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SpecNet Revisited: Bridging Flux and Remote Sensing Communities

(Review Paper)

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Abstract:

SpecNet (Spectral Network) began as a Working Group in 2003 with the goals of integrating remote sensing with biosphere-atmosphere carbon flux measurements and standardizing field optical sampling methods. SpecNet has evolved into an international network of collaborating sites and investigators, with a particular focus on matching optical sampling tools to the temporal and spatial scale of flux measurements and ecological sampling. Current emphasis within the SpecNet community is on greater automation of field optical sampling using simple cost-effective technologies, improving the light-use efficiency model of carbon dioxide flux, consideration of view and illumination angle to improve physiological retrievals, and incorporation of informatics and cyberinfrastructure solutions that address the increasing data dimensionality of cross-site and multi-scale sampling. In this review, we summarize recent findings and current directions within the SpecNet community and provide recommendations for the larger remote sensing and flux communities. These recommendations include comparing the LUE model to other flux models driven by remote sensing, considering a wider array of biogenic trace gases in addition to carbon dioxide, adoption of standardized and automated field sensors and sampling protocols where possible, continued development of cyberinfrastructure tools to facilitate data comparison and integration, expanding the network itself so that a greater range of sites are covered by combined optical and flux measurements, and encouraging a broader communication between the flux and remote sensing communities.

Introduction:

Biospheric-atmosphere gas exchange, the fundamental “breathing” of the planet through photosynthesis, respiration, and other biogeochemical processes, remains a critical science and policy issue. Climate change and disturbance alter biosphere-atmosphere fluxes of carbon dioxide, methane, water vapour, and several other greenhouse gases, and the exchange of these gases further affect atmospheric composition and climate through feedback effects (Field et al. 2007, Piao et al. 2008). Biospheric carbon dioxide fluxes (either uptake or release) are approximately ten times the anthropogenic emissions (Schlesinger 1997), and about half of these fluxes occur over terrestrial regions (Field et al. 1998).

These terrestrial carbon dioxide fluxes are extremely dynamic in time and space, and their controls are only partly understood. In many regions of the world, flux patterns appear to be shifting in response to climate change and large-scale human disturbance. For example, abundant evidence suggests that surface temperature and moisture levels are changing in northern latitude terrestrial ecosystems (Arctic Climate Impact Assessment 2005, Smith et al. 2005), and surface cover is changing (Sturm et al. 2001) with large implications for surface-atmosphere fluxes (Piao et al. 2008, McGuire et al. 2009). Much of western North America has recently experienced a prolonged drought and associated widespread vegetation mortality (Breshears 2005), which alters surface-atmosphere gas exchange and reduces ecosystem carbon sequestration and turns ecosystems into carbon source (Fuentes et al. 2006, Sims et al 2006, Luo et al. 2007). In tropical regions, deforestation and land-use change alters carbon stocks and fluxes (DeFries et al. 2002, Asner et al. 2005) and impacts the regional and global climate (Shukla et al. 1990). Given the need to minimize greenhouse gas emissions, and the desire to develop effective carbon sequestration policies, understanding biosphere-atmosphere gas exchange through validated ground and Earth observation data provides a foundation for sound policy.

The FLUXNET network of eddy covariance stations was created to help quantify biospheric carbon and water vapour fluxes and understand the controls on biospheric-atmospheric flux (Baldocchi et al. 2001). However, flux towers are typically limited to flat terrain and uniform vegetation (Baldocchi 2003, 2008), and many regions of the planet remain unsampled (Running et al. 1999), emphasizing the need for synoptic, remote sensing solutions to broaden the coverage. Futhermore, ongoing funding and maintenance of field networks remains challenging. In Canada, the Fluxnet-Canada Research Network (FCRN) and the follow-on program, Canadian Carbon Programme (CCP) were established to study the effects of climate and disturbance on carbon cycling in northern forest and peatland ecosystems. Unfortunately, the funding for CCP will end in 2010, and Canada is now facing the loss of a primary tool for studying the controls on biosphere-atmosphere exchanges in northern ecosystems. This termination is occurring at a time when such fundamental knowledge is critical for understanding the response of these ecosystems to climate change and for helping to develop greenhouse gas management options. This loss makes remote sensing solutions to carbon monitoring all the more critical. Remote sensing can help fill this gap, but only if we can develop effective “links” (calibrations) between remote sensing and fluxes. To accomplish this, the existing flux tower network must be linked to remote sensing in a modeling context to develop regional and global understanding of changing carbon and water vapour fluxes (Running et al. 1999). A key SpecNet goal has been to address this need with models driven exclusively from remote sensing, an approach which compares favourably with models driven from multiple data sources (Sims 2006b).

Originating in 2003, SpecNet was founded with the goal of understanding the linkages between remote sensing and surface-atmosphere fluxes (Gamon et al. 2006a). Originally formed as a “Working Group” at the National Center for Ecological Analysis and Synthesis (NCEAS, Santa Barbara, USA), SpecNet has evolved into a loose collaboration involving multiple investigators around the world combining remote sensing with flux and other field measurements. Typically “remote sensing” at SpecNet sites involves field optical sampling that matches the spatial and temporal scale of flux measurements, although aircraft and satellite remote sensing is also employed. Starting with a handful of field sites, mostly in the United States, SpecNet has since expanded to over 40 sites (Fig. 1), with the greatest recent growth in northern boreal and arctic ecosystems, where optical remote sensing is often problematic due to low sun angle and frequent cloud cover, and where climate change is occurring most rapidly (Arctic Climate Impact Assessment, 2005). The particular strength of optical sampling is that it provides a proxy measure of vegetation structural, physiological and phenological properties, all of which provide potent indicators of ecosystem composition, function, and biosphere-atmosphere gas exchange (Ustin et al. 2004, Ustin and Gamon, 2010). Ground-based optical sampling is particularly important in validating these relationships and adds to the value of field sampling networks.

[insert Fig. 1 here]

A primary SpecNet goal has been to compare ecosystem optical properties (primarily reflectance spectra and their derivative products) to carbon and water vapour fluxes. Most efforts to model photosynthetic carbon uptake from remote sensing derive from the observation by Monteith (1972, 1977) that gross photosynthesis (GP, or Gross Ecosystem Production, GEP, when integrated over time) is a function of absorbed photosynthetically active radiation (APAR) and the efficiency (ε) with which APAR is converted to fixed carbon:

$$GP = APAR \times \varepsilon \qquad \text{(eq. 1)}$$

APAR is typically determined as the product of PAR irradiance (PAR) and the fraction of PAR absorbed (F_{APAR}) by green vegetation.

A fundamental SpecNet objective has included validating the LUE model across ecosystems. This entails testing the basic components of the light-use efficiency model with the goal of developing a scaleable approach for evaluating surface-atmosphere carbon fluxes, and for linking field sampling to aircraft and satellite measurements.

The advantage of the model outlined in equations 1 and 2 is that spectral reflectance offers a direct way of assessing green F_{APAR} through the use of “vegetation indices” derived from spectral reflectance. Foremost among these has been the “Normalized Difference Vegetation Index” (NDVI) derived from reflectance (R) in the red and near-infrared (NIR) regions of the spectrum (Rouse et al. 1974):

$$NDVI = (R_{NIR}-R_{Red})/(R_{NIR}+R_{Red}) \qquad \text{(eq.2)}$$

In addition to exploring the APAR term, members of the SpecNet community have been exploring ways of assessing the efficiency term in the light-use efficiency model (eq. 1). There are several ways to approach this problem. Historically, many studies have assumed this to either be a constant for all vegetation (Heimann & Keeling 1989) or to be a biome-dependent constant (Ruimy et al. 1994). Clearly, LUE can vary with vegetation physiognomic or functional type (e.g. Gamon et al. 1997). However, more recent studies reveal that this term can actually be quite dynamic in time and space (Turner et al. 2003), even within a single ecosystem (Sims et al. 2006b). Environmental stresses (e.g. drought or temperature extreme) often cause carbon uptake to be reduced relative to the maximal value, resulting in variable light-use efficiency. From a physiological perspective, this reduced LUE is termed “downregulation” and can be characterized by reduced peak photosynthetic rates, reduced efficiency of the carboxylating enzyme Rubisco, and partial or complete stomatal closure (Gamon et al. 2001). Alternatively, during recovery from disturbance, an ecosystem’s LUE can be enhanced, in part through successional changes involving altered functional types and physiological performance. For example, in many ecosystems following wildfire, evergreen species are temporarily replaced by annuals or broad-leaved deciduous species as the dominant cover type, and foliar nitrogen levels can be enhanced (Rundel and Parsons 1980, Reich et al. 1990). Annual and deciduous types typically exhibit higher LUE than evergreens, and increased foliar nitrogen can also enhance LUE (Gamon et al. 1997). Consequently, an additional SpecNet goal has been to link optical sampling to gas exchange to explore the contributions of individual cover types or plant functional types to overall ecosystem carbon fluxes.

Because optical measurements can provide parameters for flux models, they provide a useful way to explore controls of biosphere-atmosphere gas exchange in a combined empirical and modeling framework. Since optical sampling is inherently non-intrusive and can be applied at different spatial, temporal and spectral scales (Gamon et al. 2006a), it can provide a useful field monitoring tool that can be easily compared to aircraft and satellite observations (Cheng et al. 2006, Fuentes et al. 2006, Strachan et al 2008, Hilker et al. 2009). Combining field optical sampling with flux measurements, and then using remote sensing to extend to larger regions (Rahman et al. 2001, Fuentes et al. 2006, Hilker et al. 2009), provides a robust “bottom-up” approach to developing a regional or global perspective of changing biosphere-atmosphere fluxes. This approach can then be compared against “top down” remote sensing approaches (Knyazikhin et al. 1998, Running et al. 2004, Sims et al. 2006b), yielding insights into contrasting controls on these fluxes for different ecosystems.

Since 2003, members of the SpecNet community have met approximately once a year, with recent meetings in Edmonton, Canada (2007), Monte Bondone, Italy (2008), and Lethbridge, Canada (2009). These meetings have spurred additional international collaborations incorporating SpecNet themes, including related efforts in the European Union (e.g. COST Action ESO903 – "Spectral Sampling Tools for Vegetation Biophysical Parameters and Flux Measurements in Europe"). SpecNet remains a "grassroots," user-driven organization, and is evolving into a data sharing collaboration and "virtual community" of scientists who apply linked optical-flux measurements in representative terrestrial ecosystems around the world. Because SpecNet relies on voluntary contributions of participants, it lacks the authority to enforce standards. Instead, its strength lies in its ability to spur innovation and communicate key findings through direct exchange, publication and web-based tools. While the primary focus continues to be linking optical sampling and fluxes, the SpecNet community has identified a number of related issues needing further attention. The purpose of this review is to summarize main outcomes of these meetings and highlight recent findings and current directions within the expanding SpecNet community. A summary of key SpecNet goals and accomplishments (Table 1) are briefly reviewed here with the hope that they will continue to advance the goals of improving the application of optical sampling to address surface-atmosphere fluxes.

[insert Table 1 here]

The LUE model as an integrating theme

The LUE model has undergone many years of development, and has been the subject of several reviews (Gamon and Qiu 1999, Goetz and Prince 1999, Hilker et al. 2008d). One of the key remaining questions is whether a single model parameterization can work for all of the world's terrestrial ecosystems, or whether the model must be "tuned" (i.e. calibrated) for different ecosystems. One approach to this question is to explore the universality of the individual model terms, and recent examples from SpecNet sites are discussed in this context below.

A significant challenge in parameterizing the APAR term from field optical measurements lies in the consideration of the photosynthetic and non-photosynthetic components of vegetation canopies. Strictly speaking, F_{APAR} of green vegetation (sometimes called "green F_{APAR}") differs from F_{APAR} as it is measured in the field because direct measurements often include *all* canopy materials (e.g. photosynthetic leaves and non-photosynthetic stems). Unless corrected to green F_{APAR}, this total F_{APAR} often provides a poor measure of absorbed light actually used in photosynthesis, and this issue explains some of the confusion in the literature regarding the "true" relationship between F_{APAR} and photosynthesis (Hall et al. 1992, Gamon et al. 1995, Chen 1996, Dawson et al. 2003), and presumably causes disagreement across sites when different methods are used. Usually such corrections require tedious harvesting, sorting, and measurements of the separate "green" and "non-green" canopy fractions (Gamon et al. 1995), but optical sampling methods now offer the possibility of rapid field assessment of this ratio (Serrano et al. 2000; Vescovo & Gianelle 2006, 2008; Gianelle & Vescovo 2007). Further testing of these optical methods across more ecosystems with contrasting stand structures is needed to confirm these results.

Once correction for the green canopy fraction has been applied, it becomes possible to explore the “true” relationship between NDVI (or other greenness indices) and absorbed light. Measurements from a variety of SpecNet sites in the Western US indicate that NDVI provides a near-linear measure of green F_{APAR} for many vegetation types (Fig. 2). It is likely that the scatter in this relationship is due variations in canopy structure and sun angle (Chen 1996, Sims 2006a), which have not been fully accounted for here, and which remain ongoing topics of research (Table 1). This observation of a significant NDVI-F_{APAR} relationship is in agreement with theory (Sellers 1987, Field 1991, Hall et al. 1992, Myneni and Williams 1994) and empirical observations (Bartlett et al. 1990, Demedriades-Shah et al. 1992, Hall et al. 1992) that suggest NDVI should be strongly related to F_{APAR} , but not all reports in the literature have found this relationship to be linear (Choudury 1987, Goward and Huemmrich 1992, Gamon et al. 1995, Chen et al. 1996). It is likely that methodological differences, including the issue of green fraction (mentioned above), spectral bands used, canopy structure, sun angle, and the scale of the measurement (individual canopy vs. whole stands or landscapes) contribute to these differences, all of which are topics needing further exploration.

[Insert Fig. 2 here]

Many variations on NDVI, including the Soil-Adjusted Vegetation Index (SAVI, Huete 1988) and the Enhanced Vegetation Index (EVI, Huete et al. 2002) have been developed, and may offer improvements over the NDVI, particularly for global applications (Rahman et al. 2005, Sims et al. 2006b). However, these indices have not been fully tested against NDVI in the context of the LUE model, and at this time NDVI remains the most widely used vegetation index for estimating photosynthetic carbon uptake. Similarly, alternative approaches based on remote sensing of shortwave albedo or canopy nitrogen offer encouraging alternatives to assessing biospheric carbon uptake that may simplify the challenge of global modeling (Ollinger et al. 2008). Comparing different vegetation indices and approaches for modeling carbon fluxes from remote sensing remains a central SpecNet goal.

Many SpecNet investigators have also been exploring ways of assessing the “light-use efficiency” term in the LUE model. One way of visualizing light-use efficiency is to plot GEP (or GP) as a function of APAR. The slope of this relationship represents the efficiency term. When this plot is made for representative vegetation types, even within a single biome, this slope can vary in characteristic ways (Fig. 3), demonstrating that, even for a single biome, the concept of a single LUE value is clearly in error. This variable LUE for different functional types within a single biome (coastal tundra near Barrow, Alaska) illustrates the weakness of a biome-based efficiency scheme. In this example, low-lying “wet” vegetation (dominated by sedges) exhibits a higher LUE than slightly elevated “dry” sites (dominated by evergreen species). Since these sites often differ in elevation by a meter or less, and since they often are adjacent in a tundra landscape, distinguishing these vegetation types represent a considerable challenge to satellites having large pixels (Huemmich et al. 2010). Similarly, moss (a bryophyte lacking developed vascular tissue) has a lower LUE than the sedge (a vascular plant). Since moss and vascular plants often co-occur in a tundra landscape, this mixture introduces errors into whole-ecosystem LUE models, providing an additional challenge to detecting LUE from conventional satellite remote sensing (Huemmrich et al. 2010). Since a primary SpecNet goal is to explore the spatial and temporal dynamics of LUE, consideration of functionally distinct vegetation types ("functional types") is a primary SpecNet focus. A primary hypothesis is that functional types can be distinguished based on their optical properties via "optical types" (Gamon et al. 2008, Ustin and Gamon 2010). This idea expands on the concept of "spectranomics" (Asner and Martin 2009) to include structural, biochemical, physiological, and phenological contributions to the optical signal detected by spectral reflectance. Determining the sufficient spectral, spatial, and temporal resolution to distinguish functional types is a related technical goal.

[Insert Fig. 3 here]

An alternative method of exploring efficiency is to use the information present in reflectance spectra to *directly* assess LUE. One way to do this is by mapping cover types and associating different LUE values for different cover types (Fig. 3), but this assumes that cover types are spectrally separable and LUE is a known constant for each cover type. Another way is to assess conditions of reduced LUE via dynamic signals present in the reflectance spectra. Alternative methods currently being explored include the Photochemical Reflectance Index (PRI), because it offers the most direct assessment of LUE, and various indices of water status and surface temperature.

Originally based on the observation that the xanthophyll cycle can be detected in intact leaves and plant stands with spectral reflectance (Gamon et al. 1990, 1992), and the fact that the xanthophyll cycle is closely tied to photosynthetic downregulation (Demmig-Adams and Adams 1996), the PRI provides a direct estimate of photosynthetic light-use efficiency at the level of fundamental photochemistry. Many studies have now shown that the PRI can be measured on whole stands, and that this index often scales with whole-stand LUE or can be used as an indicator of relative photosynthetic rates, supporting the use of PRI as a remote sensing measure of LUE (Gamon et al. 1992, 2001, Rahman et al. 2001, Nichol et al. 2002, Strachan et al. 2008, Hilker et al. 2009). However, a closer analysis of the recent literature reveals that this relationship is often confounded by sun angle (Sims et al. 2006b), view angle and canopy structure (Drolet et al. 2005, Hall et al. 2008, Hilker et al. 2008b&c, Cheng et al. 2009, Goerner et al. 2009, Middleton et al. 2009), soil background (Barton and North 2001), and pigment pool sizes (e.g. chlorophyll and carotenoid levels, Gamon et al. 2001, Stylinski et al. 2002, Sims and Gamon 2002, Sims et al. 2006a), all of which influence PRI at the stand level. Several of these confounding factors are reduced when sampling uniform, closed canopies; in these situations the vegetation stand effectively behaves like a “big leaf” (Gamon and Qiu 1999). However, much of the world’s vegetation is not comprised of uniform, closed-canopy stands, and while considerable progress has been made in overcoming these complications for individual sites, we lack a universal solution to this problem. Consequently, while single PRI-efficiency relationships sometimes emerge for a given ecosystem exposed to a stable set of conditions, multiple relationships emerge when different ecosystems are compared (e.g. Nichol et al. 2002). Even within a single ecosystem, multiple LUE relationships can emerge due to periodic stress and disturbance (Sims et al. 2006a), or due to varying contributions of different functional types (Huemmrich et al. 2010). It is likely that sun angle, view angle, three dimensional stand structure, instrument differences and sampling scale all contribute to these differences, and addressing the underlying causes remains an outstanding goal of SpecNet, in part through automation and cyberinfrastructure (further discussed below).

Scaling challenges

Applying the LUE model from satellite data and validating the results remain significant challenges, in part due to the mis-match in temporal and spatial scales between most satellite imagery and flux measurements (Fig. 4). Satellite pixel sizes have historically ranged from 30 m (Landsat) to 250 (MODIS) or 1000 m (AVHRR). Although newer satellites provide pixel sizes of less than 10 m, the imagery is often expensive or of limited availability, making multitemporal coverage quite difficult and costly. By contrast, eddy covariance methods of measuring carbon and water vapour fluxes typically sample a moving region on the scale of one to several hectares, and this sampling “footprint” moves continuously with windspeed and direction. From the perspective of most global satellite imagery, a flux tower represents a single, moving “point” sample on the ground, and it is difficult to find a close and consistent match between what a satellite measures and what a flux tower measures, particularly when multiple dates are included in the analysis. This scale mismatch provides a compelling reason for ground optical sampling at the scale of the flux tower footprint. Consequently, many SpecNet sites provide "scale appropriate" surface reflectance measurements of flux tower footprints, or of nearby regions having similar vegetation cover to the flux tower footprint. These methods, including automated sensors, mobile sensors, tilting sensors, and sensor networks (Table 1), allow the exploration of both temporal and spatial variability of optical signals, and provide a considerable data integration challenge. A technical goal remains the development of robust methods for relating fluxes to optical sampling, which often involves a formal analysis of the flux tower footprint along with some degree of data aggregation in the time domain.

[Insert Fig. 4 here]

Data aggregation in the time domain (i.e. "temporal scaling") presents many open questions. LUE models derived from spectral reflectance have been applied at a range of temporal scales ranging from "instantaneous" (seconds), to daily, weekly, seasonal, or yearly aggregation periods (e.g. Field et al. 1998, Gamon et al. 2001, Running et al. 2004, Sims et al. 2006a, Strachan et al. 2008). While, in principle, the LUE model can be applied at all these temporal scales, there appear to be "optimal" periods of aggregation that best allow comparison of flux data to optical data or satellite images (Sims et al. 2006a, Strachan et al. 2008). For example most LUE models have difficulty characterizing diurnal photosynthetic patterns, in part because flux data are highly variable at sub-daily time steps, in part because varying sun angles and light penetration during the day make interpretation of single nadir views difficult, and in part because obtaining multiple overpasses during a day is not always possible. Consequently, some degree of data aggregation is often needed to reveal consistent relationships between flux and optical data, and automated optical sampling methods combined with improved cyberinfrastructure (see below) can facilitate the exploration of suitable data aggregation methods. For example, Sims et al. (2006a) reported that, for a chaparral ecosystem, aggregation periods of about five days appear to be optimal, and Strachan et al. (2008) found that summed vegetation index values worked well when applying the LUE model. A high correlation between midday fluxes during single, midday overpasses and summed fluxes aggregated over several days enable the daily time step to work well when driving flux models from remote sensing (Sims et al. 2005). However, these observations are primarily based on statistical correlations from a limited set of ecosystems, and it is not fully understood to what extent they are determined by technical limitations of the technology (e.g. diurnal "noise" in eddy covariance data) or to what extent they represent fundamental underlying biological principles. Furthermore, we do not yet know whether all ecosystems behave similarly in this respect or if different ecosystems respond with fundamentally different time constants. These issues have important implications for how we use remote sensing to model carbon flux, and remain central questions within the SpecNet community.

In addition to temporal and spatial scale, questions of spectral scale are critical. Optical sensors differ in their spectral response, and there is no single "standard" set of bands across brands or generations of instruments. Consequently, we live in a veritable "alphabet soup" of indices, with even a single index (e.g. NDVI) having different value depending upon which sensor was used to make the measurement. While a number of studies have attempted to address the "best" spectral band for a given purpose, the lack of sensor standardization forces the user community to use sensors that may be sub-optimal for a given purpose and to compare measurements made with different instruments operating with different spectral bands. Consequently, a SpecNet goal remains the development of protocols and software tools for "translating" or "convolving" measurements between sensors. Such tools are essential if we are to explore the LUE model from different studies.

Sensor automation

To meet the optical sampling needs described above and to help assess the LUE model under dynamic conditions, several novel field sampling approaches have emerged within the SpecNet community involving sensor automation. Automation has been applied to correct for sky conditions, to explore angular effects (sun angle and look angle), and to monitor phenology. Most of these involve one of two levels of technology: simple two-band radiometers, and hyperspectral field spectrometers. Several examples are considered below.

During the BOREAS field campaign (Sellers et al. 1995, Gamon et al. 2004), Huemmrich et al. (1999) made the observation that a kind of "greenness index" can be derived from simple combinations of PAR and pyranometer sensors measuring in the visible and near-infrared, respectively. Similarly, Richardson et al. (2007) developed a greenness index based on visible color bands from a web camera. Because these types of instruments are easily available, relatively reliable and inexpensive, and can be readily integrated with a variety of dataloggers, it is possible to derive a simple, automated "NDVI" surrogate from existing, off-the-shelf sensors and loggers. Usually, these systems combine downward-looking sensors with upward-looking sensors, allowing for continuous, real-time correction of sky conditions. Continuous sampling from these types of instruments provides a powerful phenology indicator that is a useful metric of seasonally changing greenness, and that correlates well with satellite observations and seasonal fluxes (Huemmrich et al. 1999, Wilson and Meyers 2007, Richardson et al. 2009). Recently, the use of simple, automated instruments has expanded, primarily as indicators of green leaf area development, green biomass production, and APAR related to carbon flux. Currently, various wavebands, sensor types, and datalogger brands are now in active testing at many SpecNet sites. For example, by combining narrow-bandpass filters with silicon photodiodes, Garrity et al. (2010) developed an inexpensive radiometer ("QuadPod") for sampling NDVI and PRI that compared well with measurements made by a field spectrometer. Ryu et al. (2010) applied LEDs in inverse mode to create an inexpensive "NDVI meter" for tracking phenology and carbon flux in a California savanna. Because these sensors vary in design (e.g. spectral bands, radiometric response, and field-of-view), a remaining challenge lies in inter-site comparison and data integration, particularly when different sensors and measurement configurations are used. The lack of a single, readily affordable standard, along with the multiple sampling configurations currently in use, are good examples of the difficulties of building an effective network and help explain our emerging focus on metadata and cyberinfrastructure (see below).

To illustrate the utility of the simple sensors approach, we include an example from a prairie grassland (Lethbridge, Alberta, Flanagan et al. 2002). In this northern temperate grassland ecosystem, there is a strong correlation between seasonal changes in broad-band NDVI or APAR (measured with PAR sensors and pyranometers), and above-ground green biomass production and daily net ecosystem production (Figs. 5-7).

[Insert Fig. 5 here]

[Insert Fig. 6 here]

[Insert Fig. 7 here]

Since many SpecNet questions (e.g. direct assessment of LUE , moisture status or cover type) require the use of the full spectral power of narrow-band reflectance, much recent progress has been made in the automation of hyperspectral field spectrometers. Most of these methods involve the integration of two detectors, one looking up at the sky, and the other looking down at the target, to correct for changing illumination due to changing cloudiness, aerosol levels and sun angle. For example, Gamon et al. (2006b) and Sims et al. (2006a) demonstrated the use of a dual-detector spectrometer (UniSpecDC, PP Systems, Amesbury MA) from an automated “tram system” consisting of a cart on a track. This system provides repeatable, spatially explicit reflectance transects, is an ideal sampling tool for low-statured ecosystems, and is readily adapted to flux tower footprints. Because it monitors irradiance while sampling surface radiance, it is able to correct for changing sky conditions, minimizing a common source of error in field reflectance measurements.

Leuning et al. (2006) demonstrated a simple way to automate a single-detector spectrometer (UniSpec, PP Systems, Amesbury MA) from a fixed tower for multi-angle sampling (the “Multi-Angle Spectrometer” or MAS). Hilker et al. (2007) further developed this method by using a dual-detector spectrometer (Unispec DC), allowing real-time sky corrections. The spectrometer is mounted on a motorized pan and tilt unit (“AMSPEC”). These examples of automation, now being adopted at several SpecNet sites, expand the possibilities of field spectral sampling and allow new experimental approaches (e.g. diurnal and multi-angle sampling) to be explored, assisting in the retrieval of LUE.

Angular effects

The utility of multi-angle sampling for physiological retrievals are only beginning to be appreciated. While multi-angle sampling, per se, has existed for many years, most of these studies have focused on characterizing fundamental physical properties such as the Bidirectional Reflectance Distribution Function (BRDF) using goniometers (Sandmeier and Itten 1999) or other angular sampling tools (e.g. PARABOLA, Deering and Leone 1986, Deering et al. 1999). The BRDF function of a surface records surface reflectance for all possible view and illumination geometries (Nicodemus et al. 1977). While varying view and illumination angle can be a source of error, proper accounting for angular affects can also provide useful information on vegetation structure and physiology (Verrelst et al. 2008). The BRDF functions of different land cover types reveals information about three-dimensional vegetation structure and can be very useful in distinguishing vegetation types by exploiting differences in observed reflectance based on changes in view or illumination angles (Roujean et al. 1992). This information is also essential for radiative transfer models, providing combined empirical and theoretical approaches to understanding vegetation reflectance (Berk et al. 1999, Hall et al. 2008).

Bidirectional studies investigating the integration canopy structural information with physiological information are providing new insights into modeling biospheric carbon fluxes from remote sensing. Because vegetation structure readily confounds interpretation of physiological signals (e.g. Barton and North 2001), careful characterization of stand structural effects on reflectance spectra is a necessary step in extracting physiological information. Recent examples from SpecNet sites have clearly demonstrated how illumination angle (Sims et al. 2006a) or sensor view angle (Hilker et al. 2007) can interact with stand structure to confound the application of the LUE model. Through characterization of illumination and view angle effects, better physiological retrievals from optical remote sensing are now becoming possible (Sims et al. 2006, Drolet et al. 2005, Goerner et al. 2009, Hilker et al. 2009, Middleton et al. 2009). A full understanding of these effects will require further experimental work at a range of spatial and temporal scales and across ecosystems with contrasting structure and physiological behaviour (Table 1).

Building a "Virtual Community" through improved cyberinfrastructure

The trends in field optical measurements described above, namely added spectral bands, mobile sampling, sensor networks, multi-angle sampling, and increased automation and real-time monitoring, all greatly increase the dimensionality of spectral datasets, requiring far greater attention to informatics and cyberinfrastructure. In addition, the proliferation of sensor designs and measurement configurations, along with the need to relate spectral data to ancillary data (e.g. carbon or water vapour fluxes, species composition, moisture content, weather, etc.) across multiple locations and timescales, requires that we build more intelligent approaches for documenting, integrating and visualizing large, complex, and disparate datasets. To this end, members of the SpecNet community have been involved in novel solutions to these challenges, including spectral libraries and related analytical and visualization tools (Fig. 8). Additionally, several specific tasks have been identified (Table 2). The larger goal is to allow analysis of datasets at various granularities (from a single file to selected parts from across several files), from different perspectives (a single large dataset may be useful in different ways to different investigators), and in a flexible manner (allowing selection of subsets of interest in a dataset), and should also be able to accommodate structural and content changes in the dataset. Without proper attention to cyberinfrastructure, these goals simply cannot be realized by existing conventional means (e.g. flat files shared on ftp servers).

[Insert Fig. 8 here]

[Insert Table 2 here]

While a number of spectral libraries exist, few of these are available on-line in a manner easily shared with others. Furthermore, different metadata standards have been applied to these libraries. These metadata often lack adequate information or sufficient detail to enable use by scientists besides the original users. Recent SpecNet meetings have emphasized the need for web-based tools for using and sharing existing libraries and spectral formats, for incorporating and mapping between existing metadata sets and standards, and for generation of new, widely applicable standards. Also needed are flexible, intelligent tools for analyzing and visualizing spectral data, and for exploring the relationships between spectral data and ancillary data (e.g. species composition and carbon fluxes, Fig. 8, table 2).

To this end, members of the SpecNet community are working with the GeoChronos project (http://geochronos.org/). GeoChronos is an on-line platform leveraging cutting edge cyberinfrastructure technologies. These involve the Semantic Web (to link diverse and distributed data sets and to allow ontological mapping between different metadata standards), cloud computing (to provide on-demand processing, analysis, and visualization capabilities on line), and web portals leveraging Web 2.0 and social networking technologies (to facilitate collaborations involving sharing of data, methods, and applications). The ultimate goal is to facilitate a "virtual community" that can harness the power of web-based, open-source software solutions that can enable the SpecNet community to explore and share data and collaborate with one another in novel ways.

Conclusions & Recommendations

Is a universally applicable carbon flux model attainable for the terrestrial biosphere? To answer this question, exploring flux models driven by remote sensing continues to be a primary SpecNet focus. It is critical that we continue to develop the capacity for data integration and comparison as a foundation for these ongoing tests; without the ability to compare data and modeling approaches, we will not know if we have found an optimal solution. Additionally, the LUE model should be compared to other remote sensing-driven modeling approaches (e.g. Rahman et al. 2005, Sims et al. 2006b, Ollinger et al 2008) under similar conditions.

The primary SpecNet focus on carbon dioxide uptake needs to be expanded to include ecosystem respiration (Gamon et al. 2006a), water vapour (e.g. Claudio et al. 2006) and other biogenic trace gases (methane, nitrous oxide, etc.). It is possible that temporal and spatial patterns of high spectral resolution sensors, coupled with other remotely sensed data (e.g. surface temperature sensors) can yield useful information on trace gas fluxes. For example, surface moisture is readily detectable with optical sampling (Goswami et al. 2010), and moisture is a key variable affecting methane fluxes for many ecosystems (Merbold et al. 2009). Given the importance of methane in the global carbon budget and our current lack of understanding of individual ecosystem contributions to this methane budget (Solomon et al. 2007), this should be a major focus of the optical sampling community.

We urge the continued adoption of standardized and automated field sensors, sampling protocols, and metadata, whenever possible. Without the ability to provide funding and enforce standards, this has been a challenging task for the SpecNet community. However, a good starting point has been to employ the website (http://specnet.info) as a means of documenting methods and disseminating information that can help lead us to a voluntary set of standards. Particularly if standard sensors or protocols cannot be adopted, explicit and accessible metadata become critical. While much attention has been paid to the sampling methods used, a more important issue may actually be our approach as a community to a common cyberinfrastructure for sharing data and metadata in a transparent and meaningful way. We invite the community to participate in these ongoing activities, both within SpecNet and GeoChronos.

A solid understanding of the links between optical and flux measurements across a wide range of conditions is essential if we are to develop robust global models from remote sensing, and is also critical for satellite validation. Consequently, we emphasize the importance of expanding the network itself so that a greater range of sites representing a wider range of “climate space” (Running et al. 1999) are covered by combined optical and flux measurements. This necessarily requires a broader interaction between the flux and remote sensing communities. FLUXNET has a longer history and a greater distribution of sampling sites, yet not all FLUXNET sites take advantage of optical sampling for characterizing site phenology and biosphere-atmosphere fluxes. We invite new members, including members of the flux community who have not yet participated in SpecNet or utilized optical sampling, to explore these opportunities.

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Figure Legends

Figure 1 – Global distribution of SpecNet sites (red triangles). A more detailed list of sites and associated characteristics can be found at http://specnet.info.

Figure 2 - Comparison of green F_{APAR} to NDVI (from whole-canopy measurements) for a variety of vegetation types. Each symbol represents a mean of 3-5 measurements from a single species, and error bars indicate one SEM. Data were collected from SpecNet sites within California and Nevada.

Figure 3 – GEP vs. APAR for different functional vegetation types common in coastal tundra, Barrow, Alaska: “wet” microsite (dominated by sedge species), “dry” microsite (dominated by evergreens) and moss (a bryophyte lacking well-developed vascular tissues). In this plot, LUE is represented by the slopes. Adapted from Huemmrich et al. (2010).

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Figure 5 – Broadband NDVI, net ecosystem production (NEP, moles C m^{-2} d^{-1}), and green biomass (g dry weight m^{-2}) for a grassland ecosystem (Lethbridge, Alberta) in 2007. NEP was measured by eddy covariance, broadband NDVI using upward- and downward-looking PAR sensors (LI-190SA, LI-COR, Lincoln, Nebraska, USA) and pyranometer sensors (CM3, Kipp & Zonen, Delft, The Netherlands), and biomass through harvesting of above-ground standing green biomass. Negative winter-time NDVI values indicate periods of snow cover, and are typically discarded in later analyses (figures 6-7).

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Figure 7 - Net ecosystem production (NEP, moles C, m^{-2} d^{-1}) versus absorbed PAR (APAR, the product of PAR and fPAR, determined from broadband NDVI - see equation 2) for the prairie grassland in figure 5.

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Table 1. Summary of key SpecNet science & technical goals, with supporting references.

SpecNet Science goals	References
Evaluate the light-use efficiency model and its component terms across ecosystems of contrasting species composition and stand structure.	Hilker et al. 2008b, 2009, Cheng et al 2009, Middleton et al. 2009,
Understand controls on dynamic surface-atmosphere fluxes and understand stress effects.	Sims et al. 2006a, Claudio et al. 2006, Fuentes et al. 2006
Evaluate the impact of contrasting species & functional types on surface-atmosphere fluxes	Street et al. 2007, Huemmrich et al. 2009

SpecNet Technical goals	References
Develop scaling methodology (e.g. spatial and temporal interpolation, spectral convolution) for matching optical to flux measurements	Cheng et al. 2006, Sims et al. 2006, Chen et al. 2009
Determine optimal spectral bands, indices or algorithms for modeling carbon flux from remote sensing	Gamon et al. 1992, Drolet et al. 2005, Goerner et al. 2009
Evaluate sun angle, view angle, and sunlit fraction effects on physiological retrievals	Sims et al. 2006, Hall et al. 2008a, Hilker et al. 2008a&b, Cheng et al. 2009, Goerner et al. 2009, Middleton et al. 2009,
Automate field optical sampling, including mobile, tilting, and networked sensors.	Estrin et al. 2003, Gamon et al. 2006b, Leuning et al. 2006, Hilker et al. 2007
Deploy & test two-band radiometers (e.g. "phenology stations")	Huemmrich et al. 1999, Garrity et al. 2010, Ryu et al, 2010
Develop cyberinfrastructure for linking optical to flux sampling, and facilitating cross-site and multi-scale analyses.	Estrin et al. 2003, Elmagarmid et al. 2008

Table 2 - SpecNet tasks related to larger informatics & cyberinfrastructural goals.

Standardize and automate optical sampling (where possible) to facilitate comparison with dynamic surface-atmosphere fluxes and to enable cross-ecosystems comparison of the LUE model.

Automate processing tools (where possible) to track data history (“provenance”) and facilitate generation of metadata to improve data transparency.

Develop standard analytical software routines for temporal interpolation, spatial interpolation and comparison (footprint matching) and spectral convolution to facilitate comparison between instruments and methods (e.g. flux data, optical monitoring, and imaging spectrometry).

Disseminate laboratory and field calibration protocols to assist in standardization and automation optical sensors.

Standardize field metadata (where possible) and simplify ingestion of field metadata into web-accessible databases.

Develop web portals for initial viewing (e.g. data quicklooks), simple analyses, and rapid dissemination of spectral, flux, and image data.

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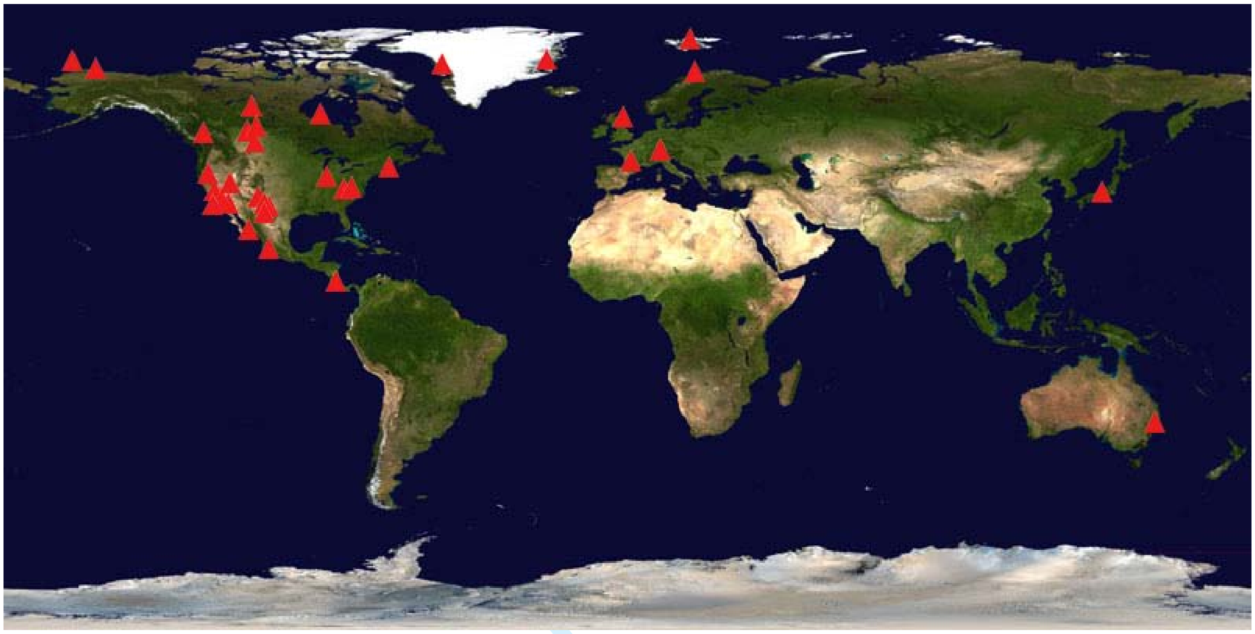

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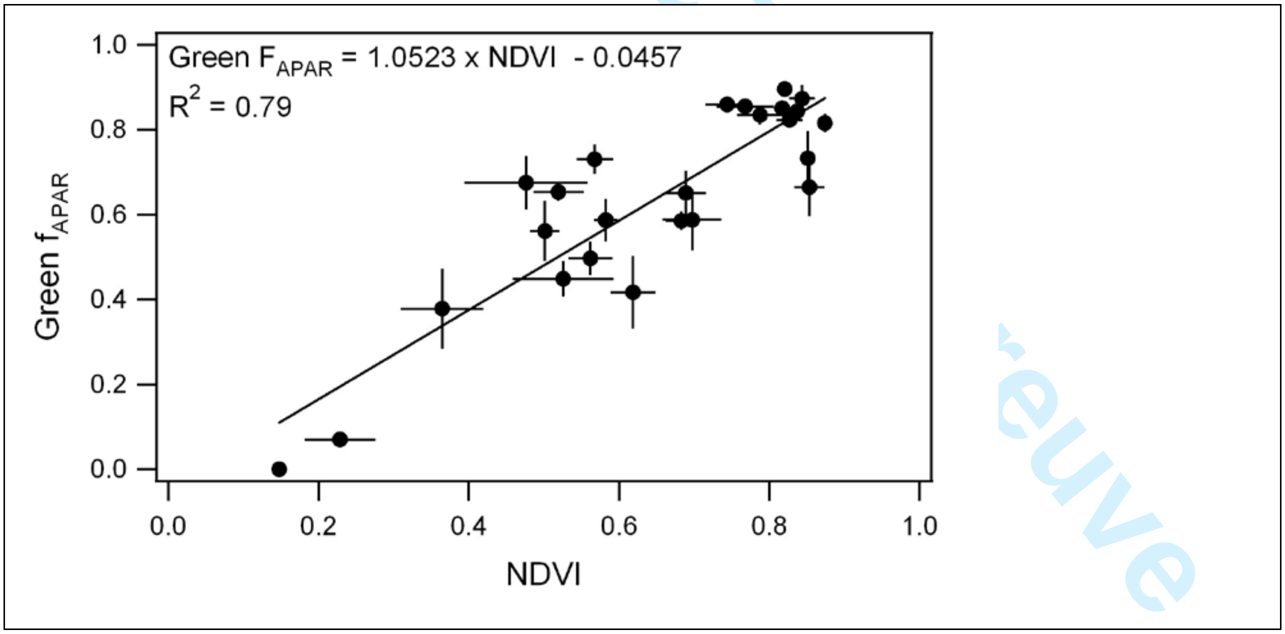

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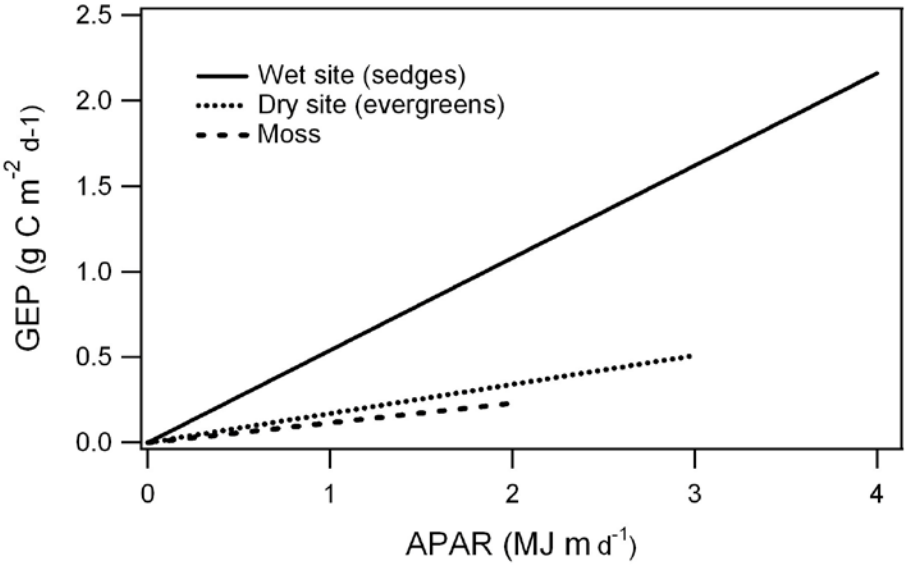

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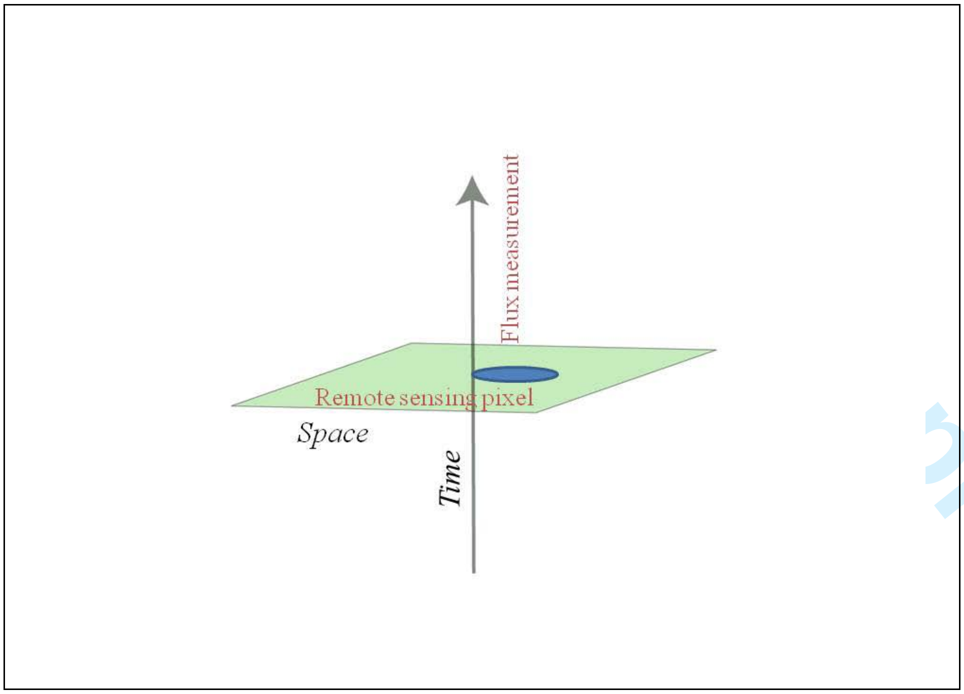

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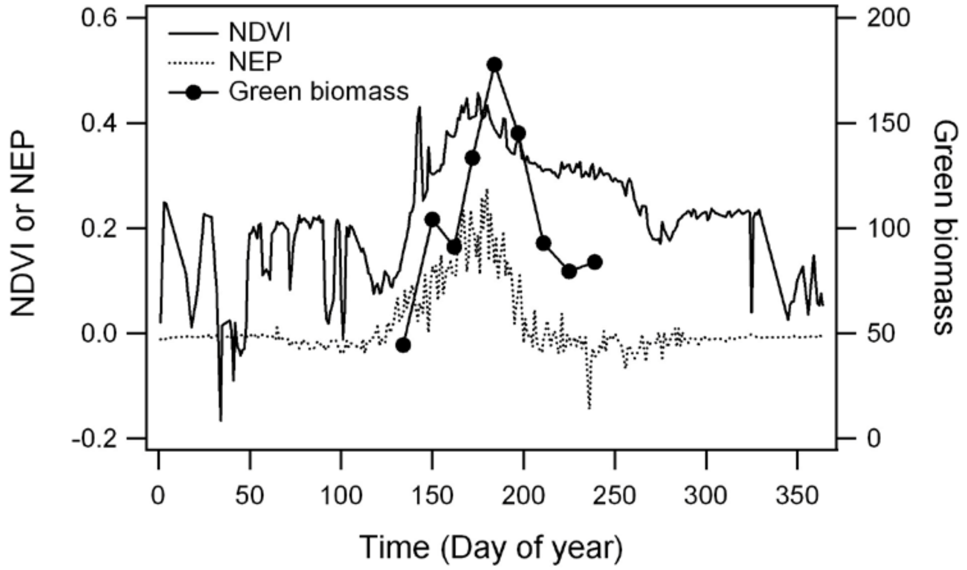

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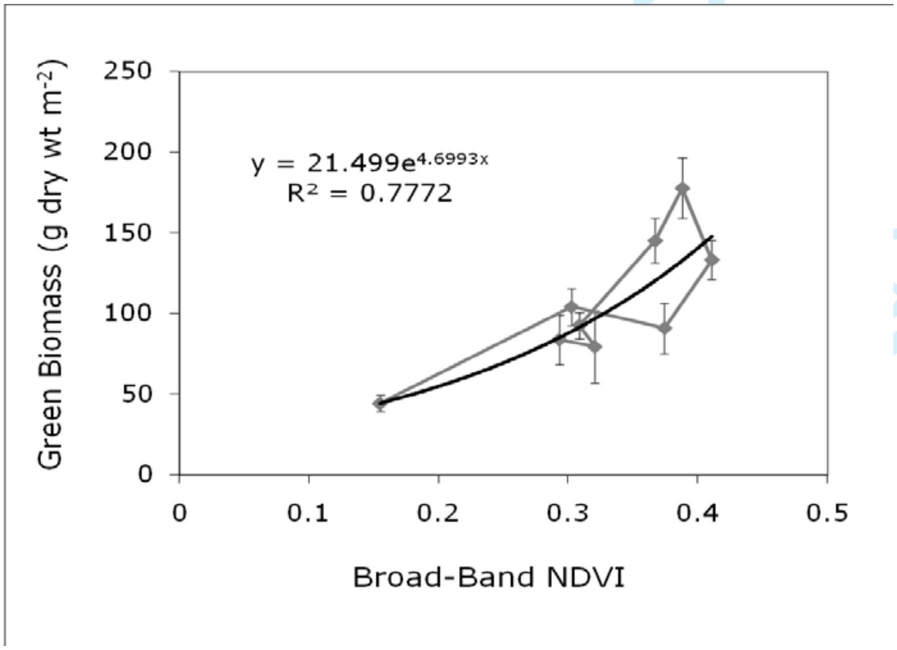

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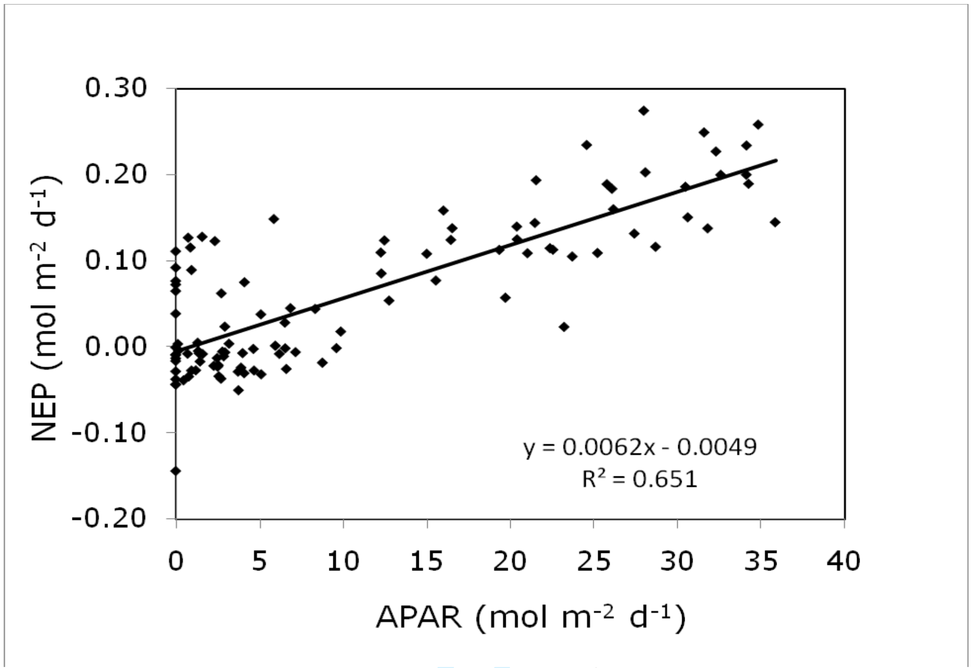

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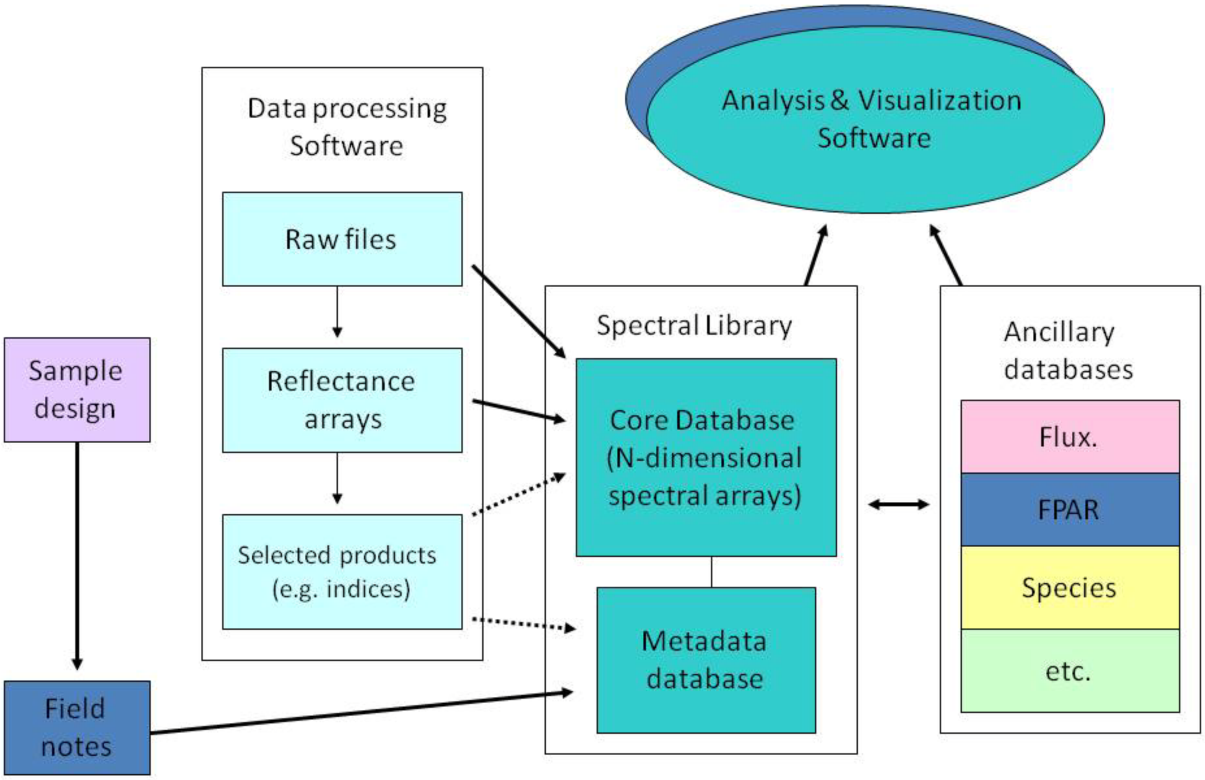

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