Next-Generation Terrestrial Carbon Monitoring

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The first glimpse for humanity of global carbon monitoring was the invaluable record of atmospheric carbon dioxide measurements on the summit of Mauna Loa, initiated in 1958 by Charles David Keeling. Terrestrial carbon monitoring at the global scale only became possible with the advent of earth observation satellites in the early 1980s. Current science now allows an integration of satellite data, ground stations, and field observations integrated by mechanistic carbon cycle models. However this observational potential has not been realized by current systems, and international investments and coordination are needed. Future policy decisions on mitigating climate change, monitoring carbon credits, and developing biofuels will put a high demand on accurate monitoring and understanding of the global carbon cycle.

"The rise in CO_2 is proceeding so slowly that most of us today will, very likely, live out our lives without perceiving that a problem may exist. But CO_2 is just one index of man's rising activity today. We have rising numbers of college degrees, rising steel production, rising costs of television programming and broadcasting, high rising apartments, rising number of marriages, relatively more rapidly rising numbers of divorces, rising employment, and rising unemployment. At the same time we have diminishing natural resources, diminishing distract-free time, diminishing farm land around cities, diminishing virgin lands in the distant country side…[viewed over thousands of years] I am struck by the obvious transient nature of the CO_2 rise. The rapid changes in all factors I [have just] mentioned, including the rapid rise in world population, are probably also transient; these changes, so familiar to us today, not only were unknown to all but the most recent of our ancestors but will be unknown to all but the most immediate of our descendants."

Keeling et al. [1968, pp. 4511–4528]

1. INTRODUCTION

Reading the sentence above, "The rise in CO_2 is proceeding so slowly that most of us today will, very likely, live out our lives without perceiving that a problem may exist" is haunting, as it reminds us how quickly the earth has changed. Degradation of the global environment is an issue of increasing scientific and public concern. There is now no doubt that the climate is changing, that ice caps are melting faster, most glaciers are receding, sea level is rising, hurricane intensity is increasing, wildfire activity increasing [*Hansen et al.*, 2005; *International Panel on Climate Change* (*IPCC*), 2007a, 2007b]. The terrestrial biosphere so far seems to be faring better, with growing seasons increasing in duration, and both global net primary production (NPP) and forest growth increasing overall globally. Hydration of the land surface is a mixed signal, with some evidence of positive water balance trends but other evidence of increasing droughts [*IPCC*, 2007a]. Global scientists are increasingly nervous that the Earth system is becoming imbalanced in ways that are unprecedented, and we do not understand, and predictability of future climate is

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getting more uncertain. The impacts of global changes on the biosphere are likewise becoming less certain, with potential for nonlinear and even threshold responses. Ultimately, the habitability of the planet may be degraded irreversibly.

The role of global monitoring in this era is to provide accurate measurements that increase our understanding of climate trends and their biospheric impacts and—of immense policy importance—to give the earliest advance warning of impending problems before it is too late for humanity to correct their actions. Charles David Keeling started the Mauna Loa atmospheric CO_2 record (the now iconic "Keeling curve") in 1957, and 30 years passed before other data sets began to give us additional windows into the operation of the global climate/carbon system. His Mauna Loa record provided critical contextual history of current trends and new understanding of the global carbon cycle. But what was truly invaluable, a gift to humanity really, was that this data set gave us a 20- to 30-year advance warning that we should pay attention to human impact on the Earth System. Given the political inertia now occurring in planning solutions to modify human socioeconomic activities to confront global warming, it is clear we needed all the advance warning we can possibly get. Specifically, it was early warning from the Keeling curve that gave NASA the political support to develop and deploy the EOS, which now provides the bulk of regular, publicly available global terrestrial monitoring.

For C.D. Keeling in 1957, studying atmospheric CO_2 was pure scientific curiosity, testing some new ideas with Roger Revelle about global carbon cycles. Now, 50 years later, we have some very pragmatic and urgent reasons to study the global carbon cycle. What happens to the Earth System when carbon slowly sequestered in organic deposits over 100 million years is released back to the atmosphere in 100 years, an acceleration factor of 10^6? Because the Earth system is very nonlinear, could we actually "break" the carbon cycle in an unanticipated and dangerous way? What can humankind now do to rebalance the global system? While we cannot answer these questions definitely, we do now have a new suite of global measurements to look at for understanding and ultimately for decision-making. What capabilities now exist to monitor the global carbon cycle and its critical components?

The objective of this paper is to summarize a generation of terrestrial carbon cycle relevant measurements that have been developed over the last 25 years, which have a history of validation activity and that are now regularly produced. Although many more extensive lists of global terrestrial observations have been developed [e.g., the *Global Terrestrial Observing System* (*GTOS*), 2008], this paper is meant to target a small core of variables most directly relevant to terrestrial carbon cycle science. These global measurements are an integral part of global carbon cycle research and are incorporated in carbon modeling at various scales. We direct readers to books such as *Field and Raupach* [2004] for more comprehensive coverage of global carbon cycle science as a whole.

2. FIRST GENERATION OF TERRESTRIAL CARBON MONITORING

It is a little ironic that the first measure of global scale terrestrial carbon dynamics was a time series of *atmospheric* measurements, the Keeling curve. The Keeling curve taught global scientists two major lessons that were obvious within the first decade of the now 50-year record. First, humankind had the capacity for, and was in fact, impacting the entire well-mixed global atmosphere, a sober new awakening of our role in the Earth System. Second, the seasonal amplitude of atmospheric CO_2 gave global scientists the first hint of the strength of the biosphere to measurably draw down global atmospheric CO_2 seasonally, indirectly providing the first measure of terrestrial carbon cycle dynamics. This principle is so important in understanding the role of the terrestrial biosphere in the Earth System that the Keeling curve is now used in introductory Earth Science texts to show seasonality of terrestrial carbon dynamics.

As more CO_2 measurement stations were installed by Keeling and by scientists at NOAA and agencies in Australia, Japan, and other countries, the different latitudes and climates illustrated a marked variation in seasonality. These geographic differences in the seasonal atmospheric CO_2 cycle became a very valuable first estimate of the changing seasonal balance of photosynthetic uptake and autotrophic/heterotrophic release of CO_2 by terrestrial ecosystems (Figure 1). Coupling a terrestrial biogeochemical model with an atmospheric transport model allowed simulation of the seasonal cycle of atmospheric CO_2 [*Hunt et al*., 1996].

As the importance of the Keeling curve became obvious, many more atmospheric monitoring sites were established globally and now constitute an international network that is the subject of the paper by Sundquist and R. Keeling in this volume. Higher precision of measurements, more continuous sampling, addition of isotopic measurements, and measurements of oxygen and other relevant gases all have been developed to make this global atmospheric monitoring network the cornerstone of regular monitoring of the global carbon system. More direct global measurements of terrestrial systems had to await a new technology.

3. SECOND-GENERATION TERRESTRIAL CARBON MONITORING

The first true measures of global terrestrial biospheric function were inadvertent, a classic curiosity-driven result of

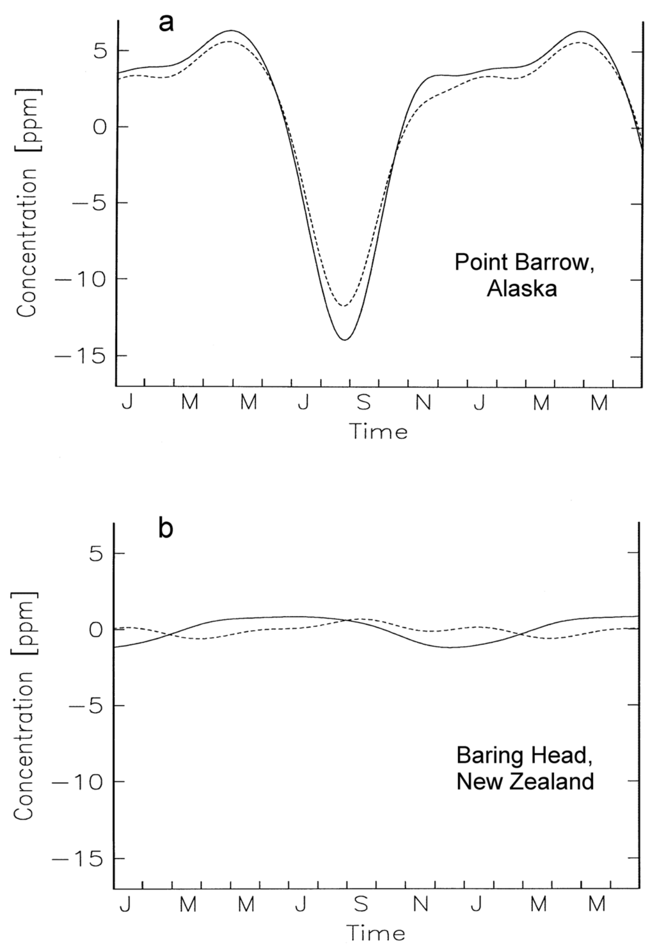


Figure 1. The seasonal amplitude of atmospheric CO_2 at (a) Barrow Alaska, arctic tundra at 70° N latitude, compared to (b) Baring Head, New Zealand at 41°S latitude. Solid lines are field measurements, dotted lines are estimated from a global biogeochemical model analysis [redrawn from *Waring and Running*, 2007, model results from *Hunt et al.*, 1996].

an ecologist taking an unplanned look at data from an early TIROS meteorological satellite. The advanced very high resolution radiometer (AVHRR) was launched on the TIROS-N satellite in 1978 to follow cloud cover and improve weather forecasting. C. J. Tucker, an ecologist who recently had done his Ph.D. on spectral properties of wheat leaves, decided in the early 1980s to look at two of the optical and near-infrared (NIR) spectral channels on the AVHRR instrument. We forget now that processing a global data set of about 110 million 1-km land pixels was a computational challenge that pushed the primitive computers of that era to their limit. One day of global processing took all night on the computers at NASA Goddard Space Flight Center. Current successes in global satellite monitoring are as much a result of the quantum leap in computer processing and data storage capacity as they are of satellite improvements.

The AVHRR provided global coverage daily, but to minimize effects of cloud screening and to maximize the signal from near nadir radiometry, 8- to 14-d maximum value composites were typically computed. Tucker defined a simple normalized difference vegetation index (NDVI) as

$$\text{NDVI} = (\text{NIR} - \text{Red}) / (\text{NIR} + \text{Red})$$

from the intensity of radiation measured on two channels (here termed NIR and Red) of the AVHRR data. Although Tucker began publishing papers that reported his new AVHRR NDVI data beginning in 1983 in technical remote sensing journals [*Tucker et al.*, 1983, 1984a, 1984b], it was the cover of *Science* magazine in January of 1985—showing the first NDVI image of the African continent—that introduced global vegetation analysis to the wider

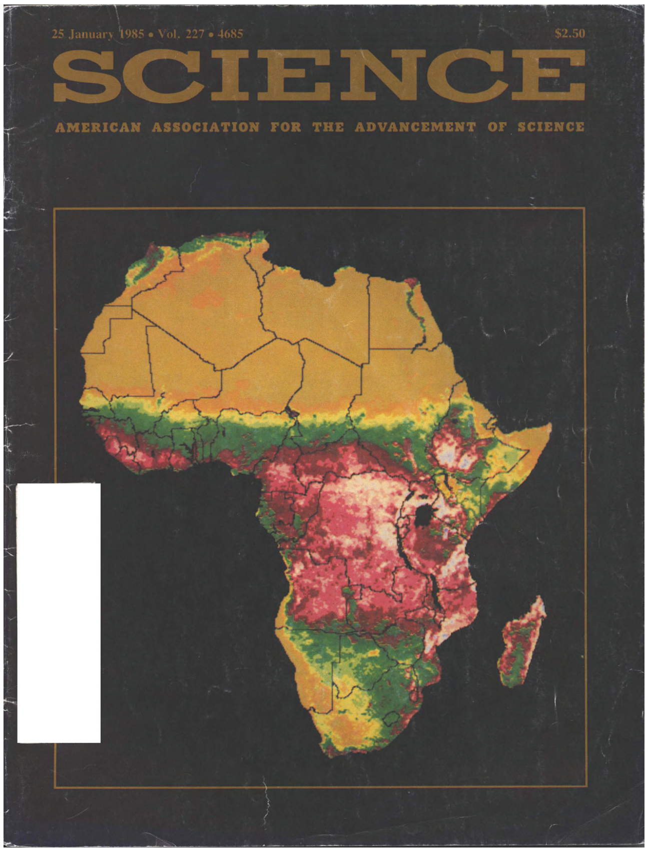


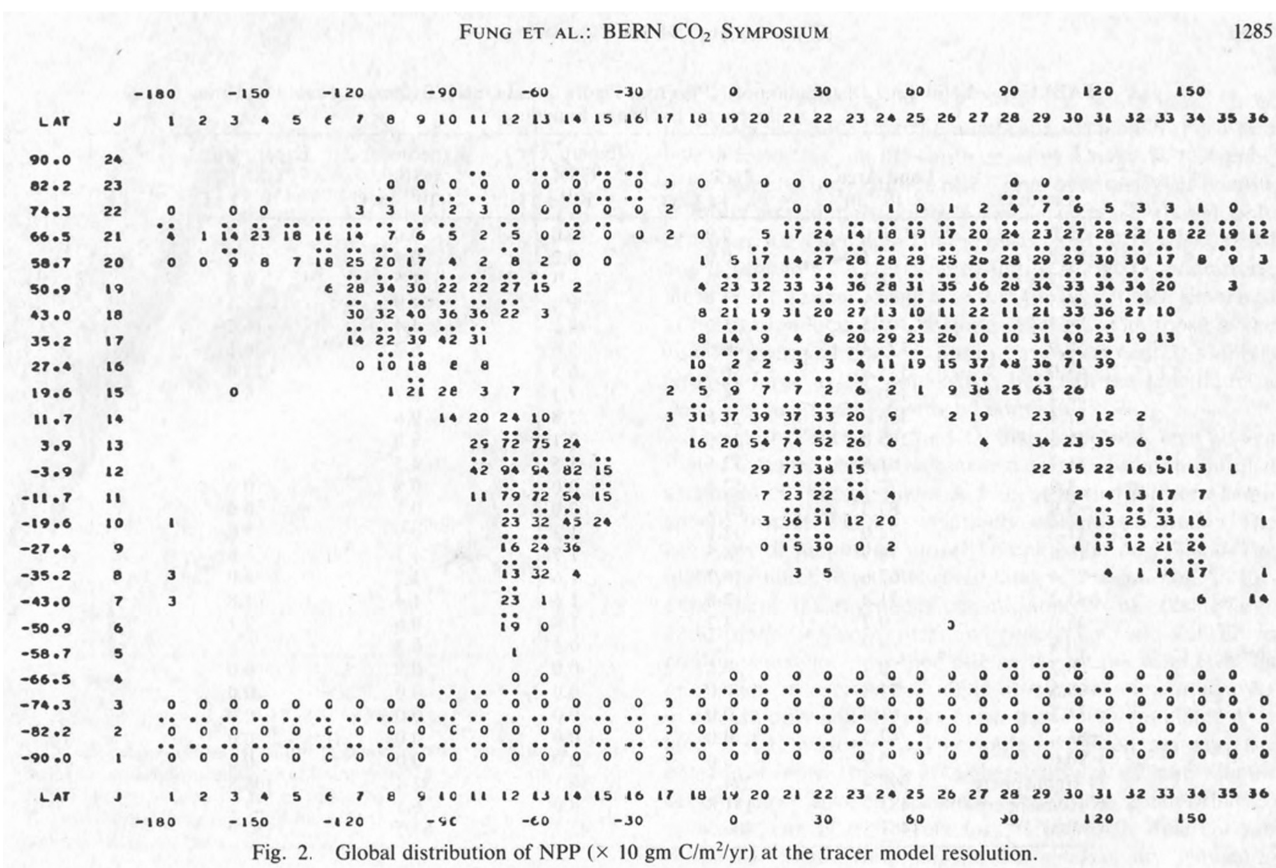
Plate 1. The first satellite-derived view of continental vegetation on the cover of *Science* magazine on January 1985 [*Tucker et al*., 1985].

science community (Plate 1) [*Tucker et al.*, 1985]. For the first time in human history, we now could look at the biospheric function of a continent all at once, rather than merely compile disparate pieces of ground information in maps and atlases.

Now terrestrial scientists had some global measure of their ecosystems to work with. The first efforts were simply to try to quantify the global vegetation cover. In the 1980s and 1990s, AVHRR was the only satellite to provide a rapid enough repeat period, 8–14 d after processing to discern the annual vegetation cycle between winter- or drought-induced dormancy and summer growing season. Beyond mapping the geographic distribution of biomes and changes in land cover, the other primary observation with these early NDVI data sets was the definition of continental growing seasons and phenology [*Justice et al.*, 1985].

The earliest attempts to evaluate an ecosystem process like NPP at a global scale were done by geographers; the famous estimates of *Leith and Whittaker* [1975] are still quoted today. These estimates of global NPP were based on regressions of temperature data from about a thousand weather stations computed to a simple estimate of annual actual evapotranspiration (AET) in mm/year and then regressed against a handful of NPP field plots. The resulting equation was used to compute and map a global estimate of NPP totalling 118 of GT/year of biomass (about 47 GT of *carbon*) for the first time, primarily from transformed and coarsely extrapolated meteorology data. *Goward et al.* [1987] correlated the global NDVI data with this first global NPP estimate and found encouragingly high correlation between the annual integrated NDVI and annual NPP for a range of biome classes.

The logical next step was to relate the seasonal atmospheric CO_2 dynamics exemplified by the Mauna Loa data to the satellite NDVI data, to see if the observed drawdown in summer CO_2 correlated with peak growing season NDVI. *Fung et al.* [1983] first used an early global circulation model in an inversion mode to predict geographically specific seasonality of the atmospheric CO_2 cycle and terrestrial NPP (Figure 2). The cover of Nature magazine for 22 January 1986 then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-90.0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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Fig. 2. Global distribution of NPP (× 10 gm $C/m^2/yr$) at the tracer model resolution.

Figure 2. The first estimate of global patterns of terrestrial net primary production (NPP) using the atmospheric CO_2 record [*Fung et al.*, 1983].

showed the results of Tucker, Keeling, and Fung's successful correlation of atmospheric CO_2 amplitudes and the global NDVI data [*Tucker et al.*, 1986]. At the time, this was the most comprehensive measure of the global terrestrial carbon dynamics ever done.

Ecologists have long used leaf area index (LAI)—the ratio of total leaf area to ground area—as a simple quantitative measure of vegetation canopy density and as a means of scaling leaf flux rates like photosynthesis and transpiration to whole canopies. Tests correlating NDVI with LAI found useful relationships for agronomic plants [*Asrar et al.*, 1984] and forests [*Running et al.*, 1986]. Subsequent studies found the seasonal trace of NDVI to be very similar to the canopy flux dynamics computed from early ecosystem biogeochemistry models, as continuous flux measurements had not yet been invented [*Running and Nemani*, 1988]. These correlative studies and theoretical derivations relating NDVI to absorbed photosynthetically active radiation (PAR) and LAI by *Sellers* [1985, 1987] provided early understanding of what NDVI quantified in global terrestrial carbon dynamics. Time integrals of absorbed PAR (APAR), which can be monitored from satellites, had been shown to correlate well with observed NPP [*Monteith*, 1977], but different relationships were observed for different vegetation types and for the same vegetation type under different growth conditions [*Russell et al.*, 1989]. Critical intensive field experiments were conducted in grasslands: the First International Land Surface Climatology Program (ISLSCP) Field Experiment (FIFE) and boreal forests, the Boreal Ecosystem-Atmosphere Study (BOREAS), to better understand the relationship between remote sensing and field biophysical properties of ecosystems [*Sellers et al.*, 1995].

Research and development in the decade of the 1980s identified key attributes for improving satellites for global terrestrial observation, with focus on a set of biophysical variables that could be reliably computed from spectral information. By 1989, NASA and a cadre of international partners committed to a new EOS with sensors designed from the lessons of these early studies [*NASA*, 1986a]. The new EOS platforms were to have better flight stability and orbital maintenance to allow higher precision imaging. The Moderate Resolution Imaging Spectroradiometer (MODIS) sensor was designed to be radiometrically superior and to be calibrated more rigorously than the previous AVHRR sensor [*NASA*, 1986b]. Additionally, for the first time, a science team was selected to write processing algorithms for key biophysical variables for continuous global production and worldwide distribution. The launch of EOS, beginning in late 1999 inaugurated the third generation of global terrestrial observation.

4. THIRD-GENERATION (CURRENT) GLOBAL TERRESTRIAL MONITORING

Although many global measurements are now being taken, a handful are of particular relevance to the terrestrial carbon cycle and are mature enough to be organized specifically for ongoing monitoring of terrestrial carbon. We list in Plate 2 a suite of currently produced measurements that are particularly important to terrestrial carbon research. (As discussed later in this paper, these products are supported now as research products with no guarantee of continuity. With long-term support, they could be the foundation of a new coordinated system for monitoring of the global terrestrial carbon cycle.)

We will briefly summarize the development of these data sets and current status of delivery. Both the current state of the biospheric system and the rate of change are important. However, change detection is much more difficult because often the rate of change is at the limit of detection for these measurements.

4.1. Satellite-Based Observations

Beginning in March 2000, regular global data sets have been produced and freely disseminated from the EOS. As of 2006, over 6000 Terabytes of data had been produced by EOS, with new data arriving at the rate of 4.5 TB/d. This unprecedented avalanche of global data has inaugurated a third generation of global terrestrial observation, and is all available for order online at (http://nasadaacs.eos.nasa.gov/). These EOS data sets have undergone extensive testing, with multiple generations of improvements and validation [*Morisette et al.*, 2006]. As improvements have been developed and implemented for each individual algorithm, the entire period of record 2000 to present has been reprocessed three to five times to produce a consistency unmatched in previous global satellite data sets.

EOS data centers have processed suites of variables in a sequential integrated way to optimize synergy between related variables. A select set of these computed variables are of high relevance to the global terrestrial carbon cycle. The suite of MODIS-derived vegetation variables is computed in the following logical order. While the MODIS raw channel data are computed to spectral reflectances each day, the refresh rates (below) of these variables vary with the biophysical dynamics of the variable in question.

Vegetation indices: 16 d
Land cover: 96 d
LAI/FPAR: 8 d
GPP (gross primary production): 1 d
NPP: 1 year

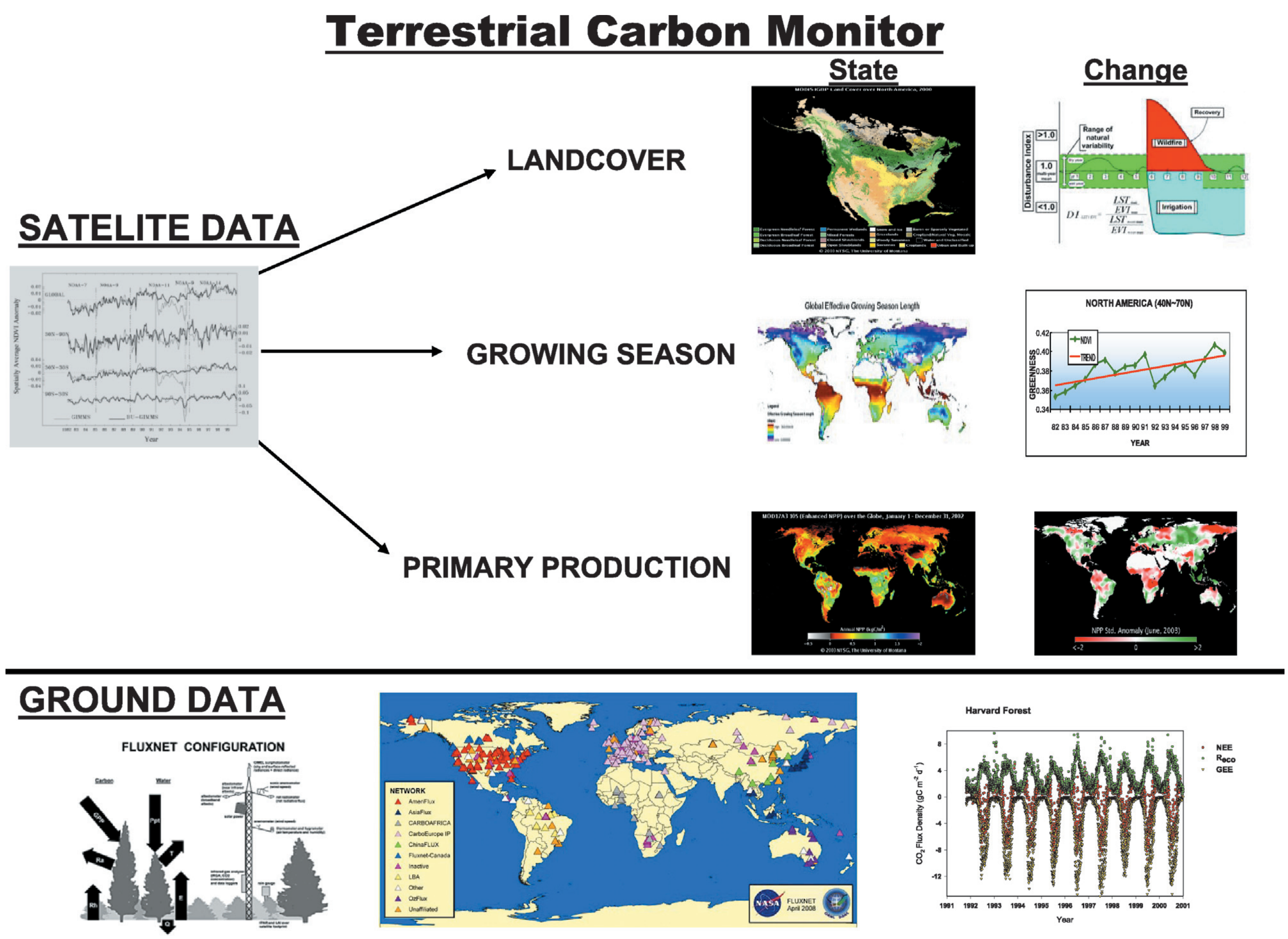

Plate 2. Currently active (third generation) measurements that are particularly important to terrestrial carbon research. These measurements could be organized as components of a prototype global terrestrial carbon monitoring system.

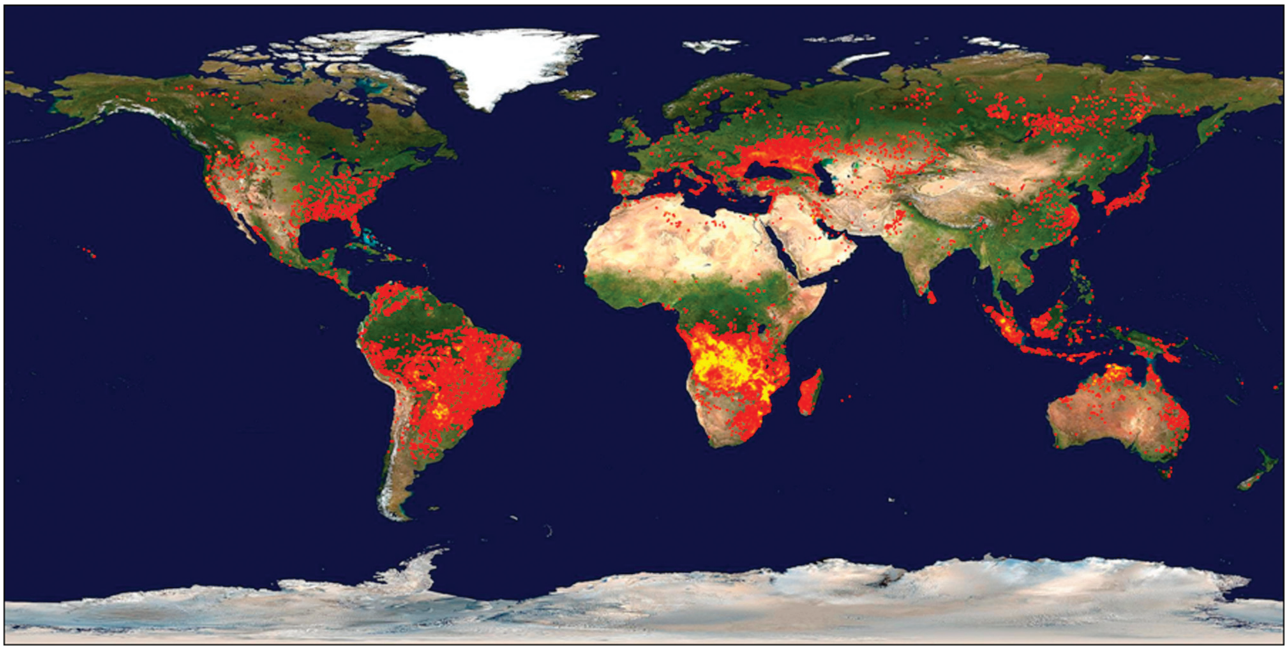

Plate 3. Global map of fire counts detected by the MODIS satellite from days 211–220 of 2006 [*Giglio et al.*, 2003]. Fires add 2–3 Pg of CO_2 to the atmosphere each year [*van der Werf et al.*, 2004].

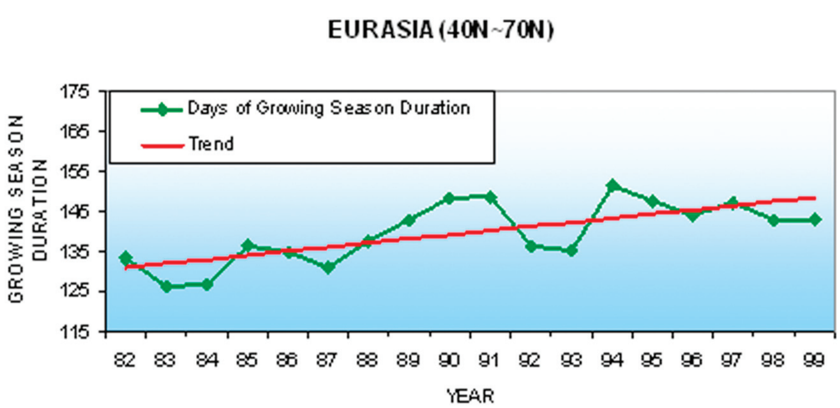

Plate 4. Increase in growing season duration in the high northern latitudes from 1982 to 1999, based on NDVI observations [*Zhou et al.*, 2001].

4.2. Land Cover

Observations of land cover and land cover change are necessary to achieve an understanding of the terrestrial components of the carbon cycle. By land cover, we refer to the characterization of the biophysical state of vegetation and other surface materials occupying the land surface. The biophysical state of surface cover strongly affects energy transfers and fluxes of gases such as CO_2 and water vapor between the atmosphere and land surface. Land cover maps are used in many earth system models as a way of estimating variables impacting carbon fluxes, such as surface roughness and conductance, usually by some sort of parameterization scheme. Land cover also affects several components of the hydrological cycle, which in turn affects the carbon cycle through evapotranspiration, soil moisture, and the movement and storage of carbon through fluvial systems.

Land cover change (see section on "Disturbance" below) refers to relatively abrupt changes such as deforestation and to more gradual changes such as those associated with tropical forest regrowth. Land cover change is important because it can lead to abrupt major releases of carbon, for example, when forest fires occur and, conversely, can result in carbon sequestration due to forest regrowth. Conventional estimates of land cover based on ground observations are notoriously inconsistent, global distributions differing for example by 10 to even 20 million km^2 [*Townshend et al.*, 1991]. Over the last two decades, satellite remote sensing has made significant contributions to our knowledge of the distribution of land cover types and rates of land cover change.

The distribution of land cover types has been more reliably depicted through the use of remote sensing systems with moderate resolutions between 250 m and a few kilometers. Following prototype continental and global depictions at coarse resolutions [*Tucker et al*., 1985; *DeFries and Townshend*, 1994], the IGBP (International Geosphere-Biosphere Program) Land Cover Working Group recommended [*Townshend*, 1994] the assembly of a global 1 km multitemporal data set from AVHRR data [*Eidenshink and Faundeen*, 1994], from which global land cover classifications were produced [*Loveland and Belward*, 1997; *Hansen et al.*, 2000]. Subsequently, global classifications have been created at 1 km resolution using data from both EOS–MODIS [*Friedl et al.*, 2002] and the "Vegetation" sensor of the SPOT system through the creation of the Global Land Cover (GLC) 2000 product by the Joint Research Centre, Ispra, Italy. Improvements in these products are being carried out including the use of ESA's Envisat Medium Resolution Imaging Spectrometer (MERIS) data in the Global cover classification product with a resolution of 300 m.

Land cover products derived from remotely sensed data need to be validated from ground observations. Efforts have been to validate global data sets notably the 1-km IGBP product [*Loveland et al.*, 1999] and the GLC 2000 product. A large sample of reliable independent land cover information appropriate for a product with resolutions of 1 km requires substantial effort. Use of data with resolutions less than 5 m offers opportunities to relate ground conditions to coarse resolution data through the intermediary of Landsat data [*Hansen et al.*, 2002].

4.3. Landscape Disturbance

A static measure of global land cover is actually of limited importance to the global carbon cycle. Significant carbon fluxes depend on rates of land cover change or disturbance. However, our ability to monitor disturbance rates globally is not yet mature. Disturbance for our purposes can be thought of as rapid land cover change, so a quarterly refreshed global land cover may quantify disturbance rates. New approaches are combining annual changes of both optical and thermal data to detect disturbances more consistently [*Mildrexler et al*., 2007]. A recent synthesis of global land cover change derived from regional and global products derived from remote sensing and other sources was created as a contribution to the Millennium Ecosystem Assessment [*Lepers et al.*, 2005]. Recent estimates are that deforestation rates from all causes may be 1–3% year^{-1} of forested land area in active regions [*Lepers et al.*, 2005].

An alternative to wall-to-wall mapping of land cover change is to use moderate resolution data to locate areas of major change and then to use finer resolution data to measure change at these hot-spot locations. For example, *Achard et al.* [2002] estimated the net annual flux for the humid tropics at 0.64 ± 0.21 petagrams (Pg) C year^{-1} for the period from 1990 to 1997. This estimate was far lower than the estimate of total annual net emission from land-use changes, primarily in the tropics, for the period from 1989 to 1998 as reported by the *IPCC* [2007b] (1.6 ± 0.8 Pg C year^{-1}).

Possibly, our best current ability to monitor global disturbance is by remote sensing of fires, which are fairly easily detected from satellites (Plate 3). The MODIS sensor will detect on average 20,000 fires per day occurring globally. Current estimates suggest that biomass burning, either wildfire or fires for agricultural management, add 3 PG year^{-1} to carbon emissions from the land surface [*Van der Werf et al.*, 2004].

4.4. Vegetation Indices and Phenology

Five satellite systems are now producing global vegetation index data sets: AVHRR (since 1981), Sea-viewing Wide

Field-of-View Sensor (SeaWIFS; since 1997), SPOT Vegetation (since1998) and MODIS (since 2000), and MERIS (since 2002). Each sensor has different radiometric characteristics, so intercalibration and intercomparisons are essential for building a stable continuous record for global change science [*Brown et al.*, 2006].

As discussed above, one of the first interpretations of the NDVI signal in the early 1980s was how well the spectral index followed the vegetation growing season. David Keeling noted that the Mauna Loa CO_2 signal also followed vegetation growing seasons, illustrating what a powerful global signal the biosphere generates. *Myneni et al*. [1997] first used the AVHRR record to detect a continental scale increase of growing seasons in the northern high latitudes based on the NDVI record from 1981 to 1991. *Zhou et al*. [2001] have extended the analysis to 1999 with similar trends (Plate 4).

New satellite-derived measures of large-scale ecosystem phenology are now possible. *Delbart et al.* [2005] used both NDVI and a similar normalized difference water index (NDWI) from the SPOT Vegetation satellite to follow larch, birch, and conifer forests in Siberia from 1999 to 2002. *Kimball et al.* [2004] used an active radar sensor to follow high-latitude seasonal freeze/thaw cycles and growing seasons for 2000–2001 in 10 predominantly evergreen forests across western North America. While the radar sensor is more coarse spatially (37 × 25 km), the radar wavelengths penetrate clouds and so provide more temporal consistency and more accurate growing season definition. *Huete et al*. [2006] used MODIS enhanced vegetation index (EVI) data to discover that Amazon rainforest canopies increase during the dry season because of less cloudiness and enhanced solar radiation; they concluded that the canopies are not as water-limited as previously thought.

4.5. Net Primary Production

NPP is the net result of photosynthetic activity by plants. NPP of large land areas is a unique integrator of climatic, ecological, geochemical, and human influences. Consequently, there is a substantial incentive to understand the magnitude and variability of NPP both for its role in carbon cycling and as the foundation of food, fiber, and fuel for human consumption. Estimation of NPP involves integration across disciplines, bringing formidable challenges for long-term monitoring. Unlike the direct measurement of properties such as atmospheric CO_2 or temperature, which are subject to well-characterized instrumental and sampling errors, NPP estimates are sensitive to a relatively broad range of errors and/or uncertainties that result from a variety of measurement techniques spanning meteorology, physiological ecology, and remote sensing. Monitoring tools and techniques for weather and canopy physiology are well established, and changes over time are easier to understand and account for.

Much of the uncertainty in estimating NPP is due to variability in estimates of solar radiation conversion to biomass. Uncertainties are typically embedded in a light-use efficiency factor which is a function of factors such as canopy chemistry and structure, respiration costs for maintenance and growth, canopy temperature, evaporative demand, and soil water availability. Most of the current generation of light-use efficiency models have three key components: (1) satellite-derived vegetation properties: land cover, LAI, and fraction of intercepted photosynthetically active radiation (FPAR), (2) daily climate data including incident radiation, air temperature, humidity, and rainfall, (3) a biome-specific parameterization scheme to convert absorbed PAR to NPP [*Running et al*., 2004].

Processing of historical satellite data is still improving from progress in scientific understanding (e.g., corrections for atmospheric and orbital effects, and relations between canopy properties and canopy reflectance). For example, considerable differences were found in interannual variability and trends of historical NPP from 1982 to 1999 estimated from the same AVHRR (8 km/10–15 d) data processed with slightly different algorithms used to account for orbital drift, corrections for aerosols, intersensor calibration, and missing data [*Nemani et al.*, 2003]. Many of these problems have been resolved with the onboard continuous calibration of new sensors on the latest satellite platforms.

Since coincident observations of satellite and ground-based NPP or other land surface characteristics are difficult to obtain, accurate monitoring relies heavily on a network of observing sites that routinely collect information useful for retrospectively validating satellite measures. An example of such routine calibration is the use of GPP, the total photosynthetic activity of plants, derived at a number of flux tower sites globally (see below for discussion of flux tower measurements). GPP derived at flux towers in Amazonia provided invaluable information for judging the performance of different vegetation index formulations from MODIS. Such ground-based data provide the anchor points over which the satellite-derived NPP are checked regularly, for estimating uncertainties and for testing changes made to algorithms or inputs.

The MODIS daily GPP and annual NPP data sets are now available for an 8-year record, 2000–2007, although trend analysis is only complete for the first 6 years. Severe droughts in China in 2000, Australia in 2002, Europe in 2003, and the Amazon in 2004 are well captured by this data. Most of the southern hemisphere has had a negative trend in NPP for these 6 years. (Plate 5).

Consequently, the overall global trend of NPP from 2000 to 2005 appears to be negative (Plate 6), which contrasts

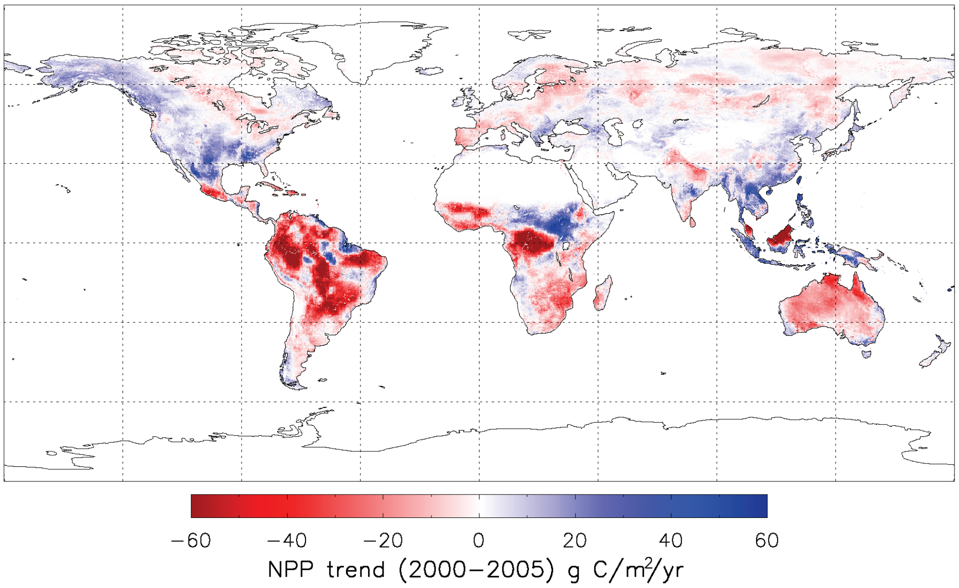

Plate 5. Spatial pattern of MODIS NPP anomalies from 2000 thru 2005 [*Zhao and Running*, 2008].

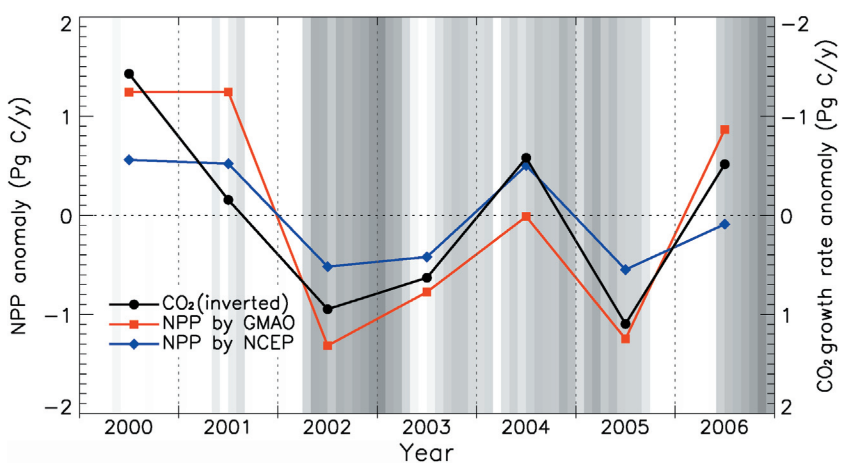

Plate 6. Interannual variations in global total MODIS NPP driven by different global meteorology sources, NCEP and GMAO, respectively, in relation to inverted atmospheric CO_2 growth rate. A Multivariate ENSO Index (MEI) is shown in gray scale, where darker shades represent higher MEI values [*Zhao et al*., 2008].

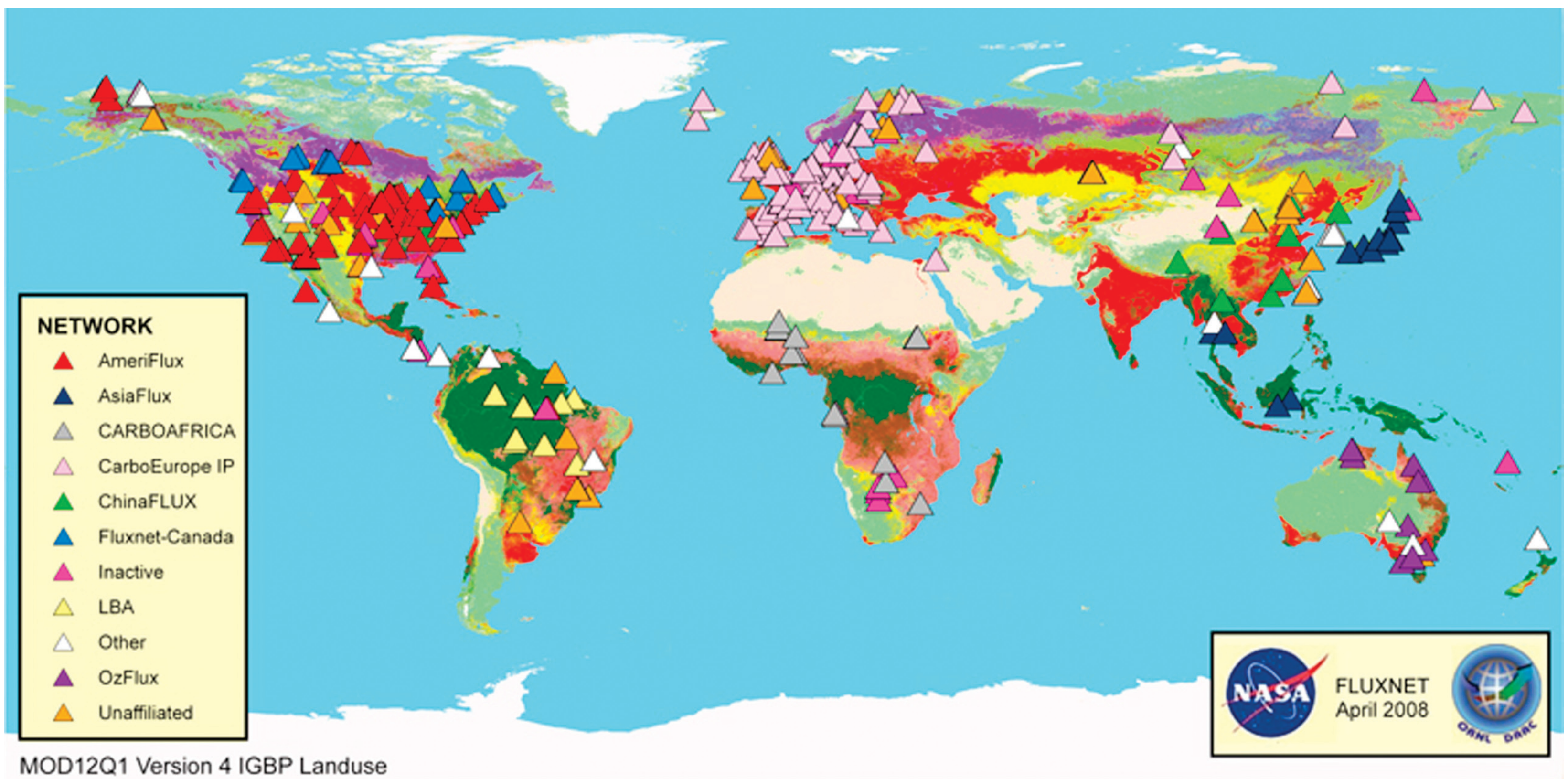

Plate 7. Global distribution of long-term carbon dioxide, water vapor and energy flux measurement sites, associated with the FLUXNET program and its regional partners. The sites overlay the International Geosphere–Biosphere Program land cover map.

with the 6% positive NPP trend *Nemani et al*. [2003] found from 1982 to 1999. The anomaly in global NPP is closely related to the inverted anomaly of CO_2 growth rate. There is no way to have scientific confidence in these global trend estimates without being able to cross-validate a satellite-based measurement with an atmospheric CO_2 measurement.

One of the most important properties defining the contribution of the terrestrial system to the global carbon cycle is net ecosystem CO_2 exchange (NEE). NEE sums the total uptake of CO_2 by photosynthesis, minus releases of CO_2 by both autotrophic (plant respiration) and heterotrophic (decomposition of dead material) sources. However, because a large proportion of CO_2 release is by root respiration and decomposition occurring below the soil surface, no theoretically satisfying and technically reliable means of remote sensing has been found for the necessary global estimates of NEE and its components. Global carbon models regularly calculate these terrestrial flux components, but these are not based on any global observations [*Friend et al.*, 2006].

The new EOS satellite platforms such as Terra, Aqua, and Aura have orbital maintenance thrust rockets to keep orbital timing consistent, unlike the Tiros platform of AVHRR that for some satellites slipped 3–4 h from their original overpass timing. Sophisticated navigation algorithms now allow accurate geo-registration, and state-of-the-art atmospheric corrections deal with effects of aerosols and other atmospheric constituents. Improvements to sensor optics, spatial resolution, and processing algorithms in MODIS result in a vastly improved (1 km/8 d) land surface representation. However, these improvements over previous global AVHRR data make crosswalking between the two sensors and the creation of a continuous record from 1981, especially challenging. Fortunately, there is an overlap between AVHRR and MODIS during 2000 to the present, where the performance of the two sensors can be assessed through radiative transfer modeling and field studies. Looking ahead to the next generation of U. S. platforms will be the National Polar-orbiting Operational Environmental Satellite System (NPOESS) scheduled to begin deployments in 2013. It will be absolutely essential to have at least 2 years of overlap between the MODIS and Visible/Infrared Imaging Radiometer Suite (VIIRS) sensors to provide time to build the crosswalking algorithms necessary for seamless data continuity at the level of precision and quality needed for climate science and trend detection.

5. GROUND-BASED OBSERVATION NETWORKS

While we have no single tool that can measure all components of natural carbon sources and sinks, scientists do now have an array of methods that can assess net carbon fluxes at various levels of spatial and temporal resolution. This scientific toolbox includes phenology observations, biogeochemical models, remote sensing, stand and soil carbon inventories, inversion modeling of atmospheric CO_2 distributions, and direct eddy covariance flux tower measurements [*Running et al*., 1999; *Canadell et al.*, 2000]. However, only a few ground-based measurements have reached a point of consistency and international coordination to be considered an essential part of global terrestrial carbon monitoring at this time.

5.1. Growing Season: Phenology

The terrestrial carbon cycle changes dramatically each spring, when annual and deciduous plants leaf out and initiate photosynthetic uptake of CO_2. The process reverses when these leaves senesce and drop in the autumn, leaving only respiration losses of CO_2 for the nongrowing season part of the year. The length of the growing season is highly correlated with the annual CO_2 uptake in temperate and boreal ecosystems. Numerous ground studies have now found that the growing season has become longer in the northern hemisphere by 1–4 weeks in the last 50 years. [*Sparks and Menzel*, 2002; *Schwartz et al.*, 2006; *Linderholm*, 2006].

Phenology, or the growing season timing of vegetation, is the most direct and observable response ecosystems show to seasonal climate. Timing of spring bud-burst and autumn leaf drop are so easily observable that both scientific and public networks have been developed over more than a hundred years to record these annual observations. The US, Canada, and Europe all have networks of ground sites that compile records of observations each year [*Cayan*, 2001]. These regional networks are in the process of coordinating a global phenology network that will provide observational consistency and standardized database development for the future [*Betancourt et al.*, 2005].

5.2. FLUXNET

Secular trends and seasonal modulations in atmospheric CO_2 concentration, observed at Mauna Loa by *Keeling and Whorf* [2005], and across the Global View network [*Tans et al.*, 1996] (http://www.cmdl.noaa.gov/ccgg/globalview/co2/), reflect the net flux of carbon dioxide entering and leaving the atmosphere. Over annual to decadal timescales, important natural sinks for CO_2 include photosynthesis by terrestrial vegetation and oceanic biota and physiochemical uptake by ocean waters. Natural sources of CO_2 include plant, root and soil respiration, fires, and out-gassing by the ocean.

The eddy covariance method has the capacity to make carbon flux measurements on a quasi-continuous basis for extended periods of time. Eddy covariance involves measuring and correlating tiny gradients in wind, air pressure, CO_2, and water vapor many times per second with fast response sensors. Over the past decade, a network of flux tower study sites has emerged and evolved into a global network called FLUXNET [*Baldocchi et al.*, 2001; *Baldocchi*, 2008]. Initially, long-term eddy covariance measurements were made on an ad hoc basis at a handful of research sites across the globe. FLUXNET started formally in 1997 and has grown from an initial confederation of regional networks in the United States and Europe to a current population exceeding 300 sites worldwide. Today, FLUXNET is comprised of regional networks in North America (AmeriFlux, Fluxnet-Canada), South America, Europe (CarboEuroFlux), Australasia (OzFlux), Asia (China Flux, and KoFlux), and Africa (AfriFlux) (Plate 7). The network spans a wide cross-section of climate zones, plant functional types, and land-use history [*Running et al.*, 1999].

Specific aims of FLUXNET are to quantify spatial/temporal variations of the physical and biological processes controlling CO_2 exchange of terrestrial ecosystems with a global network of eddy covariance flux measurement towers. The main FLUXNET products are direct measurements of carbon dioxide, water vapor, and energy fluxes, site meteorology and climate, and site history, including phenology. These data are archived, documented, gap-filled, and distributed through the Distributed Active Archive Center at Oak Ridge National Lab and are available through the internet (http://www.fluxnet.ornl.gov/fluxnet/index.cfm).

The research mission and priorities of FLUXNET have evolved as the network has grown and matured. During its initial stages, the configuration of FLUXNET was heavily biased toward coniferous and deciduous forests [*Valentini et al.*, 2000]. Later, the priority of the research focused on developing value-added products, such as gap-filled data sets of NEE, evaporation, energy exchange, and meteorology [*Falge et al.*, 2001]. The rationales for this undertaking were: (1) to compute daily, monthly, and annual sums of net carbon, water, and energy exchange; and (2) to produce continuous, gap-filled data sets for the execution and testing of a variety of biogeochemical/biophysical models and satellite-based remote sensing algorithms [*Thornton et al.*, 2002; *Papale and Valentini*, 2003].

By filling data gaps in quasi-continuous flux data sets in a similar and consistent manner, bias errors associated with multiple data processing routines were minimized. The production of coherent and comparable data sets has enabled researchers to conduct cross-site comparisons and detect such features as the role of growing season length on annual carbon exchange of temperate forests [*Baldocchi et al.*, 2001], how the temperature optimum of canopy photosynthesis and ecosystem respiration acclimate with summer temperature, and how threshold soil temperatures trigger the onset of photosynthesis [*Falge et al.*, 2002].

A key utility of FLUXNET information is to integrate ground-based and satellite-based observations to produce a new generation of derived biophysical variables driven by MODIS data for extrapolation of the fluxtower data to regional and continental scales [*Running et al.*, 1999]. During the second stage of FLUXNET, the research priority involved the deconstruction of NEE measurements into component fluxes such as GPP and ecosystem respiration, R_{eco} [*Reichstein et al.*, 2007b]. This step is required for FLUXNET to produce information for validating MODIS-based estimate of terrestrial carbon exchange; algorithms driven by satellite-based remote sensing instruments are unable to assess NEE directly and, instead, compute NPP and GPP [*Field et al.*, 1995, *Turner et al.*, 2006].

The contemporary configuration of FLUXNET has expanded to include broader representation of vegetation types and climates. The network now includes numerous tower sites over tropical and alpine forests, savanna, chaparral, tundra, grasslands, and an assortment of crops. For the wide spectrum of sites studied so far, the mean annual flux is –181 gC m^{-2} y^{-1}, across a range between +1300 and –1000 gC m^{-2} y^{-1}; negative values refer to a loss of carbon from the atmosphere to the biosphere [*Baldocchi*, 2008].

Since the network has been operating for more than a decade, it is now capable of demonstrating the impacts of climate and ecosystem factors on interannual variations of carbon fluxes. At present, the data set acquired at Harvard Forest site is over 14 years long (Figure 3), and those from the Walker Branch, Tennessee, Takayama, Japan, and many Euroflux sites are approaching 10 years in duration. With a long data record, one is able to assess how climate fluctuations (temperature, precipitation, solar radiation), antecedent conditions (drought, extreme weather events), and length of growing season affect net carbon exchange and its component fluxes (gross productivity and ecosystem respiration). *Reichstein et al*. [2007a] found a clearly evident impact on carbon fluxes in both the tower flux and MODIS GPP records during the extreme heat wave in Europe of 2003.

The data record compiled by FLUXNET overlaps the 8 years of measurements produced by MODIS. Some vegetation indices, like NDVI, "saturate" with certain canopy geometries [*Sellers*, 1987; *Gamon et al.*, 1995; *Buermann et al.*, 2002; *Myneni et al.*, 2002]. Derived products, such as GPP, are subject to absolute errors in carbon fluxes and infidelity in producing the seasonal time course when tested against direct carbon flux measurements (Figure 4).

Errors are generality attributed to how well stresses associated with soil moisture, humidity deficits, and tempera-

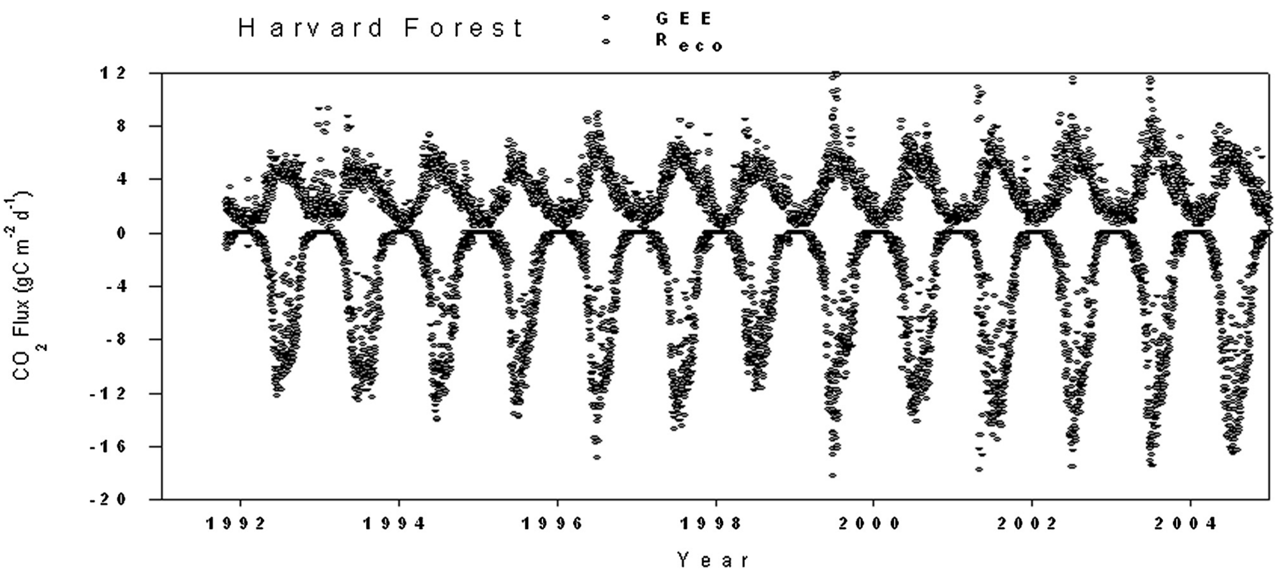

Figure 3. Long term carbon dioxide flux measurements at Harvard Forest, MA. Net ecosystem CO_2 exchange and its partitioning into gross ecosystem exchange and ecosystem respiration [methods from *Urbanski et al.*, 2007].

ture are quantified [*Xiao et al*., 2004; *Leuning et al*., 2005; *Turner et al*., 2005; *Zhao et al.*, 2005; *Heinsch et al.*, 2006]. These FLUXNET analyses allow specific improvements in processing the satellite data shown in Plates 5 and 6 by providing real quantities of ecosystem light conversion efficiencies.

FLUXNET as an organized network of research sites is now reaching the difficult administrative age where long-term continuity faces the same funding struggle that Dave Keeling faced in sustaining CO_2 measurements at the Mauna Loa site. Carbon flux measurements can no longer claim to be brand new, but the detection of critical biospheric trends relies on continuity of these high-precision measurements.

5.3. Stable Carbon Isotopes

Dave Keeling was one of the first geoscientists to recognize the power of measuring the stable carbon isotope ^{13}C in air, plant, and soil samples [*Keeling*, 1958]. Isotopic mixing lines, still often called "Keeling plots," are used to quantify the carbon isotope composition of respiring sources such as ecosystems and soils. Use of stable isotopes by biogeoscientists

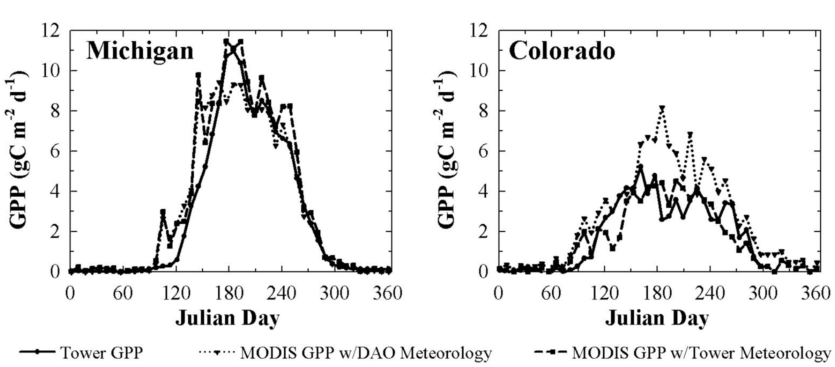

Figure 4. Comparison of daily GPP estimated from MODIS and from fluxtower measurements at a deciduous broadleaf forest in Michigan, and a subalpine evergreen needleleaf forest in Colorado. DAO refers to the global meteorology source (NASA Data Assimilation Office), or meteorology measured directly at the tower [from *Heinsch et al*., 2006].

has become very popular because stable isotopes act as tracers for studying flows of material through ecosystems and the atmosphere [*Dawson et al.*, 2002; *Farquhar et al.*, 1989; *Flanagan and Ehleringer*, 1998]. Information on the stable carbon isotope content of air, plants, and soil can be used to quantify plant water use efficiency, recycling of respired carbon dioxide within ecosystems, and the partitioning of net ecosystem carbon exchange into its components, photosynthesis and respiration. Plant material and the CO_2 respired by plants or by the decomposition of plant material are depleted in ^{13}C relative to that in the atmosphere. This depletion is due to discrimination against CO_2 molecules containing the heavier isotope, ^{13}C, when molecules diffuse across the laminar boundary layer of leaves and are carboxylated by the enzyme RUBISCO during photosynthesis [*Lloyd and Farquhar*, 1994]. Fractionation during diffusion is about 4.4 ‰ and net fractionation due to carboxylation is about 27.5 ‰. These isotopic signatures also provide a useful temporal integration of physiological processes, quantifying seasonal photosynthesis and respiration controls with a single tissue measurement.

Fossil fuel bears the ancient signature of plant photosynthesis, so it possesses a very negative isotope discrimination value. As fossil fuel is combusted into the atmosphere and accumulates, it begins to reduce and dilute the bulk signature of the atmosphere. Data from *Francey et al.* [1999] clearly show a marked change of ^{13}C of the atmospheric air samples since the preindustrial era; this signal has accelerated through our modern industrial period (Figure 5). The partitioning of CO_2 exchange between terrestrial biosphere and oceanic reservoirs in the global carbon cycle, and the identification of contributions of fossil fuel combustion to the secular trend in CO_2 are now possible because of ^{13}C isotopic analyses. Isotopic sampling is a regular component of FLUXNET field measurements.

5.4. Forest and Agriculture Permanent Plot Records

Managed forest and agricultural land contain a large fraction of terrestrial carbon stores in above- and belowground biomass and soils. Many nations have thousands of permanent plots where repeated tree and crop measures have been recorded, often for many decades, in organized inventory systems. These data sets have the potential advantage of adding tens of thousands of sampling points to a global terrestrial carbon monitoring system. Unfortunately, sampling design, plot size, revisit frequency, measurement protocols and calibration, data formats, and other aspects of these inventories are not standardized internationally [*Cianciella et al.*, 2007]. Until more progress is made in standardizing the data from these national inventory systems, their utility for global terrestrial carbon monitoring will be limited.

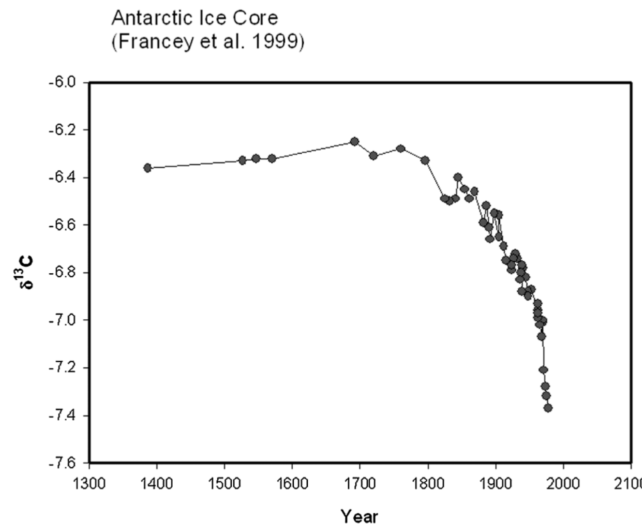

Figure 5. Temporal trend in the carbon isotope discrimination factor for ^{13}C [after *Francey et al.*, 1999].

6. FUTURE GLOBAL CARBON OBSERVATIONS

Future global observations will need to monitor two components of the carbon cycle, as they have two very different policy ramifications. NPP is most important for quantifying food and fiber production, and biofuel production. NEE, net ecosystem exchange, monitors the final land surface balance of CO_2 exchange with the atmosphere, so is most important for Kyoto protocol measures of terrestrial CO_2 sinks and sources to stabilize climate. New and often, conflicting policy ideas are rapidly developing both for mitigating CO_2 increases in the atmosphere and substituting biofuels for fossil fuels. However, the effectiveness of terrestrial productivity and carbon sinks varies widely geographically and temporally.

6.1. Terrestrial Carbon Credits and Biomass Energy Issues

New global carbon policy issues are arising continuously, exemplified by recent proposals to use plant biomass for production of cellulosic ethanol as a liquid fuel without compromising food supplies. *Pacala and Socolow* [2004] estimated that 250 million ha of land (one sixth of current global cropland) could produce sufficient ethanol to fuel all 2 billion expected automobiles in 2054. However, biomass production potential ranges widely. Fast growing plantation poplars can have ten times the annual productivity of a slow-growing alpine spruce forest. Likewise, a southern pine plantation peaks in growth at 30 years, while redwood trees continue active growth for 500 years. The capacity of different forests in different regions to grow biomass for fuel can differ by more than an order of magnitude *and* can change with time. Conversion efficiency of this biomass can also vary widely [*Patzek and Pimentel*, 2005]. Figure 6 illustrates clearly that ecosystem carbon sequestration as NEE is very different from plant carbon production as NPP, yet both are relevant to the assessment of different policy goals.

The temporal permanence of terrestrial carbon sinks is similarly difficult to assess and monitor. Accurate assessment of carbon credits to any land unit requires the ability to quantify and monitor large spatial and temporal differences in carbon sequestration potential. Natural disturbances such as wildfires, hurricanes, and insect epidemics can reduce carbon sequestration to zero. Monitoring carbon sequestration will require monitoring long-term trends in land cover, NEE, and disturbance for every land unit that claims a carbon sink. Conversely, biofuel production will probably emphasize maximum vegetation growth rates, with harvest schedules that may be annual for crops, and 10–20 years for forests. In general, carbon sequestration policies will favor leaving terrestrial ecosystems intact for as long as possible, while biofuel policies will focus on the most rapid growth and harvest schedule possible.

Thus, carbon monitoring with such opposing policy objectives on a global scale will require satellites with the spatial resolution roughly of Landsat or SPOT (on order of 20 m), combined with the daily temporal repeat cycle of MODIS or MERIS. This monitoring will also likely require active microwave sensors not limited by cloud cover or lack of solar illumination. A constellation of satellites will be required for this combination of consistency and space/time coverages.

6.2. Satellite Data Continuity

Future satellite-based measurements promise continuing improvements over the AVHRR data set. Current (MODIS, MERIS) and planned (VIIRS) sensors have the capability for onboard calibration to account for sensor degradation over time; the AVHRR measurements never had this capability. Advances in remote sensing technologies should in the future contribute much to the direct observation of the global carbon cycle. Moderate resolution optical observations suited to the creation of land cover products are planned for the longer term. The VIIRS instrument, which is part of the new US operational polar orbiter National Polar Orbiter Environmental Satellite System (NPOESS), has most of the crucial spectral bands needed for monitoring vegetation. However, recent descoping of the NPOESS program is seriously eroding what was thought to be a stable plan for the future observations [*Kintisch*, 2006]. The European space agency has Sentinel sensors planned of similar capabilities.

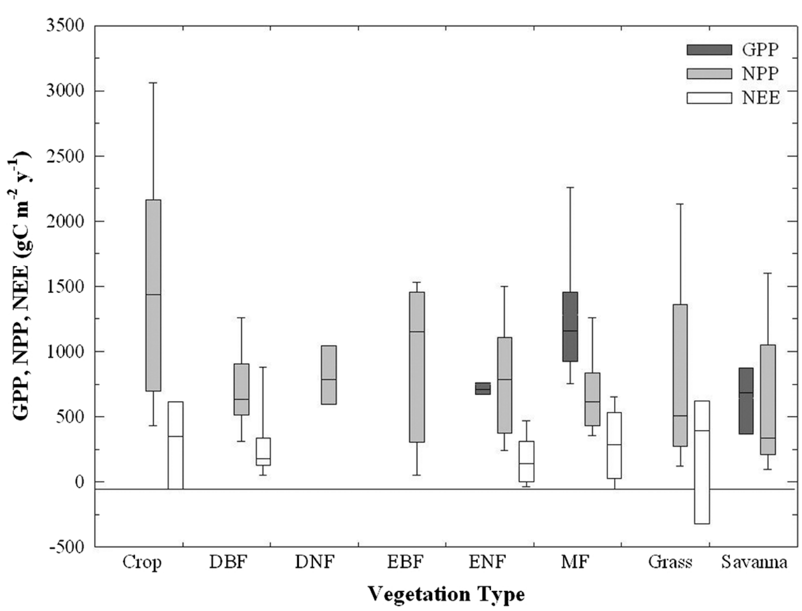

Figure 6. The range of gross primary production (GPP), NPP and net ecosystem exchange (NEE) measured for different biomes worldwide, reflecting biome and climate differences. Biomes are deciduous broadleaf forest (DBF), deciduous needleleaf forest (DNF), evergreen broadleaf forest (EBF), evergreen needleleaf forest (ENF), mixed forest (MF) [data from *Falge et al.*, 2002; *Law et al.*, 2002; *Goulden et al.*, 2006]

The Orbiting Carbon Observatory (OCO), scheduled for launch in 2008, will provide the first full atmospheric column measures of CO_2 concentrations. The passive sounding approach will measure NIR reflectances at CO_2 absorption peaks with three spectrometers. OCO will provide a 16-d repeat cycle which should resolve the global distribution of seasonal atmospheric CO_2 cycles that first were discovered in the Keeling Mauna Loa record. This interpretation of the atmospheric column measurements will depend on terrestrial carbon fluxes calculated from the type of integrated system described in this paper.

6.3. Transition Issues of Research to "Operations"

The Mauna Loa record has been called the most important geophysical data set of the 20th century. Yet, as early as 1963, after only 7 years of data, C. D. Keeling began having difficulties keeping the Mauna Loa CO_2 record funded and operating [*Keeling* 1998]. The struggle for continuity of key measurements after initial discoveries is continuing in the current generation of global carbon measurements.

Both the EOS satellites and the FLUXNET carbon flux network have originated from within the research community, where facility funding is PI based with grant renewal cycles of 3–5 years. In this proposal-based context, there is a clear selection pressure for near-term discoveries and hypothesis testing. However, global change trends can only be detected and quantified when consistent calibrated measures are maintained for decades, where historical data is reprocessed with more advanced algorithms, and where measurement precision is more important than real-time delivery. While operational continuity exists in national weather services, their short time scale forecasting focus is not conducive to maintaining high precision multidecadal climate records.

Much international planning is underway for the Global Environmental Observing System of Systems (GEOSS; http://www.earthobservations.org/geoss.shtml). Meanwhile, many of the assets for a future GEOSS that currently exist are degrading and not being replaced. The GTOS and the Terrestrial Carbon Observation panel have extensive plans for details of a global terrestrial carbon system, yet actual implementation is not occurring. The $10 trillion per year global economy is not investing the small fraction of this amount that is necessary to monitor the health of the biosphere.

We still need the kind of 20- to 30-year advance warning of global carbon cycle trends exemplified by the methodical, precise recording of atmospheric CO_2 concentration at Mauna Loa. For all of humanity, we thank you Dave! Let us hope we still have enough time to stabilize the global carbon cycle and protect the habitability of the Earth.

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