Global Ecology and Conservation 8 (2016) 212–219

Contents lists available at ScienceDirect

Global Ecology and Conservation

journal homepage: www.elsevier.com/locate/gecco

Review paper

Spectranomics: Emerging science and conservation opportunities at the interface of biodiversity and remote sensing

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ARTICLE INFO

Article history:
Received 5 August 2016
Received in revised form 19 September 2016
Accepted 19 September 2016
Available online 6 October 2016

Keywords:
Biogeography
Conservation mapping
Functional traits
Imaging spectroscopy
Phylogeny
Plant traits
Remote sensing

ABSTRACT

With the goal of advancing remote sensing in biodiversity science, Spectranomics represents an emerging approach, and a suite of quantitative methods, intended to link plant canopy phylogeny and functional traits to their spectral-optical properties. The current Spectranomics database contains about one half of known tropical forest canopy tree species worldwide, and has become a forecasting asset for predicting aspects of plant functional and biological diversity to be remotely mapped and monitored with current and future spectral remote sensing technology. To mark ten years of Spectranomics, we review recent scientific outcomes to further stimulate engagement in the use of spectral remote sensing for biodiversity and functional ecology research. In doing so, we highlight three major emerging opportunities for the science and conservation communities based on Spectranomics.

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Contents

1. Introduction

Spectranomics is an approach to conceptually and geographically link plant canopy species and their functional traits to their spectral-optical properties (Asner and Martin, 2009). With the long-term goal of advancing remote sensing in the biodiversity science arena, the Carnegie Spectranomics Project has generated tree-of-life, or phylogenetically-based, connections between the spectral properties of plants and their canopy functional traits. Here canopy functional traits refer to a constellation of at least 21 elemental and molecular properties, some of which support growth, such as nitrogen and photosynthetic pigments, and others that provide defense, like polyphenols and lignin, which have evolved in plant canopy

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http://dx.doi.org/10.1016/j.gecco.2016.09.010
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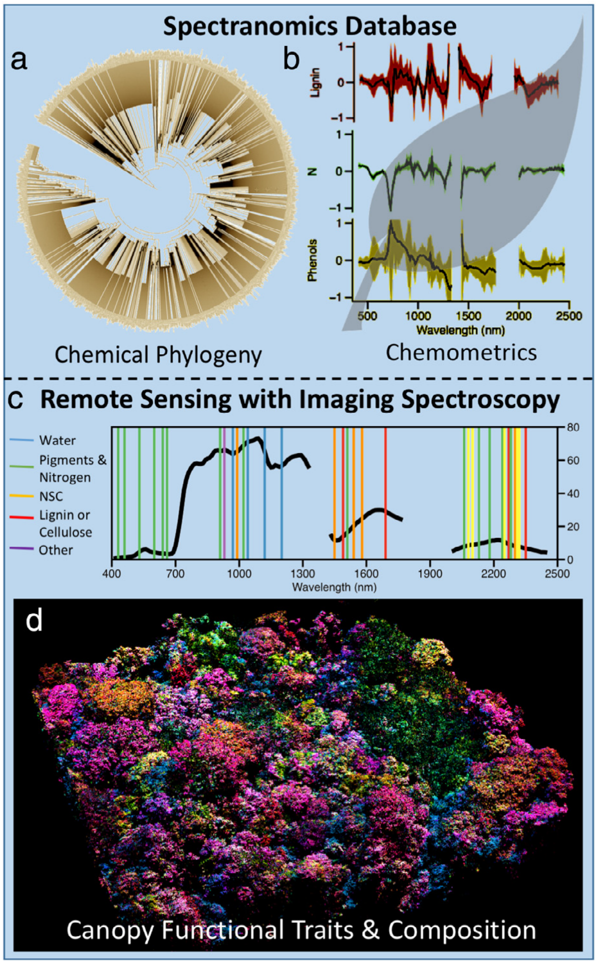

Fig. 1. The essential interactive elements of the Spectranomics Database include phylogenetic, chemical and spectral information on canopy species. (a) Twenty-one foliar chemical traits are collected, organized and analyzed phylogenetically, producing a tree-of-life based on the relatedness of functional trait signatures. This generic phylogeny shows the chemical relatedness of thousands of species in the Spectranomics Database. (b) Chemometric equations are derived to quantitatively relate canopy functional traits (chemicals) to spectral data; Example relationships are shown for foliar lignin, nitrogen (N), and polyphenols. The x-axis indicates spectral wavelength from 400–2500 nm; the y-axes indicate relative importance of the spectrum to each example chemical constituent. (c) An example remotely sensed canopy reflectance spectrum of one species (see Fig. 2 for thousands of species) is shown along with indicators of key chemical contributions to the spectrum (Curran, 1989; Kokaly et al., 2009; Ustin et al., 2009). (d) Oblique 3-D view of a one-hectare portion of lowland Amazonian forest canopy; Different colors indicate different species detected based on chemical traits using airborne imaging spectroscopy. The horizontal dashed line in the figure indicates our ability to scale the measurements from leaf (above) to canopy (below) levels (Asner and Martin, 2008; Asner et al., 2015b, 2011). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

leaves. This chemical make-up of plant canopies, and its similarity and uniqueness among species, is called "chemical phylogeny". These functional traits mediate leaf processes, whole plant function, and ecosystem dynamics, are often differentially formulated at the species level, and are an essential component of Spectranomics (Fig. 1(a)).

When we refer to spectral properties of plant canopies, another component of Spectranomics (Fig. 1(b)–(c)), we mean the mostly invisible way that plant foliage interacts with solar radiation. From the ultraviolet to the visible to the near-infrared and the shortwave-infrared regions of the electromagnetic spectrum (350–3500 nm), plants have many common and yet also unique patterns of interaction with solar energy. In plant canopy foliage, this interaction is strongly determined by 21 or more chemicals (Asner et al., 2011) that underpin plant evolution, and which power the biosphere. Chemometric studies determine how these chemicals relate to reflectance spectra, and the methods today range from traditional spectroscopic assays and newer machine learning approaches (Feilhauer et al., 2015; Serbin et al., 2014; Wold et al., 2001). Spectral properties also provide a tantalizing pathway forward to scale up from leaves to landscapes (Ustin et al., 2004), and to the planetary level (Jetz et al., 2016), but only if we can accurately and repeatedly measure and interpret the spectra of plants over increasingly larger portions of Earth (Fig. 1(c)–(d)).

In the first ten years of the Spectranomics project, we have collected, cataloged and stored more than 13,000 canopy tree and liana specimens, in over 3,000,000 tissue samples, representing about 10,000 species heavily biased to tropical sources

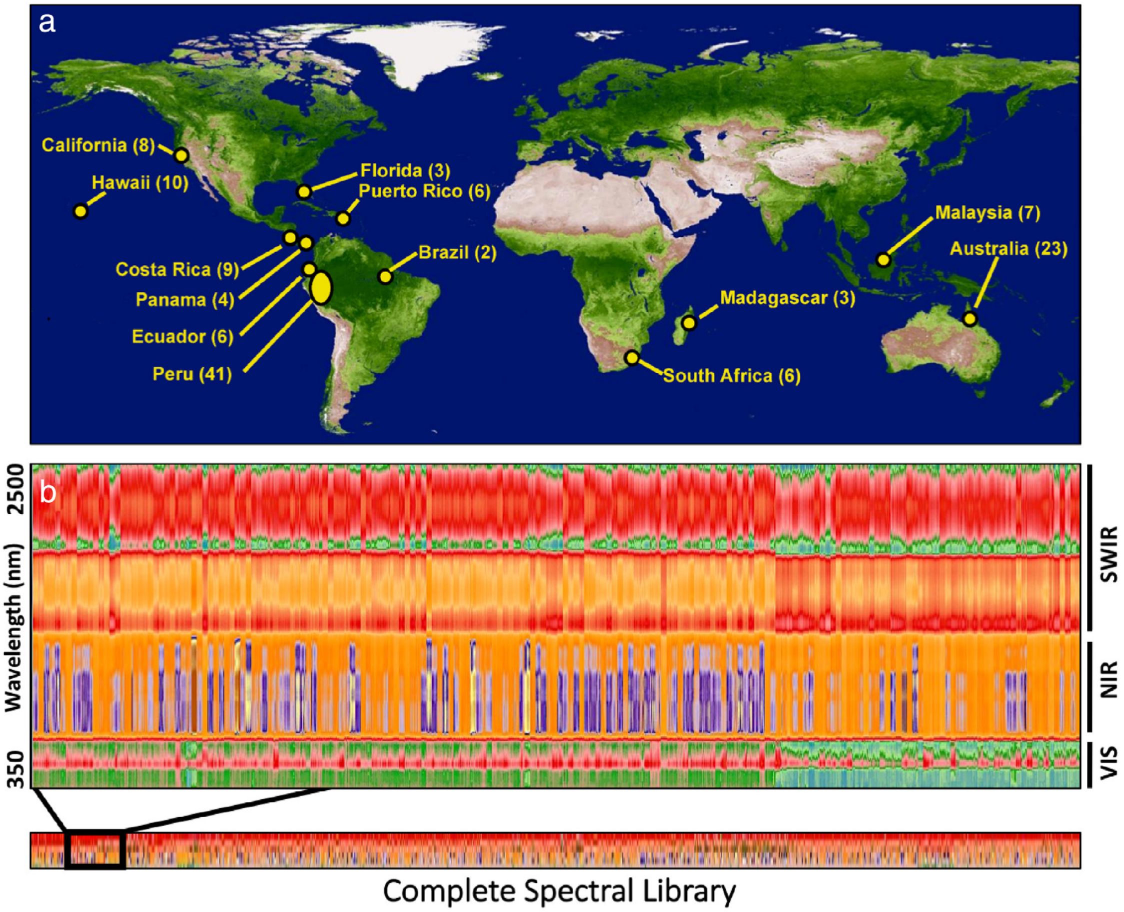

Fig. 2. (a) The 2016 global distribution of 128 forest landscapes contributing to the Spectranomics database. (b) Canopy foliar spectroscopic diversity of 5000 tree species drawn from the entire library. The vertical distribution of colors (by wavelength) indicates inter-specific variation in spectral reflectance. VIS = visible (350–700 nm), NIR = near-infrared (700–1200 nm), and SWIR = shortwave-infrared (1200–2500 nm) portions of the electromagnetic spectrum. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Fig. 2). For perspective, this number approaches the total number of tree species in the Amazon basin of roughly 11,000 (Hubbell et al., 2008), a value that would put the global tropical tree inventory at 30,000 species if we liberally extrapolate to the entire Neotropics plus the African and Asian-Oceanic tropics. The Spectranomics database focuses only on those species found in the canopy, meaning they are in full sunlight and are observable from above. Since roughly 30%–60% of tree species in a tropical forest plot makes it to the canopy (e.g. Bohlman, 2015), the current Spectranomics database contains at least half of the known tropical forest canopy species worldwide.

However, it is not only about the numbers; in the past ten years, the Spectranomics database has yielded discoveries about plant canopy traits, spectral properties, and their phylogenetic relatedness. The scientific advantage rests not in the individual data components – traits, spectra, and phylogeny – but rather in the way they are standardized, analyzed, integrated and utilized. Back in 2006, most of our prior work, and the collective work of others, had not taken a strategic, integrated approach to large spectral–functional trait database building. This was needed if patterns were to emerge that reveal plant canopy spectral function at a biospheric scale. From investigations of these fundamental patterns, Spectranomics has evolved into a new pathway to biological and ecological discovery, as well as to conservation-relevant mapping, particularly in high-diversity tropical forests.

To mark ten years of the Carnegie Spectranomics Project, we synthesize and describe major program outcomes to date, with the purpose of motivating broader scientific engagement in the use of spectral remote sensing for biodiversity research. In doing so, we highlight three emerging opportunities for the science and conservation communities based on Spectranomics. Taking the science to continental and biospheric levels could yield enormous benefits for understanding, managing and conserving global ecosystems.

1.1. *Importance of plant canopy diversity in the biosphere*

Plants have radiated into a massive array of species occupying a large part of the planetary tree-of-life. Plants are both an outcome and a driver of the rest of Earth's biodiversity ranging from microbial life to apex predators. Canopy plants – those that occupy the "high space" on a landscape at the main intersection of the biosphere and atmosphere – play a prominent role in numerous large-scale processes ranging from the Earth's climate to human food production. Canopy plants are also a foundational determinant of habitat for species that live on them and within their shadow. Forest canopy plants are particularly critical contributors because they store huge amounts of carbon, regulate water cycling at watershed to continental scales, and provide habitat for millions of other species.

Despite this basic understanding, the highly variable role that different canopy species and communities of species play in the biosphere remains uncharted in many portions of the planet. This, in turn, maintains a disconnect between biodiversity conservation and the big picture role that plant canopy diversity plays in the Earth system. For example, simply knowing that a forest canopy is present on any given landscape is insufficient for determining the role it plays in vital functions such as animal habitat, carbon storage or hydrological cycling (Schimel et al., 2013). We must know more about forest function and composition, and their interactions. Canopy functional diversity can be defined as the variation in plant canopy properties mediating their growth and survival, relative to neighboring plants and communities, and the effects of that variation on both evolutionary and ecological processes. Functional diversity connects biological diversity to ecosystems and the rest of the Earth system, including the atmosphere, hydrosphere, lithosphere, and cryosphere (Mooney et al., 1996).

Measuring, mapping, and monitoring forest canopy composition and functional diversity has been a slow, laborious, and sometimes biased process. Forest composition and related functional properties are difficult to assess because spatial and temporal variation often exceeds our ability to adequately utilize field-based approaches (Marvin et al., 2014), and traditional satellite observations do not easily reveal compositional differences or changes over time (Turner et al., 2003). Current satellite technology monitoring the biosphere is limited to detecting changes in vegetation cover as well as major differences in vegetation type and photosynthesis (Running et al., 1994; Tucker and Townshend, 2000). Tropical forest functional diversity is especially underexplored because canopies cannot easily be climbed, let alone on a repeat basis, and certainly not sufficiently in high-diversity settings where many canopy species coexist. Labor, costs and time are simply too limiting in the field; the laboratory work needed to match the field work is hard to maintain over time; and the limitations of current satellite technology are large. Innovation is needed to achieve the goal of measuring, mapping, and monitoring changes in the compositional and functional diversity of the biosphere.

1.2. *Emerging capabilities of the spectranomics approach*

Spectranomics is one solution to this challenge. As we have worked to grow the Spectranomics database, it has become an increasingly useful tool to quantitatively test relationships between plant phylogeny, canopy traits, and spectral properties at nested biogeographic scales, whether in tree communities, on mountains, or between continents. Moreover, with database expansion over the past decade, Spectranomics has transitioned to a forecasting asset that predicts what can be remotely mapped and monitored with spectral remote sensing instrumentation.

One of our larger projects in the Andes and Amazon region of Peru provides an example of this forecasting ability. This effort involved years of climbing and collecting foliar samples from 3856 canopy trees along a 3400-m elevation gradient hosting a range of conditions needed to test how environment and phylogeny interact to sort the spectral–functional diversity of forest canopies (Asner et al., 2014b). We discovered that canopy trait diversity of Andean and Amazonian forests occurs in a nested pattern driven by long-term adjustment of tree communities to large-scale environmental factors, particularly geologic substrate and climate. Critically, however, we also found that the regional pattern is generated by phylogenetically-organized differences in canopy functional traits that are essential to plant growth and defense under shifting elevation-dependent environmental conditions. In short, Spectranomics led us to understand that canopy functional traits can be nested regionally by environmental setting, but expressed locally within any given environment by their evolutionary origin.

In parallel to these functional trait findings, we discovered that the spectral properties of canopy foliage closely tracked canopy functional trait responses to macro-environmental changes (Asner et al., 2014a). And similar to the functional trait findings, we discovered that the spectral properties of foliage within communities along the elevation gradient were largely determined by phylogenetic identity. Consequently, canopy functional traits and spectral properties tracked one another at nested ecological scales, a result that forecasts what we might find if we collected map-based spectral data over a much larger geographic area using remote sensing instrumentation.

Two particular forecasts emerged from the Spectranomics work in the Andes–Amazon region. First, Spectranomics suggested that spectral mapping from current aircraft and future satellites will reveal where whole forest communities are functionally similar and where they are unique. Second, Spectranomics suggested that spectral remote sensing will reveal the presence and patterning of specific canopy species, within communities and across environmental gradients, based on their functional trait "signatures".

Both forecasts were subsequently proven correct during mapping studies. A 2016 report on Andean and Amazonian forests mapped with airborne imaging spectroscopy confirmed the forecasted ecological shifts in forest canopy functional composition, sorted geographically by large-scale environmental factors including elevation, geology, soils, and climate

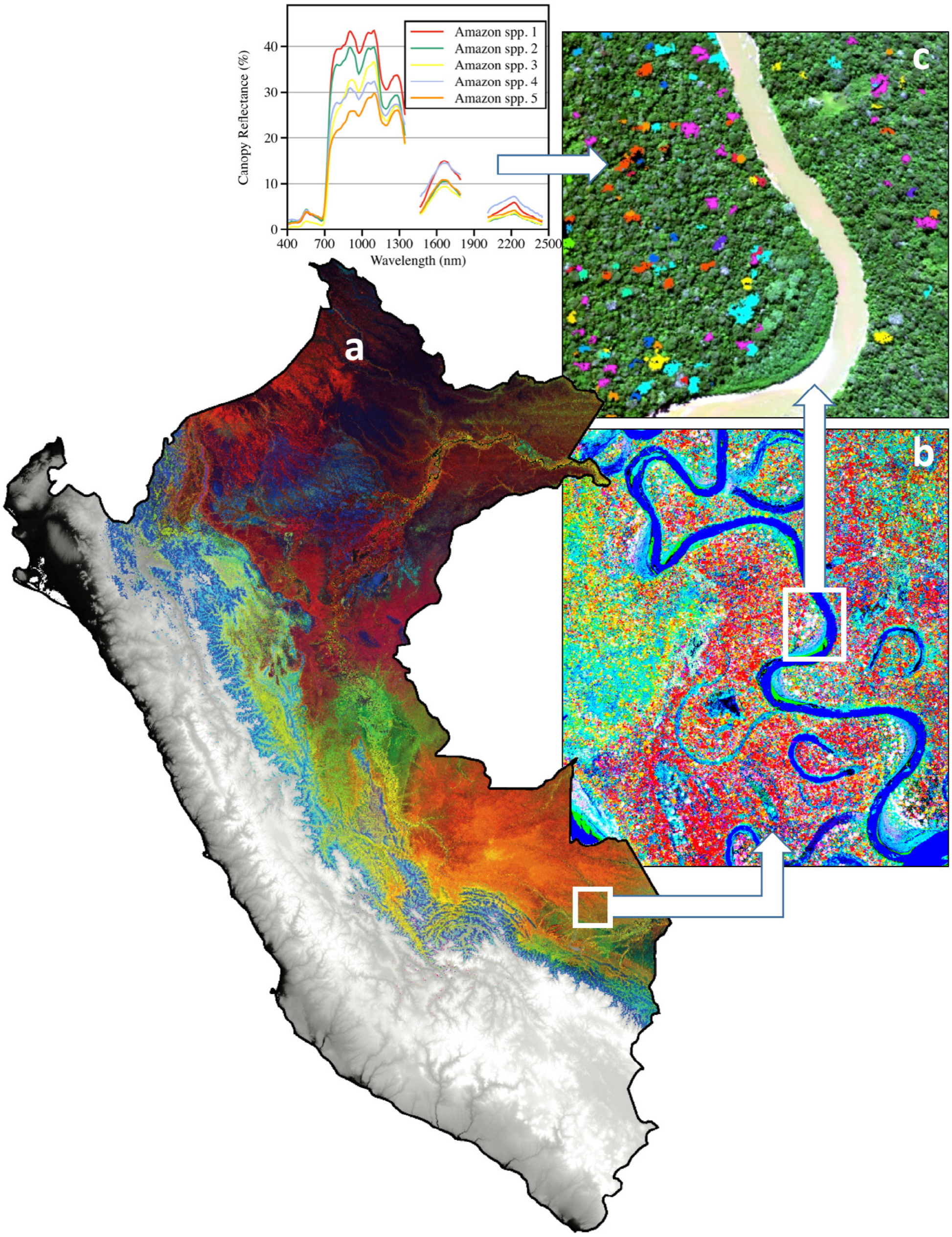

Fig. 3. Three scale-dependent views of the Peruvian Andes–Amazon region derived from airborne imaging spectroscopy using data and information from Spectranomics. (a) Peru-wide map shows the distribution of functionally-distinct forests. Different colors indicate varying combinations of remotely sensed canopy foliar nitrogen (N), phosphorus (P), and leaf mass per area (LMA) (Asner et al., 2016). (b) Zoom image from the Peru-wide map indicates major changes in canopy N, P and LMA within a lowland Amazonian forest (Asner et al., 2015a). Red colors indicate higher N + P and lower LMA relative to yellow and blue colors. (c) Individual species detections within the zoom box of panel (b), derived using species-specific canopy spectra (Baldeck et al., 2015; Féret and Asner, 2013). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Fig. 3) (Asner et al., 2016). While the Spectranomics database provided a field-based preview of how communities of species would differ from one another, the mapping step provided a first synoptic view of the geographic distribution. Importantly, the mapping phase also revealed numerous new combinations of functional traits that had not been detected in the field program. The new canopy functional trait maps are a novel steppingstone to biogeographic assembly, not only of the functional diversity of the Andes-to-Amazon, but also the biological diversity of the region.

The second forecast from Spectranomics – that coexisting species within communities can maintain relatively unique canopy functional traits and spectral properties – has been explored and confirmed in a series of studies using airborne and space-based imaging spectroscopy. From Hawaii to Panama, and from Africa to the Amazon, hundreds of target species have been mapped based on their spectral signatures, which are underpinned by a knowledge of their functional traits (Fig. 3) (e.g. Baldeck et al., 2015, 2014; Colgan et al., 2012; Graves et al., 2016; Papeş et al., 2010). Further, the new concept of "spectral species" was developed to map species richness (alpha diversity) and compositional turnover (beta diversity) in forest landscapes, without the need to detect individual species (Féret and Asner, 2014). The separability of the spectral species is determined by their canopy functional traits.

Numerous other discoveries, forecasts, and biodiversity mapping advances have been achieved in the initial ten years of Spectranomics, such as:

- The location of particular forest canopy species and their evolved canopy functional traits mirror soil nutrient resources mediated by topography, parent material, and climate (e.g. Balzotti et al., 2016; Chadwick and Asner, 2016; Higgins et al., 2014). These findings demonstrate that Spectranomics directly connects plants to ecosystem processes such as biogeochemical cycles, which is an essential link to the rest of the Earth system.
- Lianas (woody vines) are important drivers and limiters of biodiversity and carbon cycling in tropical forests (Schnitzer and Bongers, 2011). Spectranomics revealed that lianas maintain functional traits and spectral properties that are quite unique from their host tree canopies (Asner and Martin, 2012). These measured differences predicted and underpinned the subsequent mapping of lianas in tropical forests using airborne imaging spectroscopy (Marvin et al., 2016).
- DNA analyses indicate that forest canopies show strong phylogenetic organization of their foliar spectral properties, particularly in the shortwave-infrared (1500–2500 nm) wavelength region (McManus et al., 2016). This finding suggests that mapping forest canopies with airborne imaging spectroscopy may provide spatial insight to the genetic distribution and genealogy of forest canopy taxa — a frontier in remote sensing of the biosphere.
- Spectranomics data have been collected and archived under stringent field and analytical standards, which has facilitated the development new quantitative linkages between canopy foliar spectroscopy and canopy functional traits (Feilhauer et al., 2015, 2010; Féret et al., 2011).
- Analyses of the global Spectranomics database reveal that forest canopy biological diversity and functional diversity co-vary in predictable ways (Asner and Martin, 2016), and that detailed spectral properties of canopy species yield information on at least 21 functional traits (Asner et al., 2011). These database-wide findings suggest that a worldwide mapping of plant canopy traits will result in the first spatially-explicit estimates of biodiversity for Earth science.

More broadly, Spectranomics has enabled a different kind of interaction between field or laboratory studies of plants, and remote sensing of functional and biological diversity of ecosystems. The forecasting capability made possible with the Spectranomics database has been central to planning whether and how to undertake spectral mapping activities in different regions, and under what environmental conditions the remote sensing technology will yield new insight. In turn, this has transformed the interaction between field and remote sensing work from the traditional approach of "mapping and ground truthing" to one based on botanical, ecological and biophysical knowledge in the interpretation of remotely sensed data.

This interaction between Spectranomics and remote sensing also provided the scientific guidance, and initial funding, for a new class of mapping instruments, starting with a next-generation, high-fidelity Visible to Shortwave Infrared (VSWIR) imaging spectrometer, built by the California Institute of Technology's Jet Propulsion Laboratory (JPL) for the Carnegie Airborne Observatory (Asner et al., 2012). JPL then built an identical instrument for its Airborne Visible and Shortwave-infrared Imaging Spectrometer (AVIRIS; http://aviris.jpl.nasa.gov) program, as well as several copies for the US National Ecological Observatory Network (Kampe et al., 2010).

1.3. Scientific and conservation opportunities

An important outgrowth of Spectranomics is an emerging opportunity to partner discovery-based science with applied environmental conservation at large geographic scales. Conservation and management actions are usually limited in scope and effectiveness by numerous interacting financial, logistical, cultural and political factors. An increasing ability to map canopy diversity may provide an avenue to identify the location, and essential components, of high-value conservation targets. Moreover, near real-time scientific discovery from spectral remote sensing can lead to more tactical conservation decision-making. Our specific experience is that, as land-use pressures expand, intensify and change over time, a mapping capability built upon the details of forest canopy function and composition, rather than just forest cover, supports improved conservation discussions and planning. This type of approach is needed to identify current and potential threats, as well as current protections and opportunities for new protections, of species, communities and ecosystems. The evolving biodiversity mapping capabilities made possible through Spectranomics are providing a toolset to support the current portfolio of Carnegie Airborne Observatory activities (e.g., http://www.theborneopost.com/2016/04/06/3d-mapping-to-decide-on-land-use/).

The Spectranomics approach is starting to catch on in the scientific community (Zhao et al., 2016), but there is much more to do to bring activities to an operational level. First, more scientists could get involved through the building of plant canopy trait laboratories and databases, paired with a specific style of leaf-level spectral measurements in the field. Currently, there are many functional trait and spectral measurement protocols that are incompatible with the Spectranomics approach. For example, many foliar trait studies have involved the collection of samples in understory or shaded settings, in part because this foliage is easier to reach, yet airborne spectral remote sensing is most sensitive to canopy-level foliar chemical and structural traits (Jacquemoud et al., 2009). Additionally, most field-based trait studies do not include the use of a field spectrometer, which must be applied on fresh foliage to ensure connectivity to biotic and environmental conditions (Chavana-Bryant et al., 2016). Moreover, high-fidelity imaging spectrometers needed for mapping, such as CAO or AVIRIS, demand stringent and consistent field and laboratory trait measurement practices. Most of these issues can be remedied by incorporating one or more of the protocols provided on the Spectranomics website (https://cao.carnegiescience.edu/spectranomics). While we are observing increasing numbers of online accesses to these protocols (2915 downloads as of 18 July 2016), more could be done to boost capacity throughout the science community to generate data suitable for Spectranomics-type applications.

Finally, and connected to the two previous points, there are major potential benefits to developing a global Spectranomics approach to biospheric mapping and monitoring. For decades, the NASA Earth Observing System has stood at the forefront of monitoring forests and other land covers at global scales. More recently, the European Space Agency's Living Planet and Copernicus Programs have greatly boosted global coverage for observing changes in forests and their basic vegetation properties. None of these systems, nor any others currently in orbit, were designed specifically for functional trait and biological diversity mapping and monitoring. A new type of Earth observing mission, based on high-fidelity imaging spectroscopy and the fundamentals of Spectranomics, could greatly advance our ability to measure, map, monitor, manage and conserve the functional and biological diversity of Earth. The required new instrument designs have been deeply vetted (Lee et al., 2015), and demonstrated in airborne programs such as CAO and AVIRIS. The required computing infrastructure is now commonplace, and the methods and algorithms are mature. The missing piece, costing about $300 million USD, is an actual orbital Spectranomics mission, which could readily achieve a global coverage about every 15 days, or about 24 overpasses each year of every terrestrial spot on Earth.

With access to an Earth observing capability based in imaging spectroscopy, anyone could become a Spectranomicist, exploring and mapping plant canopy functional traits and biological diversity, and discovering their contribution to the Earth system. And from these undertakings, the world's understanding of the ecological impacts of humans, whether through land use or climate change, on global functional and biological diversity will be much improved. The Spectranomics approach may be an effective way to help determine global biodiversity, and to understand its role in the biosphere, thereby supporting innovative pathways to conserve it.

Acknowledgments

We dedicate this paper to the numerous scientists, engineers, technicians, students, and supporters of the Carnegie Spectranomics Project, which had its tenth anniversary in July 2016, and which has been made possible by the John D. and Catherine T. MacArthur Foundation.

References

Asner, G.P., Anderson, C.B., Martin, R.E., Tupayachi, R., Knapp, D.E., Sinca, F., 2015a. Landscape biogeochemistry reflected in shifting distributions of chemical traits in the Amazon forest canopy. Nat. Geosci. 8, 567–573.

Asner, G.P., Knapp, D.E., Anderson, C.B., Martin, R.E., Vaughn, N., 2016. Large-scale climatic and geophysical controls on the leaf economics spectrum. Proc. Natl. Acad. Sci. 201604863.

Asner, G.P., Knapp, D.E., Boardman, J., Green, R.O., Kennedy-Bowdoin, T., Eastwood, M., Martin, R.E., Anderson, C., Field, C.B., 2012. Carnegie Airborne Observatory-2: Increasing science data dimensionality via high-fidelity multi-sensor fusion. Remote Sens. Environ. 124, 454–465.

Asner, G.P., Martin, R.E., 2008. Spectral and chemical analysis of tropical forests: Scaling from leaf to canopy levels. Remote Sens. Environ. 112, 3958–3970.

Asner, G.P., Martin, R.E., 2009. Airborne spectranomics: Mapping canopy chemical and taxonomic diversity in tropical forests. Front. Ecol. Environ. 7, 269–276.

Asner, G.P., Martin, R.E., 2012. Contrasting leaf chemical traits in tropical lianas and trees: implications for future forest composition. Ecol. Lett. 15, 1001–1007.

Asner, G.P., Martin, R.E., 2016. Convergent elevation trends in canopy chemical traits of tropical forests. Global Change Biol. 22, 2216–2227.

Asner, G.P., Martin, R.E., Anderson, C.B., Knapp, D.E., 2015b. Quantifying forest canopy traits: Imaging spectroscopy versus field survey. Remote Sens. Environ. 158, 15–27.

Asner, G.P., Martin, R.E., Carranza-Jiménez, L., Sinca, F., Tupayachi, R., Anderson, C.B., Martinez, P., 2014a. Functional and biological diversity of foliar spectra in tree canopies throughout the Andes to Amazon region. New Phytol. 204, 127–139.

Asner, G.P., Martin, R.E., Knapp, D.E., Tupayachi, R., Anderson, C., Carranza, L., Martinez, P., Houcheime, M., Sinca, F., Weiss, P., 2011. Spectroscopy of canopy chemicals in humid tropical forests. Remote Sens. Environ. 115, 3587–3598.

Asner, G.P., Martin, R.E., Tupayachi, R., Anderson, C.B., Sinca, F., Carranza-Jimenez, L., Martinez, P., 2014b. Amazonian functional diversity from forest canopy chemical assembly. Proc. Natl. Acad. Sci. 111, 5604–5609.

Baldeck, C.A., Asner, G.P., Martin, R.E., Anderson, C.B., Knapp, D.E., Kellner, J.R., Wright, S.J., 2015. Operational tree species mapping in a diverse tropical forest with airborne imaging spectroscopy. PLoS One 10, e0118403.

Baldeck, C.A., Colgan, M.S., Féret, J.B., Levick, S.R., Martin, R.E., Asner, G.P., 2014. Landscape-scale variation in plant community composition of an African savanna from airborne species mapping. Ecol. Appl. 24, 84–93.

Balzotti, C.S., Asner, G.P., Taylor, P.G., Cole, R., Osborne, B.B., Cleveland, C.C., Porder, S., Townsend, A.R., 2016. Topographic distributions of emergent trees in tropical forests of the Osa Peninsula, Costa Rica. Ecography.

Bohlman, S.A., 2015. Species diversity of canopy versus understory trees in a neotropical forest: Implications for forest structure, function and monitoring. Ecosystems 18, 658–670.

Chadwick, K.D., Asner, G.P., 2016. Organismic-scale remote sensing of canopy foliar traits in lowland tropical forests. Remote Sens. 8, 87.

Chavana-Bryant, C., Malhi, Y., Wu, J., Asner, G.P., Anastasiou, A., Enquist, B.J., Cosio Caravasi, E.G., Doughty, C.E., Saleska, S.R., Martin, R.E., Gerard, F.F., 2016. Leaf aging of Amazonian canopy trees as revealed by spectral and physiochemical measurements. New Phytol. 1–15.

Colgan, M.S., Baldeck, C.A., Féret, J.-B., Asner, G.P., 2012. Mapping savanna tree species at ecosystem scales using support vector machine classification and BRDF correction on airborne hyperspectral and LiDAR data. Remote Sens. 4, 3462–3480.

Curran, P.J., 1989. Remote sensing of foliar chemistry. Remote Sens. Environ. 30, 271–278.

Feilhauer, H., Asner, G.P., Martin, R.E., 2015. Multi-method ensemble selection of spectral bands related to leaf biochemistry. Remote Sens. Environ. 164, 57–65.

Feilhauer, H., Asner, G.P., Martin, R.E., Schmidtlein, S., 2010. Brightness-normalized partial least squares regression for hyperspectral data. J. Quant. Spectrosc. Radiat. Transfer 111, 1947–1957.

Féret, J.B., Asner, G.P., 2013. Tree species discrimination in tropical forests using airborne imaging spectroscopy. IEEE Trans. Geosci. Remote Sens. 51, 73–84.

Féret, J.-B., Asner, G.P., 2014. Mapping tropical forest canopy diversity using high-fidelity imaging spectroscopy. Ecol. Appl. 24, 1289–1296.

Féret, J.-B., François, C., Gitelson, A., Asner, G.P., Barry, K.M., Panigada, C., Richardson, A.D., Jacquemoud, S., 2011. Optimizing spectral indices and chemometric analysis of leaf chemical properties using radiative transfer modeling. Remote Sens. Environ. 115, 2742–2750.

Graves, S.J., Asner, G.P., Martin, R.E., Anderson, C.B., Colgan, M.S., Kalantari, L., Bohlman, S.A., 2016. Tree species abundance predictions in a tropical agricultural landscape with a supervised classification model and imbalanced data. Remote Sens. 8, 161.

Higgins, M.A., Asner, G.P., Martin, R.E., Knapp, D.E., Anderson, C., Kennedy-Bowdoin, T., Saenz, R., Aguilar, A., Joseph Wright, S., 2014. Linking imaging spectroscopy and LiDAR with floristic composition and forest structure in Panama. Remote Sens. Environ. 154, 358–367.

Hubbell, S.P., He, F., Condit, R., Borda-de água, L., Kellner, J., ter Steege, H., 2008. How many tree species are there in the Amazon and how many of them will go extinct? Proc. Natl. Acad. Sci. 105, 11498–11504.

Jacquemoud, S., Verhoef, W., Baret, F., Bacour, C., Zarco-Tejada, P.J., Asner, G.P., Francois, C., Ustin, S.L., 2009. PROSPECT plus SAIL models: A review of use for vegetation characterization. Remote Sens. Environ. 113, S56–S66.

Jetz, W., Cavender-Bares, J., Pavlick, R., Schimel, D., Davis, F.W., Asner, G.P., Guralnick, R., Kattge, J., Latimer, A.M., Moorcroft, P., 2016. Monitoring plant functional diversity from space. Nature Plants 2.

Kampe, T.U., Asner, G.P., Green, R.O., Eastwood, M., Johnson, B.R., Kuester, M., 2010. Advances in airborne remote sensing of ecosystem processes and properties - toward high-quality measurement on a global scale. In: Gao, W., Jackson, T.J., Wang, J. (Eds.), Remote Sensing and Modeling of Ecosystems for Sustainability VII, SPIE, pp. 7809J–7801.

Kokaly, R.F., Asner, G.P., Ollinger, S.V., Martin, M.E., Wessman, C.A., 2009. Characterizing canopy biochemistry from imaging spectroscopy and its application to ecosystem studies. Remote Sens. Environ. 113, S78–S91.

Lee, C.M., Cable, M.L., Hook, S.J., Green, R.O., Ustin, S.L., Mandl, D.J., Middleton, E.M., 2015. An introduction to the NASA Hyperspectral InfraRed Imager (HyspIRI) mission and preparatory activities. Remote Sens. Environ. 167, 6–19.

Marvin, D.C., Asner, G.P., Knapp, D.E., Anderson, C.B., Martin, R.E., Sinca, F., Tupayachi, R., 2014. Amazonian landscapes and the bias in field studies of forest structure and biomass. Proc. Natl. Acad. Sci. 111, E5224–E5232.

Marvin, D.C., Asner, G.P., Schnitzer, S.A., 2016. Liana canopy cover mapped throughout a tropical forest with high-fidelity imaging spectroscopy. Remote Sens. Environ. 176, 98–106.

McManus, K., Asner, G., Martin, R., Dexter, K., Kress, W., Field, C., 2016. Phylogenetic Structure of Foliar Spectral Traits in Tropical Forest Canopies. Remote Sens. 8, 196.

Mooney, H.A., Cushman, J.H., Medina, E., Sala, O.E., Schulze, E.-D. (Eds.), 1996. Functional Roles of Biodiversity: A Global Perspective, John Wiley and Sons, Chichester.

Papeş, M., Tupayachi, R., Martínez, P., Peterson, A.T., Powell, G.V.N., 2010. Using hyperspectral satellite imagery for regional inventories: a test with tropical emergent trees in the Amazon Basin. J. Veg. Sci. 21, 342–354.

Running, S.W., Justice, C.O., Salomonson, V., Hall, D., Barker, J., Kaufmann, Y.J., Strahler, A.H., Huete, A.R., Muller, J.-P., Vanderbilt, V., Wan, Z.M., Teillet, P., Carneggie, D., 1994. Terrestrial remote sensing science and algorithms planned for EOS/MODIS. Int. J. Remote Sens. 15, 3587–3620.

Schimel, D.S., Asner, G.P., Moorcroft, P.R., 2013. Observing changing ecological diversity in the Anthropocene. Front. Ecol. Environ. 11, 129–137.

Schnitzer, S.A., Bongers, F., 2011. Increasing liana abundance and biomass in tropical forests: emerging patterns and putative mechanisms. Ecol. Lett. 14, 397–406.

Serbin, S.P., Singh, A., Mcneil, B.E., Kingdon, C.C., Townsend, P.A., 2014. Spectroscopic determination of leaf morphological and biochemical traits for northern temperate and boreal tree species. Ecol. Appl. 24, 1651–1669.

Tucker, C.J., Townshend, J.R.G., 2000. Strategies for monitoring tropical deforestation using satellite data. Int. J. Remote Sens. 21, 1461–1471.

Turner, W., Spector, S., Gardiner, N., Fladeland, M., Sterling, E., Steininger, M., 2003. Remote sensing for biodiversity and conservation. Trends Ecol. Evol. 18, 306–314.

Ustin, S.L., Gitelson, A.A., Jacquemoud, S., Schaepman, M., Asner, G.P., Gamon, J.A., Zarco-Tejada, P., 2009. Retrieval of foliar information about plant pigment systems from high resolution spectroscopy. Remote Sens. Environ. 113, S67–S77.

Ustin, S.L., Roberts, D.A., Gamon, J.A., Asner, G.P., Green, R.O., 2004. Using imaging spectroscopy to study ecosystem processes and properties. BioScience 54, 523–534.

Wold, S., Sjostrom, M., Eriksson, L., 2001. PLS-regression: a basic tool of chemometrics. Chemometr. Intell. Lab. Syst. 58, 109–130.

Zhao, Y., Zeng, Y., Zhao, D., Wu, B., Zhao, Q., 2016. The optimal leaf biochemical selection for mapping species diversity based on imaging spectroscopy. Remote Sens. 8, 216.