The Case for a Biospheric Carbon Network (BCN)

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Executive Summary

Increasing atmospheric carbon dioxide levels are causing climate change and altering global biogeochemistry ("metabolism of the Earth"), all of which threaten the sustainability of human economic and agricultural activities. A number of mitigation measures have been proposed, including a variety of voluntary and regulated carbon markets that would encourage reductions in anthropogenic carbon emissions and spur carbon sequestration efforts. Given the large exchanges of carbon between the biosphere and the atmosphere, opportunities exist for enhanced biospheric carbon sequestration (biosequestration). Biospheric sequestration provides an attractive way to begin to reduce net carbon emissions while other, long-term policy and technical solutions are still being developed.

In the absence of strong national and international solutions, regional policies have now emerged to encourage biosequestration, and Alberta and California have followed different policy paths. Opportunities for enhanced biosequestration abound in both regions, yet existing carbon sequestration programs and carbon markets do not take full advantage of the wide range of monitoring and validation tools now available, from field monitoring technologies to satellite observations. Consequently, carbon markets are not as effective as they might be. Primary challenges include the lack of a suitable cyberinfrastructure or operational methodology for integrating different metrics of carbon fluxes and stocks into a comprehensive metric of biospheric carbon uptake.

In this document, we propose an approach for integrating disparate measurements of biospheric fluxes and stocks as a foundation for unified measurement of carbon sequestration. A key recommendation is the development of a "Biospheric Carbon Network" to provide a transparent, validated metric of carbon biosequestration. This would provide an essential tool for demonstrating actual carbon sequestration, certifying emerging carbon markets, and encouraging a range of industries and activities that enable carbon monitoring.

Background

This document is a response to the Canada-California Strategic Innovation Partnership program, a recently formed program initiated by Canadian universities and the University of California to address innovative opportunities for research and commercial development. In response to this call, a proposal was submitted ("Ecoinformatics for Biospheric Carbon Sequestration"). Following approval, two meetings were held, one in Edmonton, Alberta (8-9 July 2010) and a second in Oakland, California (14-15 July 2010). Meeting participants are listed below. Further project information can be found at the project website (http://biosphericcarbonnetwork.org).

Following these meetings, this "white paper" was prepared describing opportunities for research and commercial spinoffs related to the monitoring of biospheric carbon. This document is intended as a review of the state of biospheric carbon monitoring, and provides a foundation for examining opportunities for research and commercial development related to this emerging field. A foundational assumption is that any effective monitoring system must be globally applicable, and must be able to demonstrate actual carbon sequestration.

A primary challenge has been the lack of a clear global policy solution at national and global levels; instead, we have evolving regional solutions, with Alberta and California leading two different approaches to carbon management. Consequently, in addition to this white paper, our process led two the production of two "Action Plans," one for Canada, and one for Alberta. These plans are complementary, and reflect the different policy directions and political climates represented in these different regions. The *Canadian Action Plan* proposes a research centre and not-for-profit organization with a focus on cyberinfrastructure, technology development, and opportunities for commercial and research partnerships. The *California Action Framework* identifies opportunities for integrated monitoring and modeling that could be further developed into an operational monitoring activity. Both strengthen existing research programs, scientific collaborations, and commercial partnerships. The implicit outcome will be the development of a stronger foundation for valuing biospheric carbon. The intention is to stimulate effective, practical solutions that address opportunities emerging on both sides of the border, with the ultimate goal of contributing global solutions to the challenge of reducing atmospheric carbon levels.

Meeting Participants

Meeting participants, Edmonton, Alberta (8-9 July, 2010):

Kirk Andries, Alberta Biodiversity Monitoring Institute
Glen W. Armstrong, University of Alberta
Nicholas Coops, University of British Columbia
Karen Haugen-Kozyra, KHK Consulting
Mike Kennedy, Pembina Institute
Cameron Kiddle, University of Calgary
Claude Labine, Campbell Scientific
Steve Running, University of Montana
Marian Weber, Alberta Innovates
Gilberto Zonta Pastorello Jr., University of Alberta
Baljeet Singh Malhotra, University of Alberta
Susan Ustin, University of California, Davis
Dick McIlvaine, University of California, Davis
Jason Proche, TEC Edmonton
Donnette Thayer, University of Alberta
John Gamon, University of Alberta
Angela Harris, University of Manchester

Meeting participants, Oakland, California (14-15 July, 2010):

Deb Agarwal, Lawrence Berkeley National Laboratory
Dennis Baldocchi, University of California, Berkeley
Chris Field, Carnegie Institution for Science, Department of Global Ecology
Bernd Hamann, University of California, Davis
Quinn Hart, University of California, Davis
Tom Mikes, Headwall Photonics
Kyaw Paw U, University of California, Davis
Nithya Ramanathan, University of California, Los Angeles
Rob Simmonds, University of Calgary
Susan Ustin, University of California, Davis
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Introduction

Biospheric Carbon and the Global Carbon Budget

The global carbon budget defines the pools (reservoirs) and fluxes (movement between reservoirs) of carbon in various parts of the Earth system (atmosphere, hydrosphere, cryosphere, geosphere, and biosphere) (Figure 1). Most of these fluxes involve natural processes, occurring on time scales ranging from seconds and minutes (in the case of photosynthesis) to thousands or millions of years (in the case of geological exchange of carbon with the atmosphere). Human activity, in the form of fossil fuel combustion and land use and land cover change (LULCC) is increasing the atmospheric carbon pool by remobilizing carbon that was previously stored in geological deposits and biological materials. This abrupt perturbation of the atmospheric carbon pool is causing climate warming and changes to global biogeochemical cycles that threaten to undermine the sustainability of our economy and food production systems. For this reason, much attention has been given to policies that might reduce anthropogenic carbon emissions, or that would reduce atmospheric carbon pools and enhance carbon sequestration in more stable pools.

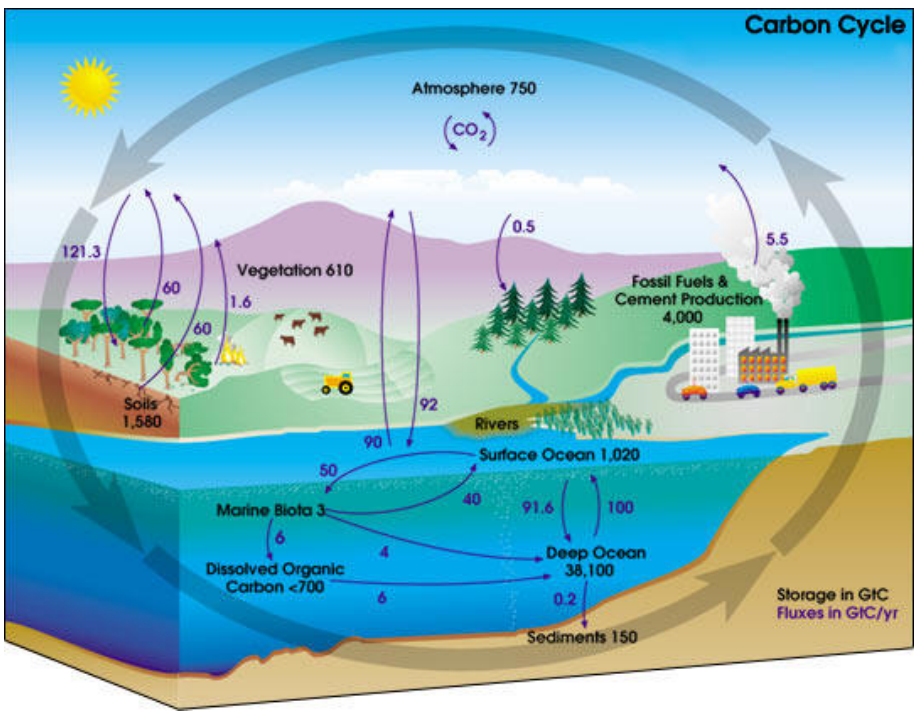

Figure 1: Global Carbon Cycle

Global carbon cycle, showing major stocks (pools, in black) and fluxes (exchanges, in purple) of carbon. Stocks are expressed in gigatonnes of carbon (GtC, where one gigatonne equals one billion metric tons). Fluxes are expressed in gigatonnes of carbon per year (GtC/yr). Note that biosphere-atmosphere fluxes are many times that of anthropogenic emissions to the atmosphere. (Illustration courtesy NASA Earth Science Enterprise, http://earthobservatory.nasa.gov/Features/CarbonCycle/carbon_cycle4.php)

Key technologies under discussion for reducing atmospheric pools include Carbon Capture and Sequestration (CCS) in geological deposits (Haszeldine 2009), and large amounts of money are now being invested in CCS technologies. For example, the Canadian province of Alberta has recently committed over 2 billion dollars in CCS technology investments (http://www.energy.alberta.ca/Initiatives/1769.asp). Alberta policy documents recognize the significant potential for biological carbon sequestration (Haugen-Kozyra & Mihajlovich, 2010), but biological options have not received anywhere near the degree of consideration and funding given to "engineering solutions" involving geological sequestration. One concern with the attention being given to CCS technologies is the tendency to ignore other cost-effective, feasible alternatives that could help address the problem of increasing atmospheric carbon concentrations and reduce the need for such large and expensive investments. Another concern is that industrial carbon capture most easily addresses point sources (e.g. coal-fired power plants and oil refineries), but cannot easily trap carbon released by diffuse carbon sources. Leakage of stored carbon presents a potential hazard to living things, and could undermine sequestration goals (Robock 2008, Hegerl and Solomon 2009, Matthews 2010, Shaffer 2010). Until CCS technologies have proven to be safe, practical, and economically feasible on the large scale needed to reach carbon reduction goals, it is imperative that we consider a broad range of options for addressing the atmospheric carbon problem. Effective biological carbon sequestration may not require the same massive technology investment, and offers an important unmet contribution to Canada's carbon reduction goals.

In contrast to Alberta's plan, California has focused its plan for carbon sequestration in state law AB32 (The Global Warming Solutions Act of 2006), through carbon offsets for business pollution that enhance biological sequestration as a key methodology. The goal of AB32 is to reduce California greenhouse gas emissions by 170 million tons by 2020. AB32 provides the foundation for long-term climate change policy in California and authorizes regulations affecting all segments of the State's economy. The state's 2010-2011 budget allocation for AB32, even under severe recession, is $36,468,000. (http://www.arb.ca.gov/cc/adminfee/revenue.htm) Implementing and enforcing the emission regulations under AB32 requires the establishment of a credible Carbon Market as well as methods to measure and validate carbon stocks and fluxes on local to global scales. California policy clearly identifies the need for further research into biospheric sequestration, and calls for "implementation technologies, accounting methodologies, and appropriate life cycle analysis" to identify the "future role of sequestration techniques in state climate policies" (Climate Action Team, Biennial Report, Executive Summary, April 2010). Agricultural and forestry sectors are recognized as key facets of an overall carbon reduction plan. The development of a "Biospheric Carbon Network" to accurately monitor carbon sequestration and predict future sequestration provides an essential step towards a viable Carbon Market goal.

Enhancing *biospheric carbon sequestration (biosequestration)*, defined as *carbon absorbed and stored by biological systems*, is one broad category of alternatives considered here. Examples include increasing biological carbon storage via afforestation, no-till agriculture, appropriate biofuel generation, biochar amendments (Fowles 2007), and reductions in deforestation and other forms of soil and vegetation disturbance (Figure 2), all of which provide near-term options to reduce the rate of increase in atmospheric trace gases (Lorenz & Lal 2010). In this document, we focus on the terrestrial biosphere's role in carbon exchange and storage, and on the potential for this biospheric carbon to contribute to net reductions in atmospheric carbon and climate stabilization. Instead of advocating a particular policy or sequestration method, our goal is to highlight ways in which integration of current monitoring technologies can inform policy, stimulate economic opportunities, and contribute to enhanced biosequestration.

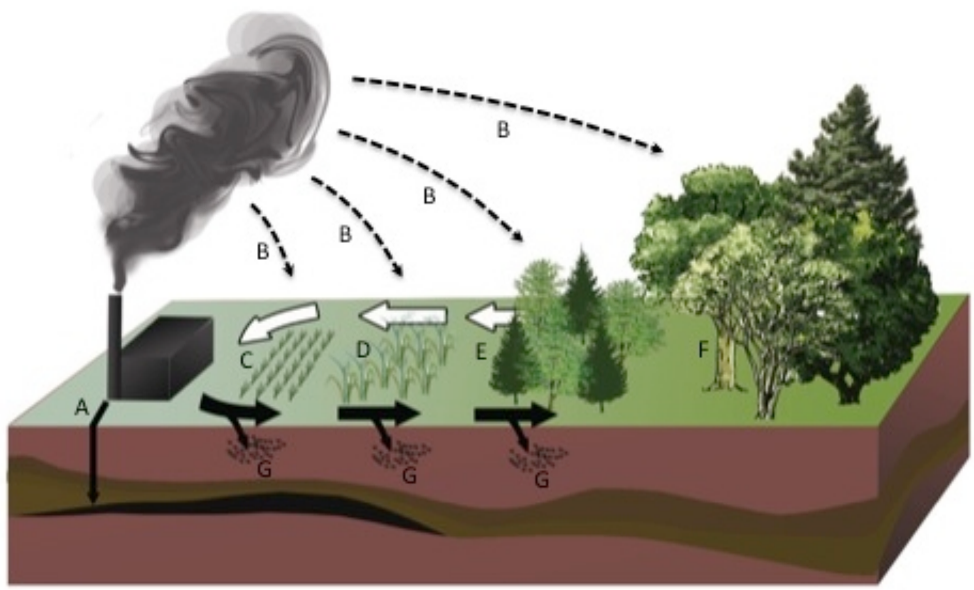

Figure 2: Geologic and Biospheric Carbon Sequestration

Schematic showing both geologic (A) and biospheric (B) sequestration of carbon dioxide, with arrows indicating the direction of carbon flux associated with various biological and industrial processes. Geologic storage injects carbon dioxide into geologic deposits from industrial point sources (A). Biological storage involves photosynthetic carbon uptake (B), coupled with a wide variety of management options, ranging from reduced tillage (C), biofuels (D), vegetation regrowth (E), maintenance of mature vegetation stands (F), and the application of biochar (G). By recycling carbon back into the biosphere (black arrows), overall carbon sequestration is enhanced and net atmospheric emission is reduced.

To put biospheric carbon in context, the carbon stored in terrestrial vegetation alone is roughly 15 percent of the surface global carbon pools (defined here as the relatively accessible carbon in the biosphere, atmosphere, surface oceans and soils), with much larger amounts stored in the deep ocean or stable geologic carbon reservoirs (Figure 1). If soils are included with vegetation as part of the "biological carbon," then the amount of carbon in the terrestrial biospheric pool is roughly 55% of the accessible carbon, and three times that of the atmosphere. Biospheric carbon *pools* range from relatively stable (e.g. soil carbon, that can remain in place for decades to hundreds of thousands of years, depending upon temperature, moisture and disturbance frequency), to relatively labile (e.g. carbon in above-ground vegetation) that can be quickly lost to the atmosphere during disturbance (Kurz et al. 2007 & 2008, Lorenz & Lal 2010). Similarly, long-term biospheric carbon pools trapped in northern soils can be quickly remobilized when climate change leads to melting permafrost and a deepening active layer (Schuur et al. 2008). This wide range of potential biospheric responses illustrates both the risk and opportunities inherent in biological approaches to carbon sequestration, and emphasizes the need for appropriate monitoring technologies if we are to make effective use of biological carbon sequestration.

Humans are adding carbon to the atmosphere at a rate of approximately 5-6 billion metric tons (gigatons) per year (Figure 1). These anthropogenic carbon fluxes include fossil fuel combustion (used for energy generation, transportation, and heating), and land-use change (e.g. destruction of vegetation due to fire or deforestation, or conversion of forests to agriculture). By contrast, *biological fluxes*, which include photosynthetic carbon uptake (sequestration) and respiration (carbon loss to the atmosphere), are many times larger than annual anthropogenic carbon releases (Figure 1). The balance of these biological fluxes provides an approximate measure of net carbon gain by ecosystems, although other smaller fluxes must also be considered for a full accounting (Randerson et al. 2002). By manipulating biological fluxes slightly, through afforestation, reduced tillage, and other forms of land management, it is possible to enhance biosequestration in biomass and soils (Figure 2). On the other hand, sudden disturbance or poor management can cause rapid losses of biospheric carbon to the atmosphere, effectively reducing the amount of carbon sequestered by the biosphere (Kurz et al. 2007&2008, Lorenz & Lal 2010). The challenge in quantifying short-term disturbance effects (Running 2008) and other "unseen fluxes" (Randerson et al. 2002) hinders an understanding of global carbon budgets, and limits the ability of current monitoring methods to contribute effectively to carbon markets. Our understanding of biospheric carbon can be improved by a more efficient integration of monitoring information within an appropriate conceptual and computational framework, or "cyberinfrastructure" – a distributed, web-based informatics system.

Our focus here is on the science and cyberinfrastructure needed to properly manage biospheric carbon in ways that encourage biospheric sequestration and reduce atmospheric carbon dioxide levels. We limit the bulk of the discussion to the primary biological fluxes - photosynthesis, respiration/decomposition, and major disturbance events (drought, insect outbreaks, fire, deforestation, etc.) - because these are accessible with remote sensing and account for the bulk of the biosphere-atmosphere carbon exchange. Given the dynamics and complexity of the biospheric carbon stocks and fluxes, we need a suitable informatics capability if we are to properly and accurately incorporate biospheric carbon into a successful carbon accounting system. This informatics system must be *global* in scope, yet able to resolve the local and regional effects of disturbance and management regimes. It must be *scaleable* both in its ability to span from local to global extents, and in its capability to expand and incorporate new and divergent information sources and technology solutions.

The Emergence of Carbon Markets:
In recent years, a number of policy and market mechanisms have been contemplated to reduce anthropogenic carbon emissions and enhance carbon sequestration. Regulatory mechanisms under discussion have included a tax on carbon emissions ("carbon tax"), and a fine on emissions exceeding a threshold amount, with the money being used to develop technologies or mechanisms that reduce emissions or enhance sequestration ("cap and trade"). Additional market mechanisms have also emerged, including the development of voluntary carbon markets where individuals or corporations can purchase carbon credits or offsets, often linked to sequestration programs. In response to these efforts, there is a burgeoning industry in carbon offsets and a growing interest in biosequestration. However, because there is no agreement on which of these market or regulatory methods should be adopted, and a shortage of certification methods to validate their effectiveness, there is considerable uncertainty and risk in the current carbon markets.

The challenges of certification and verification, and disagreement over how to implement effective carbon offsets, hinder the development of effective markets (Gillenwater et al. 2007). This is confounded by the lack of a universally accepted policy; despite a history of international negotiations (Kyoto, Copenhagen, and Cancun), no globally accepted policy solution has emerged. Instead, we have a patchwork quilt of policy responses, largely based on compliance schemes created and regulated by political mandate and operating on regional, national, and occasionally international scales (see Appendix A). These policies often reflect the regional, social, political and economic climate, and generally do not fully incorporate biospheric carbon stocks and fluxes and the variety of emerging technologies for monitoring biospheric carbon. Without full consideration of *all* major stocks and fluxes on a global scale, and without clear ties to demonstrable metrics of success or failure, the existing policies are unlikely to achieve the ambitious targets for atmospheric carbon reduction needed to stabilize the climate.

A partial list of regional efforts includes Alberta's Climate Change Central, California Global Warming Solutions Act (AB32), and the Western Climate Initiative. Clearly, we have a current opportunity to better align these regional efforts with existing metrics of biospheric stocks and fluxes, and regional policies can be a good starting point for identifying global solutions. However, a successful policy in one region can be readily undercut by failure elsewhere (the "leakage" problem, Murray et al. 2004). To be effective, a global problem requires a *global* response incorporating all major stocks and fluxes, including biospheric carbon. This is particularly evident when considering the large biospheric stocks and fluxes (Figure 1); policies neglecting biospheric contributions, or addressing only certain sectors (e.g. forests) are necessarily incomplete and likely to result in failure to achieve atmospheric reduction goals. Until a clear, global carbon policy emerges, the carbon markets and offset industries will continue to be fragmented and inefficient and have less than optimal effectiveness, as they are largely based on incomplete and often inaccurate information. Improved methods of tracking biosequestration can help build a global solution and provide new economic opportunities.

Recently in Cancun, limited progress was made in adopting the current UN REDD framework (http://www.globalcanopy.org/themedia/file/PDFs/LRB_lowres/lrb_en.pdf) as a tool for reducing tropical deforestation, but this is far from a global solution since most of the world's biosphere is excluded from this framework. The REDD protocol for estimating biospheric carbon stocks is largely based on forest inventory methods requiring intensive field sampling (Gibbs et al. 2007). These methods can be extremely subjective, and are often susceptible to fraud. Since they are limited to forest stands, they leave the status of most of the world's vegetation and soil carbon stocks unreported and therefore inaccessible to carbon markets.

In contrast to these field methods, satellites provide globally consistent metrics related to biospheric carbon stocks and fluxes (Field et al 1998, DeFries et al, 1999, Running et al. 2004). However, since many offset projects are local in scope, the coarse scale of global satellite measurements makes them difficult for carbon markets to use (Gibbs et al. 2007). Furthermore, the frequent cloud cover in much of the world (particularly the Arctic and Tropics) limit the availability of satellite coverage. Consequently satellite data have had only limited application in current REDD protocols, and remote sensing solutions represent a range of technologies with considerable unrealized potential for carbon markets, particularly when combined with other methods. These include airborne monitoring, field sampling, and field sensor networks that can provide the necessary validation for satellite products, as further discussed below (see Current State of Biospheric Carbon Monitoring, below).

The voluntary carbon offset market exists outside of compulsory compliance markets. It provides concerned companies and individuals with a method for offsetting their carbon use on a voluntary basis. Although the voluntary market remains smaller than the compliance market, it is growing rapidly in financial terms and is taking a leadership role in terms of quality assurance (Gillenwater et al. 2007, Hamilton et al. 2007). Establishing and maintaining a universal, verifiable standard will enhance the market's credibility and have direct impact on the capacity to trade. However, no reliable standards for quality assurance in the carbon market have yet been established (Gillenwater et al. 2007), and this market remains poorly linked to metrics of biospheric carbon. Consequently, a purchaser of voluntary offsets has little chance of confirming that measurable carbon sequestration has actually occurred.

The contributions of the voluntary market suggest that, with the right information on biospheric carbon, carbon markets could dramatically and quickly improve their effectiveness. From a climate perspective, an effective and sustainable carbon market is defined by its ability to encourage actual reductions in atmospheric carbon levels. An effective carbon market also requires accurate and timely information on biospheric carbon stocks and fluxes. Such information can be provided from current monitoring technologies that are poorly used by the existing markets. A range of technologies, including satellite and aircraft data, as well as existing field monitoring networks (e.g. FLUXNET and SpecNet) could be applied far more effectively to address the certification problem, and this could help evaluate the success or failure of emerging carbon offset schemes.

Current State of Biospheric Carbon Monitoring

In recent decades, carbon cycle scientists have developed many methods for estimating the amount of carbon stored in the biosphere. Traditional methods focus on standing carbon stocks, with gains or losses in stocks (due to fluxes) estimated by repeated sampling. Examples of stock estimation include forest inventory methods and the UN REDD protocol that is largely based on inventory methods (Table 1; see Appendix B for more details). While standard protocols have been established (e.g. US Forest Service Inventory and Assessment, or UN REDD protocols), these methods are easily subject to human sampling errors or fraud. Stock estimates vary widely (Appendix C), demonstrating that we lack clear regional or global datasets on biospheric carbon at the range of scales needed for carbon markets.

Fortunately, new technologies have emerged that offer to supplement traditional stock methods and improve biospheric carbon assessments. In recent decades, a wide variety of tools for monitoring carbon fluxes and stocks have been developed. These tools include direct flux measurements via chamber measurements and eddy covariance, field sensors and sensor networks, and a wide range of aircraft and satellite remote sensing methods (Table 1, Figure 3). Particularly when used in combination, these new methods offer powerful ways to detect both carbon stocks and short-term stock fluctuations to assess evolving biosequestration. These emerging methods are briefly reviewed here; a more detailed summary can be found in Appendix B.

Table 1. Sampling methods for assessing biospheric carbon stocks and fluxes.

Method	**Reference**
Forest inventory methods	
Direct harvest	Gibbs et al. 2007
Allometric relationships	Cairns et al. 1997, Mokany et al. 2006, Gibbs et al. 2007
Look up tables	Houghton et al. 1999, Gibbs et al. 2007
Soil carbon assessment	Post et al. 1999, IPCC 2006
Direct gas exchange methods:	
Eddy covariance	Baldocchi 1988, 2008
Chamber gas exchange	Field et al. 1989, Livingston & Hutchinson 1995
Field remote sensing	
Simple radiometers	Huemmrich et al. 1999, Gamon et al. 2011
Field spectrometers	Gamon et al. 2006b, 2011, Leuning et al. 2006, Hilker et al. 2007
Cameras	Richardson et al. 2009
Aircraft & satellite remote sensing	
Optical	Running et al. 2004
Thermal	Anderson et al. 2008
LIDAR	Lefsky et al. 1999
RADAR	Dobson et al. 2002

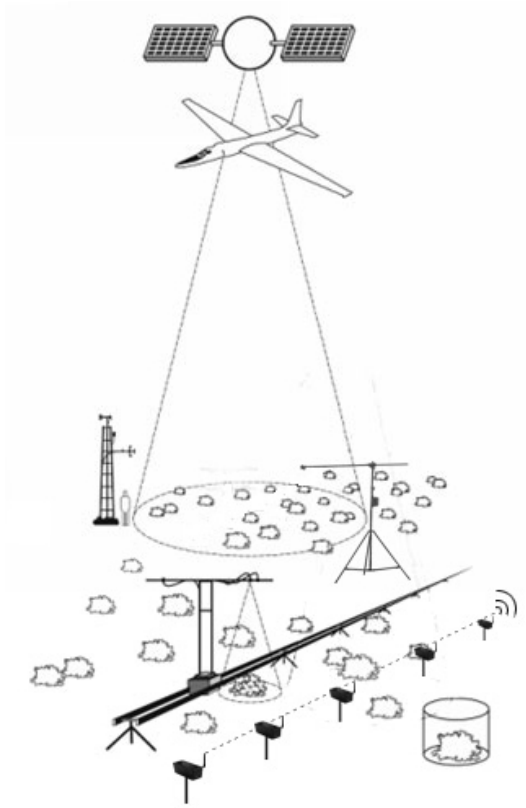

Figure 3: Sampling Methods

Sampling methods used for monitoring carbon stocks and fluxes. Satellites and aircraft (top) are coupled with automated ground optical sampling, including phenology station (tripod on right), robotic tram system (cart on rail in foreground). These measurements can be related to direct flux measurements, including eddy covariance (tower on left) and chamber gas exchange (bottom right) through a variety of "top-down" and "bottom-up" scaling methodologies (see text). A wide range of wireless sensor options (linear array in foreground, parallel to tram track) can be added in flexible configurations to sample spatial fields of irradiance, temperature, moisture, and other variables. Figure modified from Gamon et al. (2006a).

Direct gas exchange measurements are the current "gold standard" for monitoring carbon dioxide and water flux between the biosphere and the atmosphere. In particular, eddy covariance, with its ability to directly measure entire ecosystems, has become the current method of choice. (Baldocchi 2008) The global FLUXNET network (including several regional and national networks around the globe – Appendix E) currently has hundreds of sites around the world where biosphere-atmosphere carbon dioxide fluxes are being measured, covering a wide range of climates and vegetation types (Running et al. 1999, Baldocchi 2008). However, equipment and labour for direct flux measurements are expensive, and these methods have technical requirements that limit their application to a relatively small number of "uniform" landscapes. (Baldocchi et al. 1988) Consequently, these methods are best combined with other sampling methods to allow extrapolation to larger regions.

Remote sensing methods enable a broad view of carbon stocks and fluxes, and these methods allow sampling over a wide range of spatial scales (from individual canopies or vegetation stands, to the whole globe). There are four main remote sensing technologies used for this purpose: passive sensors measuring solar reflectance in the visible and reflected solar infrared ("optical remote sensing"), passive sensors sampling in the thermal infrared ("thermal remote sensing"), active sensors measuring in the visible and near infrared ("LIDAR remote sensing"), and active sensors in the radio wavelength range ("RADAR remote sensing"). Each has particular advantages and disadvantages that are discussed in more detail in Appendix B. Current biosequestration methods use models to estimate stocks or fluxes where remote sensing contributes to spatially scale estimates to larger regions. No matter how sophisticated the model, most applications use only the simplest remote measurements of "canopy greenness" determined from a ratio of two spectral bands, with the normalized difference vegetation index (NDVI) as the most widely used input. Thus, while this index significantly contributes to monitoring, much of the remaining data from satellites has not yet been fully exploited for carbon monitoring.

Estimates of global net primary production (NPP, a metric of carbon storage), which uses a model driven by a time series of NDVI images combined with weather data, have been a standard product of NASA's MODIS sensor for almost 10 years (Figure 4; Running et al. 2004, Heinsch et al. 2006), yet MODIS NPP is not currently used by carbon markets, in part due to its relatively coarse scale (1 km pixel size) that is difficult to match with local land ownership and management. Furthermore frequent cloud cover in many parts of the world, notably the Tropics and Arctic, limit the coverage and quality of the data products during much of the year, limiting the temporal coverage in some regions. For this reason, efficient interpolation methods and networks of ground, aircraft and satellite sensors are needed to solve data gaps. A wide range of other satellite sensors provides additional data sources that can be used for estimating carbon stocks and fluxes. Since many of these are commercial satellites, high data costs and data restrictions (licensing and intellectual property issues) often limit their utility for ready, transparent carbon assessment. However, these limitations could change quickly with increased competition, market demand, and pressure for more cost-effective data. The Google Earth example of widely available satellite imagery demonstrates the potential for cost-effective applications based on satellite imagery. Together, satellite technologies offer considerable potential for contributing to carbon markets that has not yet been realized.

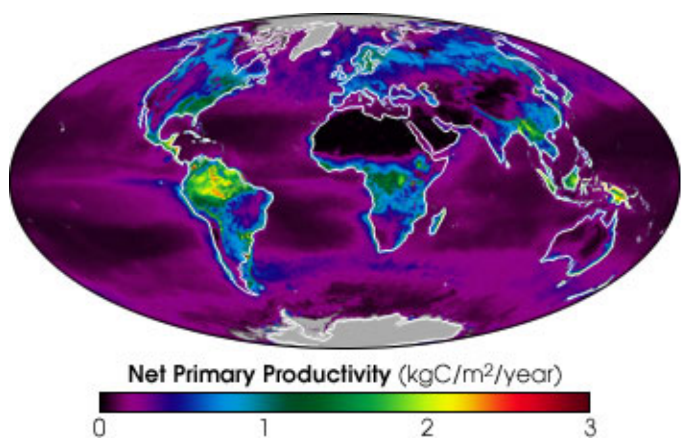

Figure 4: Global Net Primary Productivity

Image of global Net Primary Productivity (NPP) derived from MODIS, image released April 2003 (courtesy NASA Earth Observatory).

One challenge of linking remote sensing to direct carbon flux measurements is the vast difference in spatial scales between satellite sensors and field measurements. Additionally, direct flux measurement samples a single point in space continuously over time, whereas remote sensing typically collects measurements across large regions, but at a single snapshot in time. To help bridge this sampling gap, airborne sensors, networks of field sensors and scaling methodologies are being developed.

A wide array of airborne remote sensing systems are now in operation by commercial, NGO, universities, and government entities. Airborne instruments fall into several classes: digital photogrammetric mapping cameras, multispectral scanners, imaging spectrometers, thermal imagers, and LIDAR (or RADAR) instruments (Table 1). Simple instruments like digital cameras now operate at sufficiently high spatial resolution to provide detailed, plot-level information (e.g. crown size estimation and tree height mapping using stereo imagery). Multispectral imagers offer a powerful way to obtain extensive information about canopy structure and other site conditions that could be useful in modeling carbon stocks and fluxes. Imaging spectroscopy and LIDAR provide the highest level of physical information about the site, also at high spatial resolution (often now at 1m or smaller pixels). These methods provide detailed representations of physical structure, stand composition, and physiological conditions that can be used to derive carbon stocks and fluxes (Asner et al. 2010; see also Figure 5 &Figure 6). Many airborne sensors are close analogs to existing or planned satellite sensors, greatly expanding the sampling flexibility and coverage, and providing high-resolution regional datasets that can be used for validating and extending satellite measurements to finer spatial scales. Additionally, they allow a range of innovative measurement approaches (e.g. diurnal or multi-angle measurements) that can further enhance the interpretation of data pertaining to carbon stocks and fluxes.

Because airborne instruments are able to acquire data at higher spatial and spectral resolution than generally found in satellites, they can be more easily compared to field data. Issues like drought, insect infestation, wildfire, or impacts of land-use change can be readily characterized by high-resolution aircraft data. In this way, the impacts of specific land management regimes or local disturbance on carbon stocks and fluxes can be evaluated in greater detail, providing more direct links to offset projects at the scale of small plots or local communities, which is currently difficult to do from coarse-scale, global satellite sensors.

Until recently, this potential of airborne systems for biospheric carbon monitoring has been largely untapped. A primary reason is that there has been little consistency in the type of sensors available, their measurement characteristics, or the format of their image products. It is also difficult if not impossible to get permission to fly remote sensing instruments in many regions, and costs of maintaining airborne programs can be prohibitive for individual investigators. However, these costs are coming down, and several recent airborne carbon monitoring programs are now demonstrating the power of these platforms for both extensive and detailed surveys (Figure 5 Figure 6), demonstrating new opportunities for research, monitoring, and validation. If access can be further improved, products standardized, and costs further reduced, fleets of regionally-based aircraft (including UAVs) could make significant contributions to monitoring biospheric carbon stocks and fluxes.

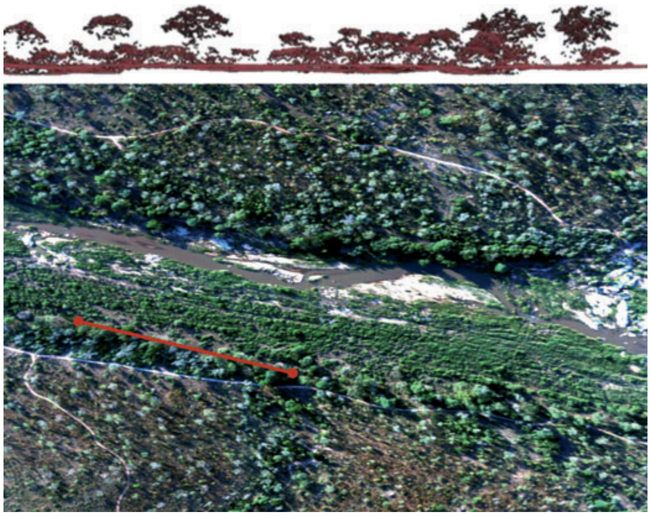

Figure 5: Airborne Sensor Image (Kruger National Park, South Africa)

Images of Kruger National Park, South Africa, taken with the Carnegie Airborne Observatory, illustrating the ability of airborne sensors to quantify canopy structure and depict detailed spatial patterns. The canopy cross-section from the LIDAR sensor (top) was taken from the red transect (bottom) and depicts foliage density and vegetation height. Color variation in the bottom image reveals patterns associated with species composition, canopy structure and physiological state. Images courtesy of Greg Asner (Ustin & Gamon 2010).

Figure 6: Airborne Sensor Image, False Color Infrared (Alberta, Canada)

False color infrared image (red stripe overlaid on top of Google Earth) from a helicopter flight over the boreal forest near Hinton, Alberta, in May 2010. Note the clear resolution of individual tree crowns (in red), illustrating the high spatial resolution (approx. 20 cm) possible with airborne imaging spectrometry. Carbon flux can be derived from spectral reflectance (invisible Z dimension of the image). Image centre location approximately 53°55'14.44"N, 116°13'31.36"W, elev. 1209m. Unpublished data, J. Gamon (University of Alberta) and D. Stonehouse (VeriMap Plus, Calgary, Alberta), using an imaging spectrometer (MicroHyperspec, Headwall Photonics, Fitchburg, Massachusetts).

Field sampling networks (e.g. FLUXNET & SpecNet) study the relationships between satellite or aircraft remote sensing, field optical measurements, and carbon stocks and fluxes. The SpecNet network (http://specnet.info) is a collaboration of scientists and sites around the world utilizing field optical sampling methods at the scale of the eddy covariance tower "footprint" (sampling region). SpecNet addresses the scale mismatch between remote sensing and flux measurements through scale-appropriate sampling. These networks also provide a powerful way to integrate field measurements and remote sensing, validate satellite and aircraft sampling, and identify areas needing further investigation (Cheng et al. 2006, Gamon et al. 2006a, 2011).

Optical sampling methods now exist at many levels of technology and cost, ranging from simple, inexpensive radiometers to more expensive spectrometers and imaging spectrometers (Table 1). Many of these instruments can provide simple, robust metrics of dynamic surface properties (e.g. vegetation greenness) that can be used to derive accurate estimates of biospheric carbon exchange. This point is illustrated in Figures 7 & 8, demonstrating how simple radiation sensors can be configured into low-cost monitoring stations ("phenology stations," Huemmrich et al. 1999). These sampling stations can be used to estimate biospheric carbon uptake as Net Ecosystem Exchange (NEE, an approximation of Net Ecosystem Production, NEP, Randerson et al. 2002). Low-cost field sensors are now being applied across many ecosystems, offer a range of scientific and commercial opportunities for carbon monitoring, and provide an additional untapped data source for carbon markets. Together with remote sensing and flux measurements, field optical sampling networks can provide an important contribution to the development of scaleable biospheric carbon metrics.

Figure 7: Phenology Station, Alberta, Canada

"Phenology station" sampling NDVI using simple, 2-band radiometers in an alfalfa field (Edmonton, Alberta, Canada). Many brands of these sensors now exist. These stations can be operated alone, or linked into an expandable global network using satellite links. When properly calibrated against eddy covariance, phenology station sensors can provide reliable estimates of biospheric carbon uptake, and can be used to fill gaps in flux measurements (Figure 8: Measured vs. Modelled NEE). The stations can also be compared to aircraft and satellite sensors (Figure 3: Sampling Methods) to validate remotely sensed products, and enable wider regional extrapolation of carbon flux measurements.

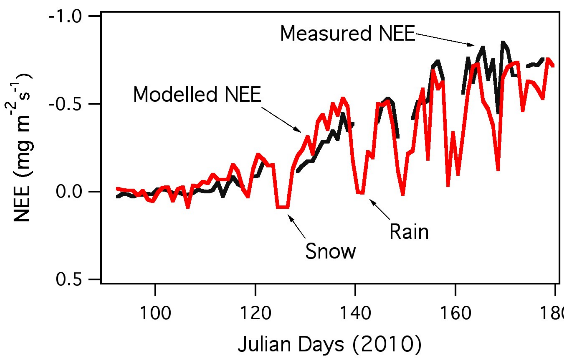

Figure 8: Measured vs. Modelled NEE

Temporal trajectory of measured (black) and modelled (red) net ecosystem exchange (NEE) for a growing alfalfa field in summer, 2010. Negative NEE values indicate carbon dioxide uptake by the ecosystem. Measured NEE derived from eddy covariance (depicted in Figure 3: Sampling Methods) and modeled NEE derived from a phenology station (Figure 7) using the LUE model. Note how the model can be used to fill measurement gaps during periods of snow and rain. Castro & Gamon, in preparation.

A focal message of this document is that any single method by itself has limitations, and that combining data from different methods can yield a more complete and extensive picture of biospheric carbon than any single method alone. Because of the need for global coverage, field methods alone are not sufficient, and must be coupled with remote sensing, typically in some kind of integrative modeling framework. Given the wide range of sampling methods for biospheric carbon that now exist, there is a growing need to integrate data from these various approaches to provide quantitative, validated, and transparent information on biospheric carbon stocks and fluxes. Regardless of what policy or market mechanism is in force, effective and transparent validation methods will be needed, and that this can be achieved, in part, through the suitable integration of existing technologies. Among the carbon science communities, many methods of "upscaling" stocks or fluxes from single sites to larger regions are now being explored, offering a wide range of methods to link flux, optical, and remote sensing measurements into a more coherent picture of biospheric carbon (Rahman et al. 2001, Fuentes et al 2006, Xiao et al., 2008 & 2010, Baldocchi et al. 2010, Beer et al. 2010). Expanding this capacity to integrate carbon sequestration data from a range of effective monitoring technologies, and the ability to validate estimates through independent assessments, are core themes of this proposal.

The Biospheric Carbon Network (BCN)

We propose a "Biospheric Carbon Network" (BCN) to foster collaboration and data integration from these various sampling methods to provide quantitative, validated, and transparent information on biospheric carbon stocks and fluxes. To be effective, BCN would require the development of cyberinfrastructure tools for this integration (see Cyberinfrastructure Needs, below). The goal is to develop a cost-effective, consistent, and transparent methodology to estimate biospheric carbon fluxes and stocks that can be applied globally, but with the ability to embed higher resolution data to allow the retrieval of specific, detailed site information where more detail is needed. We envision BCN as the necessary foundation for the next generation of carbon monitoring and verification tools for use by carbon markets, policymakers, and carbon scientists. BCN allows an integration of biospheric carbon flux data from many sources, including satellite, flux towers, field data, and carbon stock estimates (Figure 9). BCN could also accommodate ancillary data allowing the interpretation of the *causes* of change. These ancillary data might include information on vegetation type, land management practices, land ownership, land-use and land cover change, and other types of disturbance (drought, insect outbreaks, and fire).

BCN offers to integrate these disparate carbon flux and stock measurements through a unified, scalable modeling framework (Figure 9), providing a means to compare different estimates, and to evaluate biosequestration at different levels of detail. Global carbon fluxes can be estimated from global satellite coverage (e.g., 1km MODIS global NPP estimates). This global product provides a coarse view of global trends in biospheric carbon uptake and loss (Zhao & Running 2010), and is available for use through NASA's Earth Observing System Data Information System (EOSDIS). At a finer (e.g. continental or regional) scale, satellite data can be processed at higher spatial resolutions (e.g. ranging from approximately 1 m to 250 m). Aircraft sampling provides an additional way to obtain regional coverage. These regional-scale satellite and aircraft products can be "nested within" global products, providing information on biospheric carbon flux that matches the scale of land ownership or political boundaries, allowing the evaluation of different land management regimes, disturbance events, or policy choices on biosequestration. For additional fine-scale measurements, and for validating local and regional assessments, BCN would incorporate data from direct field assessments and automated field sampling networks (e.g. FLUXNET and SpecNet).

Effective data integration requires standardized metrics within a common conceptual framework. For stock estimates, the BCN framework could incorporate validated allometric relationships between remote assessments (e.g. LIDAR sensors) and plot inventories, as is currently being done (Asner et al. 2010). For carbon flux assessments, the BCN framework could utilize a set of linked models, driven from remote sensing and field data, to produce carbon flux estimates (e.g., GEP, NEP, NEE, and Respiration) that could then be validated against independent measurements (Figure 9: Schematic of Biospheric Carbon Network (BCN)Figure 9). Useful examples of a unifying framework for flux estimation include the light-use efficiency model (Monteith 1977), or respiratory models based on key environmental or physiological variables including temperature, moisture, and GPP (Running et al. 2004). The global flux tower network (FLUXNET) will undoubtedly play a primary role in validation, as has previously been proposed (Running et al. 1999, Turner et al. 2005). The outcome would be a set of standard metrics derived from multiple sources. The strength of this approach is that, by using a single framework, disparate data sources can be integrated into a more comprehensible and transparent metric. This ability to combine different metrics over a range of spatial and temporal resolutions would provide a level of validation that is currently not possible with single-method approaches. This unified, validated approach to generating consistent carbon metrics could meet a variety of needs, including carbon markets, policy analyses, and scientific studies.

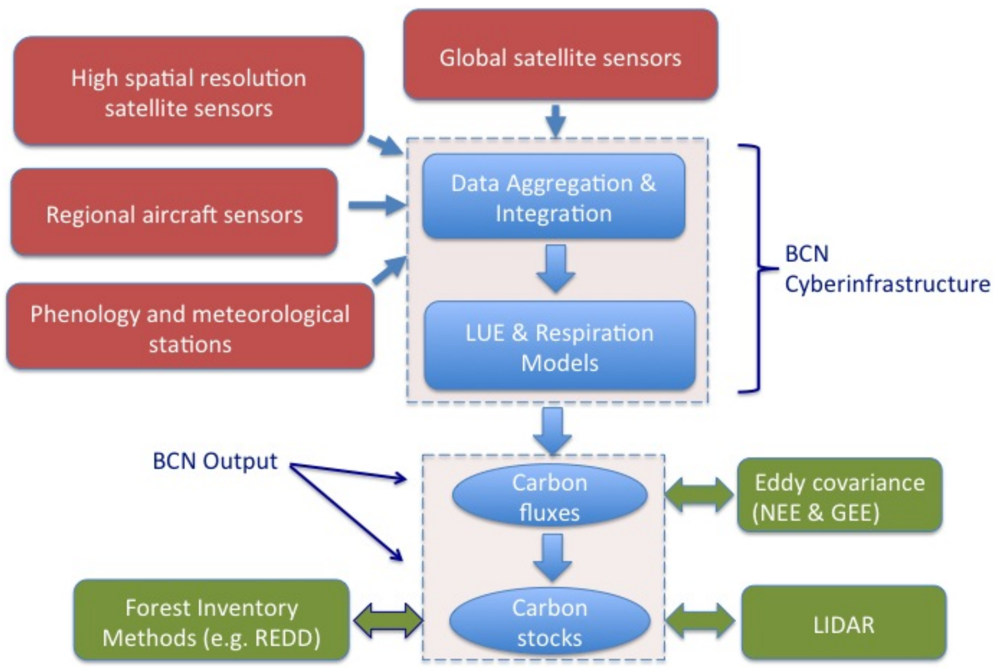

Figure 9: Schematic of Biospheric Carbon Network (BCN)

Schematic of Biospheric Carbon Network (BCN), illustrating the core cyberinfrastructure (top box) for integrating data and calculating carbon flux indices (GEP, NEP, and respiration) using the light-use efficiency (LUE) and respiration models, as an example of an integrative framework for calculating carbon fluxes (note that additional approaches for modeling fluxes and stocks can be accommodated and compared). Below that (bottom box) are the BCN products (carbon indices), including carbon fluxes (expressed on a daily basis), and stocks (e.g. fluxes integrated over yearly or longer time periods). These products can be compared to independent estimates from field inventory methods or eddy covariance or LIDAR (green boxes). Data sources are indicated in red, and include global satellite sensors (primarily MODIS), high-resolution satellite sensors (e.g. SPOT, Ikonos, Quickbird, and RapidEye), regional aircraft sensors (e.g. imaging spectrometers, LIDAR, or radar), and automated field (e.g. phenology and meteorology stations). Examples of primary data for the BCN models would include NDVI, EVI, PRI, surface temperature, and indices of surface moisture. These can be converted into absorbed radiation (APAR) and efficiency (ε), providing the two terms of the LUE model in standard format. Blue arrows indicate direction of data flow through aggregation, integration, and modeling steps. Validation datasets for comparison to BCN products (double green arrows) are indicated in green.

Cyberinfrastructure Needs

The BCN cyberinfrastructure is designed to generate validated, transparent metrics of biosequestration. Further details are provided in Appendix D, and key features are summarized here. A fundamental step in establishing the BCN cyberinfrastructure will be to define the steps needed to convert data from multiple sources into a set of common metrics and units suitable for integration into standard products (fluxes and stocks). For stock assessment, measurements might include: tree diameter, height, and volume, and allometric relationships between above- and below-ground biomass (Gibbs et al. 2007). When using the light-use efficiency model for flux estimates, examples of common metrics derived from optical sensors include F_{PAR} (the fraction of absorbed radiation), APAR (the amount of absorbed radiation), ε (the light-use efficiency), GEE (gross ecosystem exchange, the initial uptake of carbon by photosynthesis) and NEE (net ecosystem exchange, the net carbon uptake or loss once respiration is included). These variables must be clearly defined with in a common modeling framework; only then can an automated cyberinfrastructure for a uniform and transparent product (Biospheric Carbon Index) be effective.

An effective cyberinfrastructure must be scaleable in two senses: 1) it must be able to integrate across multiple spatial and temporal scales inherent in the wide range of sampling methods, and 2) it must be expandable to accommodate new technologies, data, and processing approaches as they emerge and replace older methods. For this to work, the focus must be on unified metrics that transcend particular technologies, not the technologies themselves. Automating data retrieval and analysis will be essential to providing data at a cost consistent with the value of potential carbon credits.

One outcome of an integrated approach that accommodates multiple data inputs would be a “rating system” (e.g. quality flag system) that could evaluate the degree of agreement of different data sources. When two or more methods yielded close agreement, the carbon sequestration estimate for that particular parcel would receive a high rating, reflecting a high degree of confidence in the method. This would lend a degree of validation that is often missing from the current carbon offset market. When comparisons yield low ratings (indicating conflicting results), this would direct attention to where further research or measurement is needed. In this way, the system could be self-correcting, leading to further improvements over time.

The Biospheric Carbon Network could provide a foundation for improved certification of carbon markets. Potential clients and collaborators will include members of the carbon science community, as well as developers of carbon offset protocols and participants in the existing and developing carbon markets. Fortunately, a number of significant cyberinfrastructure projects are underway in the computing, remote sensing, and carbon cycle science communities. Several groups have nascent cyberinfrastructure efforts related to biospheric carbon, including FLUXNET (with Microsoft support), SpecNet (initially supported by NCEAS), and GeoChronos (supported by Canada’s WestGrid). To the extent possible, BCN should take advantage of collaborative opportunities with these existing cyberinfrastructure efforts, and consider commercially available solutions such as Microsoft's AZURE, Google App Engine or Amazon Web Services, and products offered by initiatives like Google's Google Earth Engine or Cisco's ALERTS (see Appendices D & E for further details).

Benefits & Drawbacks:
One of the biggest risks of any biosequestration program lies in the possibility that sudden disturbance or accelerating climate change itself may cause rapid releases of the more labile biospheric carbon pools. In this sense, a biospheric carbon offset can represent a short term, “high risk” investment. The potential for large, abrupt carbon releases has been identified for several biomes, including boreal forest (Kurz et al. 2007, 2008), arctic permafrost (Schuur et al. 2008, Zimov et al. 2006) and a wide array of drought-prone ecosystems (Zhao and Running 2010, Breshears et al. 2005). Despite this risk, biosequestration presents a feasible near-term solution to attain part of the sequestration goals needed to avoid dangerous levels of climate change, and provide an interim solution while other methods are being developed (Lorenz & Lal, 2010).

We note that the potential for significant carbon releases exist from other non-biological sources, including geological carbon capture and sequestration (Robock 2008, Hegerl and Solomon 2009, Matthews 2010, Shaffer 2010) and methane clathrate releases (Kvenvolden 1993, Harvey and Huang 1995). Compared to these other risks, the potential for sudden biospheric carbon release may actually be relatively small when considered globally, although this is certainly an area needing further study (Running 2008).

Another potential drawback of this approach lies in the challenge of assessing “invisible” stocks and fluxes (Randerson et al. 2002), including soil carbon storage and lateral carbon transport – processes not easily addressed with current observational technologies. However, in most biomes, these may not be significant to the annual biosphere-atmosphere fluxes, so may not be critical in determining fundamental changes in biosequestration, the information of interest to carbon markets. Furthermore, by expanding the BCN modeling framework, these processes can be incorporated as technologies mature or as new information demonstrates their importance to carbon budgets and carbon markets. Meanwhile, comparison of BCN products to inventory data and other field measurements can provide a partial solution to this challenge.

A challenge of BCN will be to develop a *cost-effective* cyberinfrastructure. Many current monitoring and verification method are expensive relative to the carbon value they seek to quantify. By linking to uniform methods with large economies of scale (e.g. remote sensing), and assuming the cyberinfrastucture can take advantage of cost-effective computing (e.g. cloud computing, see Appendix D), BCN could eventually reduce the transaction costs associated with carbon offsets, leading to more efficient and attractive markets.

In addition to the core benefit of reducing atmospheric carbon, biospheric carbon storage also offers multiple side benefits that are currently hard to quantify and are not included in current carbon markets. For example, no-till agriculture, afforestation, and maintenance of mature vegetation stands have positive effects on water retention and water quality, often with considerable economic benefits (Foley et al. 2005). Afforestation and maintenance of vegetation provide habitat and – done correctly – help maintain biodiversity (Foley et al. 2005). Intact forest stands also have measureable effects on regional and global temperature and rainfall patterns by controlling the ratio of latent to sensible heat (Shukla et al. 1990, Bonan 2008), thus lending a further degree of climate stability. By providing a method for improved monitoring of land uses leading to biospheric carbon gains and losses, the BCN would help quantify these and other ancillary benefits.

Conclusions & Recommendations:

An initial step for developing an effective biospheric carbon monitoring system for the carbon market would be to develop regional pilot projects in Alberta and California that could be extended to include the western states and provinces of North America. One reason for focusing on these regions is that nascent market frameworks currently exist (see Appendix A). If successful in meeting the market needs, this approach could be expanded to other regions, and eventually to the whole globe, particularly as global policies and markets develop. A key step in being able to expand beyond the pilot stage will be the demonstration of a successful cyberinfrastructure and the utility of key products (e.g. BCI).

Several existing cyberinfrastructure efforts exist, yet these tend to be focused on specific technologies. A key focus in the development of BCN would be to implement collaborative partnerships with existing networks, research groups, and commercial projects to better integrate information from different methods. An initial step in cyberinfrastructure development would be to clearly define a core set of fundamental data inputs and models needed to produce functional products. These inputs would include field measurements, aircraft sensors, and satellite data. Corporate partners would include sensor manufacturers, airborne service companies, and satellite product vendors. Key science partners might include FLUXNET, SpecNet, NASA's EOSDIS teams, and emerging carbon monitoring networks in Europe and around the world. Existing computational efforts offering potential support or collaboration might include Microsoft's AZURE, Cisco's ALERTS, Google's Google Earth Engine, and Canada's WestGrid.

As currently envisioned, BCN offers the potential for several possible commercial spinoffs. Commercial entities that would benefit from a comprehensive program to unify carbon monitoring data include aircraft monitoring companies, optical sensor and sensor network manufacturers, and hardware and software architects developing the core informatics and cyberinfrastructure. Additional commercial applications of these technologies could arise in the agriculture, forestry, ranching, and insurance industries. Particularly in its early stages, we propose that the core research and partnership goals of BCN can best be realized through a research centre or institute approach (e.g., a "Biospheric Carbon Institute"), most likely affiliated with a university campus (e.g. University of Alberta or University of California). Additional opportunities also exist for a non-profit organization focused on developing the necessary cyberinfrastructure for data integration and dissemination that would be the core activities of the BCN. These alternatives are further explored in the corresponding *Canadian Action Plan* and *California Action Framework*.

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Disclaimer

While we have made reasonable attempts to check sources and facts, this document has not yet undergone a full peer review. Any errors are the responsibility of the project leaders.

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