

Spectroscopy of Humid Tropical Forests

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1. Abstract

Tree canopies play an enormous role in the maintenance of tropical forest biodiversity and ecosystem function, and are thus central to conservation, management and resource policy development of tropical regions. However, high-resolution mapping of tropical forest canopies is difficult because traditional field, airborne and satellite measurements cannot resolve the species over the large regional scales commensurate with conservation goals and strategies. Newer technologies such as High-fidelity Imaging Spectroscopy (HiFIS) and Waveform Light Detection and Ranging (wLiDAR) have just now reached performance levels that could revolutionize tropical forest diversity mapping from the air, but the methods and taxonomic database needed to apply the technology are not yet ready.

The Carnegie Airborne Observatory (CAO; <http://cao.ciw.edu>) is the first fully-integrated HiFIS-wLiDAR sensing system developed for regional ecological research and mapping. The CAO is capable of measuring the location, chemical composition and three-dimensional structure of each tree in a tropical forest canopy, but conversion of the 3-D chemical information to taxonomic diversity has only been achieved in a few small forest stands in Hawaii. The two most important factors currently limiting our ability to map tropical forest canopy diversity with the CAO and similar future technologies are: (1) a database that establishes the broadest linkage between spectral, chemical and taxonomic properties of canopies in tropical forests; and (2) new algorithms that take advantage of a taxonomic database to map canopy diversity over large regions.

To address these limitations, I have established the Carnegie Spectranomics Project to collect, measure and disseminate information on the spectral-chemical properties of tropical forest canopy trees throughout the world. The regions of interest include Pan-Amazonia, Central America, tropical Africa, the Caribbean, SE Asia, Oceania, and the western Pacific. New algorithms for extracting taxonomic information from the spectral-chemical properties of plants collected for this database will advance our airborne mapping approach. This new online spectranomic database and algorithms will provide the technical material needed to map and monitor changes in tree biodiversity in key tropical forest conservation areas worldwide. This new spectranomics approach will revolutionize how tropical forests are measured and monitored by aircraft for conservation, management and resource policy development.

2. Background

The high biological diversity of tropical forests challenges our ability to make ecological observations, understand ecosystem function, develop conservation strategies, and manage these systems (Myers et al. 2000). We know relatively little about the local and regional taxonomic diversity of many forests in the tropics, or how tree diversity is responding to climate change and human activities (Curran et al. 1999, Clark 2004). Recently, we have also come to realize that the chemical diversity of tropical forests is tightly linked to their taxonomic diversity (Asner and Martin 2009). However, our ability to accommodate both chemical and taxonomic diversity in our understanding of tropical forest function is hindered by too few measurements at regional scales.

The potential ties between the taxonomic and chemical diversity of tropical forest canopies are also important to conservation, management and resource policy development. The success and sustainability of conservation lands rests in maintaining a portfolio of taxonomically, and thus chemically, diverse plant species that provide critical habitat and sustain ecosystem function. However, changes in the diversity of tropical forests are thought to be occurring as a result of climate change, invasive species and other factors (Wright 2005). Even with protection and sustainable forest use, conservation lands may lose species and become biologically impoverished unless management can be applied at the right time and in the right places. The taxonomic composition of conservation lands is difficult to inventory and assess in tropical forest regions. Ground-based monitoring of canopy diversity is limited by poor geographic coverage and the inaccessibility of tall trees. Current satellite measurements do not contain the information needed to dissect a landscape of forest canopies into taxonomic maps.

Airborne remote sensing has been used for many years to assess the extent and even the composition of forest ecosystems (Wulder and Franklin 2003). Certain types of species are likely to stand out in basic color-infrared images, such as when broadleaf trees are observed on a landscape that is mixed with needleleaf species. However, spectral differences among tropical forest canopy species, which are often all broadleaf evergreen trees, are far more subtle, and thus often invisible in traditional photographs.

A newer technology called High-fidelity Imaging Spectroscopy (HiFIS) measures the reflectance of the Earth in hundreds of narrow spectral bands, thereby resolving the subtle spectral features associated with the chemical composition of materials (Fig. 1). HiFIS systems have only recently been built to performance specifications that allow for reliable remote chemical determinations of plants

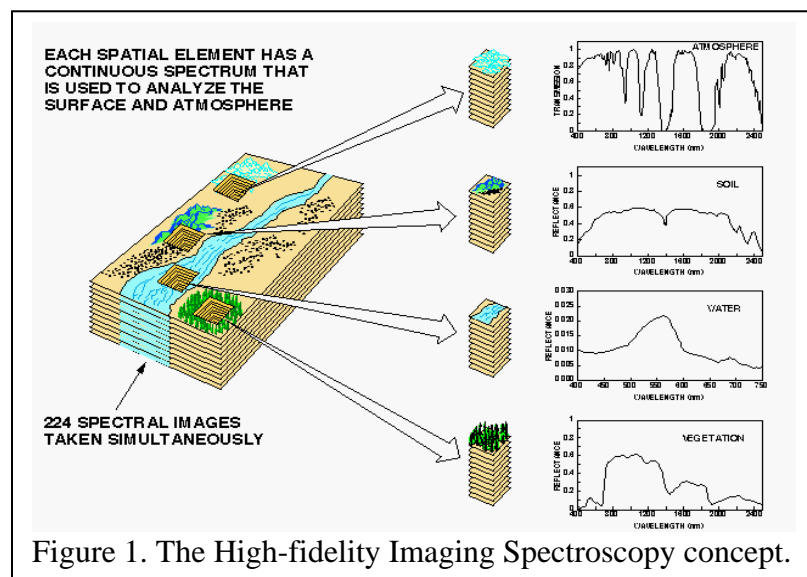


Figure 1. The High-fidelity Imaging Spectroscopy concept.

and ecosystems from aircraft (Asner et al. 2007). Although HIFIS has come of age technologically, the methods for extracting chemical, and thus taxonomic, information from the remote sensing data have only been developed in a few small regions of the world, such as in Hawaii (Asner and Vitousek 2005, Carlson et al. 2007). The challenge of mapping species in continental tropical forests remains particularly daunting, given the high diversity of these regions.

Very recently, we established a new theoretical and observational link between spectral, chemical and taxonomic diversity of tropical tree species in way that is generic and scalable. The approach uses the Carnegie Airborne Observatory (CAO; <http://cao.ciw.edu>), to map species based on their chemical “fingerprints”. The CAO is the first airborne system that combines HIFIS with Waveform-Light Detection and Ranging (wLiDAR) to provide three-dimensional maps of canopies and their chemical signatures (Fig. 2; Asner et al. 2007).

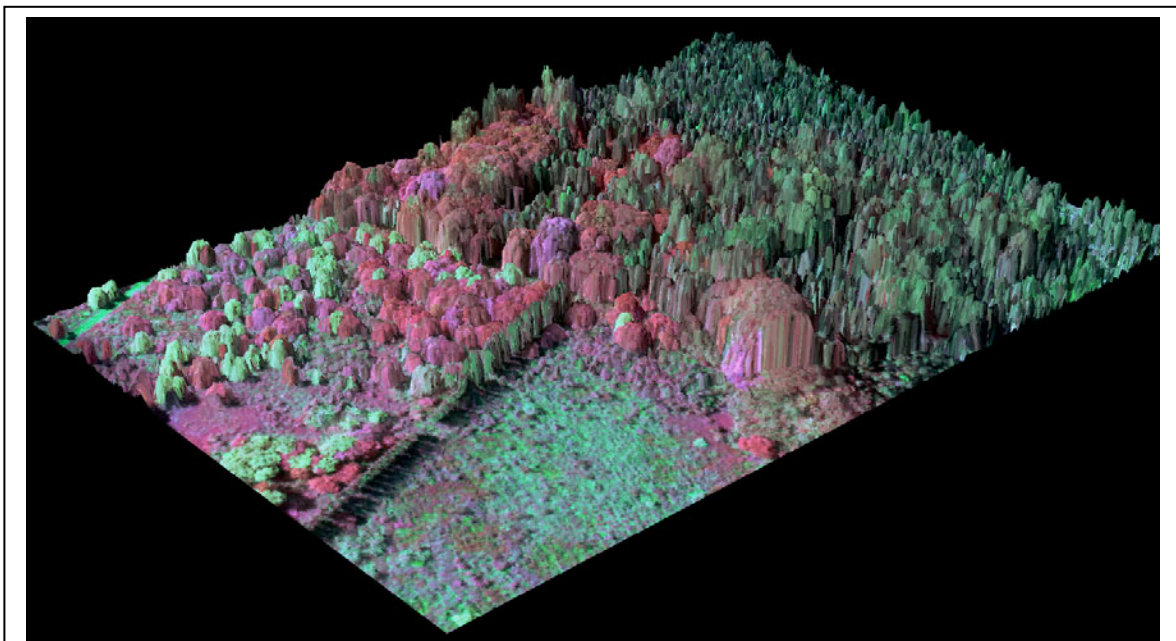
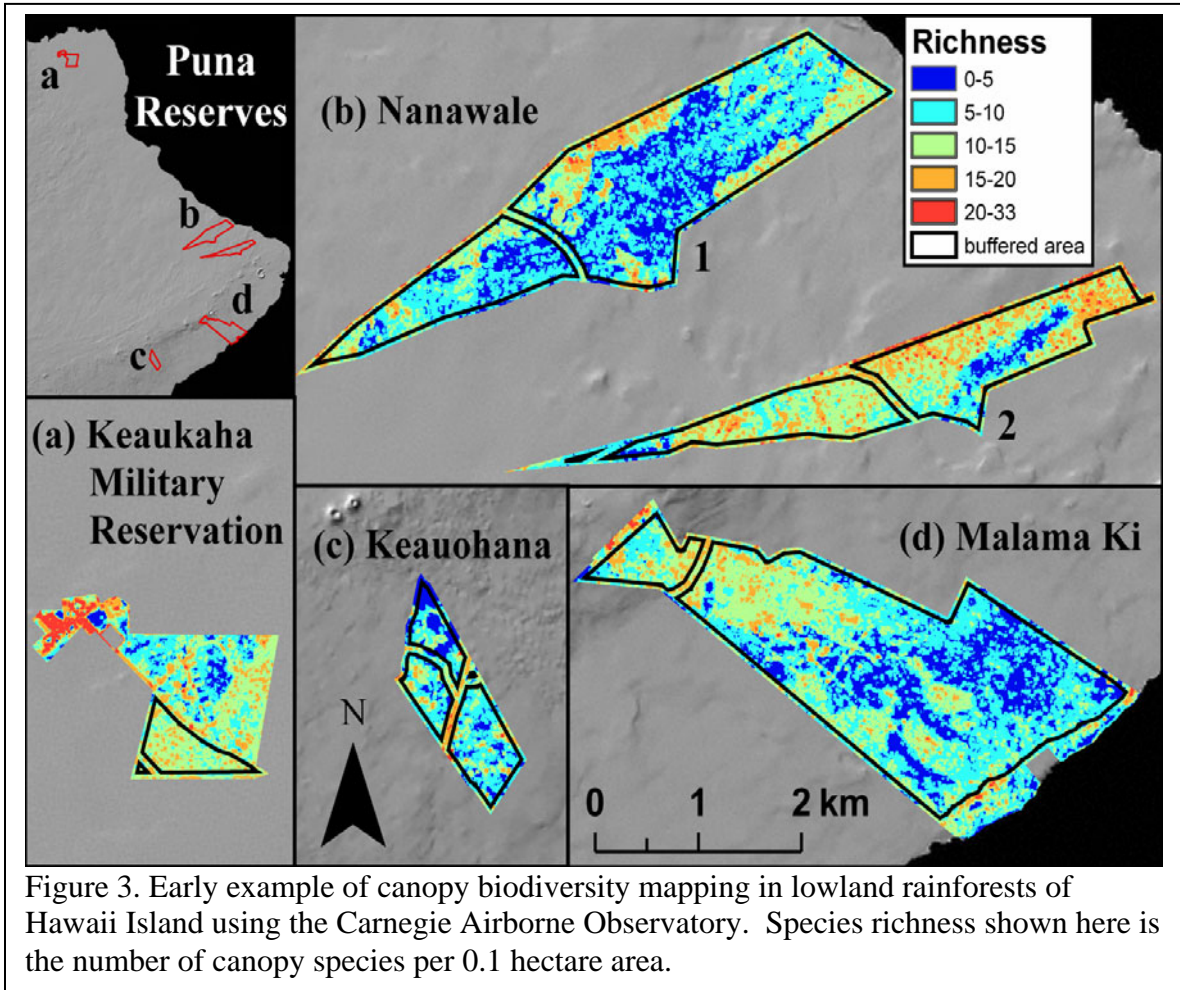


Figure 2. Three-dimensional chemical mapping of canopies from the Carnegie Airborne Observatory.

The CAO is highly mobile, and could be taken to nearly any region of the world to map forest canopy composition at just 0.5-1.0 m resolution. The CAO is the first of its kind designed specifically to address the biodiversity problem. However, the two most important factors currently limiting our ability to map tropical forest canopy diversity with the CAO and similar future technologies are: (1) a database that establishes the broadest linkage between spectral, chemical and taxonomic properties of canopies in tropical forests; and (2) new algorithms that take advantage of a taxonomic database to map canopy diversity over large regions.

We have discovered that canopy spectral-chemical properties express the presence of specific plants (Asner and Martin 2009). We are often able to separate the canopies at the species and genus levels, allowing for airborne mapping of canopy species diversity in rainforests of Hawaii (Fig. 3). These early steps provide the proof-of-concept that airborne

spectranomics is possible, starting with the database and scaling up to thousands of hectares of tropical forest. This approach could revolutionize how tropical forests are measured and monitored by aircraft for conservation, management and resource policy development.

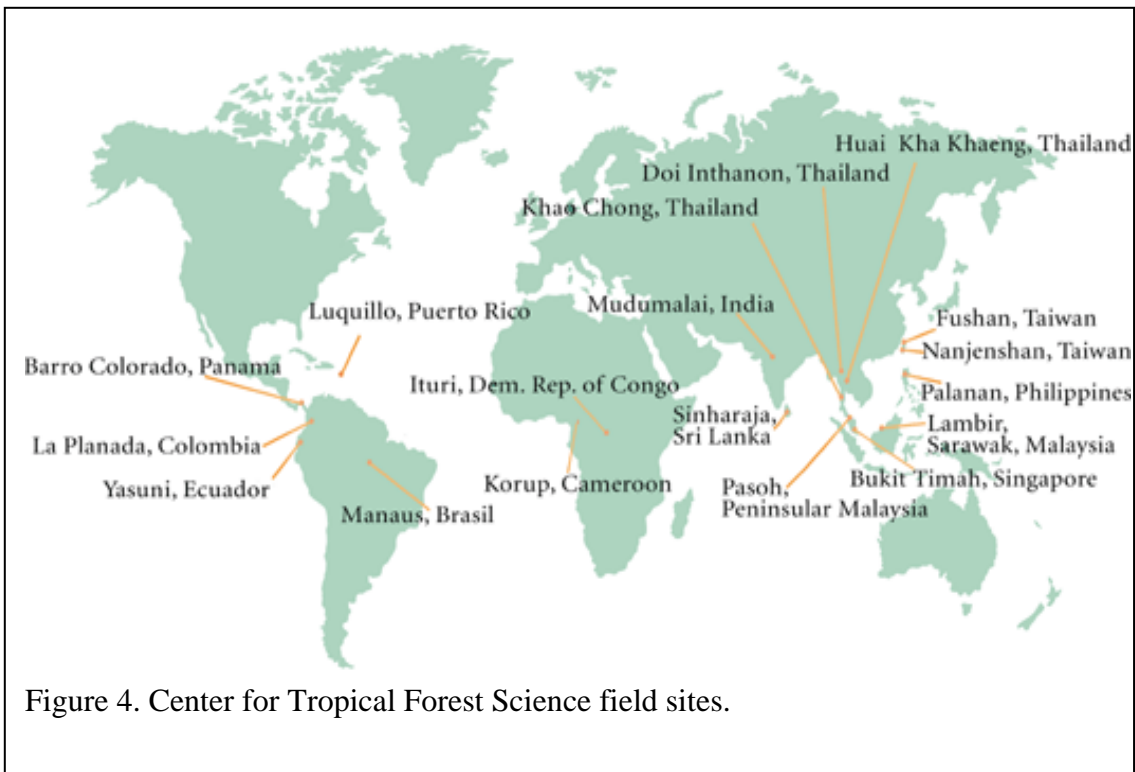


3. Technical Approach

3.1 Global Field Sites

The value of the global Spectranomics Project will increase with the number of tropical forest sites incorporated into it, and with the taxonomic diversity of the species contained within these sites. It will not be possible to sample every canopy species found in the humid tropics, but this is not necessary initially. We believe that a strategic sampling over approximately 10,000 tree species, with more intense sampling among the most common and the most rare species across key families, will produce a database that can be employed almost anywhere in the world.

For the global database, our strategy is to organize the field data collections around the vast inventory of trees identified and marked in the globally distributed 50-ha plots of the Center for Tropical Forest Science (CTFS), Smithsonian Tropical Research Institute (www.ctfs.si.edu; Fig. 4), plus several megatranssects extending through Peru where tree diversity is very high, and finally across a series of additional focal sites currently under investigation by collaborating scientists (e.g. Monteverde and Osa, Costa Rica; Borneo, Indonesia; Gabon, Africa). This vast network of field sites contains thousands of tree species in the most common plant families found throughout the humid tropics. Collaborators from the World Wildlife Fund, STRI, the Field Museum, and many universities are assisting in the development of sites and project plans.



3.2 Data Collection and Measurement Techniques

3.2.1 Field Measurements

Our Carnegie research team deploys to each tropical forest site for a period of 1-3 weeks to collect canopy foliage from hundreds of trees. At each research site, tree species are identified by a taxonomist and 3-5 branches per tree are collected from top sunlit portion of each canopy using a shot gun, sling shot or tree climbing. Fully expanded, mature, sunlit leaves are taken from each branch for immediate determination of spectroscopic properties (350-2500 nm; ASD FS3s and custom-built integrating spheres). Leaf samples are immediately frozen in liquid nitrogen or on dry ice in the field. These samples are stored at -80°C until analysis for photosynthetic pigments (one set of three samples for chlorophylls and carotenoids and one set of three samples for anthocyanins), secondary compounds, and DNA sequencing. The remainder of each leaf collection are dried and prepared for eventual laboratory analysis.

3.2.2 Laboratory Measurements

Dried and frozen leaves returned to the Spectranomics Laboratory at the Carnegie Institution's Department of Global Ecology, Stanford, CA USA. Samples are analyzed for a suite of chemical properties including: multiple pigments, nutrients, metals, isotopes, secondary compounds, and water. The DNA bar-coding is also performed to enhance our ability to build phylogenetic trees depicting the chemical, spectral and taxonomic diversity of tropical forest trees.



Figure 5. Field and mobile laboratory work of the Carnegie group during the pilot studies on leaf and canopy spectranomics.

The output from the field and laboratory steps is a spectral-chemical dossier for each species, as shown in Fig. 6. The chemical fingerprint is comprised of a series of leaf properties, and the spectral signature of the species is made from the reflectance and transmittance properties. The database also includes leaf scans and photos of the type shown in Fig. 6, with some improvements for lighting conditions and composition.

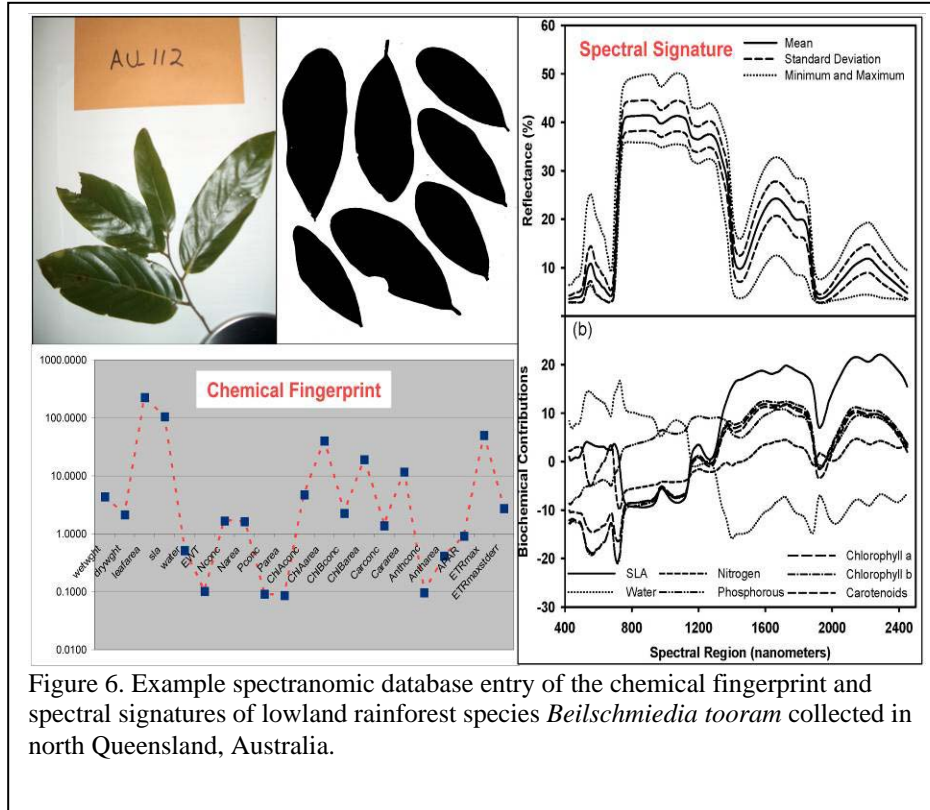
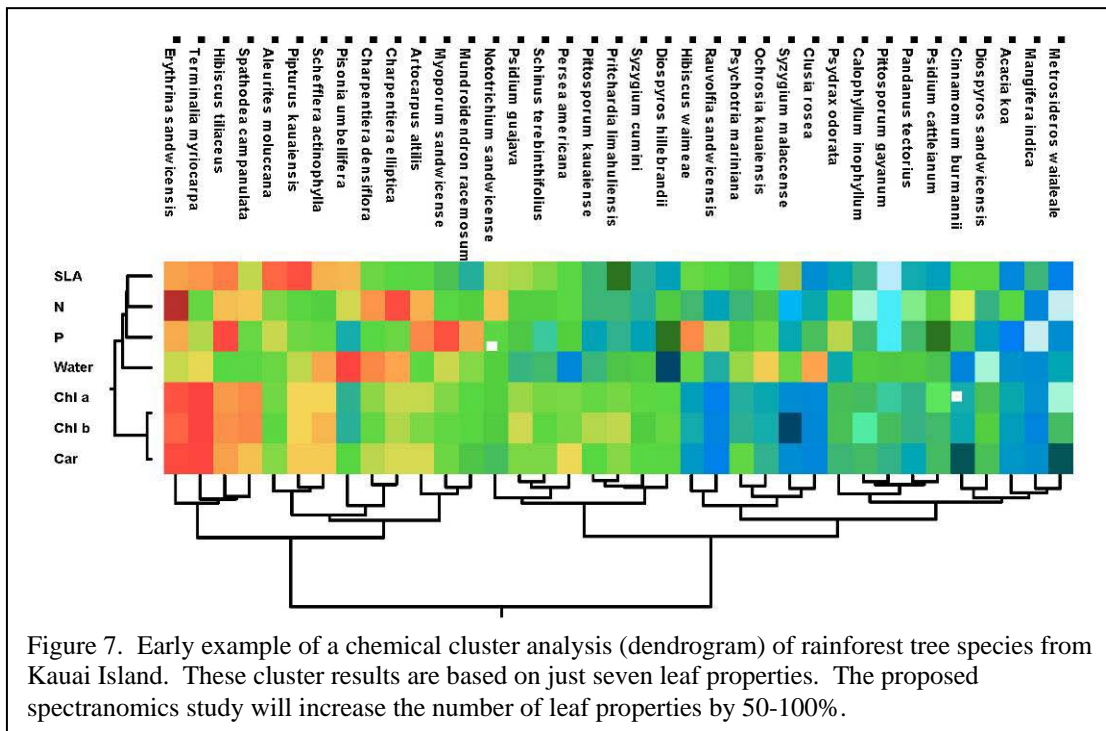


Figure 6. Example spectranomic database entry of the chemical fingerprint and spectral signatures of lowland rainforest species *Beilschmiedia tooram* collected in north Queensland, Australia.

3.3 Algorithm Development

We have developed a hierarchical cluster analysis technique to link the chemical and spectral fingerprints of species to their taxonomic class. This analysis produces a dendrogram depicting the organization of species, and the corresponding color map shows their chemical or spectral signatures (Fig. 7, next page). Typical uses for this type of analysis include phylogenetics. Here, however, the cluster analysis provides the means to simultaneously use multiple plant chemical or spectral characteristics to quantitatively sort species into groups based on their degree of association. Species cluster more closely if their complete chemical fingerprint or spectral signature is similar.

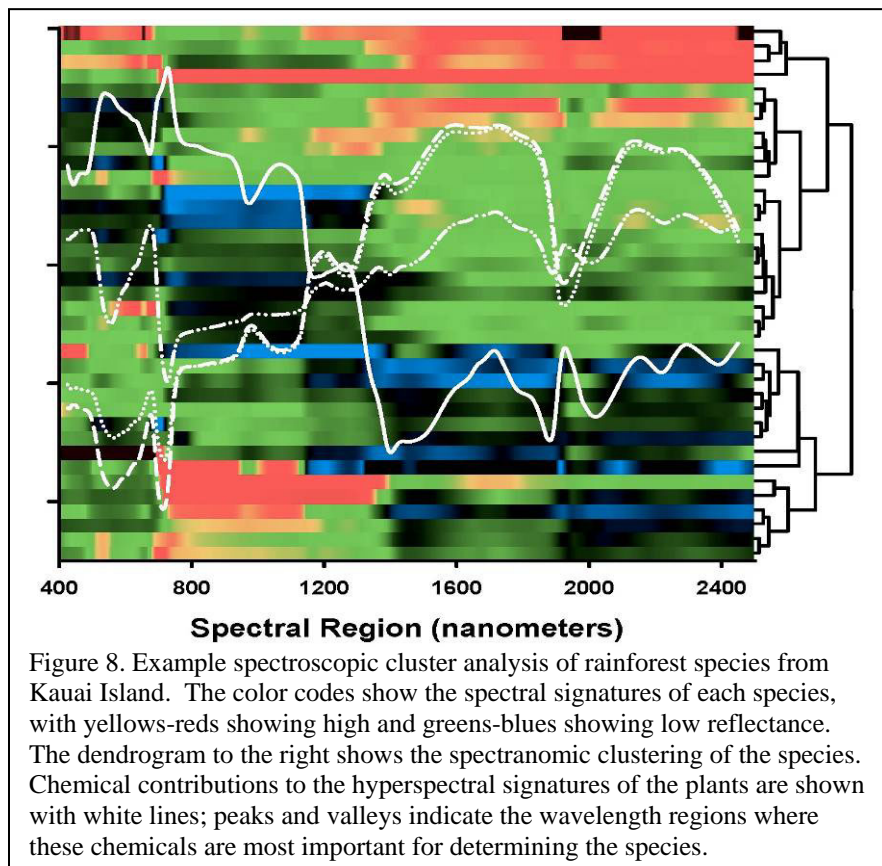


The distance between two clusters is the analysis of variance sum of squares between the two clusters added up over all the variables:

$$D_{KL} = \frac{\| \bar{x}_K - \bar{x}_L \|^2}{\frac{1}{N_K} + \frac{1}{N_L}}$$

where D is the statistical distance between each cluster pair K and L , x_K and x_L are the mean vectors for the clusters, and N_K and N_L are the number of observations per cluster.

Multi-parameter Partial Least Squares (PLS) regression is used to determine the relative contribution of each chemical constituent to the spectral signatures of the rainforest species. Although some chemicals are correlated, most are not, and thus form a unique chemical fingerprint for each species (Fig. 8).



4.4 Database and Website Development

We have developed a data system for the Spectranomics Project that allows for online searches based on taxonomic family, genus and species as well as site names and geographic location (<http://spectranomics.ciw.edu>; Fig. 9). The data can be extracted and organized by chemical or spectral properties. There is also a photograph and leaf scan of each sample species. There is also a web-based map server to allow for the database user to locate samples and species by geographic location and place name.

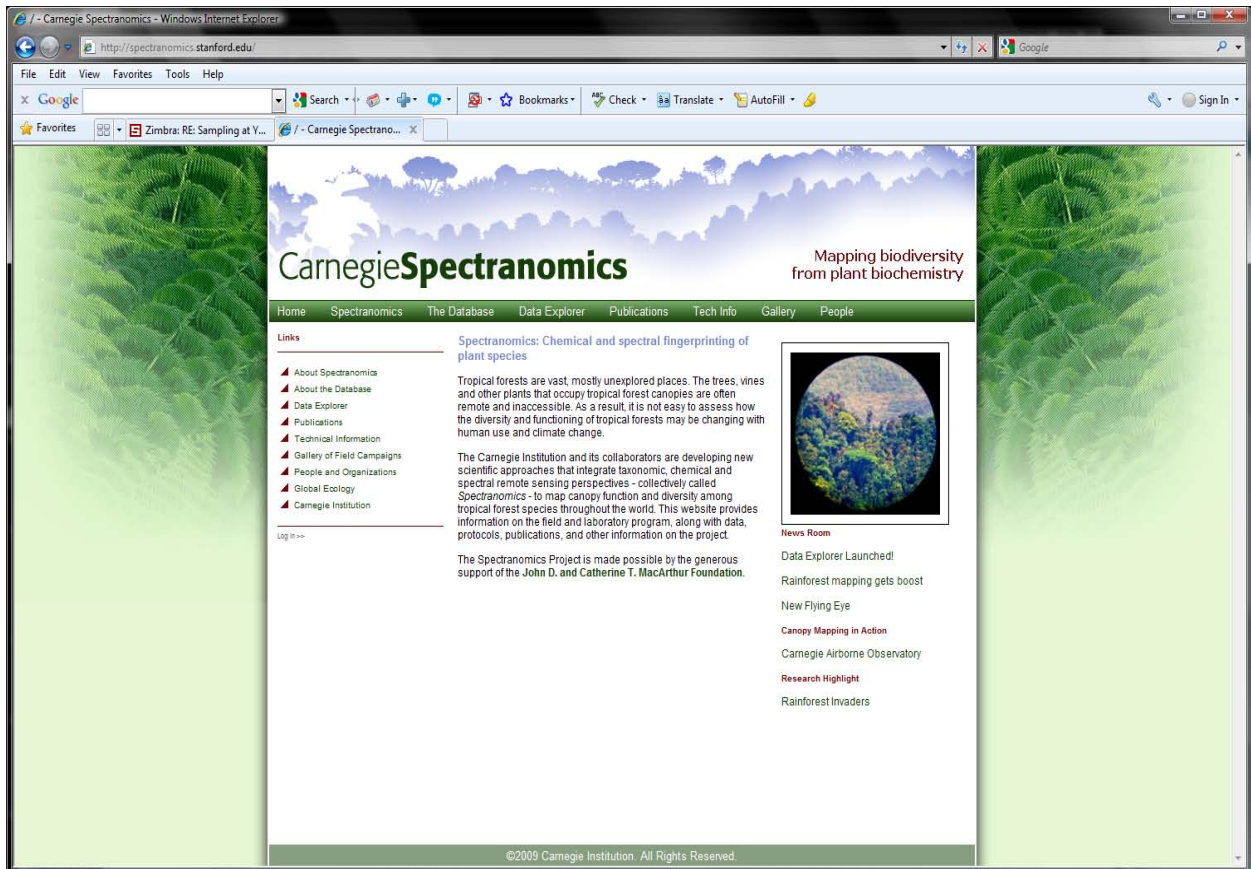


Fig. 9. The spectranomics website and data portal.

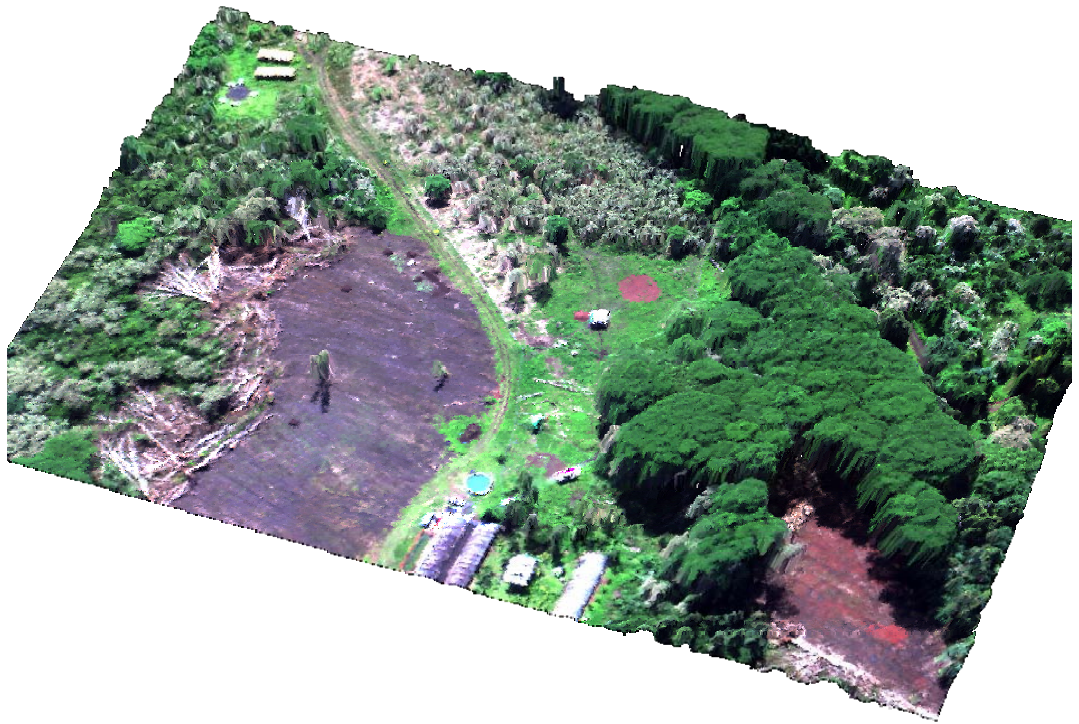
4. Project Significance

The tree canopy is a central component of any tropical forest, and thus it plays a major role in defining the broader biodiversity and functioning of the system as a whole. Today, the best way to measure the diversity of a tropical forest canopy is to survey it in the field. However, even a 50 hectare survey can take many months to complete, and this is a microscopic fraction of the forest canopies that exist today. Current aircraft or satellite technologies cannot provide the required information on which species are present or the levels of total species richness or abundance. New technologies, including the Carnegie Airborne Observatory, are breaking long-standing barriers by providing super high resolution, three-dimensional information on the chemical, structural, and taxonomic composition of tropical canopies (Fig. 10). The CAO can cover 20,000 hectares per day of flying, which is a

lifetime of ground survey work. Moreover, other organizations in different countries are replicating the CAO technology, so these instruments are going to be more common in the near future. However, the databases and techniques for converting airborne 3-D chemical measurements to taxonomic diversity are not ready.

The Spectranomics Project will service the specific ecoregions of ongoing conservation interest as well as the broad scientific community, providing the global database needed to bring airborne spectranomic mapping to reality worldwide. The database will plug directly in to the CAO and follow-on airborne technologies for use over many conservation units in tropical regions. This project will ultimately be just the first major phase of a much larger effort to deploy aircraft sensors in key regions across the planet, for mapping and monitoring the impacts of management decisions in the context of climate change, invasive species, and a host of other drivers of global environmental change. The spectranomics approach will also facilitate, via completely open-source data access and use, a sea change in how scientists and NGOs monitor tropical forests for conservation and management purposes. The time is ripe for a major shift in our capabilities at science and policy development levels.

Figure 10. 3-D imaging of tropical forest and cleared land from the Carnegie Airborne Observatory.



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