to spatially-distributed modeling of net primary production (NPP) at the landscape scale and its application in validating EOS NPP products. *Remote Sens. Environ.* 70:69–81.

Ruimy, A., Saugier, B., and Dedieu, G. (1994), Methodology for the estimation of terrestrial net primary production from remotely sensed data. *J. Geophys. Res.* 99:5263–5283.

Running, S. W. (1998), A blueprint for improved global change monitoring of the terrestrial biosphere. *NASA Earth Obs.* 10(1):8–11.

Running, S. W., Justice, C. O., Salmonson, V., et al. (1994), Terrestrial remote sensing science and algorithms planned for EOS/MODIS. *Int. J. Remote Sens.* 15: 3587–3620.

Schimel, D. S. (1998), The carbon equation. *Nature* 393:208–209.

Schimel, D. S., VEMAP Participants, and Braswell, B. H. (1997), Continental scale variability in ecosystem processes: Models, data, and the role of disturbance. *Ecol. Monogr.* 67:251–271.

Tans, P. P. (1998), Oxygen isotopic equilibrium between carbon dioxide and water in soils. *Tellus* 50:163–178.

Tans, P. P., Bakwin, P. S., and Guenther, D. W. (1996), A feasible global carbon cycle observing system: a plan to decipher today's carbon cycle based on observations. *Global Change Biol.* 2:309–318.

Tans, P. P., Fung, I. Y., and Takahashi, T. (1990), Observational constraints on the global atmospheric CO_2 budget. *Science* 247:1431–1438.

Thomlinson, J. R., Bolstad, P. V., and Cohen, W. B. (1999), Coordinating methodologies for scaling landcover classifications from site-specific to global: steps toward validating global map products. *Remote Sens. Environ.* 70:16–28.

Townshend, J. R. C., and Justice, C. O. (1988), Selecting the spatial resolution of satellite sensors required for global monitoring of land transformations. *Int. J. Remote Sens.* 9:187–236.

Turner, D. P., Cohen, W. B., Kennedy, R. E., Fassnacht, K. S., and Briggs, J. M. (1999), Relationships between leaf area index and Landsat TM spectral vegetation indices across three temperate zone sites. *Remote Sens. Environ.* 70:52–68.

Turner, D. P., Dodson, R. D., and Marks, D. (1996), Comparison of alternative spatial resolutions in the application of a spatially distributed biogeochemical model over complex terrain. *Ecol. Model.* 90:53–67.

VEMAP (1995), Vegetation/Ecosystem Modeling and Analysis Project: comparing biogeography and biogeochemistry models in a continental-scale study of terrestrial ecosystem responses to climate change and CO_2 doubling. *Global Biogeochem. Cycling* 9:407–437.

Waring, R. H., and Running, S. W. (1998), *Forest Ecosystems: Analysis at Multiple Scales*, 2nd ed., Academic, San Diego, 370 pp.

Waring, R. H., Law, B. E., Goulden, M. L., et al. (1995), Scaling gross ecosystem production at Harvard Forest with remote sensing: a comparison of estimates from a constrained quantum-use efficiency model and eddy correlation. *Plant Cell Environ.* 18:1201–1213.

White, J. D., Running, S. W., Thornton, P. E., et al. (1998), Assessing simulated ecosystem processes for climate variability at Glacier National Park, USA. *Ecol. Appl.* 8:805–823.

Appendix: List of Acronyms

BAHC	Biospheric Aspects of the Hydrologic Cycle (IGBP)
BOREAS	Boreal Ecosystem Atmosphere Study
DAAC	Distributed Active Archive Center
EOS	Earth Observing System
ET	Evapotranspiration
ETM+	Enhanced Thematic Mapper
FPAR	Fraction photosynthetically active radiation
GAIM	Global Analysis and Modeling Project (IGBP)
GCM	General circulation model
GCOS	Global Climate Observing System (WMO)
GTOS	Global Terrestrial Observing System (WMO)
GCTE	Global Change Terrestrial Ecosystems (IGBP)
GPP	Gross Primary Production
GPPDI	Global Primary Production Data Initiative (IGBP)
IGAC	International Global Atmospheric Chemistry (IGBP)
IGBP	International Geosphere–Biosphere Program
IGBP-DIS	IGBP Data Information System
ILTER	International Long Term Ecological Research
LAI	Leaf area index
LTER	Long Term Ecological Research
MODIS	Moderate Resolution Imaging Spectroradiometer
NEE	Net ecosystem exchange
NPP	Net primary production
SVAT	Soil–Vegetation–Atmosphere transfer model
TOPC	Terrestrial Observing Panel for Climate (WMO)
VEMAP	Vegetation/Ecosystem Modeling and Analysis Program