2.3 Terrestrial Ecology Observing Systems (TEOS)

The Terrestrial Ecology group applies ENS to the measurement of critical ecological processes. In 2008-09 we targeted integrated sensing systems that could measure complex phenomena, such as tree physiology (above and below ground) and soil microbial activity and respiration. One of the critical needs in this area is the ability to measure two types of information simultaneously: long-term trend analyses, and short-burst events.

Based on technical progress in previous years, the TEOS group was able to shift focus from designing networked technologies to field-testing a number of systems and evaluating their potential to measure critical ecological phenomena. Simple coupling of the physiology of trees and microbes requires a wide array of sensors (for \( CO_2 \) concentrations, temperature, and moisture at differing depths and spatial arrangements, sap-flow) coupled with nearly continuous camera observing platforms (leaf phenology, root and fungal microscope-resolution imaging, nesting bird behavior), and point measurements of taxon locations (EcoPDA), point measurements of photosynthesis under varying light regimes and among species, and bedrock/coarse root imaging (ground-penetrating radar). These coupled human/camera/sensor measurements have to be accumulated readily during long periods of relative stasis, but then have to be able to detect responses during critical events ranging from sunflecks, to freeze/thaw events, to monsoonal rains, to major storms.

An example is the relationship between soil respiration and tree dynamics (Fig 1). Sap-flow sensors were placed in the trees surrounding a soil respiration sensor network. Previous work has shown that there are both daily and seasonal lags in soil respiration. Changes in soil temperature and moisture did not explain the variation in soil respiration, the normal variables modeled for soil respiration. What does appear is that the soil respiration is low but starts increasing with melting snow, coupled with fungal growth, new roots, and increasing activity of the evergreen pines and manzanitas. The big jump in soil respiration appears to be associated with leafing in the deciduous oaks, followed by a drop as soil dries out. However, activity still remains surprisingly high even under extremely low soil moisture (<5MPa). Soil camera systems show that fungal activity remains high and roots are relatively static. Activity appears to depend upon deep roots (found developing into fractures in the granite using GPR) and hyphae (from soil pits) within the granite matrix accessing deep water coupled to hydraulic redistribution and maintaining microbial and root respiration. Monsoonal precipitation events drive later spikes in soil respiration, although there is a slow drop in respiration as sap-flow declines in the plants indicating lower stomatal opening, which was coupled to reduced photosynthesis in spot measurements.

We are currently working to link the above data with leaf and flowering phenology measurements taken using in situ cameras. An example is presented of bud burst and leaf flush in rhododendron that is being expanded to the species (such as oaks) on the AMARSS transect. Further, by using these in situ cameras to measure leaf greening, and calibrating the camera “greenness” to satellite-based “greenness” MODIS products, the thousands of webcam images may be integrated to extract higher quality continental-to-global scale phenological data that can provide a detailed information on greening trends.

Animal behavior is dependent upon both behavioral traits that are functions of individual species or even populations. The timing of those traits also depends upon environmental cues. Nesting is an obvious behavioral
trait that is characteristic for a species in response to environmental cues. However, species interactions modify those behaviors making clear correlations in nesting behavior with environmental cues difficult at best. By continuous monitoring of behaviors, coupled with environmental sensors and observations, such as plant phenology, a better understanding of lags and competitive interactions may be generated.

Finally, spot observations, identifications, and measurements are absolutely essential to characterizing environmental change. But for this to be undertaken at the global scales essential to document the implications of global change, accurate identifications need to be coupled to detailed location information, by both experts and less-well trained participants. Coupling imagery, data management systems, and GPS receivers (EcoPDA) provides new linkages between human observers, camera observation systems, and large-scale data acquisition and availability. By interfacing with organizations such as Conservation International, and developing highly portable data acquisition technology, data transfer capacity, and taxonomic electronic “guidebooks”, EcoPDA provides the linkages between detailed sensor technologies with satellite information of phenological change, with a widespread human workforce to bring ecological data collection and analysis to the global scale.
TEOS 01 Terrestrial Ecosystem and Imaging Applications: Regulation of plant/microbe dynamics and carbon flux

TEOS 01.1 People:
- Principal Investigators: Michael Allen, Eric Graham, Phil Rundel, Darrel Jenerette, Tom Harmon
- Faculty: Michael F. Allen, Center for Conservation Biology, UCR; Professor; Phil Rundel, Department of Life Sciences, Professor, UCLA; Darrel Jenerette, Center for Conservation Biology, Assistant Professor, UCR; Tom Harmon, Professor, University of California-Merced; Deborah Estrin, CENS, UCLA, Professor; Louis Santiago, Center for Conservation Biology, Assistant Professor, UCR; Edith Allen, Center for Conservation Biology, UCR; Professor and Cooperative Extension Specialist
- Researchers: Eric Graham, CENS, Associate Development Engineer, UCLA; Michael Hamilton, University of California Berkeley; Einav Mazlish-Gati, Center for Conservation Biology, PostDoctoral Researcher, UCR; Amit Chatterjee, Center for Conservation Biology, PostDoctoral Researcher; Karrin Alstad, Center for Conservation Biology, PostDoctoral Researcher
- Staff: Michael Taggart Center for Conservation Biology, Engineer; Thomas Unwin, Center for Conservation Biology, Engineer; Kuni Kitajima, Center for Conservation Biology, Staff Research Associate; Rebecca Fenwick, Field Station Director, James Reserve NRS, UCR.
- Graduate Students: Niles Hasselquist, Center for Conservation Biology; Laurel Goode (Salzman), Center for Conservation Biology; Thomas Schoellhammer, CENS, UCLA.
- Undergraduates: Diana Louie, Center for Conservation Biology; Jasmin Quon, Center for Conservation Biology; Norman Ho, Center for Conservation Biology.

TEOS 01.2 Overview
Our general approach has been to design and build an array of sensors ranging from physical measurements at high frequency to biological imaging at lower frequency but high resolution to describe soil-fungi-plant-atmosphere dynamics related to describing carbon exchange and sequestration at high temporal-spatial resolution. During this year, we completed the conceptual and technical steps for constructing and placing a soil sensor network. Our goal during this year was to test the system by addressing important ecological questions. In the remainder of this section, we describe our initial application of the embedded sensor array to ecological questions, and then briefly outline our next suite of steps for comprehensive examination of questions that only sensor networks can address.

TEOS 01.3 Approach
We have installed a suite of off-the-shelf sensors for temperature ($T$), moisture ($θ$), $CO_2$, $NO_3^-$, $NH_4^+$ and a suite of integrated atmospheric measurements including barometric pressure, air temperature, humidity and photosynthetically-active radiation (PAR). We have also integrated a series of individual leaf measurements to scale photosynthesis to the stand level using an observational network to estimate leaf areas by species. We have also installed minirhizotron access tubes to track root and rhizomorphs production and mortality. We have designed a new Automated MiniRhizotron (AMR) that takes high-resolution, microscope-level images for observing individual fungal hyphae to track production and mortality of fungal hyphae in-situ. These measurements are being scaled up both by using an array of these sensor networks, and by contrasting the outputs from these networks against an eddy-covariance flux tower maintained by Michael Goulden (University of California-Irvine).

TEOS 01.4 Systems Description and Experiments
Infrastructure: Support of the photovoltaic-based electrical system installed last year at the James Reserve (JR) has proven to be more time consuming than anticipated. Generator start failures, faulty equipment and firmware upgrades have all been addressed to keep electricity flowing to the various sensor systems and servers associated with CENS experiments at the off-the-grid Reserve.
Maintenance and support of CMS2, camera system and AMARSS are all on-going efforts. Added to this has been assistance with planning the switchover to the CR campus backbone for both network and telephone systems. It is anticipated that changing from our current suppliers will result in saving about $1,300.00 per month in infrastructure costs.

Because CENS utilizes such a large percentage of JR bandwidth and server access, CENS staff provided limited technical support during the absence of the Natural Reserve System (NRS) Information Manager due to injury. While the time involved was not notably significant, it was critical in keeping data flowing and accessible to both researchers and CENS educational outreach programs.

Because researchers conducting remotely controlled experiments at off-Reserve locations routinely rely on CENS personnel based at JR to help trouble-shoot non-responsive equipment, support was provided for various CENS experiments (NIMS-RD, plant phenology, bird box cameras, micro-servers and tower cams, CMS) and various associated networks and power distribution systems throughout the Reserve.

**AMR design and testing:** The prototype Automated MiniRhizotron (AMR) began capturing experimental images in the summer of 2008. While much of the data was truly groundbreaking and useful, it also allowed us to uncover some design challenges associated with extended use. In particular, premature motor failure associated with wiring harness binding, missed steps (and therefore inaccurate repositioning and location repeatability) caused by mechanical binding, image blurring due to switching to a newer (USB2) version of the microscope camera.

Because of the necessary design changes brought to light by field testing the AMR prototype we have had to revise drawings which delayed the start of machining for production units. While the delay was unfortunate, we believe it will result in better long-term reliability.

We have initiated building of ten additional units for deployment on the James Reserve and for NEON, Inc. testing in Boulder, CO. At each location are 3 conventional minirhizotron tubes; housing for AMR units is in place along with two sets of sensor nodes. The entire system was described in Allen et al. (2007). While units are added as they are constructed, existing components can be studied to understand a range of ecosystem processes and physical, chemical, and biological regulatory parameters. AMR units are currently under construction.

**Data quality and gaps:** One concern that always follows use of sensor technology is the reliability and long-term viability of the sensor data. Two issues are of special concern. First, detecting when a sensor is providing unreliable readings. CENS engineers (Potte) have provided useful insights into evaluating reliability of sensor data as have others (e.g., Ellison et al. 2006- SciWalker) and a number of systems are under development for addressing this issue.

But another follow-up issue is interpolating data to reliably understand ecosystem phenomena when sensors cannot readily be replaced because removing the sensor would itself change the nature of the readings from the
surrounding sensors. In these cases, it may be more useful to continue depending on the interpolation rather than destroying the measuring array. Soil sensors are an example of this quandary. When a sensor fails, it cannot be removed without compromising the other buried sensors. Tom Schoelhammer and Deborah Estrin developed a program entitled “Vigilance” that incorporates missing data methods to evaluate the impacts of data loss and tests that against a pre-specified tolerance level. He then tested this model using the soil respiration data from the soil sensor array. Interestingly, different sensors have remarkably different effects on the measurement outcomes that can be predicted before deployment, which has huge impacts on choices of sensors, densities, and replacement issues. For example, inaccuracy due to temperature sensor failure does not significantly affect the understanding of spatial variation in respiration. However a missing CO₂ sensor has a dramatic impact. Thus, if a temperature sensor fails, one can live with a failed sensor. However, redundancy needs to be built into the CO₂ sensor network depending upon the lifespan of the study. Additional analyses and incorporation of this model are underway.

Incorporating N and AMR: Understanding of and predicting carbon flux requires measuring more than CO₂ and physical variables. N availability regulates N uptake. Soil fungi are far more efficient at obtaining that N than are roots, but exchange N with plants in exchange for C. The N taken by the plants is essential for building the photosynthetic machinery to fix CO₂ building plants and fungi. Therefore, to determine C fluxes and sequestration, ultimately all relevant parameters need to be measured. Generally, CO₂ fluxes alone are measured, and on occasion, plant production and root production. However, we are coupling CO₂, T, θ, NO₃⁻, NH₄⁺ with images of leaves, roots, fungal rhizomorphs, and even individual hyphae (Fig T2). The most unique feature is integration of frequent (daily) observations with continuous sensor data. Importantly, these do not exist in identical temporal or spatial scales, so understanding the dynamics of each parameter both separately and in relationship to the other variables are critical.

TEOS 01.5 Accomplishments
Sensor network for describing dynamics: Each sampling location was built using three conventional minirhizotron tubes and an AMR tube, and was instrumented with two sets of soil sensors consisting of solid-state CO₂ (Vaisala, CARBOCAP model GMM 220, range 0-10,000 ppm), soil temperature, and soil moisture (Decagon, ECHO) sensors at 2, 8 and 16 cm soil depths. All were emplaced in November 2005. The CO₂ sensors have been calibrated every six months after deployment to ensure the quality of the measurements. We calculated soil respiration from the soil using a CO₂ gradient flux method based on concentrations of CO₂ in the soil profile. The critical sensor data are T, water content (θ), CO₂ concentration, and atmospheric temperature (t), pressure (p), and humidity. The baseline soil information includes soil texture and water-holding characteristics. Together these can be used to calculate tortuosity, to determine soil and water impediments to gas flux.

The fluxes were modeled using Fick’s first law of diffusion. The details of these measurements and modeling are described in Vargas and Allen (2008, Vadose Zone).

The CO₂ flux modeled from sensor data correspond closely to CO₂ flux measured by soil chambers (LiCor 8100) (Fig T3).
Just as importantly, we observed a strong seasonal hysteresis with a lag in springtime respiration response to increasing temperature, and a lag in fall drop as microbes accessed soil moisture through small pockets unavailable to plants or via hydraulic lift.

**Addressing the spatial/temporal/biological interactions/complex terrain issue**

In collaboration with Professor Michael Goulden (UC Irvine), we began to evaluate C fluxes in the complex terrain of the James Reserve. We measured photosynthesis curves under varied light and temperature regimes, under different levels of soil moisture. Annual photosynthesis for the AMARSS transect was modeled using the photosynthetic data coupled with the changing light regimes from the camera systems previously described and moisture using the soil moisture sensors. Tower flux estimates of daytime photosynthesis + respiration, and nighttime measurements of respiration were contrasted against the modeled photosynthesis responses and soil respiration measurements. Over the year of measurements, the assimilation rates from the model and the tower were relatively similar and showed a similar annual trend. But respiration rates were dramatically different (Fig T4). Two hypotheses (not mutually exclusive) are being studied. First, intra-canopy leaves absorb much of the soil resired CO₂. We will test this hypothesis using natural abundance δ¹³C to see if there is a soil respiration signature in the mid-canopy leaves. Secondly, CO₂ drainage with the cold-air drainage previously reported by Graham and Rundel is a likely sink of CO₂. We will measure this potential flow using a low-level eddy-covariance system to track horizontal and vertical fluxes near the ground surface in likely airflow channels.

**Spatial dynamics**

It is known that soil respiration is dependent upon the vegetation biomass and composition. Further, that there may be lags in carbon fluxes due to diel carbon fixation and allocation patterns. By using the sensor network arrayed along a gradient at the site, where the vegetation shifts from a forest to a meadow, we also found that those lags were vegetation based. In the forest, there was a strong hysteresis effect in that as nighttime temperatures cooled off, respiration dropped rapidly. During the daytime, as plants began photosynthesis, soil respiration increased rapidly then peaked. Alternatively, in the meadow, dominated by grasses and forbs, the warming and cooling effects on soil respiration were the same. In the case of forests, using temperature alone as a predictor of respiration is likely to provide misleading results. However, in the
meadow, respiration is tightly coupled to temperature shifts. Thus, running a simple regression of Rs versus T provides a misleading measure of Rs. Lags differ in different ecosystems

Temporal dynamics
Using the conventional minirhizotron observations, we evaluated the temporal dynamics of root and rhizomorphs production and turnover. The literature of root turnover is dominated by an argument over whether isotopic retention models or minirhizotron are a true estimate of root turnover because the two approaches give quite different results. Further, the data in the literature show little correspondence between root production and dieback and respiration. One problematic issue is that minirhizotron observations are widely spaced (generally monthly to quarterly). Then a linear model is applied between the sampling times to age the roots or rhizomorphs. We undertook weekly minirhizotron observations, interspersed with daily campaigns, and coupled with continuous (not interspersed) measurements of CO₂ respiration, from which we could measure CO₂ production at different depths, thereby separating out root, mycorrhizal and saprobic activity. For this analysis, we processed ~70,800
images to track the fates of 721 individual fine roots. We also used AMR observations to verify some timing aspects of fungal dynamics (based on approximately 700,000 images).

We found several important outcomes. First, it is clear (Fig T6) that both production and turnover occur as dynamic, event-driven dynamics, not an evenly spaced production/death rate. Furthermore, these dynamics are not in equilibrium – they shift seasonally and between years.

In addition, we found that, in fact, there was good agreement between δ14C data and minirhizotron observations. The lack of fit in previous studies may be, in part at least, due to the infrequent minirhizotron observations coupled with an assumption of gradual change in ecosystem processes. Our data clearly show that both production and turnover are pulse driven, and vary among locations and with meteorological events.

The second analysis we were able to undertake using these data was to look at the physical and biological variables regulating the dynamics of CO2 production (biological respiration). Here we differentiate soil respiration (Rs) from CO2 production (PCO2). This is because Rs is strongly affected by T via diffusion, and by q because moisture forms a barrier to diffusion of the CO2 gas. Biologically, both roots and microbes (the largest biomass element are fungi, and the more observable are rhizomorphs) produce CO2 through cell respiration, regulated by their standing crop, growth, and mortality. T influences respiration by regulating enzyme activity via Q10 dynamics. q regulates roots and rhizomorphs via hydration. PAR indirectly affects CO2 production through impacts on photosynthesis.

As we previously reported, there are both seasonal and diel lags in soil respiration. One major assumption in the CO2 flux literature is that respiration can be predicted from temperature and moisture conditions, but lags and biological growth and mortality are ignored.

Using structural equation modeling (SEM- Fig T7), we found that the variable most closely associated with PCO2 was rhizomorphs dynamics. T and q directly drive rhizomorphs- and there is minimal lag in either production or mortality in response to changing T and q. However, roots show a large lag. Thus, while root production and mortality may relate to respiration at a seasonal to annual basis, predicting PCO2 is much closer tied to T, q, and microbial dynamics.

**Biological Interactions**

One goal is to integrate aboveground and below ground dynamics using multiple sensors that depict plant and soil activity. Sap flow technology measures water fluxes through plants, which is linked to the acquisition of CO2 at the whole-plant level. As plants open stomata to obtain CO2, water is transpired, pulling water through the vascular system. Sap flow measures the water moving through the vascular system, and therefore represents an indicator of CO2 fixation. A large fraction of the fixed C is allocated to roots and mycorrhizal fungi. By measuring sap flow of a number of trees comprising the soil networked location, we may be able to both look for temporal correlations, and feed information to photosynthetic models to look at water by CO2 interactions. In Fig T8, we report the initial seasonal trends (averaged daily sap flow measurements and soil respiration).

**Extreme Events: Hurricane Wilma**

In addition to measuring short-term dynamics, sensor networks may also allow measurement of responses to severe events. We deployed a soil sensor network at the El Eden Ecological Reserve to test functionality in tropical...
forests. Shortly after deployment, Hurricane Wilma, the most intense storm ever measured in the Caribbean Ocean, directly hit our research site. Most sensors worked into the storm, until batteries shorted out. But, then worked again after battery replacement when we could access the site. We learned about the components that caused sensor data loss, mainly too little solar input as the storm approached, and batteries in protective units that were not hurricane proof. But, both should be relatively easy issues to fix.

But, the data collected before the storm, into the storm, and then subsequent, allowed us to model soil respiration dynamics and are leading to new questions about the roles of extreme events in C and N flux models.

**TEOS 01.6 Future directions**

**Engineering activities**

- Deployment of AMR production units is scheduled for early summer of 2009.
- Modification, re-tooling, augmentation and relocation of the JR cold air drainage (CAD) are underway to better understand the relationship between CO2 and wind events. Some components from the original CMS system will be reused to help keep costs down and in a sense, extend the life of the original JR CENS sensor system.
- Development and preliminary design of a smaller and more portable AMR (AMR egg) is underway.
- Development and preliminary design of a CO2 reduction chamber is underway.

**Integrative data analyses**

Our primary goal is to maintain and extend observational and sensor networks, so that we can address the carbon fluxes and sequestration from the bedrock to the atmosphere. This includes three steps planned for next year. First, the completion and deployment of the remaining AMR units along the AMARRS/NIMS transect to track the production, mortality, and turnover of individual fungal hyphae and mycorrhizal symbioses. Second, we will place an additional soil sensor unit adjacent to the Goulden tower. Coupled with that unit will be an eddy-flux unit and multiple anemometers and T probes to measure downhill CO2 flow that compromises the tower flux measurements in complex terrain. The data outputs will be tested against d13C measurements of canopy fixation to determine the importance of respired soil CO2 in the intra-canopy and downhill flow dynamics. Finally we are exploring use of complex analysis and modeling approaches to integrate the data collected, and examine the characteristics of a number of ecosystem models.

**TEOS 01.7 External Partnerships:**

Michael Goulden, University of California-Irvine; Susan Trumbore, University of California-Irvine; Hank Loeshler, NEON, Inc.; Rodrigo Vargas, University of California-Berkeley; Dennis Baldocchi, University of California-Berkeley.

Organizations: NEON, Inc., Boulder Colorado, Kearney Agriculture Foundation, UC Agriculture and Natural Resources.
TEOS 02 Avian Nestbox Studies at the James Reserve

TEOS 02.1 People

- Principal Investigator: John Rotenberry
- Faculty: John Rotenberry, Department of Biology, UCR
- Staff: Michael Taggart Center for Conservation Biology, Engineer; Thomas Unwin, Center for Conservation Biology, Engineer; Rebecca Fenwick, Field Station Director, James Reserve NRS, UCR.
- Graduate Students: Sharon Coe, Department of Biology, UCR.

TEOS 02.2 Overview

Avian studies being conducted at the James Reserve using imagers and environmental sensors have focused on species of birds that typically nest in holes (also known as cavities) in trees ("cavity nesters"). These species often occupy human-constructed nesting boxes when they are made available. Numerous studies use such data due to the ease with which the nest contents can be viewed relative to natural tree cavities.

- Employ image capture from wired video cameras in nestboxes to obtain data for biological applications.
- Collect data necessary to analyze and improve functionality of Cyclops as biological sensors for avian studies.
- Use embedded network sensing of environmental variables to correlate with video-based remote sensing
- Evaluate microclimatic influences on nesting activity and nest success in secondary cavity nesting birds.
- Collect data to test video content analysis software approaches for automated classification of avian behavioral activities from nest box video images in real time at remote nest sites.

TEOS 02.3 Approach

Our work is focused on recording still images inside nestboxes using either wired or wireless camera systems to record bird behavior, primarily during the breeding season in spring months. In addition, we are measuring environmental characteristics of the immediate nesting environment (i.e., inside the nestbox) including temperature, humidity, and dew point, as well as near the nesting environment (i.e., outside of the nestbox). Light intensity (Photosynthetically Active Radiation, PAR) and soil moisture content are also measured near the nestboxes. The environmental data and associated nestbox images are being used to answer questions about bird breeding behavior and breeding success.

TEOS 02.4 System(s) Description and/or Experiments

Images and data continue to be collected as in previous years. No specific experiments have been conducted during the past reporting year.

TEOS 02.5 Accomplishments

Completed the first formal statistical analysis of patterns of hatching asynchrony as a function of patterns of diurnal and nocturnal nestbox occupancy patterns of nesting Western Bluebirds and Violet-green Swallows. Our research question was: Does nestbox occupancy prior to clutch completion lead to hatching asynchrony in cavity nesting species? Hatching asynchrony is a significant life history trait as it typically results in within-brood size hierarchies. Such size hierarchies are associated with reduced survival of later-hatched (smaller) nestling, and usually result from onset of incubation with laying of penultimate egg. Cameras mounted in ceiling of nestboxes recorded images every 8-15 minutes, from which we calculated the proportion of images showing a bird in the nestbox during laying, and at 7 days after clutch completion (when incubation should be fully in progress). Diurnal occupancy was recorded between 10:00-16:45 hours; nocturnal occupancy was assessed by the presence of a bird in the nestbox at 01:00 hours.
Western Bluebirds showed higher *diurnal* nest occupancy as early as 2 days before Violet-green Swallows. Mean diurnal occupancy for bluebirds (n = 17) was significantly (P < 0.01) greater than for swallows (n = 11) on the penultimate day of laying, as well as on the ultimate day, but not on the first day. Violet-green Swallows showed greater *nocturnal* occupancy than Western Bluebirds. In 100% of swallow nests, one or both adults occupied the nestbox all nights between the laying start and clutch completion, whereas bluebird nocturnal occupancy ranged 0-100% of nights over the same period. *Both species showed hatching asynchrony.* However, under the typical synchrony definition (“all eggs hatched within a 24-hour period”), more swallow nests were *synchronous* than asynchronous. In contrast, if we define a synchronous nest as one that hatched within 1 calendar day (not 2), then more swallow nests were *asynchronous*. A nest whose eggs hatch over 2 calendar days can be expected to show greater nestling size variation, since the nestlings from two eggs that hatch near each other during the daytime should be closer in size compared to two eggs that hatch on separate calendar days; the intervening nighttime hours when nestlings go unfed are not equal to daytime hours when parents do feed regularly.

**TEOS 02.6 Future Directions**

No new initiatives are proposed at the James Reserve. Monitoring and data collection at the Reserve will continue until existing funding is completed.

Remaining energies will be devoted towards two tasks:

- Sifting through existing image and variable databases to answer biological research questions posed at the outset of the project.
  - Nestbox use during the non-breeding season (night-roosting)
  - Environmental variation among nestboxes with respect to nest site selection and adult breeding behavior
  - Inter-species competition for nestboxes
  - Laying patterns and behavior
  - Incubation (onset of behavior)
  - Fledging (variation in fledging date among nestlings within a nest)
- Exploration of the redeployment of the system (a) to monitor open-cup nests, and (b) to establish a monitoring network on a different reserve with less technically sophisticated infrastructure. The latter addresses the question of whether this or a very similar system can be exported to potential users.
TEOS 03 EcoPDA for Environmental Applications

TEOS 03.1 People
- Principal Investigator: Jeffrey Goldman
- Staff: Taimur Hassan, Eric Graham, Eric Yuen

TEOS 03.2 Overview
Today's handheld computers incorporate low-power processors, wireless communication capabilities, and flexible sensor interfaces, making them extremely useful in a wide variety of personal and industrial applications. The convergence of personal data assistants (PDAs), cellular telephones, and ultra-mobile PCs has resulted in the appearance of handheld devices that are highly programmable, contain integrated sensors, such as cameras, microphones, and global positioning system (GPS) receivers, and can communicate with a variety of peripheral devices and platforms. To date, environmental monitoring efforts have incorporated these sophisticated devices in basic ways, but they have not yet capitalized on the substantial computational, sensing, and communication capability contained in the devices realize gains in data quality and to enable entirely new data collection methods. With EcoPDA, we have moved beyond what is currently commercially available for industrial data collection and supply chain management applications to create an advanced handheld sensing and computation platform for environmental scientists. There is a great deal of opportunity to innovate on the environmental data collection methods that scientists can use with mobile devices. First, consider the relatively straightforward example of using handhelds as a primary data documentation tool in biodiversity sampling—the process of estimating the type and abundance of plants and animals in a habitat. Direct sensors for such tasks are generally unavailable (though CENS is an innovator in the use of sounds and images for this purpose) so manual observation is required. Even when investigators acquire physical and chemical data about a habitat of interest via an embedded sensing system, manual biological sampling is still required to complete many environmental studies. Currently, the vast majority of such in-field sampling efforts are initially recorded by hand on paper before being re-encoded digitally in the laboratory. The use of a handheld computers as the primary data collection tool can eliminate the error-prone paper-to-digital encoding step, offer automated data collection, and improve data quality in the following ways:

- Prompting a user to enter both data and metadata according to standard protocols and formats
- Automating routine tasks (e.g., time and date stamping)
- Checking data validity (e.g., using drop-down menus or pre-determined rules)
- Automatically geo-referencing data
- Enabling convenient collection of multiple data types (e.g., alpha-numeric, image, and sound) as primary or contextual information
- Securing data through regular and automatic upload via wireless connections
- Additionally, handheld computers can offer more advanced support through wireless connectivity to other handheld computers, peripheral handheld sensors (e.g., RFID readers), embedded sensing systems (e.g., SensorKit), data stores (e.g., SensorBase), and even online resources (e.g., species identification keys) if Internet connectivity is available. Greater power may lie in real time computation occurring in the field (on a single device or on a laptop receiving data from several devices simultaneously) with the resulting information being fed back to investigators to inform the sampling process. For instance, field crews surveying a vegetation transect can be instructed when their sampling is sufficient based on a statistical determination of population parameters such as species abundance and distribution metrics. Such real time sampling design or real time statistical testing can result in both saving valuable field-crew time and in creating more robust data sets relative to an a priori sampling design approach. All of these areas—improving data quality, exploiting networked operation, and developing approaches for statistical computing in data collection—are central to CENS research and development objectives, and all can significantly improve data collection for environmental
scientists. Furthermore, the center’s work on handheld computers for environmental applications and participatory urban sensing can be mutually beneficial in that both areas study how to capture and use location information and images, how to provide useful user interfaces, and how to develop applications for mobile operating systems.

**TEOS 03.3 Approach**
The Tropical Ecology Assessment and Monitoring (TEAM) network, a division of Conservation International, is a distributed federation of tropical ecologist with the mission to monitor and explain changes in tropical biodiversity. For several years we have collaborated with members of the TEAM network on EcoPDA development. In October 2007, we began a project to develop mobile applications in support of protocols for sampling of butterflies, and vegetation.

**TEOS 03.4 Accomplishments**
EcoPDA is a Windows Mobile application that uses a SQL compact database stored locally on the device. It has been developed to support the implementation of two TEAM protocols, the butterfly and vegetation using Visual C#. The application has been developed with future updates in mind. When changes in protocols take place, whether it is through the renaming of various data collection fields, or of inclusion of new fields, it can be easily accommodated through modifications of certain rows and tables in the database itself rather than through source code. EcoPDA supports English, Spanish and Portuguese with capacity for more languages. When users turn on the application, they see a menu that lets them chose the sampling period (as defined by the protocol), the observers as well as the protocol they would like to initiate. Once they make their selection, they are taken to the respective protocol’s interface. There is a map view that lets users select the current trap they are visiting, and jump to the trap’s data entry screens. In the butterfly protocol, there are three ways to interact with the application to access data, one is via a table view (like a spreadsheet), one is a form view (like a web form), and one is a spatial view (incorporating simple, interactive diagrams of plots/subplots showing fixed locations and allowing dynamic redrawing based on the data entered). The data entry screens offer time saving features such as combo box lists that automatically fill in the appropriate order, family and genus for captured butterfly species. Other time saving features include an automated form that helps users fill in commonly used codes for trap conditions as well as a picture thumbnail viewer that can be used to aid the recognition of certain species of butterflies.

For the vegetation protocol, similar to the butterfly protocol, users first see a map rendition of a selected plot of land where the census is to take place. The user can then select a particular subplot within the plot, views a map that shows all of the trees and lianas within the plot. Users can select a single tree/liana specimen, and are taken to a screen where the vegetation data is displayed as part of a spreadsheet or form. Time saving features such as those in the butterfly application are included within the GUI, as well as other features such as data input range checking, which compares the data entered to the previous year’s data for a particular tree, pre-filling of certain data fields that only rarely change from year to year, such as Point Of Measure (POM) and vegetation condition codes. The application’s export routines are complete. This feature allows data to be transferred to a field station’s desktop in XML format. This file is easily opened in Excel and conforms to the current TEAM export format standards. The system and its data has been developed using input from several members of the field data collection team. User interviews revealed a range of preferences for types of keyboards and the trade-off between screen size and device bulkiness. Since the system has been developed for the Windows Mobile, it allows for great flexibility in choosing the hardware. The HP 211 enterprise PDA is a device we found very acceptable, with a large screen which connects with any Windows desktop. TEAM field sites are remote and have limited connectivity.
(some have internet at a field station, none have internet at the site of sampling), thus data are written to the on-board flash memory and some form of removable media (removable backup). This allows EcoPDA to store backups to the media every few minutes to reduce the chances of data being lost during a census. The EcoPDA application has been packaged into a self-installing cabinet file and redistributed for evaluation at various TEAM field sites. In addition, an ‘emulator’ file has been also created and placed on a public webpage. The file allows desktops with special Windows Mobile Emulator software installed on them, to render within the OS, a fully interactive representation of how the application is to behave within a Windows Mobile device.

TEOS 03.5 Future Directions
We used EcoPDA as a learning platform for a summer internship program. The result of the work done by three teams of interns gave us ideas as to how we could enhance EcoPDA in later iterations. One team of interns used EcoPDA to capture geo referenced images via an external webcam as well as an external GPS receiver. These images can then become part of the data collected on species and uploaded to the desktop. The second team developed a system whereas XML files generated on a desktop could be transferred and read by the EcoPDA on startup. The file would contain data such as plot and personnel information that are specific to a particular site. This flexibility would be a convenient way updates can be pushed to PDA from the TEAM headquarters. The third team developed on-board processing capability for picture recognition. Sensors such as laser range finders and barcode readers have also been tested, with possible deployment for data collection in future versions. Students eventually were able to use the modifications, along with some source code changes for using EcoPDA for taking beach pollution measurements using different sensors connected to a PDA.

TEOS 03.6 External Research Partnerships
Tropical Ecology Assessment and Monitoring Network, Conservation International
TEOS 04 Plant Phenology using Ground-Based Cameras

TEOS 04.1 People
- Principal Investigator: Eric Graham

TEOS 04.2 Overview
The use of imagers as biological sensors has been a main focus of CENS in the last year. One aspect of this is the identification of methods and approaches to identifying plants in natural area images and quantifying aspects such as total leaf area, numbers of flowers, and changes in seasonal vegetation cover. We have been exploring the use of color transformations and probability distributions to segment natural images for quantifying plant phenology.

TEOS 04.3 Approach
Natural scene images have uncontrolled lighting. To avoid some of the more extreme lighting conditions, we have been capturing images from the James Reserve webcams in the early morning and late afternoon. Nevertheless, shadows and changes in the color of the illumination make classification of plant parts difficult in that the color variation within the image is principally dominated by variations in luminance due to lighting conditions.

To address this problem, a variety of transformations of the RGB color space have been used by other researchers. Linear transformations, relying upon color difference to reduce the effect of luminance, as for the Yxy, HSV, HSL, ATD, and Lab color spaces. An alternative approach is to normalize the color channels to cancel the effect of illumination intensity, as for the NDI, Normalized RGB, Excess RGB color spaces. This alone, however, does not compensate fully for outdoor lighting variation and so an approach using semi-supervised clustering of chromaticity values to characterize plant and background pixel colors was attempted. As a further test, an ideal color space will have adjacent colors that are more similar to the natural colors found in outdoor scenes, such that smoothing of the color space probabilities will result in better prediction of plant parts from background.

TEOS 04.4 System(s) Description and/or Experiments
We have created three training sets of images: (1) a set of rhododendron leaf images from bud burst to full leaf flush with soil and branches in the background, (2) a set of wallflower images, where wallflowers are yellow against a soil background, are a very small percentage of the images, and counts of flowers is more important than numbers of pixels identified, and (3) a set of Ceanothus flower images that contain blue flowers against a background of green leaves.

We have created a system where these training sets of images are masked for the regions of interest and then pixel counts of values of color components (e.g., only a Red value of 150 in the Red-Green-Blue color space) are created for masked regions and whole images. The counts of pixels in the masks for values of a specific color component are then divided by the counts for the entire image for the same values of color, resulting in a probability that a pixel value in a color component belongs to the foreground or background. These probabilities are then used to predict foreground vs. background in non-training set images (we used >50% probability to classify foreground from background).

The color spaces tested include three-dimensional color volumes, many derived from the Commission Internationale de l’Éclairage (CIE) systems of

Figure. 1. Relative ranks for color spaces for separating various plant parts from the background in natural images.
modern colorimetry: RGB (native to the camera), Lab (CIE uniform color space), Hue-Saturation-Value (HSV), Hue-Saturation-Luminance (HSL), Achromatic-Tritanoptic-Deuteranoptic (ATD), i123 (Ohta et al. 1980), XYZ (CIE tristimulus), Yxy (CIE chromaticity).

Two-dimensional color areas were also tested, many just the chromatic coordinates of the above 3D color volumes: TD (of ATD), xy (of Yxy), HS (of HSV), HS2 (of HSL), ab (of Lab), ExRGB (a 2D plane representation of the 3D Excess Red, Excess Green, and Excess Blue color volume [Excess Red is defined as 2R-G-B, others are similar]), ATD2D (a 2D projection of the ATD color volume), Normalized RGB (a 2D projection of the 3D color volume [Normalized Red is defined as R/(R+G+B), others are similar]), Normalized Difference Index (NDI; Perez et al. 2000).

Additionally, a one-dimensional color value was tested, a shadow-invariant transform (Marchant and Onyango 2000).

A segmentation quality index was used to assess the ability of a color space to segment the foreground from the background. Quality ranges from 1.0 for a perfect match between the user-generated mask and the automatic image segmentation to 0.0 for no match:

\[
Q_{\text{seg}} = \frac{\text{correct segmentation count}}{\text{correct count} + \text{incorrect count}}
\]

Where the incorrect count is of those pixels identified by the mask but not the segmentation plus those by the segmentation of the image and not by the mask.

TEOS 04.5 Accomplishments

Testing continues, however results with different vegetation indicate that a few color spaces are better at distinguishing plant parts from background, specifically the ab, ExRGB, and HS color spaces (Figure 1). Additionally, due to the limited training sets used for creating pixel probabilities, some color space values are absent, creating “holes” in the predictive matrix (Figure 2). Such holes contribute to the success of a color space for correctly segmenting images.

TEOS 04.6 Future Directions

Work is almost complete. We will add an image sequence for testing the separation of green leaves of oak from that of pine or cedar. We will then re-run the tests with the color spaces “smoothed” to remove the holes in the color spaces to then decide on a best color space to use for our natural images.

After this work is complete, we will then use this method for identifying and quantifying the phenology of various species of plants captured by the James Reserve tower cams and other available cameras.
TEOS 05 Use of High Dynamic Range Imaging in Ecological Studies

TEOS 05.1 People

- Principal Investigator: Eric Graham
- Staff: Eric Graham, Eric Yuen
- Graduate Students: John Hicks

TEOS 05.2 Overview

The use of tiered systems of sensing, comprised of high-resolution, high accuracy “spot” sensors placed in the environment coupled with a lower resolution but wider “field of view” sensor, such as a camera, has been proposed as an efficient method of measuring heterogeneous environments. We have designed such a system and deployed it at the James Reserve, where multiple photosynthetically active radiation (PAR) sensors were deployed in the understory near a bracken fern colony alongside a pan-tilt-zoom (PTZ) camera that recorded fern frond reflectance using high dynamic range (HDR) imaging. We have now made a correlation between the reflectance from the ferns and the PAR they received, allowing us to model fern frond photosynthesis over the entire understory colony.

TEOS 05.3 Approach

Measuring light in a heterogeneous understory, specifically sunflecks, is difficult because of the transient nature of the patches of light and the spatially complex patterns they create. Capturing the spatial distribution of sunflecks would require many fixed PAR sensors or a fewer number of mobile PAR sensors. Alternatively, a camera with a wide view of the environment, if calibrated with fixed PAR sensors for the reflectance of a uniform surface, can be used with each pixel acting as a PAR sensor. One issue with using cameras as sensors is that automatic gain, shutter speed, aperture, and white balance (all designed to make visually appealing images) remove the necessary data that can be used for calibration purposes. Overriding the automatic setting and creating HDR images by combining multiple images of the same scene captured with different shutter speed and aperture combinations allows us to calibrate the resulting image to the actual light intensity received by the camera. A calibration of received light intensity to that measured in situ will allow us to correlate pixel values to PAR values.

HDR images are created in a number of steps. To capture a regular image, a digital camera employs a number of red, green, and blue sensors behind a lens. The camera reads the amount of light hitting each sensor, and translates these values into an image. Each image contains a number of pixels and each pixel contains a red, a green, and a blue byte value that ranges from 0 to 255. We assume the existence of a non-linear transformation from the light read at the sensors to the final byte values of the image. The first step to create an HDR image is to capture a number of images at various exposures, and use the images to recreate this transformation curve. The inverse of the transformation will take a byte value from 0 to 255 and return the actual value read at the sensor. An example of this transformation can be seen in figure 2.

To create the actual HDR image we again take a number of images of a scene using various exposure settings. For every pixel location, we look at every image and translate the byte value back into a sensor value multiplied by the
exposure settings. Since we know that the camera sensors are most accurate when returning values from the middle of their range (e.g., 127), we weight values near 127 more than values near 0 or 255 (the edge of the sensor range). In theory, for every pixel location we will find at least one image with exposure settings that give around a 127 byte value. In the end, the HDR image is a weighted average of the byte values translated back into sensor values using the calibrated transformation from above.

The advantages of HDR images are many. They allow us to capture meaningful images in almost any lighting condition, even when half the image is in direct sunlight and half the image is in dark shade (a condition that would cause a normal image to lose information). Since we have more detail, many automatic image processing algorithms work better. Also, the HDR image algorithm conveniently provides us with a relative luminance value at each pixel. In theory, this should directly relate to the actual amount of sunlight reflecting off an object. The main disadvantage of HDR images stems from the fact it can take up to 30 seconds to take the required images. This allows within image movement, such as plants waving in the wind, to cause blurring and other artifacts.

**TEOS 05.4 System(s) Description and/or Experiments**

Six Licor PAR sensors were deployed at approximately 1 m height in different locations around an area of bracken ferns at the James Reserve. The sensors were attached to a Campbell Scientific datalogger which collected PAR data at 2 s intervals from all sensors and relayed the data via Bluetooth to the NIMS 1 PC/104. The NIMS 1 also carried a Sony PTZ camera, which was tasked with constantly capturing images over the course of a day of areas of bracken ferns that included PAR sensors. Each capture was composed of a sequence of images that included multiple shutter speed and aperture combinations.

To properly combine the images into a single HDR image, each pixel at a specific position in an image must match the same pixel in each of the other images. However, the wind tends to cause the camera to sway as well as the ferns themselves. Camera movement causes the image to be shifted slightly and can be corrected using freely available open source image alignment tools. Hugin tools, a package originally designed to stitch together images to create panoramic views, works well for this. We have created a set of scripts that use these tools to automatically align the images and to drop any images that are too far off to be accurately aligned. Dealing with the ferns themselves moving in the wind is theoretically possible using the latest image techniques, but we have not felt it worthwhile to explore that route. We simply drop images that have too much within image movement.

Once the images are aligned, we use another set of open source tools to transform them into a single HDR image. Again, we have created scripts to automate this process. The scripts reads in the aligned images, creates the HDR...
image, and for every HDR image creates a log file containing details such as the time range in which the HDR image was taken. Once the HDR image is created, we can find a relative luminance value for every pixel.

To create a calibration of HDR luminance to PAR, masks of fern surfaces near the PAR sensor were manually created and applied to a subset of images. Then average pixel luminance values indicated by the masks are regressed against PAR values taken concurrently. An example of calibration data is in Fig. 2.

**TEOS 05.5 Accomplishments**
Calibration indicates that a linear relationship exists between luminance values in the HDR images and PAR.

**TEOS 05.6 Future Directions**
Next steps include applying the calibration to the HDR images captured through the day and then comparing the PAR distributions to the locations of bracken ferns. Photosynthetic light response curves have already been established and the calibrated pixels will be fed into this physiological model, assuming no other limitations to photosynthesis, and net carbon for a day will be estimated. Percentage of net photosynthesis under direct versus sunfleck conditions and minimum light requirements will be calculated.
TEOS 06 Networked Naturalist

TEOS 06.1 People
- Principal Investigator: Eric Graham
- Faculty: Deborah Estrin.
- Researchers: Eric Graham, Eric Yuen, Nithya Ramanathan
- Graduate Students: Sasank Reddy, Olmo Maldonado
- Undergraduates: Edi Rocha Guerrero, Adam Brenner, Saro Meguerdichian, Guadalupe Hernandez

TEOS 06.2 Overview
National field campaigns, such as Project BudBurst harness the power of Citizen Scientists to create valuable ecological data for scientific investigations while providing participatory learning experiences for volunteers. Ubiquitous technologies like Internet connectivity, mobile phones, and “Web 2.0” social networks are poised to transform the reach and effectiveness of these campaigns. Networked Naturalist was the first attempt to create a web + mobile data collection system for the CENS collaboration with Project BudBurst. The Networked Naturalist will enhance participation in Project BudBurst by making data collection exciting through immediate text and graphical feedback as well as by expanding the range of methods available for data collection (web, email, mobile phone text and images). Access to expert and peer-based discussions will engage participants, add to their knowledge, and reinforce the community of participating individuals. The overarching goal of The Networked Naturalist is to enhance participatory learning experiences via Citizen Science campaigns and transform the associated learning process.

We wish to increase participation and retention in Citizen Scientist campaigns through three avenues afforded by the use of new technologies:

- Opening the methods for successful data collection, as through the web, email, mobile phones, and automatic data uploads from user-owned hardware.
- Providing immediate feedback on data through automated analysis and real-time display of graphical and map-based representations of participant’s data.
- Leveraging the tremendous participation in social networking sites to further enhance the user experience, as well as expand and retain participation.

TEOS 06.3 Approach
We are creating a robust data collection system to enhance citizen science learning for users, to ensure data quality and improve data submission techniques, transforming Citizen Science campaigns for the digital era.

TEOS 06.4 System(s) Description and/or Experiments:
Networked Naturalist is an open-source platform to manage Citizen Science data collection campaigns. Our primary goal is to design Networked Naturalist to be easy for anyone to use, and easy for developers to extend.

Networked Naturalist will support the three phases of a Citizen Scientist campaign:
• **Creation** – defining the campaign and recruiting participants
• **Data collection** – participating through easy to use interfaces
• **Data analysis** – processing, compiling, modeling, visualizing and sharing results

Networked Naturalist will need to manage terabytes of data, hundreds-to-thousands of participants, occasional software revisions, and changing data analysis algorithms. These features combined will while support many simultaneous campaigns.

Currently, Networked Naturalist users can:

- Use the website to set up plants that they would like to observe.
- Submit SMS, MMS, and email messages with observations, attached images, and reminder notes on their plants.
- Receive confirmation messages, error messages, or query responses over SMS and email.
- Access, sort, filter, and visualize individual data or everyone's data over a web interface.
- Modify or delete old observations.

**TEOS 06.5 Accomplishments**

Our pilot campaigns have indicated that campaign organizers and system designers are able to easily and systematically manage all of the entities, system components, and information flow involved in supporting a campaign from start to finish.

Networked Naturalist is extensible, built on top of Code Igniter ([http://codeigniter.com/](http://codeigniter.com/)), an open source PHP Framework for web applications. Code Igniter uses the Model-View-Controller approach, which allows separation between logic and presentation. The data is stored in a MySQL database which is managed through PHPMyAdmin. By separating data management from the web pages, Networked Naturalist is easier to manage and modify.

**TEOS 06.6 Future Directions**

We will be newly adopting the system pioneered by Sasank Reddy for incorporation existing web-based services and systems into our data flow.

**Near-Future Capabilities:**

- Protect participant privacy. Sensitive information submitted to the project includes: location coordinates of personal plants; personal login and contact information.
- Include social forums on the website, and a better interface to other social networking sites such as MySpace, Facebook, and Friendster.
- Incorporate GIS visualizations that will draw on external data-streams, from freely available meteorological data to user-uploaded spatial data sets.
- Allow alternative data inputs, such as from personal webcams or from image sharing websites such as Flickr, with some automated analysis of such data.
- Continue with increasing robustness features to save data during crashes and identify faulty inputs.
- Store data in the database with an open API so that anybody can access their own data and “anonymized” versions of others’ data using a programmatic interface.

**TEOS 06.7 External Research Partnerships**

Sandra Henderson at UCAR, lead on Project BudBurst (pending grant proposal, future collaboration is also planned)
TEOS 07 North American Webcams

TEOS 07.1 People

- Principal Investigator: Eric Graham
- Staff: Eric Graham, Eric Yuen
- Graduate Students: Erin Riordan, John Hicks

TEOS 07.2 Overview

Expanding on the plant phenology monitoring program established at the James Reserve, we have accumulated a list of over 1400 freely available webcam image streams on the Internet that include some sort of plant life in their field of view. We are collecting images twice daily from each of these cameras and will compare the spring “green-up” as observed with this ground-based system to that observed by standard, freely available remote sensing products.

TEOS 07.3 Approach

Webcams were collected using standard Internet search engines. Images were geo-located by IP address and other metadata and then assigned to a time zone. An image is retrieved at 10 am and 2 pm from each camera based on its local time zone. Archived images are now being processed to determine the “greenness” of the image with the per-pixel transformation of Excess Green. This greenness signal is then fit with a double sigmoid function similar to that used for fitting remote sensing data. Remote sensing data for the surrounding pixels associated with each camera will then be compared to this ground-based data. Analysis of faults and reliability of data compared to remote sensing products is one goal of this project.

TEOS 07.4 System(s) Description and/or Experiments

The URL of each camera and its associated metadata is stored in a MySQL database. Twice a day, a wget is scheduled to retrieve an image from each URL. Images were stored on the file system with a link to the image location and image metadata stored in a database. After each image is collected, the average excess green of the image is calculated and stored with the image metadata in the database. Excess green was calculated for each pixel as:

\[ 2G - R - B \]

where G is the green channel value of the pixel, R the red channel value, and B the blue channel value. This was calculated for the entire image and then averaged to receive a single value for each image.

For select cameras, a mask was created to separate out a specific vegetation types. For these images, only the pixels of the target region (vegetation) were averaged. If multiple masks exist for an image, the average excess green value of the image was calculated with each mask separately.

Remote Sensing

Satellite-derived vegetation metrics have enabled the detection of phenological events over large geographic extents. Among the highest temporal resolution remote sensing products are those from the MODIS (or Moderate Resolution Imaging Spectroradiometer) instrument aboard the Terra and Aqua satellites. These satellites make daily passes over the entire Earth’s surface, allowing for the production of daily remote sensing imagery. These daily products, however, are inherently noisy, as sensor malfunctions, cloud cover, atmospheric conditions, etc. reduce their functional temporal resolution. For biological processes where fine scale temporal shifts can have huge ecological impacts, such as the timing of phenological events, high quality daily monitoring is necessary. Internet webcams, which have the capacity to produce multiple images in a day and are likely to be less sensitive to cloudy weather and potentially certain atmospheric conditions, may have an important advantage over satellite imagery in detecting these fine scale shifts. In addition, they share a number of advantages over on the ground monitoring,
such as enabling the monitoring of remote or large areas at a high frequency with low man-power and cost. Currently, internet webcams represent an untapped resource in ecological and environmental monitoring.

**Remote Sensing Data**

We will compare camera “greenness” to satellite-based NDVI “greenness” calculated from three different MODIS products: 500m resolution daily surface reflectance (MOD09GA), 500m resolution 8 day composite surface reflectance (MOD09A1) and 500m resolution 16-day composite vegetation indices (MOD13A1).

MODIS data is freely available through the Warehouse Inventory Search Tool (WIST: [https://wist.echo.nasa.gov/~wist/api/imswelcome/](https://wist.echo.nasa.gov/~wist/api/imswelcome/)), a client for searching and ordering earth science data from various NASA and affiliated centers. All MODIS data products come in 10 x 10 degree (latitude x longitude) tiles, stored in a compressed data format HDF-EOS (Hierarchical Data Format – Earth Observing System). Each HDF file contains ‘science data sets’ (SDSs) that include product quality information by pixel. The 8-day surface reflectance composite product is available at an aggregated conterminous US coverage in WGS84 projection from the University of New Hampshire’s (UNH) Earth Science Information Partner (ESIP), EOS-WEBSTER ([http://eos-webster.sr.unh.edu](http://eos-webster.sr.unh.edu)).

The MOD09GA and MOD09A1 products include surface reflectance in both the red (620nm–670nm) and near infrared (841–876nm) ranges, MODIS bands 1 and 2 respectively. A satellite-based Normalized Vegetation Index (NDVI) can be calculated as follows:

\[
\text{NDVI} = \frac{(\text{NIR} - \text{RED})}{(\text{NIR} + \text{RED})}
\]

Where NIR = near-infrared reflectance and RED= red reflectance. The MOD13A1 16-day composite product includes two vegetation indices (VIs) that have been calculated from the MOD09 daily surface reflectance product: NDVI and enhanced vegetation index (EVI).

In the 8-day surface reflectance and 16-day vegetation index composite products, a filter has been applied to each pixel collected over the course of 8 or 16 days (respectively), so that only the highest quality, cloud free pixels are then retained in the final image. This is often necessary, as image quality is sensitive to numerous factors such as cloud cover, atmospheric conditions, and sensor malfunction, making it difficult to obtain high quality data at a daily temporal resolution. Because of their generally higher quality, these composite products are often more commonly used despite their lower temporal resolution. Temporal shifts in phenological events, by even just a few days, however, can be highly relevant biologically. Such fine scale changes would not be detectable from composite images and may be difficult to detect in the noisier daily satellite images.

By comparing green-up and senescence signals from camera and satellite imagery at a daily scale, we can compare data quality and reliability from both sources. We aim to illustrate the ability of webcams to detect fine scale phenological shifts. We will also compare green-up estimates of daily camera and satellite images with those from the ‘cleaner’ 8 day and 16 day composite satellite images to determine the cost of sensitivity with increased product quality.

**Image processing and data extraction**

One disadvantage of satellite imagery products is that they often available in data formats that are difficult to manipulate and require a number of processing steps before they can be utilized in a geographic information system (GIS) or before data can be extracted from them. The native sinusoidal projection of MODIS data products can be difficult to work with. For the daily surface reflectance and 16-day vegetation index products, all data files must first be reprojected to a more standard projection (wgs84) using free software MODIS Reprojection Tool (MRT v 4.0; [https://lpdaac.usgs.gov/lpdaac/tools/modis_reprojection_tool](https://lpdaac.usgs.gov/lpdaac/tools/modis_reprojection_tool)).

Some processing is performed on MOD09 daily and 8 day products (and thus the derived MOD13 vegetation index product) prior to their distribution to correct for atmospheric scattering and absorption and fine cirrus clouds (Vermote and Vermeulen 1999). Quality assurance data sets about initial atmospheric conditions, cloud cover, sensor function, etc. are available for each product, stored as an additional SDS within the HDF file. These files are in a bit-format and include information for the images pixel by pixel and must be ‘unpacked’ before data extraction.
We used free software tools to unpack data quality information available through the MODIS Land quality assessment group (LDOPE tools; Roy et al. 2002).

All HDF files must then be converted to a more ‘readable’ format before data corresponding to our webcam locations can be extracted. We are using a script to run ncdump (downloaded software) to extract the data in the HDF files into human readable ascii files. Surface reflectance, vegetation index, and quality information can then be extracted from each pixel corresponding to the geographic location of each georeferenced webcam. For MOD09 surface reflectance products we extract values for band 1 and band 2, then calculate an NDVI value following the above equation. For the MOD16 vegetation index product, we extract the pre-calculated NDVI value.

The quality information for each product can be used to set a minimum threshold for acceptable quality of satellite-based measures. This cleaned data can then be curve-fit and compared to webcam green-up and senescence signals.

**Satellite Product Quality Information:**
Following Soudani et al. (2008) we fit a double sigmoid function to the extracted NDVI values to extrapolate dates for phenological events. The same approach is applied to the Excess Green measurements per camera. The double sigmoid is calculated as:

\[
\text{NDVI} = (w_1 + w_2) + 0.5 * (w_1 - w_2) * [\tanh(w_3 * (t - u)) - \tanh(w_4 * (t - v))]
\]

Where tanh is the hyperbolic tangent, \( t \) is the time (day of year), \( (w_1 + w_2) \) is the NDVI minimum in the non-leafy season, \( (w_1 - w_2) \) is the total amplitude of the NDVI signal, \( u \) and \( v \) are the dates corresponding to the highest rates of change of NDVI equal to the dates of the two inflection points when NDVI increases (date of spring) and decreases (date of fall).

**TEOS 07.5 Accomplishments**
We have successfully collected images twice daily from about 1400 webcams across the continental US and Canada since February 15th, 2008. We are continuing to collect data from these cameras.

A subset of the cameras has been chosen to test out methods for data extraction. Masks were created to remove portions of the image that were not vegetation in order to reduce signal noise. One such data stream is indicated in Figure 2, where Excess Green has been calculated for the areas that include

<table>
<thead>
<tr>
<th>Cloud state</th>
<th>Aerosol Quantity</th>
<th>Cirrus Clouds</th>
<th>Snow/Ice</th>
</tr>
</thead>
<tbody>
<tr>
<td>cloud</td>
<td>climatology</td>
<td>none</td>
<td>present</td>
</tr>
<tr>
<td>clear</td>
<td>low</td>
<td>small</td>
<td>absent</td>
</tr>
<tr>
<td>mixed</td>
<td>average</td>
<td>average</td>
<td></td>
</tr>
<tr>
<td>not set (assumed clear)</td>
<td>high</td>
<td>high</td>
<td></td>
</tr>
</tbody>
</table>

**Band Quality**
- highest quality
- dead detector
- solar zenith >= 85 degrees
- solar zenith >= 85 degrees and < 86
- missing input
- missing climatological data
- value out of bounds
- faulty raw data
- not processed due to deep clouds
vegetation and a double hyperbolic function to calculate NDVI has been fitted to the data (in red).

We are now working on manually separating deciduous from evergreen species in this subset of images in order to clean the signal even further. An Intel Scholar student is working on simple filters, akin to the filters used in remote sensing, to further clean the data.

We have downloaded 8-day composite surface reflectance images from February 1, 2008- December 31, 2008 from EOS-WEBSTER and prepped files for data extraction by pixel. We requested daily surface reflectance and 16-day vegetation index composite images by tile for February 1, 2008 to present from WIST. We have also performed preliminary image processing steps for the first month’s worth of data for the daily surface reflectance product.

**TEOS 07.6 Future Directions**

Once some simple filters for the ground-based images have been established to provide a cleaner data set, we will apply them to the 1400 webcams to create a larger data set of ground-based NDVI values. We will then make a comparison of ground-based and remote sensing estimates of spring. We wish to compare the reliability statistics of ground-based imaging with satellite observations, the pros and cons, and where each system has its strengths and weaknesses.