2.3 Terrestrial Ecology Observing Systems (TEOS)

Our goals for the 2010–2011 TEOS activities were to expand our testbed network to extend and integrate our observing systems at the James Reserve, testing ecological theory, expand our network to additional testbeds with different environmental conditions, and to scale from the microscopic-level observations and measurements to continental-scale analysis of phenology which can be used in understanding dynamics of global change (Figure 2). These goals emphasize our focus on research and technology application, education, and outreach.

The first goal was to expand our testbed. The sensors have been widely accepted and used. However, coupling those measurements with direct observations of soil processes using systems similar to our Automated MiniRhizotron (AMR), has not previously occurred. We made several design changes from our previous prototype unit, adding stability, networking capacity, and accessibility by outside researchers. These have been incorporated and most of the images acquired and currently being taken are available to anyone interested in downloading (http://ccb.ucr.edu/amarss.html). We expanded the network across the James Reserve and at additional locations. At the James Reserve, the prototype is still operating in the meadow adjacent to the weather station. At the AMARSS transect, 4 AMR units and soil sensor nodes are actively running focusing on observing and measuring soils at the same locations as the Networked InfoMechanical System (NIMS) cable and instrumentation (with complete energy-balance measurements), the phenology camera, sapflow flux sensors, standard above-ground sensors (PAR, T, RH, PPT) and a newly installed within-canopy eddy co-variance measurement system. All measurements correspond to previous measurements of leaf area (canopy camera), CO_2 assimilation measurements, with T, and PAR through the seasons, and within the footprint of a canopy-scale eddy covariance measurement system (Michael Goulden, UCI).

We added an additional set of AMR and soil sensor nodes at the La Selva Biological Station. This deployment was stimulated by the PASI course (described below), but remains running.

Finally, we provided an AMR unit to NEON as a test deployment with their soil sensor network, which is identical to that we deployed at the James Reserve.

With the expansion of automated data and image retrival, our James Reserve network capacity was no longer adequate to handle the traffic volumn and computational needs. We moved the servers to the UCR campus. Although modifications of software to the AMR units and data management, all data and observations are available.

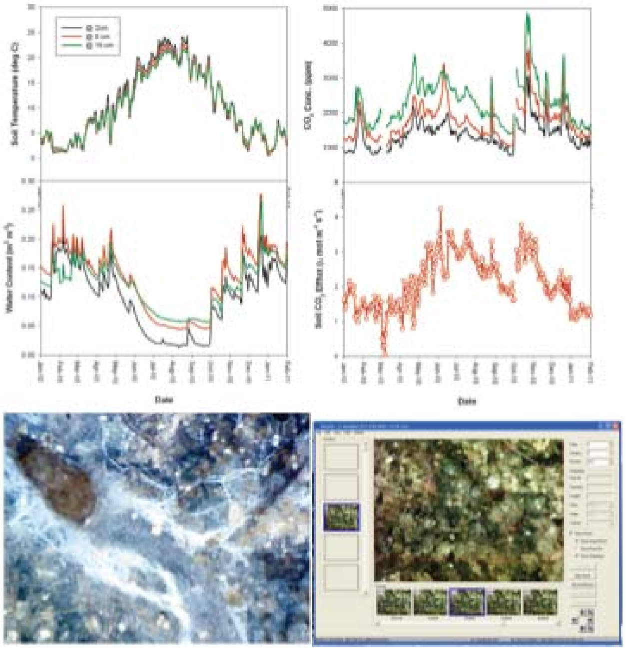

Figure 2. 2010 integrated sensor studies of soil fungi and the processes they catalyze, at the James Reserve. Show is the daily averages (5min intervals) for T (upper left), soil CO_2 (upper right), θ (middle left), and R_s (middle right). Shown are images of an ectomycorrhiza, with the mantle and radiating hyphae (lower left) and an automated tracing (using @RootFly) outlining an arbuscular mycorrhizal network. Individual hyphae can be traced through time (lower panel) and dynamics of C production and turnover in fungal biomass directly measured to integrate into ecosystem models. These data extend the initial measurements started in the 2010 report to minute-hour-scale data for describing short- (events, diel dynamics) and long- (season, environmental change) scale processes.

From the prototype unit, we have been able to document diel *in situ* arbuscular mycorrhizal (AM) hyphal growth dynamics. In 2009, growth preferentially occurred during mid-afternoon, corresponding to the time of maximal photosynthesis (based on PAR and sapflow measurements). In 2010, no diel pattern was found, but the site was cooler and wetter. No diel pattern of mortality was observed, although seasonal dynamics strongly correspond to decreasing soil moisture (θ). As an obligate plant symbiont, arbuscular mycorrhizal fungi utilize new photosynthetic C, not older decomposed C, which should reflect the allocation timing and processing of C (Figure 2).

Soil respiration (R_s) measures show strong diel dynamics. In the meadows, dominated by AM grasses, diel hyphal production was also observed. Little diel or seasonal hysteresis occurred in R_s suggesting minimal lag in C fluxes. Alternatively, in the forest, we see little evidence of diel hyphal growth dynamics, and the ecto-mycorrhizal (EM) associations with the woody plants appear to be very long-lived (years), and even rhizomorphs have nearly a year life-span. R_s shows strong daily and seasonal hysteresis, suggesting long lags in C allocation from leaves to roots to fungi in these architecturally-complex systems. Importantly, with snow cover, soil CO_2 production (R_p) continues even though the soil CO_2 does not diffuse through the snow layer. This results in a very high concentration of soil CO2, and a degassing as patches of snowmelt appear. We are currently working on a suite of different ecosystem models both to find some optimal ways of integrating our diverse datasets, and as a means ot testing C flux estimates generated by the models (Figure 2).

Integrating camera and sensor systems has become a critical tool for undertaking ecological research in the field. Our observing systems range from the *in situ* microscopes (AMR units) that are coupled with soil sensors, to field cameras for studying phenology dynamics that are coupled with measurements of soil respiration and activity as well as sap-flow sensor measurements, to events such as snowfall and snowmelt that are coupled to Rs as well as Rp dynamics. From our initial deployment at the James Reserve, new deployments in Chile (with the Chilean LTER group) and with the La Selva Biological Station in Costa Rica shows promise for further development. As a new activity, we are focusing on utilizing color variation to generate a more detailed assessment of finer phenological resolution in collaboration with UC Berkeley. By using these images and color detection approaches, we are comparing local camera measurements to satellite imagery (especially MODIS products) to scale from individual plant phenology to site-scale dynamics.

These camera observing systems can even be scaled to provide warning systems. For example, currently fires must be visually distinguished before warnings can be sent. However, smoke has very different atmospheric properties from clouds, or cloudless days. Both pattern recognition and wavelength differentiation might become feasible from a deployment of camera systems to provide early warning systems for wildfire detection. Given that detection is the first line of defense for control, this approach would make fire protection a more viable option for the future.

Finally, we developed a course in sensor networks and cyberinfrastructure at the La Selva Biological Station in Costa Rica for students and postdocs both from the US and across Latin America through the Pan-American Advanced Studies Institute (PASI). The expected outcomes were: (1) Tropical ecologists enrolled would be able to expand their ecological questions by using embedded sensors; (2) Tropical ecologists would become familiar with the design, set up and management requirements of embedded sensor networks that are appropriate for the temporal and spatial scale of their hypotheses; (3) Groups of tropical ecologists with common interests would be facilitated to encourage partnerships, research alliances and the establishment of their own collaborative networks; and, (4) Critical questions in tropical ecology would be identified where novel applications of sensor networks could have transformative effects

Thirty-one graduate students, post docs and young faculty were selected to enroll in the PASI course, drawn from a pool of 80 applicants. These students were roughly split between Latin American and American students, with the groups including the representation of 14 countries. The instrumentation deployed at the La Selva station remains in place for students and researchers to continue to use.

Together, we believe that we have been able to develop, then demonstrate the viability of sensor networks, including observing systems as components of sensor networks, in ecological research and training. We will continue our integrated studies both technically, and into new systems.

TEOS 01 Soil Imaging – AMR design and testing

Team Members

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- Michael Taggart, Staff*
- Thomas Unwin, Staff

** Primary Contact*

Overview

The past year has seen the completion and deployment of production Automated MiniRhizotrons (AMR) in locations domestically and at the La Selva Biological Field Station in Costa Rica. We've also completed major improvements and refinements to the AMR control software with the development of RootView3. Because the majority of our new deployments were at locations outside our original test site at the James Reserve, some new technical challenges were brought to light that were met with equally creative solutions. All of this reinforced the fact that developing a new instrument for field research is an iterative process and one that always takes longer than initially planned.Set the project in the context of ongoing research at CENS and in the field at large. Describe goals and objectives and how they may have changed from prior years.

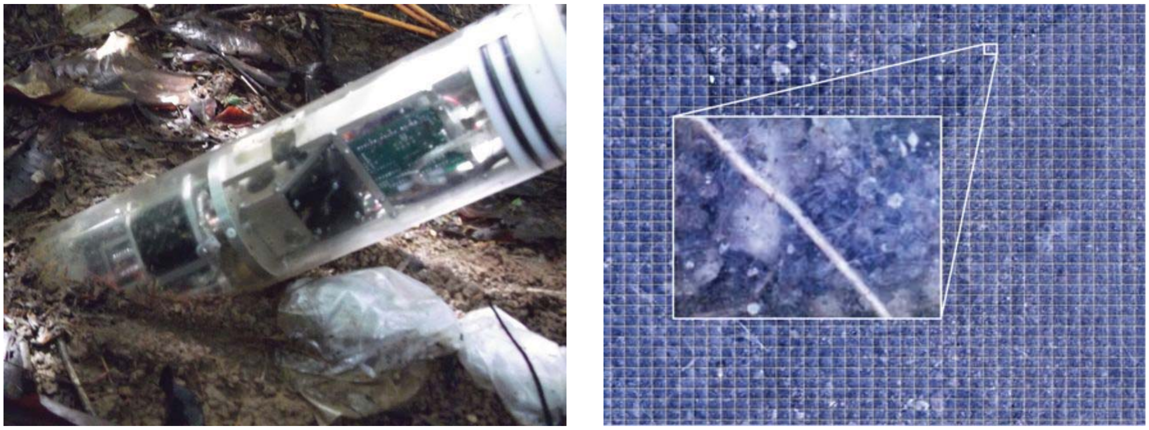
Approach

Balance the need for research and publication with the business of creating production quality instruments and accompanying software within a dwindling budget while making the best use of and maintaining existing resources.

System(s) Description and/or Experiments

The year began making "as built" changes to the engineering drawings, adding new drawings to reflect added items such as the shipping container and ancillary equipment housings, and updating notes regarding deployment, assembly and packaging. There was also the ongoing process of calibrating and bench testing each production unit in our labs prior to deployment and configuring a small PC for use with each AMR. Three AMR systems were deployed at the La Selva Biological Field Station in Costa Rica. One AMR was delivered to the National Ecological Observatory Network in Boulder, CO for environmental testing and two additional systems were deployed at the James Reserve in Idyllwild, CA. The La Selva installation marked the first deployment outside the United States and the first testing in a tropical environment. Several challenges were presented ranging from shipping to dealing with deployment in a rain forest, but all were overcome. The end results were a more robust packaging system for shipment, enhanced weatherproofing for ancillary equipment and a system for keeping said equipment from sitting directly on the forest floor making it less susceptible to infestation by insects and inundation by rivulets of rain water. Major strides were made in work started last year on the RootView3 (RV3) control and interface software for the AMR. Some highlights are the ability to: automatically archive images, generate time series images and movies from within the RV3 program, more easily program sub-scans based on previously generated mosaics, see mosaics in time series as well as a multitude of bug fixes and minor interface improvements.

(l) Production units waiting to be placed into tubes at La Selva. (r) Three AMR systems being deployed at La Selva. (Tom Unwin (forefront) and Kuni Kitajima.)



(l) Close-up of an AMR in-situ at La Selva. (r) Image taken using the Prototype AMR (Mosaic in background).

Database/Data Collection/Data Storage

Because AMR research is transitioning from an experimental to production environment, the CENS/AMR data and file servers were moved from their longtime location at the James Reserve to the UCR Computing Center since it is better suited to accommodate the increased bandwidth needs of additional deployments.

Utilities and Networks

Training and responsibility for CENS installed infrastructure items was successfully transferred to the resident James Reserve staff.

Collaborative Efforts Utilizing CENS Infrastructure

A production unit was delivered to NEON for environmental testing and analysis. A field deployment at NEON is anticipated in late 2011.

Accomplishments

Deployment of 10 AMR production units completed. Servers transferred from James Reserve to UCR. Transfer of CENS related infrastructure to James Reserve staff was completed. RootView2 was completed. RootView3 specifications were completed and work is in progress.

Future Directions

Complete work on RV3. Support of current and future production AMR deployments. Continue refinement of AMR systems.

TEOS 02 La Selva soil and root dynamics: What happens in soil, stays in soil

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Overview

We placed three sensor nodes and AMR units at the La Selva Biological Station in April of 2010 to test the applicability of these technologies to an ecosystem of dramatically different conditions from those of the James Reserve where we have conducted previous technological assessments. This includes clay soils, high precipitation, and relatively constant warm temperatures. Another importance of the La Selva site is that all of our information is a direct contribution to a newly established tower flux network, and a large database on ecological dynamics.

Approach

Soil AMR units and sensor networks were deployed as previously described for the James Reserve at the La Selva Biological Station, Costa Rica.

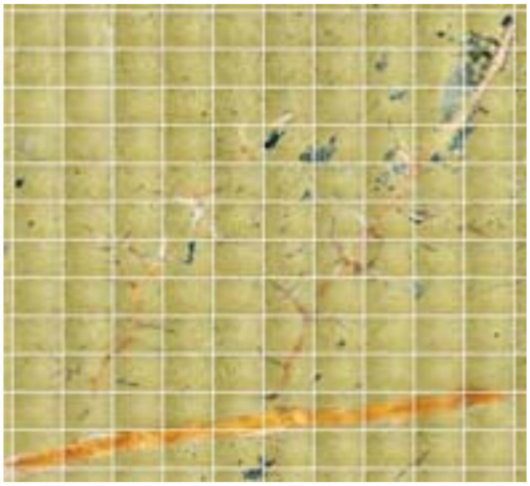

Figure 1. Image from AMR La Selva 4 from 4 January 2011 of clay lens (yellow), brown (older) and white (newer) roots, and fungal hyphae that are visible at higher resolution of individual images. Each square is 1 by 1.2mmm in size, at 100x magnification.

System(s) Description and/or Experiments

We deployed the sensor network and AMR units in April of 2010. All units were allowed 4 months to equilibrate with surrounding conditions. The AMR unit is a track-based in situ microscope that images roots and soil organisms. Images at La Selva are taken daily to measure changes in rates of processes. A soil sensor network, comprised of three soil temperature sensors (HOBO® Weather Station 12-bit Temperature Smart Sensor), three soil moisture sensors (HOBO® Weather Station Soil Moisture Smart Sensor), and three CO_2 sensors (Vaisala®, GMP222) were buried at 2 cm, 8 cm, and 16 cm depths. We used a data logger to program the sensor network to collect data every 5 minutes. Soil CO_2 efflux was modeled based on Fick's law of diffusion. Our best fitting model was a quadratic function of soil temperature. A LI190SB-L Li-Cor Quantum Sensor (Campbell Scientific, Logan, Utah) was mounted approximately 3.3 m above ground and connected to a CR1000 Data Logger (Campbell Scientific, Logan, Utah). Sensor measurements are taken at 5 min intervals to describe changes in dynamics. By measuring soil organisms and conditions at a high frequency resolution, we can study changes in biological responses through the range of changing environmental conditions. Images are transfered to our CENS computers at UCR. All images and sensor data are available to interested parties and can be accessed at http://ccb.ucr.edu/amarssdata.html.

Accomplishments

Several surprises can be found within the data. The first was that soil CO2 levels were far higher than we have measured in arid soils. This difference was so large that we had to replace the initial CO2 (0-10,000ppm) sensors with lower resolution but higher level CO_2 sensors (to 50,000ppm) that are able to read under the higher levels.

The clay formed a layer coating much of the AMR tube. This constrained observations of the soil. However, roots grew down through the soil and along the tubes and were observable along the wall of the tube (Fig 1). Fungal hyphae (both arbuscular mycorrhizal and saprotrophic) also grew along the tubes. Gaps in the clay lense developed allowing observation of fungal hyphae into the soil. We observed daily changes in root and hyphal growth and mortality. We are currently quantifying those changes.

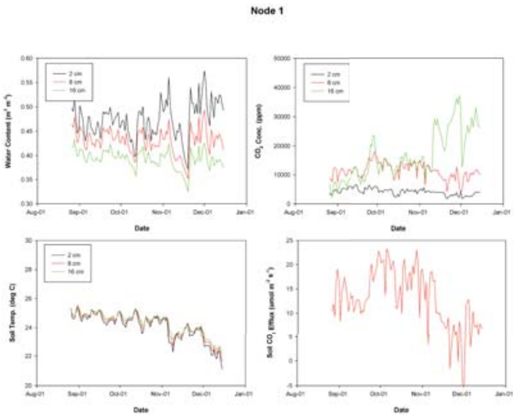

Figure 2. Sensor node 1 from La Selva deployment showing water content, CO2 concentrations, soil temperature, and soil respiration from late August through mid-December 2010.

Soil sensors showed very interesting dynamics during this period (Fig 2). The combination of high clay content and high precipitation (the current deployment has occured through the rainy season) meant that gas exchange is diffusion limited. CO2 and O2 cannot readily exchange with the atmosphere in the canopy. As a result, CO2 builds up within the soil, especially following rainfall events. Importantly, the production of CO2 may exceed the diffusion as shown in some instances where CO2 levels are higher at 8cm than at 16cm. For example in early December 2010, CO2 accumulated at greater rates than diffusion following high rainfall events. Root and microbial activity is highest in the 8-12cm depth, where soil CO2 builds up at high levels.

Future Directions

We will continue working on studying the output from this observatory/sensor deployment by quantifying root and fungal growth and mortality with the dynamics measured by the soil sensor network. We will contrast these dynamics with those measured by the flux tower. We are especially interested in how these systems will behave during the dry season. While these systems will not be nearly the low soil moisture observed in our James Reserve (California) site, the heavy clay soils should provide a very interesting contrasting in soil environmental dynamics.

TEOS 03 Diel dynamics of mycorrhizal fungi: Integration of Imaging and Sensors

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Team Members

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Overview

Arbuscular mycorrhizae (AM) are biogeochemical drivers of P, N, C in the rhizosphere. Despite their role, the temporal dynamics of AM hyphae, from the seasonal to 24 h diel scale, is largely understudied. Even less is known about biophysical controls (e.g., soil temperature, soil water content, irradiance) modulating hyphae dynamics. Difficulties elucidating these relationships are complicated by the inability to observe hyphae (the individual strands produced by AM) without concomitantly disturbing hyphae function and the difficulty in replicating soil samples in space. Consequently, most studies are conducted at coarse temporal scales, with limited replication, and conducted in artificial settings such as laboratories or greenhouses—conditions unlikely to confer a thorough understanding of hyphae dynamics in natural systems. Using our new automated minirhizotron, we studied patterns of AM hyphae growth and dieback at a very high temporal resolution (6 h diel intervals), and 2) identified relationships between diel hyphae dynamics and biophysical variables (i.e., soil temperature, soil water content, and photosynthetic photon flux density). We hypothesize that hyphae growth is variable across the 24-h diel cycle, and that this variability is related to fluctuations of biophysical variables in the rhizosphere. Our study's findings are the first product of the robotically controlled imaging system, developed under the AMARSS Terrestrial Ecology Observing Systems Research Group within CENS. This study demonstrates the utility of imaging and sensor technology integration, revealing critical ecological processes and improved understanding spatio-temporal dynamics of the terrestrial ecosystem.

Approach

To obtain repeated observations of hyphae at a diel temporal resoultion, we employed a non-destructive sampling technique using a robotically controlled imaging system (i.e., automated minirhizotron), which captures RGB images of AM hyphae at user-specified locations (i.e., within the AMR tube) and times. We augmented observations of hyphae with an above- and belowground soil sensor network to explore relationships between hyphae dynamics and potential biophysical controls.

System/Experiments

Image data sets (4,148 images each) from an automated minirhizotron (AMR) were organized into mosaics and visually evaluated for arbuscular mycorrhizal (AM) hyphae in May of 2009 and 2010. From the subsamples, 20 and 30 images (3.01 x 2.26 mm, 0.125 mm depth, 100X magnification) with AM hyphae were randomly selected for the 2009 and 2010 analysis, respectfully. Images have a unique x/y position and images for each position were queried from 87 scans to compile 20 (or 30 in 2010) time series (n = 20) of approximately 80 images each for the period of 1 – 31 May at a temporal resolution of 1 to 5 images per day. To measure diel patterns of hyphae elongation and dieback, each time series was uploaded to Rootfly (Clemson University, Clemson, South Carolina), an ecological software application for minirhizotron image processing. To measure total hyphae length, each hyphae branch in the initial image was digitized manually. Digitized lines were copied to subsequent images and changes in length and new hyphae branches were edited or digitized.

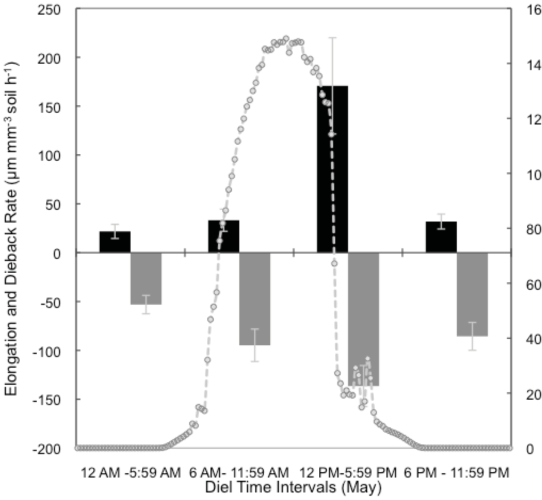

Figure 1. Diel elongation (black bars) and dieback (grey bars) rates of arbuscular mycorrhizae hyphae (µm mm-3 soil h-1) measured from image time series (n=20, May 2009) captured with an automated minirhizotron in a mixed conifer forest (UC James San Jacinto Mountains Reserve, Idyllwild, CA). Error bars 95% confidence intervals. Mean photosynthetic photon flux density (PPFD, 2009).

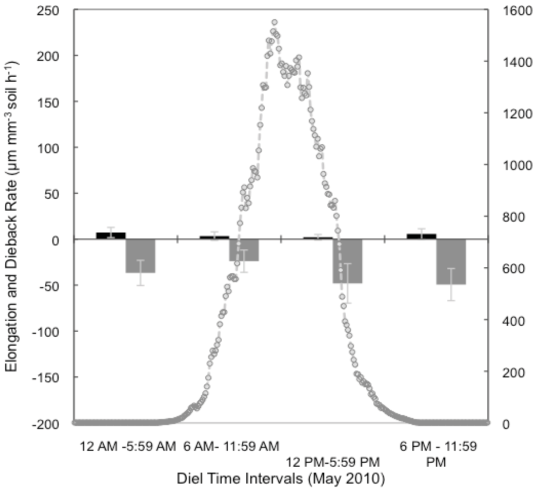

Figure 2. Diel elongation (black bars) and dieback (grey bars) rates of arbuscular mycorrhizae hyphae (µm mm-3 soil h-1) measured from image time series (n = 30, May 2010) captured with an automated minirhizotron in a mixed conifer forest (UC James San Jacinto Mountains Reserve, Idyllwild, CA). Error bars 95% confidence intervals. Mean photosynthetic photon flux density (PPFD, 2010).

Total hyphae length was calculated by summing the length of all hyphae branches after each scan. The difference in time between subsequent scans was calculated to determine growth or dieback rates, and changes in rates observed in less than 15 minutes or greater than 6 h were excluded from analyses. Our soil sensor network, (temperature, moisture, CO2) collected data every 5 minutes during the month of May in 2009 and 2010. Soil CO2 efflux was modeled based on Fick's law of diffusion. The Quantum Sensor measured photosynthetic photon flux density (PPFD, µMol/m2/sec) in the 400 to 700 nm waveband every 10 minutes from 1 -31 May 2010.

Accomplishments

Diel Patterns of Arbuscular Mycorrhizal Hyphae

Over 3,000 images capturing AM hyphae were manually digitized. Over 700 observations of hyphae elongation and dieback met the time interval criteria (15 min < t < 6 h) to be allocated to a 6 h diel interval. In 2009, both elongation rate, 170.79 ± 49.2 (1 SE) µm mm-3 soil h-1, and dieback rate, -136.51 ± 21.00 (1 SE) µm mm-3 soil h-1, were greatest in time interval III (12:00 -5:59 pm) (Fig 1). Hyphal elongation rate was significantly different across time intervals (Kruskal-Wallis chi-squared = 10.7884, df = 3, p-value = 0.01293). Specifically, time interval III was between 8 and 5 times greater than elongation rates in intervals I, II, and IV. Hyphal dieback rates were also significantly different across time intervals (Kruskal-Wallis chi-squared = 10.3968, df = 3, p-value 0.0154). In 2010, hyphae diel patterns differed from patterns observed in 2009 (Fig 2). Elongation rates were greatest in the I interval, 7.23 ± 3.2 (1 SE) µm mm-3 soil h-1, and dieback rate, -49.45 ± 10.4 (1 SE) µm mm-3 soil h-1, was greatest in time interval IV (12:00 -5:59 pm). The lowest rate for elongation, 2.13 ± 1.7 (1 SE) µm mm-3 soil h-1, and dieback, 23.96 ± 7.3 (1 SE) µm mm-3 soil h-1, occurred in the III and II interval, respectively. As observed in May 2009, both elongation (Kruskal-Wallis chi-squared = 8.7846, df = 3, p-value = 0.03230) and dieback rates (Kruskal-Wallis chi-squared = 8.5903, df = 3, p-value = 0.03526) in May 2010 significantly differed across diel time intervals.In general, our results reveal that AM hyphae growth and dieback occurs at rates that may exceed 150 µm mm-3 soil h-1 (or 2.5 mm mm -3 min1). Furthermore, AM hyphae dynamics are highly variable across the 24 h diel time interval and small fluctuations in the soil environment, even those short in duration, may enhance or curtail net hyphae growth. These findings suggest that perturbations in the rhizosphere environment may cause dramatic responses in AM hyphae dynamics that would likely result in feedback effects on AM-hyphae host plants.

Biophysical Variables of the Rhizosphere

Soil conditions were significantly different between 2009 and 2010. Diel soil temperatures were significantly lower in 2010 than in 2009 (Paired Student's t-test; t = 65.1227, df = 23, p-value < 2.2e-16). Soil water content and soil CO2 efflux was significantly greater in 2010 than in 2009 (Paired Student's t-test; t = -230.9656, df = 23, p-value < 2.2e-16; t = -11.5172, df = 23, p-value = 4.993e-11). In 2009, minimum PPFD was 0.18 µMol/m2/sec occurred at 4:00 am and maximum PPFD, 1490.39 µMol/m2/sec, occurred at 11:30 am. PPFD exceeded 1000 µMol m-2 sec-1 from 8:40 am to 2:00 pm. When averaged among time intervals I, II, III, IV, PPFD was 4.7 ± 1.4 (1SD), 945.7 ± 189.8, 582.9 ± 155.8, and 3.5 ± 1.0 µMol/m2/sec, respectively. These results suggest that disparities in rhizosphere conditions may explain some of the differences observed between 2009 and 2010 hyphae diel dynamics.

Future Directions

In the coming year, we will:

- explain relationships between diel hyphae patterns and biophysical variables
- explore seasonal and spatial (e.g., depth) patterns of hyphae growth and dieback
- use data mining techniques (i.e., feature extraction) to develop original software to automate the hyphae digitizing process

TEOS 04 Carbon Flux and C Pipe: Integrating sensor outputs to models

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** Primary Contact*

Overview

Our goal is to integrate meteorological, soil sensor, and eco-physiological data collected at the James Reserve and build a landscape level model that predicts carbon and water fluxes in the forest.

Approach

Following data are continuously collected at the reserve since 2004: (1) soil CO2 efflux, (2) sap flow density, (3) photosynthetic rate (intermittent), (4) eddy covariance CO2 and H2O flux and 5) micro-meteorology data. To build a model, we used Hydrus 1D [Simunek et. al. 2005] as our base model and we combined this and a biochemical model [Katul et. al. 2003] to estimate carbon and water fluxes.

System(s) Description and/or Experiments

The AMR unit is a track-based in situ microscope that images roots and soil organisms. Images at the James Reserve are taken daily to measure changes in rates of processes. The sensor network comprise a matrix of sensors for T, θ and CO2 at 3 locations by 3 depths. A soil sensor network, comprised of three soil temperature sensors (HOBO® Weather Station 12-bit Temperature Smart Sensor), three soil moisture sensors (HOBO® Weather Station Soil Moisture Smart Sensor), and three CO2 sensors (Vaisala®, GMP222) were buried at 2 cm, 8 cm, and 16 cm depths. We used a data logger to program the sensor network to collect data every 5 minutes. Soil CO2 efflux was modeled based on Fick's law of diffusion. Our best fitting model was a quadratic function of soil temperature. A LI190SB-L Li-Cor Quantum Sensor (Campbell Scientific, Logan, Utah) was mounted approximately 3.3 m above ground and connected to a CR1000 Data Logger (Campbell Scientific, Logan, Utah). The Quantum Sensor measured photosynthetic photon flux density (PPFD, µMol/m2/sec) in the 400 to 700 nm waveband every 10 minutes. Sensor measurements are taken at 5 min intervals to describe changes in dynamics. By measuring soil organisms and conditions at a high frequency resolution, we can study changes in biological responses through the range of changing environmental conditions. We utilized data from these sensors to model water dynamics at points representing actual sensor node sites.

From this effort:

Soil water movement is governed by the Richards equation:

$$Cw * dh/dt = d/dz * \{ K(h) * (dh/dz - 1)\}, \qquad [1]$$

where Cw is water capacity, h is water pressure head, t is time, z is depth, K(h) is hydraulic constant. K(h) is a function of water pressure head and varies widely depending on soil type. James Reserve has a shallow (~ 50 cm) loamy sand soil. To solve this, we need a boundary condition, which is given by either constant flux (precipitation) or constant head (evaporation governed by air temperature and humidity).

Plant water uptake rate S at depth z is given by [Feddes,1978]:

$$S(z) = \alpha * R(z) * PET, \qquad [2]$$

where α (0<α<1) is a stress factor that varies with water pressure head available in the soil and with plant physiology (conductance vs. matric potential curve), R(z) is a root density at depth z, and PET is potential evapotranspiration of tree. PET is related to FAO standard PET (PET*) by

$$PET = Kcorr * PET^* \qquad [3]$$

where Kcorr is a correction factor for converting from well-watered standard crop to forest trees under stress. Since water stress factor is already taken into consideration by the α factor in eq. [2], Kcorr is a constant represents the difference between standard crop and forest trees. PET* is a given by the Penman equation and it is a function of meteorological condition and leaf area index (LAI). LAI at the James Reserve was estimated from the satellite data.

Plant water uptake rate, S, is related to sap flow density (Jw) we observed by

$$S = \text{sap wood are / ground area} * Jw = \text{SAI (sap wood area index)} * Jw \qquad [4]$$

Photosynthetic rate, An, is related to Jw by

$$An = Jw * (Cs - Ci)/(1.6 * Ds) \qquad [5]$$

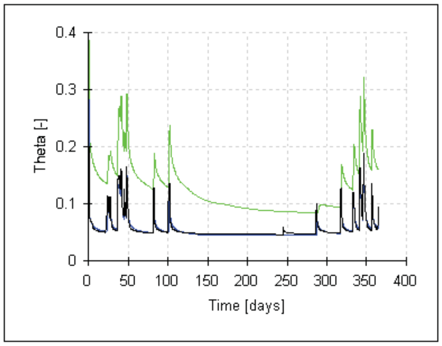
where Cs is leaf surface CO2 concentration, Ci is intercellular CO2 concentration, and Ds is stomatal conductance. Cs is approximated by CO2 concentration in air. The same An is also expressed in terms of biochemical CO2 demands by

$$An = \alpha 1 * (Ci - \Gamma^*)/(Ci + \alpha 2) - Rd \qquad [6]$$

where α1, α2 and Γ* are biochemical constants that is a function of temperature, and Rd is dark respiration rate and is ignored for simplicity. By solving eq. [5] and [6], Ci and An are obtained. There are two unknowns in eq. [1] through [6], Kcorr and SAI. Since these are multiplying factors and can be collapsed to one factor. Thus, our goal is to estimate this factor based on observed soil water content and sap flow data. The objective of the optimization is to minimize the sum of squared errors, SS

SS = {yi(obs) – yi(est)}^2, where yi(obs) and yi(est) are observed and estimated soil water content and sap flow rate, respectively.

Observation Nodes: Water Content



Actual Root Water Uptake

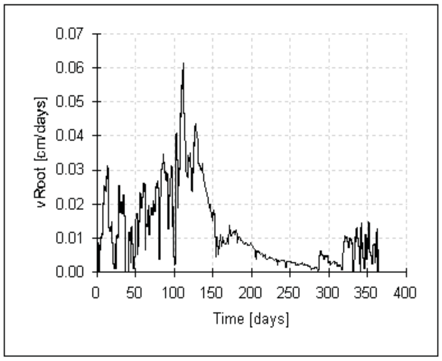


Figure 1. Actual root water update by trees in 2009.

Accomplishments

We observed that fungal rhizomorphs were most closely correlated with soil respiration, whereas root dynamics showed significant lags to changes in soil T and θ. Accurate determinations of the carbon fluxes in soil need to incorporate these lags if accurate models of the impacts of changing climates on root, microbial and respiration dynamics are to be undertaken.

In addition to measuring changing root and fungal dynamics to CO2, we also looked at sapflow measurements and leaf phenology (using in situ cameras) as a way of relating soil dynamics to above-ground dynamics. There were not strong correlations, due in part to the use of deep water by large trees, hydraulic redistribution of water, and the continuous responsiveness in the conifers, whereas the oaks had distinct new leaf production (spring) and leaf fall (autumn) which was reflected in soil dynamics, but not as strong as would be expected.

As a way of integrating the disparate data, we iniitated point models. We started with HYDRUS 1D. Figures 1 and 2 show examples of estimated water content and plant water uptake profile in 2009 using Hydrus 1D. While this model moves water accurately, in comparison with the sensor data, carbon flows are not well represented.

Future Directions

We will continue assessing soil respiration in response to root and fungal dynamics, and changes in soil temperature and moisture, precipitation events, and radiant energy. We will finalize the optimization process and investigate how environmental factors might affect outcomes. We also compare these results with ones obtained with the DAYCENT model to generate a more accurate estimate of carbon fluxes.

TEOS 05 Ecological Studies Using Digital Cameras

Team Members

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- Erin Riordan, Graduate Student
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** Primary Contact*

Overview

Shifts in the timing of spring and fall have implications for many ecological processes and relationships, including productivity, species interactions, and community structure. Linking phenology observations with meteorological data and ground processes is important to understanding how these relationships will change. Previously, we have used digital cameras to detect fine-scale timing of phenological events at local and continental scales.

Work on using digital cameras as environmental sensors at CENS has branched into three avenues of investigation: (1) collaboration with researchers in Chile at a Long Term Ecological Research (LTER) station who have digital image archives, (2) collaboration with researchers in Berkeley who maintain a series of webcams, and (3) work with high dynamic range imaging (HDR) that will be obtained from both the James Reserve and the La Selva Biological Station, Costa Rica.

Figure 1. A typical watering treatment and digital image, from which ground cover is being analyzed.

Approach

Collaboration with Chilean LTER

The Chilean team has image data sets obtained on a season al basis to estimate total plot plant cover (plant, soil, rocks, litter, etc.) in different watering treatments (Figure 1). We are helping them alalyze the image to remove shadows and classify the coverage.

Collaboration with Berkeley researchers

We are involved in evaluating the ability of digital cameras to provide fine-scale phenology observation of target species in two heterogeneous environments where coarse resolution remote sensing observation fails. Separation of species-specific phenology signals and estimation of spring and fall events will be facilitated through the use of simple color processing techniques and modeling.

HDR

We continue to collect daily images from the James Reserve and are analyzing the seasonal color shifts in relation to the micrometeorological data, however focus is now on the techniques of image separation and HDR. Additionally, we are working with the 6 Pan-Tilt-Zoom cameras at the La Selva Biological station in Costa Rica established on the MRI towers project.

System(s) Description and/or Experiments

Collaboration with Chilean LTER

The RGB color space, although native to many image capture systems, does not separate chromaticity or color, from the luminance (lightness and darkness) component of color. Unfortunately, the color variation within an image taken under natural, uncontrolled lighting conditions is principally dominated by variations in luminance, making reliable classification using the RGB color space difficult. A variety of transformations can be used to reduce the effect of luminance in natural light images.

We transformed the RGB data and the region-of-interest (ROI)-based data into different color spaces to test their effectiveness in the models for plant cover prediction. Three-dimensional color spaces included: Normalized RGB, Hue-Saturation-Luminance, Yxy, Lab, ATD, and NDI. Each component of each color space was tested individually as well as in the chromaticity pairs, excluding the luminance component when present. If there was no specific luminance component, then pairs of color components were tested together.

The RGB and alternative color space components were fit to the plant cover data using a recursive partitioning tree to create a set of predictive "rules" for determining what combinations of the values of the color channels were optimal for separating plant cover from background soil. We used R and the rpart module to create a binary decision tree using an initial complexity parameter (as a proxy for the number of binary splits, indicating further divisions have less benefit relative to the increased complexity of the tree) of 0.001. An alternative method was also employed for determining plant cover by manually select regions of interest (ROI) within images that represent plants and other ROIs that represent background or soil and calculate the frequency of color values within each group. A simple Bayesian approach (naïve Bayes classifier) was then be used to predict when a combination of color components in similar images was most likely plant or most likely soil. The frequencies of all combinations of RGB and the alternative color space components in the original images were then established for both groups of ROI using a program written in Python. The probability than any color component combination was to be defined as plant cover was defined as the frequency of that combination occurring in the plant cover ROI relative to the frequency of that combination occurring in all ROIs, both plant and soil. A threshold of 0.5 was established for later classifying a color component combination as either plant cover or background.

Collaboration with Berkeley researchers

We use three different color spaces (excess RGB, Lab, HSL) to detect seasonal changes in vegetation of a focal oak species at each study site (Q. kelloggii at James Reserve and Q. douglasii at Tonzi Ranch). Regions of interest (ROIs) containing the focal species will be manually drawn. Vegetation signals will be identified by first averaging per pixel values of each colorspace component (e.g., ExG, L) across image ROIs to create a phenology time series. We then model the timing of spring green-up and fall senescence with a sigmoid function following methodologies used in previous digital camera- and satellite-based phenology studies. The sigmoid approach is relatively robust to signal noise, and phenology metrics (e.g. start of spring) can be estimated from model parameters. We then compare camera detection with that from remote sensing Moderate Resolution Imaging Spectroradiometer (MODIS) products used for large-scale environmental monitoring. MODIS daily surface reflectance at 250 m spatial resolution (MOD09GQ) will be used to for per pixel measurements of vegetation, calculated as the Normalized Difference Vegetation Index (NDVI; [near infrared reflectance – red reflectance]/[near infrared reflectance + red reflectance]). Dates of spring and fall will be estimated from modeled times series inflection points.

HDR

Due to the limited dynamic range of image sensors, HDR techniques have been developed to consolidate images that have been varyingly exposed into one image that can fully describe the dynamic range of the scene. While this method is traditionally used to improve the visual quality of a scene, we are more interested in its merit in representing the amount of light reflected by components in a scene. By calibrating HDR images with PAR sensor data, we are able to convert the relative reflectance into an absolute value, allowing us to not only represent the full dynamic range of the scene, but also determine the absolute amount of solar radiation reflected at each spot in the image. This information can be used to more accurately measure the amount of energy absorbed by the flora in observed scenes. We are currently testing this approach with datasets collected from the James Reserve and the La Selva Biological Station in Costa Rica.

Accomplishments

Collaboration with Chilean LTER

The optimal RGB binary decision tree created with rpart using the SamplePoint RGB components to predict plant cover consisted of 32 splits with a relative cross validation error of 0.54 (Fig. 1A). The RGB decision tree was able to correctly predict 83.21% of the SamplePoint plant cover classification. The two color components that ranked the highest in correctly identifying plant cover were HSL nad Yxy (Figure 2.)

Collaboration with Berkeley researchers

Cameras are able to detect Q. kelloggii phenological signal at James Reserve, where there is no discernable phenological signal from satellite imagery. Different colorspaces show varying success in detecting Q. kelloggii spring and fall events. In particular, ExR and b from Lab show strong peaks that correspond with the timing of fall coloring events. ExG and a from Lab show sharp increases that correspond to spring green-up. Tonzi Ranch, in contrast, shows strong seasonal signals in satellite measured NDVI. The phenological signals of Q. douglasii and annual grasses, however, cannot be distinguished from satellite. Cameras are expected to provide species-specific phenological signals for the ecosystem. Challenges with camera-based detection stemmed from variation in color caused by automatic color balance camera settings and changes in luminance.

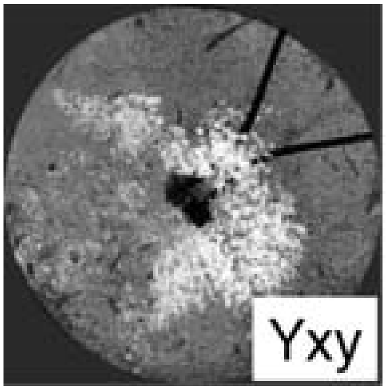

Figure 2. Bayes prediction using the Yxy color space : note the elimination of the shadow and highlighting of the vegetation (compare to Figure 1).

Future Directions

Continued work with color separation of the Chilean plots and the Berkeley locations will allow us to analyze seasonal trends and eventually annual productivity.

HDR promises to allow us to retrieve absolute values of reflectance from vegetation and thus facilitate a a back-calculation of what solar input photosynthetic tissues are recieving. A final carbon budget for the field of view of the camera on an hourly, daily, and seasonal basis will then be possible.

TEOS 06 Early Detection of Wildfires

Team Members

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** Primary Contact*

Overview

Early detection of wildfires can significantly minimize the damage to property and life caused by such fires. Currently, the efforts towards achieving this goal have been primarily restricted to deploying networks of cameras/sensors and manually monitoring them for fire activity. While such monitoring systems allow for detecting fires at an early stage, they are tedious from the perspective of the human operator and prone to human error. Additionally, such systems also suffer from the fact that they cannot be scaled to monitor extremely large areas. The scope of this project is to develop algorithms and systems for monitoring outdoor environments using real-time/time-lapse video data and detecting the presence of wildfires. Figure 1 shows a typical example of a wildfire in a natural environment.

Figure 1. Sample image of a wildfire from a camera monitoring the region surrounding Lyons Peak, CA. Image taken from hpwren.ucsd.edu

This is a highly challenging problem as even in the absence of wildfires, the image data exhibit an extremely large amount of variability due to different sources. Some examples of such sources include, but are not limited to, changes in illumination over a single day, weather changes and seasonal changes. In addition, each location is affected by the presence of nuisance factors such as the sun, cast shadows and moving objects such as trees. Figure 2 illustrates the variability we encounter in images taken under normal conditions. From this figure we see that even when there is no fire, the amount of variability we have to deal with is extremely large.

Approach

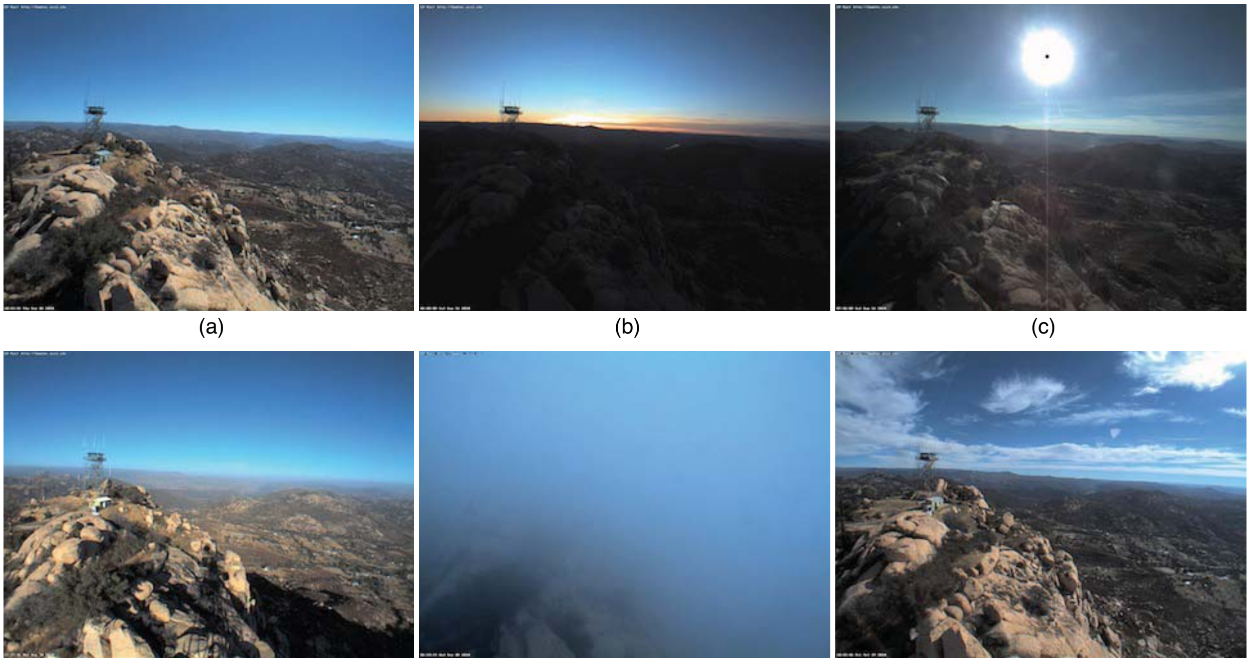
In order to detect wildfires in real-time/time-lapse video sequences, we propose to model all the variability one encounters under normal conditions such as illumination, weather and seasonal changes. The primary motivation for choosing such an approach is because modeling wildfires is extremely difficult as their characteristics are largely influenced by existing environmental conditions such as wind, temperature, etc. Furthermore, from the data collection perspective, it is easier to obtain video sequences under normal conditions than video sequences that contain wildfires. Once we are able to successfully model all normal variations, wildfires can be detected as any deviation that exists in the video sequence after accounting for all the normal variations.

Our approach to model the normal variability is based on the concept of canonization. The key idea behind canonization lies in converting different video sequences into a common reference model. For example, video sequences of all days in a year can be converted into a single reference frame where the length of the daylight is the same and the maximum illumination is constant. This would allow us to account for seasonal and daily variations. After this process, we plan to learn dynamical models (linear/switched systems) to learn the temporal evolution for different weather conditions. This would enable us to build a single model that accounts for all the normal variations and as stated earlier, once such a model is learnt, the task of wildfire detection reduces to an anomaly detection problem.

System(s) Description and/or Experiments

Feature Selection

We are currently investigating which single feature or combination of features of an image sequence would be best suited for modeling the different variations one encounters in a given scene. Towards this end, we are in the process of exploring the characteristics of several low-level features such as intensity, optical flow and feature trajectories in video sequences that have been acquired under normal conditions and under wildfires. Our initial results allude to the fact that optical flow (and its variations) might be a useful candidate feature.



(a) (b) (c)

(d) (e) (f)

Figure 2. Sample image taken under normal conditions at Lyons Peak, CA. (a) Typical clear day without any nuisances (b) Illumination changes at dawn (c) Nuisance present due to the sun (d) Nuisance present due to cast shadows (e) Poor visibility due to rain and clouds and (f) Light cloud cover. Image taken from hpwren.ucsd.edu

Benchmark

We are also in the process of running several relevant algorithms on outdoor webcam video sequences to evaluate their performance and at the same time highlight the drawbacks of such methods. Methods that are under consideration include but not limited to background subtraction algorithms, dynamic texture classification algorithms, change detection algorithms and existing (indoor) fire detection algorithms.

Accomplishments

Our accomplishments so far have been identifying sources of data for the project, preliminary benchmark results and exploiting auxilary information for solving our problem. As stated earlier, we believe that using optical flow will be a good candidate for modeling the different variability we will encounter during the course of a normal day. This conclusion is from our benchmarks so far. In parallel, we have also been trying to leverage weather data for annotating the images. This is an extremely critical step in our pipeline, as the models we build will be based on the annotations we build. Currently, there are no annotations on an image and this would be necessary for us to separate the different conditions.

Future Directions

Our future directions include obtaining data (time-lapse video sequences) taken by a single static camera at a particular location over a single year. We have identified The High Performance Wireless Research and Education Network (HPWREN), a National Science Foundation funded network research project as a source of our data. HPWREN has several cameras deployed in and around the San Diego area for monitoring wildfires. In addition to video data from such cameras, we also plan to collect weather data at these locations. This would help us validate our algorithms and use additional information from such data to help us in our model building phase.

Once we have the required data, we plan to first perform the canonization step of our framework. This would enable us to proceed to the model building stage of our pipeline. For the model building stage, we currently have a few candidate models that we plan to use such as linear dynamical systems and switched linear dynamical systems. However, we would first need to validate the usefulness of such models on the data. Since our goal is not the reconstruction of the image sequences using a class of models, we plan to evaluate the usefulness of our model by comparing the correlation of the model output between similar sequences in the training data.

The final step in our framework will then be the anomaly detection step. We envision that most of our efforts in this step of the piepline would be reserved for the following year of the project. Our primary focus this year will be on modeling all the natural variability we seek to encounter in normal video sequences.

TEOS 07 New Technologies in Tropical Forest Research

Team Members

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Overview

Sensor networks offer a powerful combination of distributed sensing capacity and open possibilities for countless applications in ecological research. The frontiers of ecology expand as biologists think of new applications and engineers develop the necessary tools, extending what can be done with sensor networks. Ecology and engineering iteratively inform and transform each other. Nested data streams from local sources, adjacent networks, and remote sensing sources, multiply the capacity of ecologists to observe systems in near real-time and address questions at temporal and spatial scales otherwise unobtainable. All these advances are providing a new and better understanding of our ecological systems by revealing previously unobservable phenomena and promoting a new generation of ecological questions.

Tropical ecology has lagged behind other environmental areas of research in the use of embedded sensors due to a variety of factors including llimited accessibility and the difficulty of working with sensors and instrumentation in rainforest conditions. This project has focused on ways to incorporate novel technologies to make research more effective expediting our understanding of tropical ecosystems.

Figure 1. Tropical rainforest canopy at the La Selva Biological Station in Costa Rica. This is the site of the new infrastructure of three instrumented canopy towers and walkway. The tropical forest sensor network project has carried out the deployment of instrumentation on these towers as well as the fiber optic system connecting the towers to servers in the laboratory area of the field station

Approach

The approach used by this project has involved two activities, each aided by funding from NSF. The first was the involvement of the project in working with Costa Rican staff at the La Selva Biological Station to complete the installation of sensors on the three canopy towers and to develop the protocols for the servers that collect the sensor data via a fiber optic cable back to the laboratory area of La Selva. The conceptualization and development of the NSF MRI-funded canopy tower project was described in a previous annual report.

The second area of activity was to hold a Pan-American Advanced Studies Institute (PASI) course at La Selva to introduce tropical ecologists to recent developments in sensor networks and cyberinfrastructure. This course, *PASI: - Expanding the frontier of tropical ecology through embedded sensors*, focused on exploring potential new applications in tropical ecology, and how the field can be reshaped as we generate hypotheses to uncover new aspects of the ecology of tropical forests. It was expected that this PASI would have its highest impact among Latin American tropical ecologists, because in Latin America this technology is just emerging.

The expected outcomes were: 1) Tropical ecologists enrolled would be able to expand their ecological questions by using embedded sensors; 2) Tropical ecologists would become familiar with the design, set up and management requirements of embedded sensor networks that are appropriate for the temporal and spatial scale of their hypotheses; 3) Groups of tropical ecologists with common interests would be facilitated to encourage partnerships, research alliances and the establishment of their own collaborative networks; and, 4) Critical questions in tropical ecology would be identified where novel applications of sensor networks could have transformative effects

System(s) Description and/or Experiments

Thirty-one graduate students, post docs and young faculty were selected to enroll in the PASI course, drawn from a pool of 80 applicants. These students were roughly split between Latin American and American students, with the groups including the representation of 14 countries (Figure 2).

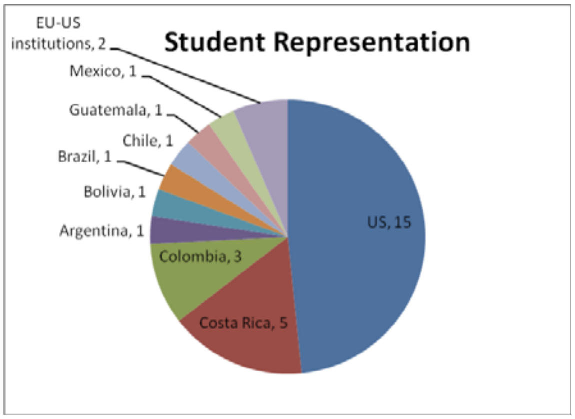

Fig. 2. Nationalities of students admitted to the PASI

The course was held over a two-week period from August 15-31, 2010, and involved 16 participating faculty who were each responsible for covering specific topics within the broader theme of the course. Six of these faculty had major connections with CENS, and formed the core faculty contingent for the course. Other participating faculty came from the University of California, Florida International University, University of Southern California, New York State Museum, University of Puerto Rico, and NEON. The emphasis was on a breadth of coverage of technological approaches rather than a detailed exploration of any single theme.

The course was organized so that each faculty member led the participants for one day, commencing by giving them a general topic introduction and synthesis of current research in their field, and then moving the classroom into the field or laboratory for hands-on practical demonstrations and workshops in setting up sensor arrays and collecting data. These workshops were usually followed by classroom analysis of data and where applicable student presentations on their findings. Some faculty members grouped together over several days because their technical material had strong overlaps, and worked by rotating among small groups of students.

To facilitate student exchange of ideas, and to give them the opportunity to showcase their own work, we asked each student to give a 10-minute presentation. These presentations took place the first week, in one hour after-dinner sessions. In the second week the evenings were used to enable further data analysis and presentations of faculty led student projects and round table discussions of key themes relating to the utilization of sensor technology and promotion of the development of new research ideas.

In addition to the lectures and hands-on exercises, a critical component of the the PASI was a series of round table discussions on key themes relating to the utilization of sensor technology and the development of new research ideas. Students and faculty were given a discussion guide in advance in order to make the evening session more productive. Discussion questions included:

Q1 In what ways are sensors employed in ecological research?
Q2. Why use sensors?
Q3. How should sensors be employed in ecological research?
Q4. What are the benefits of using sensors and sensor networks?
Q5. What are the potential pitfalls of using sensors
Q6. What kinds of projects can afford sensors?
Q7. How should large amounts of sensor data be shared?
Q7. Which of the modes/ways above best describe how you might employ sensors in your work?

Accomplishments

Five CENS staff and faculty have worked with the staff of the Organization for Tropical Studies to make the NSF MRI-deployment of instrumented towers a reality. This effort involved a considerable amount of staff training, both via Skype conferencing and in the field at La Selva.

This PASI course leveraged previous NSF investment from CENS as well as at La Selva. For the last 40 years, NSF has supported large-scale research at La Selva on a variety of topics and using a diverse set of tools, including more recently embedded sensors. With this PASI we were able to train a new generation of scientists on how to incorporate sensor technology into their research and to develop future NSF proposals and to maximize the potential of this new infrastructure.

Future Directions

CENS faculty and staff continue to work with La Selva staff to assist in the operation of the instrumented canopy towers. An NSF Macrosystems proposal has now been submitted to develop a La Selva research program using these facilities. Planning is also underway for a small PASI follow-up course to be held at La Selva in June 2011.

2.4 Contaminant Transport Assessment and Management (CONTAM)

The Contam research area focuses on developing technology to observe and manage mass and energy distributions and fluxes across a range of temporal and synoptic scales. In 2010–2011, the contaminant transport group continued its emphasis on integrated sensing and model-driven analysis. Projects continued to focus on high resolution river observation and modeling with respect to whole stream metabolism, groundwater-surface water exchanges, and hydrodynamic mixing. In addition, new emphases have emerged in the areas of (1) managed aquifer recharge aimed at increasing the sustainability of groundwater supplies and (2) integrating remote (aerial) sensing products with CENS embedded sensing strategies in order to extend our approaches to larger spatial scales (i.e., watershed).

The **major accomplishment** in the Contam application area for 2010–2011 was **the installation of a major new observational network at a managed aquifer recharge site in Fresno, CA**. After more almost 2 years of uninterrupted data from the Palmdale water reclamation and irrigation site, and the dairy wastewater irrigations sites near Merced, CA, we shifted sensing resources to the managed aquifer recharge site in Fresno, CA. This newest Contam site is called **MARnet** (managed aquifer recharge network). One of the observational nodes is shown Figure 3 during the initial flooding of the infiltration pond. At this site, we aim to successfully demonstrate integrated modeling and observational techniques which **will enable managed aquifer recharge with reclaimed water to be used more readily in arid and semi-arid climates, thereby increasing the sustainability of water resources**.

Figure 3. The new CENS-CITRIS managed aquifer recharge network (MARnet) prototype presently installed at the Fresno city wastewater treatment facilities.

Overall the Contam group focused on three projects over the past year, including (1) the new managed aquifer recharge site, (2) continued development of high temporal resolution dissolved oxygen data collection and net daily metabolism estimation at high spatial resolution, (3) developing new approaches to integrating CENS' embedded sensing approaches with larger scale remote sensing data.

After transitioning sensor to the MARnet site, we also focused effort on the interpretation of long-term data at the Palmdale and Merced dairy sites. Findings from these sites are summarized in one doctoral dissertation and two M.S. theses. These focus on the development and testing of long-term simulation models and data assimilation methods for forecasting the effects of irrigating with reclaimed water on groundwater quantity and quality in terms of nitrate and salinity levels, and on the long-term problem of soil salinization. Our results indicate that **by hardening the demonstrated approaches we can build robust embedded sensing systems reporting higher level information than simply moisture changes over time, reporting instead on the sustainability of current practices** and proposing modifications to improve upon the current approach. Furthermore, to enable scale up of the MARnet approach we have developed parsing algorithms that sort hydrologic and geospatial properties and socioeconomic features over large areas, such as counties, to identify the most promising areas for developing MAR operations. In the coming year this aspect of Contam research will continue to operate and assess the MARnet prototype while working with local water agencies to identify additional test sites. In particular, we are interested in identifying a floodwater diversion site to contrast with the existing wastewater reclamation site.

In the second project area, we have extended our aquatic sensing capabilities on the Lower Merced Rivers, having installed a long-term water quality monitoring station in September 2010. This station is enabling us to continuously examine water quality parameters at high temporal resolution in a critical agricultural reach of the river. In addition, we have continued our synoptic monitoring efforts over this river reach on a roughly quarterly basis, including both water quality and imagery to capture human influences in the form of inputs (canals, drain pipes) and outputs (pumps and diversions). **By combining the temporal and synoptic data we are learning to separate the influences of human disturbances from natural background processes.** At this time we are focusing mainly on temperature, dissolved oxygen (DO), and nitrate changes in the river, and using the ecosystem metrics associated with net daily metabolism (primary production, community respiration) as a method for quantifying the river's response to natural