Global vegetation monitoring: toward a sustainable technobiosphere

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The concept of sustainable resource management can be applied at multiple scales. Monitoring is an essential component of sustainable natural resource management schemes, and as we begin to confront the need to manage natural resources at the global scale, the importance of monitoring at the global scale is also growing. The combination of satellite remote sensing, in situ measurements, and simulation modeling has the potential to deliver an annual assessment of status and trends for several measures of terrestrial biosphere structure and function relevant to sustainability. However, there is, as yet, no internationally coordinated effort in place to perform that analysis. Synthesis activity of that kind would support the development of global environmental governance institutions, including both non-governmental organizations and international bodies.

Front Ecol Environ 2011; 9(2): 111–116, doi:10.1890/090171 (published online 22 Apr 2010)

The scientific community has long recognized the nature of the global-scale, geophysical experiment that humanity is performing with greenhouse-gas emissions (Revelle and Suess 1957), and we are now beginning to see both geophysical and biophysical changes in the Earth system (Clark *et al.* 2004). The terrestrial biosphere (here defined as all life on Earth's land surface) is responding to anthropogenically driven changes in the atmosphere, and also to widespread land-cover and land-use change (Turner *et al.* 1990). The global scale of human impacts on the biosphere suggests the need for globally integrated monitoring of these impacts and, eventually, coordinated plans for mitigation and adaptation. Unfortunately, there is, at present, only a patchwork of mostly research-oriented efforts to monitor the terrestrial biosphere. A new level of coordination is required.

■ Managing the Earth system

Prior to the recent arrival of *Homo sapiens*, the biosphere was a complex adaptive system (Levin 1998), with a metabolism based on the capture of solar energy and the cycling of nutrients (Kleidon 2004). Global ecologists continue to debate Gaia Theory: specifically, the role of the biosphere in maintaining the global climate in a range favorable to itself by way of its influence on the chemical composition of the atmosphere and on the surface energy balance (Schneider *et al.* 2004). This debate has at least made clear that the biosphere has a strong regulatory influence on global biogeochemical cycles and global climate (Pagani *et al.* 2009).

In a nutshell:

- Satellite-borne sensors are capable of high spatial and temporal resolution monitoring of vegetation at the global scale
- International coordination of terrestrial monitoring efforts has begun, but has not kept pace with the accelerating rate of human-driven changes
- An annual "pulse of the planet" assessment of global vegetation – based on satellite remote sensing – would advance the development of global environmental governance institutions

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The potential influence of humanity on the biosphere and on global biogeochemical cycles has been of scientific interest since at least the early 20th century, when Russian biogeochemist Vladimir Vernadsky likened technologically advanced humanity to a "geological force" (Vernadsky 1945). Indeed, the rapid development of technology through cultural evolution has led to the formation of a technosphere, ie a globe-girdling web of human artifacts, including buildings, machines, roads, and electronic devices (Figure 1). Like the biosphere, the technosphere follows a thermodynamic imperative to use energy in the service of maintaining and increasing order (Williams and Frausto da Silva 2006).

The elaboration of the technosphere as a result of technological "advances" can be seen as a system composed of science, engineering, industry, and government. Science develops a mechanistic understanding of nature, engineering devises ways to use that knowledge, industry organizes the resources to manufacture and distribute the products of engineering, and government provides the infrastructure. The underlying foundation of this integration is the dynamic of capitalism, which is built on business interests and consumerism. To put it mildly: "under conditions of neo-liberal deregulation, heightened competition, and economic globalization, [that system] exhibits a strong tendency toward expansion" (Strydom 2002).

The relationship between the technosphere and the biosphere has gained attention in recent years because of

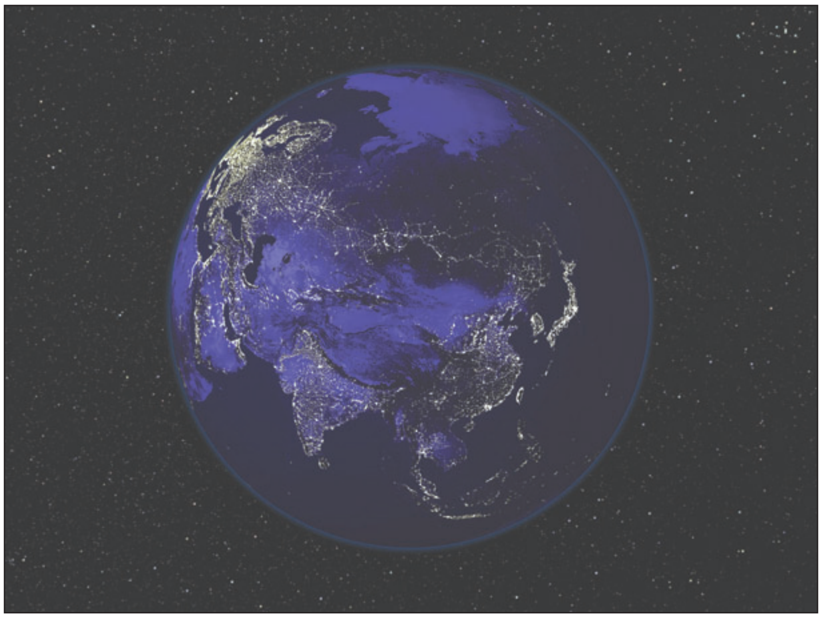
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Figure 1. *The distribution and density of lights at night indicate the pervasive presence of the technosphere.*

their growing interdependence. We increasingly think of humanity and the technosphere as dependent on the biosphere, in that ecosystem services, such as food production and provision of clean water and clean air, are critical for human survival. Encouragingly, the recognition and valuation of these ecosystem services (Costanza *et al.* 1997) has provided an impetus towards resource conservation. We are beginning to think of the biosphere as threatened by the technosphere, and certainly the current wave of extinctions is testament to our destructive capacity. Technosphere disasters such as Chernobyl also come to mind.

In the context of Earth's history over geological time, there doesn't seem to be an issue with actual survival of the biosphere in the face of the current anthropogenic perturbation. Much of its metabolism is microbial, and Earth history suggests that the microbial world can withstand even a 95% reduction in the number of higher-order species. Stressed ecosystems (eg a polluted lake) often degrade into a state of lower biodiversity and energy throughput (Rapport and Whitford 1999). Thus, a stressed biosphere would likely persist, but for human purposes it would be less hospitable than the vibrant biosphere we inherited.

Although the technosphere represents a threat to the current configuration of the biosphere, it could also be argued that there is a growing dependence of the biosphere – and its associated ecosystem services – on a properly functioning technosphere. If all the sewage treatment plants around the world failed, for instance, there would certainly be a rapid decrease in water quality and in the viability of aquatic habitats for many organisms. Human management of the technosphere is therefore closely related to its management of the biosphere.

The technobiosphere is a contemporary fusion of the biosphere and the technosphere. Energy inputs to the coupled system are a combination of solar energy and fossil fuels. A key mode of interaction between the biosphere and the technosphere is the global carbon (C) cycle. Anthropogenic transfers of C to the atmosphere by way of fossil-fuel combustion and deforestation are nearly 10 Pg C yr^{-1}, a substantial flux relative to global terrestrial net primary production (NPP) of about 60 Pg C yr^{-1} (Roy *et al.* 2001). Anthropogenic C emissions are essentially driving Earth's atmospheric composition and climate system toward conditions the biosphere has not experienced for at least 50 million years (Zachos *et al.* 2008).

We can frame the question of technobiosphere management in terms of assessing the sustainability of the management scheme. Sustainability can have social and economic dimensions, but here we are concerned with its ecological aspects, ie the ability to manage natural resources so that all humans share at least a modest standard of living without compromising the potential of those resources to provide equal benefits to future generations (NRC 1999). We have really just begun to understand what sustainability means at the level of ecosystems, landscapes, bioregions, and the planet as a whole. Beyond the challenge of achieving sustainability under a stable climate, lies the problem of dealing with a rapidly changing climate.

At any geographical scale, a key issue in the sustainability of terrestrial ecosystems is maintaining vegetation cover and productivity. Loss of vegetation cover often means the beginning of ecosystem degradation, including loss of soil and its associated capacity for storing nutrients and water. Loss of cover also means a net transfer of C from the land to the atmosphere, along with changes in the surface energy balance. If these changes are spatially extensive, they can induce changes in regional climate (Pielke *et al.* 2002). Reductions in net primary productivity mean a reduced flow of energy through ecosystems, and, from a thermodynamic perspective, less energy to maintain structure and function (ie order).

Natural resource management schemes typically include a monitoring component, and the Earth science community has recently gained the capacity to monitor the terrestrial biosphere – a step toward its management at the global scale. The National Aeronautics and Space Administration's (NASA's) Earth Observing System (EOS) uses multiple Earth-orbiting satellites and includes a free data distribution system over the internet that provides real-time imagery for many applications (eg Townsend and Justice 2002). EOS and other observation systems are complementary to an emerging set of data assimilation models that prepare satellite data to produce spatially and temporally continuous simulations of the Earth system's physical, chemical, and biological processes

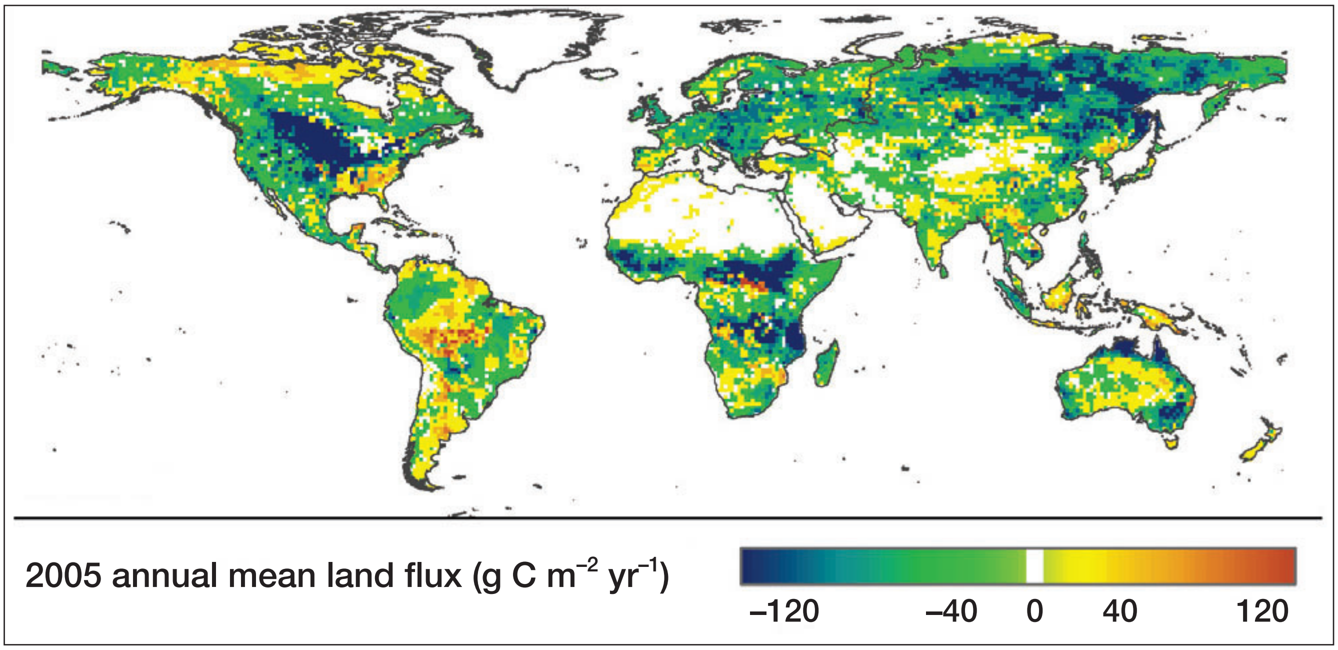

Figure 2. *Annual mean land flux for 2005 from CarbonTracker (http://carbontracker.noaa.gov; Peters* et al. *2007). Land flux includes net ecosystem exchange (NPP – heterotrophic respiration) and direct fire emissions. Negative values are C uptake by the biosphere and positive values are C release. Estimates are based on remote sensing, distributed climate data, observations of CO_2 concentrations, mapping of fossil-fuel emissions, and modeling. The year 2005 was relatively dry over the Amazon Basin, leading to increased C release.*

(Figure 2). The information collected from global monitoring and modeling therefore provides a means to evaluate the effects of the technosphere on the biosphere and is becoming part of a critical feedback loop between global society and the biosphere. However, there is not an operational terrestrial biosphere monitoring network in place.

■ Monitoring the terrestrial biosphere component of the technobiosphere

Key indices of the technobiosphere that inform monitoring for ecological sustainability include vegetation cover (%), biomass, vegetation land use, NPP, and net ecosystem production (NEP, the net effect on C storage of gains through photosynthesis and losses through ecosystem respiration). Changes in vegetation type and cover are important in terms of tracking rates of urbanization, deforestation, and desertification, as well as insect outbreaks and wildfires. Land-use change, such as converting primary (ie old-growth) forest to tree plantations, relates to sustainability in the context of issues including preservation of biodiversity and rates of C uptake.

Changes in global terrestrial NPP are of interest as indicators of biospheric inputs to the technosphere and of biospheric sensitivity to climate variability or change. About 40% of global terrestrial NPP is diverted from local ecosystems to the technosphere (eg biofuels) or to human consumption as food or fiber (Imhoff *et al.* 2004), and much of global NPP is managed locally in one way or another. Global analysis with the satellite-borne Advanced Very High Resolution Radiometer (AVHRR) sensor has suggested that global NPP increased approximately 6% over the 1982–1999 period, primarily in response to climate variation (Nemani *et al.* 2003). Large, ongoing changes in NPP related to agriculture, notably conversions of forest to cropland and introduction of irrigated areas, are also likely. After multiple years of satellite-data observations, a yearly NPP anomaly (ie the sign and magnitude of the difference between the current year value and the multiple year average) can be calculated for each pixel. That mapped information is informative with respect to geographic patterns in biosphere metabolism (Figure 3).

Changes in global NEP and C stocks (principally biomass and soil) are of interest because terrestrial biosphere C sequestration is currently offsetting ~30% of anthropogenic emissions associated with fossil-fuel burning, cement manufacture, and deforestation. Uncertainty about the magnitude of that terrestrial offset is low at the global scale because the other components of the near-term atmospheric C budget – the increase in atmospheric CO_2, the anthropogenic sources, and the ocean sink – are reasonably well known. However, we do not yet have a solid understanding of the geographic distribution or underlying mechanisms of the terrestrial C sink and, consequently, how long it will continue is unknown. If the terrestrial C sink begins to diminish, atmospheric CO_2 concentrations will begin to rise faster, putting more pressure on global efforts to reduce fossil-fuel emissions.

Remote sensing is the foundation of efforts to monitor vegetation-related indices of global sustainability (Running *et al.* 1999). Several satellite-borne sensors with moderate spatial resolution (ie pixels on the order of 250–2000 m across) are now producing daily and weekly coverage of Earth's land surface. In the case of the MODIS

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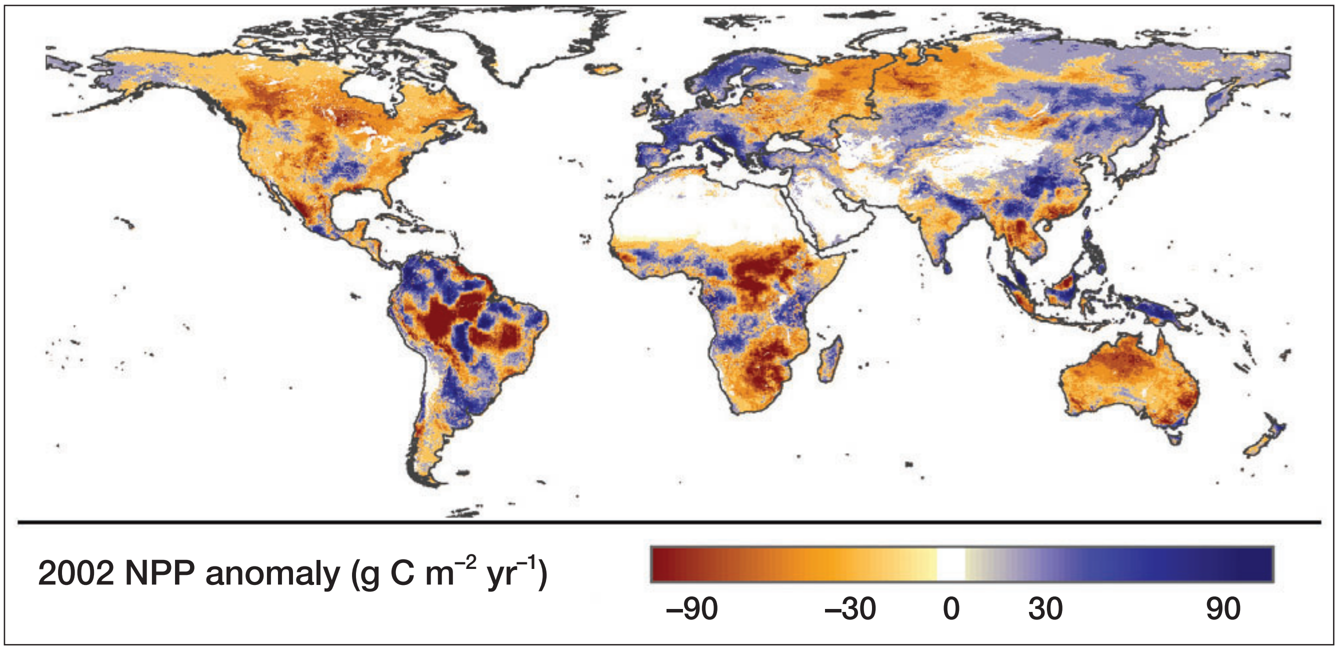

Figure 3. *Net primary production anomaly for 2002 from MODIS data (Zhao and Running 2008). Reference period is 2000–2006. Estimates are based on remote sensing, distributed climate data, and modeling. The year 2002 was relatively dry in western North America and Australia.*

(Moderate Resolution Imaging Spectroradiometer) sensor, all imagery (ie reflection in specific wavelengths) is freely available in near real time on the internet (https://lpdaac.usgs.gov/). The MODIS data were available beginning in 2000 and are used to produce annual maps of land-cover type, vegetation cover (%), and NPP at a spatial resolution of 1 km (Townsend and Justice 2002). Global NEP is more difficult to estimate with remote sensing than NPP because the release of CO_2 through heterotrophic respiration is not as closely linked to surface reflectance as is the case with NPP. Nevertheless, first-order, continental-scale NEP maps are also beginning to be produced using MODIS data (Potter *et al.* 2008).

Other moderate resolution sensors with global coverage include SeaWiFS, VEGETATION, and MERIS, all of which have associated products related to vegetation monitoring. There are ongoing, internationally coordinated efforts to compare products from these sensors and perform ground validation (eg Morisette *et al.* 2006), but considering the magnitude of the research issues associated with application of remote-sensing data, these efforts are quite limited. There is no dedicated institution that performs an annual synthesis of terrestrial biosphere monitoring products.

Fine resolution satellite sensors (10–100 m) are an essential complement to the moderate resolution sensors for monitoring vegetation change. The scale of the spatial heterogeneity associated with forest disturbances – including conversion to cropland, harvesting, and wildfire – is often much less than 1 km (Goward *et al.* 2008). The Landsat series of sensors operate at a spatial resolution of about 30 m and have permitted the monitoring of land-cover and land-use change since the early 1970s (Wulder *et al.* 2008). Like MODIS data, Landsat data are now freely available over the internet (through the US Geological Survey). The Landsat sensors are augmented by higher spatial resolution (1–2 m) commercial sensors, such as IKONOS. This scale is at the level of an individual tree or house. One general scheme for global-scale monitoring of land-cover change is to use moderate-resolution imagery for complete coverage and fine-resolution imagery in areas where extensive and rapid change is detected (Hansen *et al.* 2008)

In addition to these passive optical sensors (ie measuring reflected solar radiation), there are active radar and lidar sensors that are used in mapping vegetation biomass, canopy height, and canopy structure. The Geoscience Laser Altimeter System (GLAS) sensor was designed to track changes in glacier height, but has been adapted for estimating global vegetation biomass (Lefsky *et al.* 2005). As with optical sensors, huge data flows of raw imagery and research oriented products are available, but relatively little synthesis capacity is currently in place.

Development of remote sensing-based biosphere monitoring products, such as global NPP and NEP, requires much more than just satellite imagery (Running *et al.* 1999). In situ observations of C fluxes at eddy covariance flux towers, which continuously measure the exchange of carbon between the atmosphere and the land surface over an area of about 1 km^2, provide a basis for calibration and validation of the C cycle process models that integrate information on surface greenness, climate, and soil properties. Observations of atmospheric CO_2 concentration, when integrated with observations of climate, estimates of surface fluxes, and atmospheric transport models, allow evaluation of the modeled surface C fluxes and permit inversions to infer fluxes directly (Peters *et al.* 2007; Figure 2). The development of high-level products, such as

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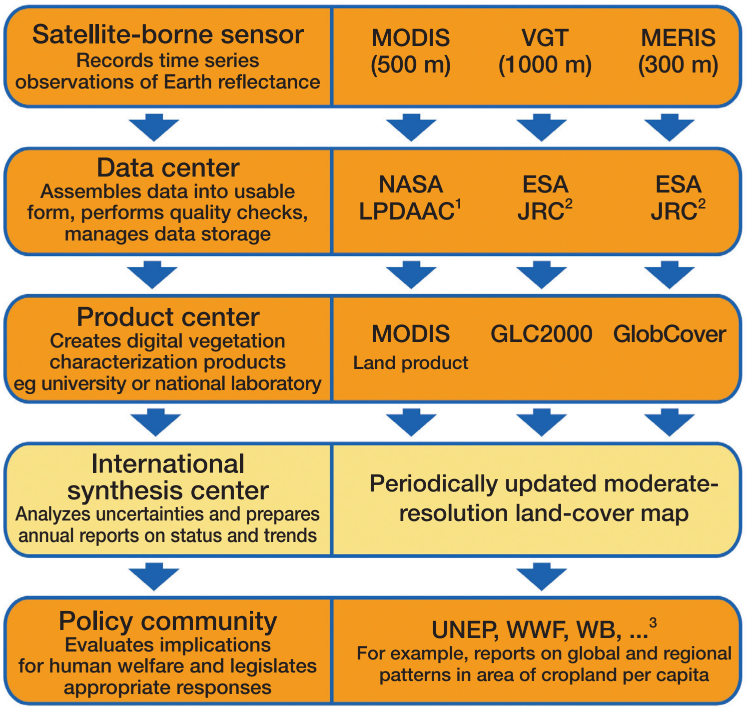
mapped NPP and NEP, is being done at multiple laboratories around the world. Here, I am advocating that we should maintain support for those programs, intensify coordination among them, and regularly synthesize their multiple products so we can take an annual "pulse of the planet".



[1] US National Aeronautics and Space Administration, Land Processes Distributed Active Archive Center

[2] European Space Agency, Joint Research Centre

[3] United Nations Environment Programme, World Wildlife Fund, World Bank

Figure 4. *Case study of global land-cover monitoring. Arrows represent data flows. General case is to the left and the sequences for specific sensors (with spatial resolution) are to the right. The proposed international synthesis center is highlighted.*

■ Terrestrial monitoring and global environmental governance

The current model for global environmental governance is largely based on organizations associated with the United Nations. This model is increasingly complemented by the efforts of transnational, non-governmental organizations (NGOs), for example, organizations that certify wood as being harvested sustainably. The process of building a scientific consensus and following up with international negotiations and development of policy decisions has been successful in some cases (eg stratospheric ozone depletion), and will be prominent in the ongoing efforts to address global climate-change issues. This model relies heavily on a high level of synthesis of scientific observations.

Climate change provides a particularly compelling case for international coordination, specifically with respect to terrestrial monitoring (DeFries *et al.* 2006). The UN Framework Convention on Climate Change, signed in the early 1990s by 154 countries – including the US, China, and India – contains a provision that requires annual estimates of C emissions from both fossil-fuel combustion and land-cover/land-use change. This agreement is very relevant to terrestrial biosphere monitoring, because the deforestation source constitutes about 20% of the total anthropogenic C emissions, and remote sensing is needed to track deforestation and to estimate associated C flux.

The Kyoto Protocol, which was aimed at reducing global greenhouse-gas emissions, had very limited provisions for C offsets associated with forestry, and therefore did not require much biosphere monitoring. At the follow-up 2009 UN Climate Change Conference, in Copenhagen, Denmark, the concept of C offsets for reducing deforestation and forest degradation (REDD) was supported in the final Copenhagen Accord. Regional cap-and-trade agreements are also beginning to be implemented, with a variety of vegetation-based C offsets. It is therefore becoming increasingly important that effective monitoring of C stocks and fluxes – from the project level, to the national level, to the global level – is implemented.

Various national-level centers, such as the NASA-funded Land Processes Data Archive and Distribution Center, assemble and distribute global monitoring datasets, but these institutions generally do not have an analytical function. The international Global Earth Observing System of Systems (GEOSS) is currently formulating policies regarding data sharing and data interoperability that will facilitate access to critical satellite data. Likewise, the Community on Earth Observation Satellites (CEOS) is committed to coordinating among national space agencies to "ensure availability of current and future data supply on a basis adequate for the implementation and operation of continuous [C flux monitoring] services". However, there remains the need for a project or institution that would advocate for a coherent monitoring system and assemble the various products from different agencies to produce annual synthesis reports (Figure 4). A recent international workshop (www.ntsg.umt.edu/VEGMTG/) focused on the need for ensuring continuity in the satellite observations (by no means a certainty, eg Wulder *et al.* 2008) and for the synthesis of products across complementary sensors. The NASA Decadal Survey (NRC 2007) supported development of new sensors, but also emphasized the importance of measurement continuity, which is critical to implementation of an operational monitoring scheme.

The United Nations has traditionally been a strong advocate for global monitoring and is a logical home for a synthesis effort. However, operational programs in the UN are still quite limited. The Food and Agriculture Organization (FAO) has generally monitored global crop, forestry, and fishery production by assembling national-level inventory data into global summaries. In moving toward developing more integrated global monitoring, FAO has supported the formation of the Integrated Global Observing System (IGOS), which aims at comprehensive monitoring of the climate, oceans, and land. IGOS is broken out into about 20 subsidiary organizations, the most relevant here being the Global Terrestrial Observing System (www.fao.org/gtos/index.html). GTOS is currently seeking funding to support the establishment of one or more international data centers, responsible for synthesis of global vegetation-monitoring products (GTOS 2008).

■ Conclusions

The technobiosphere is a complex adaptive system, and the human component has not yet achieved a sustainable relationship with its other living elements. Monitoring is usually a key component of effective environmental management schemes and the rising tide of global-change issues suggests the need for a global terrestrial monitoring institution. There are several measures of sustainability at the global scale that are potentially observable by satellite-borne sensors, notably the status and trends in land cover, land use, biomass, NPP, and NEP. The information derived from an effort to synthesize relevant data on these measures of sustainability would support development and implementation of environmental policy and goals by both NGOs and international bodies.

■ Acknowledgements

Thanks to D Bella (Oregon State University) and S Running (University of Montana) for discussions on this topic, and to the Cooperative Institute for Research in Environmental Sciences at the University of Colorado for fellowship support.

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