Hyperspectral Remote Sensing of Terrestrial Ecosystem Carbon Fluxes (HRS TECF)

Section I: Background and Overview

ABSTRACT

This proposal is directed to Emphasis Area 2: Existing Instrument Applications, with the goal of developing approaches using continuous high spectral resolution imaging from the Hyspectral Imager for Coastal Ocean (HICO) to determine carbon fluxes and light use efficiency for different terrestrial vegetation types under varying environmental conditions. This study utilizes spectral approaches to directly measure biochemical changes in vegetation reflectance associated with photosynthetic downregulation, leaf nutrient status, and leaf pigment content. Changes in these spectral characteristics are related to stress responses, seasonal dynamics, and variations in vegetation types. Vegetation stress responses govern the dynamics in carbon dioxide fluxes as directly measured by eddy covariance techniques at flux tower sites on the ground. Vegetation function also varies throughout a day following diurnal changes of light, temperature, and humidity and controls carbon exchange between ecosystems and the atmosphere. Other than the International Space Station (ISS), no orbital system is currently capable of delivering consistent consistent high spectral resolution observations of a number of sites at different times of day, uniquely providing the ability to assess both seasonal and diurnal responses for a variety of terrestrial ecosystem types. ISS provides the only space platform suitable for this study, and HICO the spectral capability, to observe diurnal and seasonal patterns of vegetation stress responses, because the ISS orbit is not sun-synchronous, differing from most Earth remote sensing satellites. The results of this study will produce a greater understanding of ecosystem response to environmental stresses, improve estimates of carbon fluxes, and measure landscape biodiversity by detecting physiological differences in species and plant functional types over regions. These results have both economic and policy ramifications, as they lead to the development of approaches for monitoring crops and forests function and productivity as well as agreements for the use of managed ecosystems for climate mitigation.

BACKGROUND

Terrestrial carbon fluxes represent key variables for describing the functioning of ecosystems. They are factors in understanding ecosystem responses and feedbacks to climate change (Friedlingstein et al. 2006, Alexander et al. 2013, Bounoua et al. 2010). Environmental stresses and plant responses that control carbon fluxes are also related to important economic factors such as crop yield (Dufranne et al. 2011, Yao et al. 2012, Chang et al. 2007) and forest production (Thomas 2011, Goetz and Prince 1996). Terrestrial carbon fluxes vary widely both spatially and temporally. Remote sensing of spectral reflectance is a key tool to study these variations, as it is able to non-intrusively and repeatably observe ecosystems over time.

Current approaches to describing terrestrial gross ecosystem production (GEP, the carbon taken up by plants from the atmosphere through photosynthesis) use modeled parameters to simulate expected reductions in carbon uptake due to environmental stresses, such as low temperatures or low humidity. Jung et al. (2007) found that changing these meteorological drivers in terrestrial ecosystem models results in substantial differences in estimates of GEP, and, in particular, uncertainties in estimating the light use efficiency (LUE, the ratio of GEP to the amount of light absorbed) were a key difference between models. In an effort to quantify errors in modeled carbon fluxes and their sources Lin et al. (2011) identified the largest cumulative errors come from parameters controlling LUE. Martel et al. (2005) found that the Moderate Resolution Imaging Spectroradiometer (MODIS)-Land GEP product estimates in late season were about twice as high as *in situ* eddy covariance measurements. Although the estimates of air temperature used in the GEP model closely tracked the ground data, the maximum LUE parameter used in the MODIS algorithm was much higher than that indicated by the tower measurements (Martel et al. 2005). Remote sensing approaches that directly determine key biophysical variables, such as LUE, will significantly improve the determination of GEP.

Vegetation biophysical and biochemical characteristics define ecosystem productivity and reflect its responses to the environmental conditions it experiences. Changes in vegetation function are governed by the underlying physiological processes and require hyperspectral capabilities with frequent repeat observations to be discerned.

Vegetation pigment levels can infer plant physiological status and identify periods of stress and reduced photosynthetic activity. Pigment concentrations play an important role in plant photosynthesis and protection. There are three major classes of plant pigments: chlorophylls, carotenoids, and anthocyanins (Blackburn 2007, Gitelson 2011). Chlorophyll concentrations control potential photosynthesis and provide an indirect estimate of plant nutrient status (Filella et al., 1995; Moran et al., 2000). Carotenoids in plants have both photosynthetic and photoprotective functions. They are structural components of the photosynthetic antenna and reaction center complexes (Bartley and Scolnik, 1995). Xanthophyll pigments are types of carotenoids that are important in photoprotection (see below). Anthocyanins play a variety of roles in plants and are a common pigment in all leaves. For certain species or growth stages anthocyanins may even become the dominant type of pigment. They can alter the light environment within a leaf and thus regulate photosynthesis and limit photoinhibition and photobleaching (Barker et al. 1997, Steyn et al. 2002; Close and Beadle 2003). These plant pigment concentrations can be estimated using spectral reflectance measurements (Blackburn 2007, Ustin et al. 2009, Gitelson 2011), and a few studies have derived pigment concentrations from space for a single time of day (e.g. Gökkaya et al. 2014, Campbell et al. 2013).

In circumstances when the leaf absorption of photosynthetically active radiation (PAR) exceeds the capacity of the photosynthetic processes to use that energy, reactions in the xanthophyll cycle cause the pigment violaxanthin to reverse epoxidation to form zeaxanthin via antheraxanthin. This process protects the leaf's photosynthetic biochemical machinery by releasing excess energy as heat. The process is also reversible when PAR levels are reduced (Grace et al. 2007, Coops et al. 2010). The spectral properties of these pigments cause an observable change in leaf reflectance at 531 nm as the relative amounts of the different xanthophyll pigments varies (Gamon et al. 1992, Peñuelas et al. 1995, Middleton et al. 2011). Photochemical Reflectance Indices (PRI) are spectral indices designed to detect this reaction, although the PRI signal also comes from carotenoid/chlorophyll ratios and conformational changes in chloroplasts (Filella et al. 2009). PRI is a normalized difference ratio of two narrow visible wavelengths (typically 531 nm – the detection band, and a reference band, often at 570 nm). A number of field and remote sensing studies have demonstrated that PRI is strongly related to foliage or ecosystem LUE (Gamon and Qiu 1999; Nichol et al. 2000; Rahman et al. 2001, 2004; Raddi et al. 2001, Grace et al. 2007, Hilker et al. 2008, Garbulsky et al. 2008, 2011, Peñuelas et al. 2011). PRI has been successfully calculated from orbital observations from MODIS by using the MODIS's ocean bands over land. MODIS band 11 centered at 531 nm is the detection band, however a 570 nm band is not available on MODIS so for a reference band one of the MODIS bands such as those centered at either 488, 551, 645 or 678 nm (bands 10, 12, 1, and 13, respectively) have been used (Rahman et al. 2004, Drolet et al. 2005, 2008, Goerner et al. 2010, Huemmrich et al. 2009, Middleton et al. 2011). Because of the large pixel size and sub-optimal reference bands MODIS PRI has significant uncertainties (Huemmrich et al. 2009). PRI was also observed from orbit using Hyperion hyperspectral observations (Asner et al. 2005, Campbell et al. 2013) and strongly associated with vegetation photosynthetic function for both hardwood and conifer forest sites (Campbell et al. 2013).

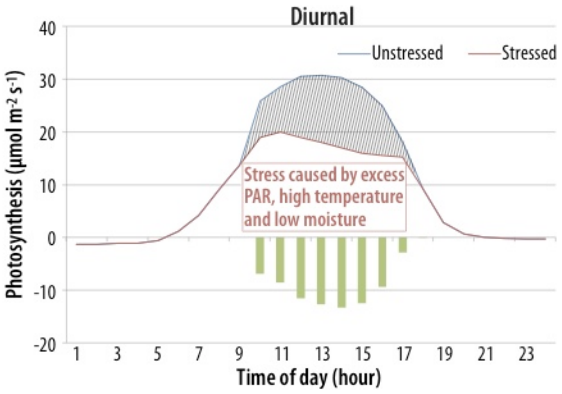

Figure 1. Diurnal GEP is very different under stressed and unstressed conditions. The large discrepancy is shown for ecosystem carbon uptake (in hatched area, green bars).

Terrestrial vegetation responds to changing environmental conditions in different ways and at different timescales. Successional vegetation changes may take decades, while structural changes, such as seasonal variability in leaf area, occur over days to months. Vegetation biochemistry and function can change during the day (have diurnal cycle), including changes in vegetation water and chlorophyll content. The dynamics in the xanthophyll cycle pigments can occur over periods from seconds to hours. The magnitude, rate, and duration of these responses are related to ecosystem processes such as carbon balance and evapotranspiration. The responses over a day are the least well understood by present remote sensing science. Stress responses over the course of a day can result in significant decreases in daily GEP (Figure 1). Figure 1 also shows how an observation made at 10 AM, the nominal overpass time for Terra and Landsat, could indicate little plant stress, while an observation made in the early afternoon would show much higher stress levels. These discrepancies accumulate when calculating annual GEP resulting in significant errors. Thus, the use of multiple observations over the course of a day (as is possible from ISS HICO) may provide early detection of stress responses that foreshadow serious disturbance events such as fires or insect outbreaks. The goal of this study is to take advantage of the variability of ISS overpass times to examine the information content of observations made at different times of the day. To detect and diagnose the causes of ecosystem responses to climate change, and disturbances, requires the ability to observe and monitor high temporal frequency changes in vegetation physiology.

Further, variations in the response of different types of vegetation to environmental stressors (both human and naturally induced) provide a more advanced method of vegetation mapping by creating "functional maps" of spatial patterns of carbon exchange (Ustin and Gamon 2010). Suites of plant species can be organized into assemblages possessing similar forms and functions, referred to as plant functional types (PFTs). PFTs may be discriminated by structure and foliage pigment concentrations, with unique seasonal changes and stress responses offering additional leverage for identification. Due to the importance of plant pigments, descriptions of temporal and spatial variations in pigments provide key information for a wide range of terrestrial ecosystem studies and applications (e.g. Asner and Martin 2008, 2011). The combination of temporal, spatial, and spectral information from HICO on ISS will allow us to generate descriptions of PFTs for our study regions, improving our understanding of the spatial and temporal variability of carbon fluxes and landscape productivity.

Studies using mid-morning acquisitions of high spectral resolution imagery for select flux tower sites found strong relationships between vegetation spectral properties and GEP (Campbell et al. 2013). We studied a range of vegetated sites using a combination of Hyperion reflectance data with carbon fluxes measured with ground-based eddy covariance towers. A number of narrowband, derivative vegetation indices (VI), and feature depth parameters closely described the seasonal profiles in vegetation function and GEP in three very different ecosystems, including a hardwood forest and tallgrass prairie in North America, and a Miombo woodland in Africa. Our results demonstrated the potential for scaling the carbon flux tower measurements to local and regional landscape levels. The specral parameters with strongest relationships to GEP were derived using continuous reflectance data, including wavelengths associated with plant pigment contents (using primarily the visible-near infrared spectral region available on HICO), and were able to describe over 90% of the variance in GEP using site specific algorithms and over 70% for all sites combined. Hyperion, being in a sun-synchronous orbit, observed the sites at the same time every day, thus, only allowed us to examine seasonal variations.

Existing and expected satellite systems do not provide the combination of frequent, high resolution narrow band observations and the high repeat imaging frequency required to study the fundamental causes of vegetation physiological dynamics. MODIS and the Visible Infrared Imaging Radiometer Suite (VIIRS) provide frequent observations, but only in a few broad spectral bands with large pixel sizes. Hyperion provides narrow band hyperspectral data, but these data are collected infrequently and at a fixed time of day. Aircraft mounted instruments such as the Airborne Visible InfraRed Imaging Spectometer (AVRIS) and Compact Airborne Spectrographic Imager (CASI) are capable of providing data with high spectral and spatial resolution at multiple times of the day, however they are only available for small areas and are rarely flown with the frequency and duration to observe daily to seasonal vegetation dynamics. HICO on ISS is uniquely able to provide repeatable observations of widely distributed sites through the growing season and at different times of the day to observe vegetation over a range of different illumination and stress conditions.

Section II: Detailed Project Plan

REASEARCH QUESTIONS

The goal of the proposed study is the development of an improved model of carbon uptake by terrestrial ecosystems, where the level of carbon uptake is determined using optical signals from satellites. To achieve this goal we will address the following science questions: Do optical signals, from hyperspectral reflectance, describe variations in ecosystem carbon fluxes? If so, are there differences in these relationships related to diurnal versus seasonal changes in vegetation? Are these relationships consistent over different vegetation types?

To address these questions we will use HICO's continuous narrow-band visible and near infrared reflectance images for select flux tower sites to directly detect the optical signals of stress responses of terrestrial vegetation. We will develop statistical models that relate spectral observations with ground-measured ecosystem carbon fluxes from the towers. We will take advantage of HICO observations from ISS overpasses occurring at different times of the day, to examine how the time of day, and thus the solar irradiance, affects the relationships between the spectral signals and carbon fluxes.

If successful, our approach will significantly simplify the modeling of carbon uptake and improve the results from existing photosynthesis models, by providing estimates of ecosystem productivity in a way that is spatially explicit and independent of current models and model inputs. This approach contrasts with current models in that the models attempt to predict the occurrence and effects of stress events in vegetation based on simulations of vegetation responses to meteorological variables, while our approach determines fluxes based on direct optical observations of vegetation physiological responses to stresses. The key breakthrough is the determination of ecosystem productivity (GEP) using only remotely sensed inputs. This leads to a direct determination of fluxes remotely, from orbit or aircraft, while at the same time describing spatial heterogeneity at a spatial resolution not presently possible with existing measurements or models and model inputs.

This research will lead to an advancement in remote sensing science, moving from the existing products that describe basic structural characteristics, such as land cover type and leaf area, to observing physiological responses in plants. A key advancement from this study will be the ability for first time to analyze spaceborne observations collected during different times of day, when plants experience different types and levels of stress, due to varying light levels, temperatures, and humidity. By observing the responses to changes in these environmental variables over relatively short seasonal timeframe, we will develop a better understanding of plant responses to transient stress events, improving the possibility of detecting the early onset of vegetation stresses. The development of robust algorithms for detecting ecosystem stress responses and determination of productivity using remote sensing is valuable for ecological monitoring and commercial land management.

RESEARCH STRATEGY

To achieve our research goals we will acquire HICO hyperspectral imagery for areas that include operating flux towers that use the eddy covariance technique to measure ecosystem carbon dioxide fluxes for homogenous regions around the tower. We propose to work with three sites out of the list shown in Table 1. The list of potential sites represents our flexibility to cooperate with other HICO investigators to optimize the instrument usage in its support of multiple studies. The goal of this study is to separate diurnal and seasonal patterns in spectral reflectance and carbon fluxes. Thus, we are interested in collecting HICO imagery during intensive periods during the growing season when there are frequent ISS overpasses occurring at different times of the day (see Figure 2). For this reason we have focused on sites toward the northern part of the ISS orbital path where this type of coverage occurs. We will request data only during the growing seasons, and, as shown in Figure 2, there are periods during the summer where there are frequent observation opportunities from ISS occurring at different times of day. By collecting multiple observations over a short seasonal period at different times, we will be able to separate diurnal and transient changes from seasonal changes in the vegetation.

HICO is a pushbroom sensor covering the 350-1080 nm spectral range at 5.7 nm spectral sampling and a signal-to-noise ratio (SNR) >200:1 for a 5% albedo scene. It has a spatial resolution of approximately 100 m, depending on the altitude of the ISS and the elevation of the terrain (Gao and Li 2010). These characteristics make HICO a good choice for this study as its spectral range, resolution, and SNR meet the requirements for optical determination of plant pigment concentrations, and its spatial resolution is similar in scale to the observation footprint of the flux towers. To obtain the surface reflectance spectrum, the atmospheric effects need to be removed. HICO's top of atmosphere radiances will be converted to surface reflectances using the well established software ATmosphere REMoval (ATREM) algorithm (Gao et al. 1997), designed for pushbroom imaging spectrometers with cross-track spectral calibration variation. ATREM is designed to account for the differences in illumination geometry associated with the varying off nadir looks of HICO, and has been extensively tested for

Potential Study Sites	Vegetation Type	Latitude	Longitude
Parker Tract, NC	Evergreen needle-leaf forest	35.803	-76.668
Beltsville, MD	Crops	39.030	-76.850
Konza Prairie, KZ	Grassland	39.080	-96.560
Morgan Monroe, IN	Deciduous broadleaf forest	39.323	-86.413
Bondville, IL	Crops (corn/soybean)	40.000	-88.292
Mead, NE	Crops (corn/soybean)	41.180	-96.440
Harvard Forest, MA	Northern hardwood Forest	42.530	-72.170
Bartlett Experimental Forest, NH	Deciduous broadleaf forest	44.065	-71.288
Metolius/Cascades, OR	Evergreen needle-leaf forest	44.452	-121.557
Howland Forest, ME	Evergreen needle-leaf forest	45.204	-68.740
Univ. of Mich. Biological Station, MI	Deciduous broadleaf forest	45.560	-84.714
Wind River Crane Site, WA	Evergreen needle-leaf forest	45.820	-121.952
Wisc: NTL LTER - Park Falls	Deciduous broadleaf forest	45.945	-90.272
Campbell River, BC, CA	Evergreen needle-leaf forest	49.520	-124.902
Leithbridge, AB, CA	Grassland	49.709	-112.940
Groundhog River, ON, CA	Mixed boreal forest	48.217	-82.156

Table 1. Potential study sites with a description of their vegetation type and their locations. All sites have operating flux towers that continually make weather and ecosystem CO2 flux measurements.

correction of HICO data collects of various land covers. ATREM uses the 6S radiative transfer model (Kotchenova et al. 2006), constrained by the date, time of day, elevation and observation geometry, to account for the changes in solar illumination, and explicitly simulate the absorption and scattering effects of atmospheric gases and aerosols. The quality of the retrieved parameters will be evaluated, studying the derived spectral signatures and the depth and position of the known atmospheric features and if required additional corrections will be applied (e.g. to account for aerosol scattering and thin cirrus clouds; Ryan et al 2014, Gao et al. 2012). Pixels will be extracted from the HICO surface reflectance imagery for the area around the flux towers. The pixels will be geolocated by matching land surface features with those features in Google Earth (Campbell et al. 2013).

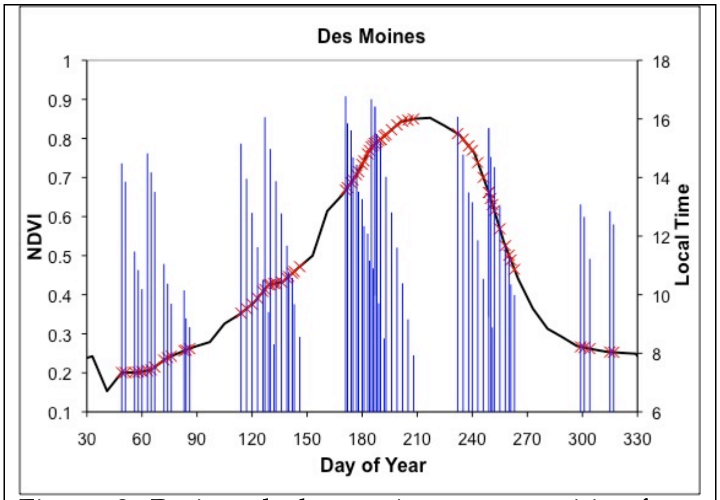

Figure 2. Projected observation opportunities from ISS with less than a 30° view zenith angle for a location near Des Moines, Iowa, USA, (approximately 41.6°N) are indicated by the blue vertical lines. The x-axis location indicates the day of year of the overpass and the height of the line shows the time of the overpass. The black curve shows seasonal vegetation dynamics as the 10-year average Normalized Difference Vegetation Index (NDVI) from MODIS for the area. The overpass days at which HICO can sample the seasonal profile in vegetation properties at different times during the days are marked with red "X's".

All of the study sites have operating flux towers where CO$_2$, water, and energy fluxes are measured using eddy covariance methods. The flux towers also routinely collect a suite of meteorological measurements including: air temperature, humidity, soil temperature, wind speed and direction, air pressure, and incident photosynthetically active radiation. These towers are located in fairly uniform vegetation stands that are larger than the 100 m HICO pixels. We will acquire flux tower data collected over the full growing season, and in particular during the day of overpasses. Data from these towers are routinely publicly available through web sites and we are coordinating directly with the tower captains to insure timely data availability (see letters of commitment).

The flux tower measures the movement of carbon, in the form of CO_2, between the atmosphere and the ground. CO_2 transfer into the ecosystem is a measure of photosynthetic activity. Variations in these carbon fluxes, measured from the towers, can be used to determine quantitative values of vegetation stress responses. From the flux tower data we calculate the LUE as the ratio of the carbon uptake by photosynthesis to the amount of photosynthetically active radiation absorbed by the plants. As plants become stressed, their LUE drops.

The carbon flux and meteorology measurements from the towers will be matched with the spectral data from HICO. There are a number of approaches for processing the spectral reflectances to enhance specific features such as spectral vegetation indices (algebraic combinations of different spectral bands), derivatives of reflectance spectra, and spectral feature continuum removal analysis. These derived spectral parameters as well as the band reflectances themselves will be used as inputs for statistical analysis to determine the optimum approach for deriving fluxes and LUE from spectral data. We have successfully performed these types of analyses using ground and satellite data (Entcheva et al. 2004, Campbell et al. 2007, 2013, Huemmrich et al. 2009, 2010ab, 2013, Cheng et al. 2010). To develop and test these relationships we will require a number of observations that occur under a range of conditions. We will evaluate the best approaches for each site (different vegetation types) and for all sites combined (global approaches). Finally, to extend the results we will apply these algorithms to entire HICO images to examine the changing spatial-temporal patterns in carbon fluxes over the landscape. We will cluster these patterns to map physiological biodiversity of the areas surrounding the flux towers (Ustin and Gamon 2010).

To aid in the discrimination between diurnal and seasonal vegetation changes within the footprints of the towers we will use the flux measurements, which are reported at 30 minute intervals. To extrapolate this analysis to the entire HICO image, we will extract MODIS reflectance data (500 m pixels at 8-day intervals) for the areas around the study sites. The MODIS data will be used to calculate vegetation indices that are related to basic structural changes in canopies, such as green leaf area (MODIS NDVI, Figure 2). This gives us a larger spatial extent of information on the timing and rates of vegetation green-up and senescence (not available from the flux towers) to put the scattered HICO images into a seasonal context. The MODIS data are freely available through NASA web sites (http://daac.ornl.gov/MODIS/). We will use the tower flux and meteorology data to trace the seasonal and diurnal patterns at the targeted sites during periods between HICO observations.

The investigators have years of successful collaborations and both have extensive experience in processing and analyzing imaging spectroscopy data and data from flux towers. Thus, the work plan will simply be based on a flexible sharing of the tasks.

SCHEDULE

The schedule is designed to cover two growing seasons to increase the opportunities to get cloud-free observations of chosen study sites (Table 2). The project begins with the selection of the flux tower sites to be targeted (list in Table 1), working closely with HICO's management to devise an optimal data collection plan. Through the first growing season we will monitor HICO data collection activities and process and evaluate imagery as they are collected. We will test the correction approaches and optimize the processing strategy. During the fall and winter we will acquire the processed flux tower data, process HICO data to surface reflectance, extract pixels representing the tower sites, merge the two datasets, and conduct the statistical analysis of the data.

	Apr-15	May-15	Jun-15	Jul-15	Aug-15	Sep-15	Oct-15	Nov-15	Dec-15	Jan-16	Feb-16	Mar-16	Apr-16	May-16	Jun-16	Jul-16	Aug-16	Sep-16
Site selection	x	x											x	x				
Monitoring data collects and pre-processing			x	x	x	x	x							x	x	x	x	
Processing image and flux data								x	x	x	x	x					x	x
Writing papers and presentations									x	x	x	x					x	x

Table 2. Schedule for proposed activities.

In December we will present our preliminary results at the American Geophysical Union (AGU) Fall meeting. Based on the results of the first year's analysis, we will make requests for other HICO data collects, to fill in gaps, extend and validate the results. In the last months we will process that summer's data collections, finalize the analysis, present our results at the Ecological Society of America (ESA) Annual meeting, prepare a manuscript and submit it for publication in a peer-reviewed journal. We believe we can achieve this schedule, because in the second year all of the workflows for data analysis will have been already established, so the major effort will be writing up the final results.

OUTPUT AND DELIVERABLES

This project will result in the development of improved models for the assessment of terrestrial ecosystem carbon fluxes resulting in carbon flux maps over imaged regions that will be used to evaluate regional spatial heterogeneity. Because of differences in overpass times HICO will provide a look at how spatial patterns of fluxes vary with time of day. This result will inform and guide new strategies for monitoring vegetation function. The results of this study will be presented at two major scientific meetings (AGU and ESA) where the use of HICO and ISS as a unique remote sensing platform for terrestrial ecosystem studies will be demonstrated to the scientific community and the new observation strategies discussed. The results will also lead to publication in a peer-reviewed journal.

Section III: Economic Impact of Project Success

The short-term results of this work will be presentations in major scientific meetings and the publication in a peer-reviewed scientific journal. However, this research is leading toward operational sensors and algorithms that will provide direct economic benefits. The development of robust algorithms for the early detection and diagnosis of vegetation stress events (in time for interventions, such as irrigation or application of pesticides) along with indications of the severity of the stress responses will ultimately provide significant economic value for forestry, agriculture, and land management by reducing risk and improving yield. Additional economic value will also be derived from improved estimates of crop and forest productivity for farmers, commodities brokers, and governmental agencies.

The ability to explicitly map physiological conditions across fields has applications for precision farming, leading to decreased waste and environmental pollution, while increasing production. In natural ecosystems, observations of spatial heterogeneity in growth and stress responses may be an indicator of biodiversity, a critically important descriptor of ecosystem health that is extremely difficult to measure using existing field techniques (Ustin and Gamon 2010).

The success of the project will demonstrate a new strategy for acquisition of observations of terrestrial vegetation. It represents a shift from the current methods and technologies, providing a new direction and drivers in the field of vegetation remote sensing, advancing technology developments in the use of multi-temporal space borne observations of ecosystems, and in particular the use and analysis of diurnal observations. This has the potential for dramatically improving the detection of plant stress responses over observations made at a single time of day, as is presently done with almost all Earth observing satellites. In addition, a multitemporal observation strategy, processing workflows and analytical approach, will be important for laying groundwork for the analysis of future data collected from ISS, as well as from future multi-satellite constellations, such as an advanced form of Planetlab's satellite network.

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