Biodiversity

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What are the key challenges or questions for Earth System Science across the spectrum of basic research, applied research, applications, and/or operations in the coming decade?

Anthropogenic forces are driving rapid, widespread reductions and redistributions of biodiversity across the globe[1,2]. These changes are degrading the functioning of terrestrial ecosystems[3] and causing increasingly profound impacts on the Earth system and ecosystem services[4,5]. The international community has called for urgent action to address the problem of dangerous biodiversity loss[6,7] including functional biodiversity loss[8]. Functional biodiversity represents the variation in biological structures and functions, including key plant traits like leaf morphology and biochemical composition (e.g. leaf nitrogen content). These traits are functionally related to plant growth rates, phenology, tolerances to climatic stress, mortality, and ultimately, the fate of vast amounts of carbon currently stored in plant biomass and soils. Functional diversity is strongly associated with taxonomic and phylogenetic measures of biodiversity[9,10], but links more directly to ecosystem processes including carbon, water and energy exchange with the atmosphere and can thus feed more directly into Earth system models[11]. Understanding the functional composition and diversity of Earth's ecosystems, particularly its forests, is vitally important for tracking the status and resilience of Earth's ecosystems, and for predicting how these life support systems will function in the future. We currently lack the global scale data we need to do so. Without such data, we cannot track changes in functional biodiversity now and into the future or effectively connect functional biodiversity knowledge with existing models of Earth systems.

Why are these challenge/questions timely to address now especially with respect to readiness?

Currently-available global functional biodiversity data are grossly incomplete and non-representative taxonomically, geographically, environmentally, temporally, and functionally. Datasets on species traits continue to grow[12–14], but available data for vascular plants observed locally under represent the number of species by an order of magnitude, conspicuously for species-rich tropical regions (Fig. 1). As a result, the

~100,000 plant species in the megadiverse tropics are represented by only 1-3 plant functional types in current Earth System Models, severely curtailing their predictive ability on decadal to centennial timescales[15–20]. This spatial and environmental data gap and bias is exacerbated by even scarcer data on temporal and geographic variation of functional traits within species. Data on other biodiversity attributes such as species occurrence, abundance and biomass hold similar biases[21,22].

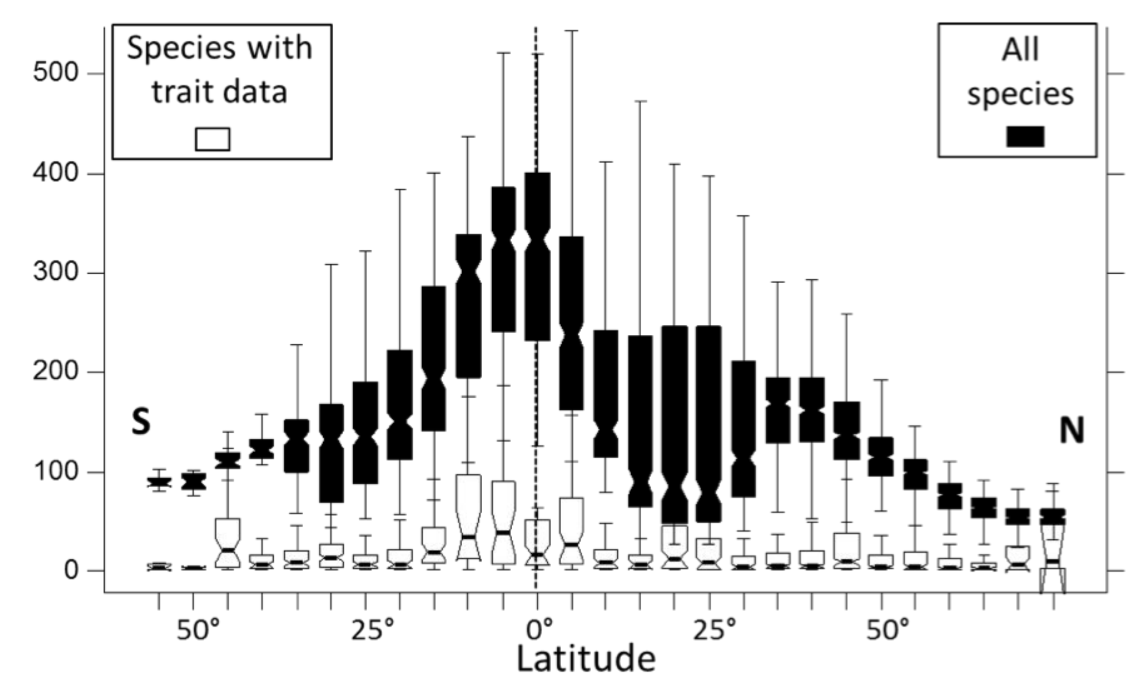

Figure 1: **The data gap--**latitudinal variation in the richness of all vascular plant species (black; after[23] and those with data for at least one trait measured locally (white; from TRY[12], June 2015) within 110km grid cells (N = 11,626). While species diversity is highest in the tropics, the number of species with no functional data measured locally is also highest there, limiting understanding of both biodiversity and of ecosystem function and services.

Even in areas in which current data are relatively complete, widespread biodiversity change driven by anthropogenic pressures is rapidly rendering existing data obsolete and outpacing gradual information gains afforded by *in situ* biodiversity sampling. Furthermore, existing "global" data has not been collected consistently or systematically, but is instead compiled post hoc from thousands of disparate research activities, often not designed to address long-term trends or large-scale patterns. This severe sampling inhomogeneity is not readily overcome statistically and continues to impose severe limits on inference and application in global biodiversity science[22–24]. An integrated system for rapidly and consistently imaging, classifying, mapping and monitoring plant functional diversity globally is urgently needed[25].

The state of technology and science readiness is high. Imaging spectroscopy is a well-established, continuously advancing technology capable of monitoring terrestrial plant functional diversity on a global scale[26–28]. Similar techniques are under development for characterizing marine phytoplankton, seagrasses, and coral reefs[29,30]. The technological tools, informatics infrastructure, theoretical basis, and analytical capability now exist to produce consistent, repeated, global data on functional biodiversity of Earth's ecosystems. Spectroscopic remote sensing offers high-dimensional information [31], required to move beyond low-dimensional biophysical remote sensing and provide information more proportional to the biological diversity (~250,000 plant species) of the planet. Spectroscopic measurements will help fill critical knowledge gaps, aid the assessment of global environmental change, and improve predictions of future change. Continuous, near-global coverage in space and time has the potential to transform basic science on diversity and function and redesign capture of the properties of the terrestrial biosphere in Earth system models. Now is the time to give this science target highest priority.

Why are space-based observations fundamental to addressing these challenges/questions?

Adequate coverage of plant functional diversity cannot realistically be achieved by increasing the investment in *in situ* observations. The areas with sparse present-day sampling are large, often have limited accessibility, and require arduous fieldwork by trained teams to collect ground-based data. Near populated areas and research field sites, approaches such as citizen science or automated cameras can provide some critical data, but these techniques cannot be uniformly or broadly applied, and in any case are insufficient for observing current high rates of change, tasks for which space-based data are ideally suited. Spaceborne measurements can reduce bias errors associated with relatively sparse *in situ* systems through their spatial coverage and large sample size, and can be used to assess bias and extrapolate limited local information. Space-based systems can also simultaneously measure drivers of ecological change alongside biodiversity and ecosystem responses. The evolution of remote sensing systems that combine estimates of drivers of ecological change and ecosystem responses can, in concert with appropriate and coordinated *in situ* and calibration/validation efforts, allow the testing of ecological theory at previously inaccessible scales. The spatial coverage, resolution and direct observation of change, demonstrated for biophysical land surface properties by LANDSAT and MODIS, are critical for improving knowledge of global ecosystem function using spectroscopic and related techniques.

Do existing and planned U.S. and international programs provide the capabilities necessary to make substantial progress on the identified challenge and associated questions. If not, what additional investments are needed?

A number of planned international missions, such as ENMAP (Germany; 2018) and HISUI (Japan; 2018), and airborne sensors will have some capability for mapping plant functional diversity. However, none of these will provide the repeated global coverage needed to monitor functional diversity change through time. The proposed HyspIRI mission, called for in Tier 2 of the 2007 Decadal Survey, would provide these capabilities. Importantly though, the earliest possible launch of such a space-based spectroscopic capability is urgent. A global baseline dataset obtained while biogeographic distributions are still in the early stages of change will provide correlations between distributions of species' traits and climate. This dataset will serve as a data-based constraint on the sensitivity of many plant species to climate and as an initial state of the terrestrial biosphere for prognostic ecosystem models. The sooner such a dataset is collected, the more scientific information it will provide[25].

Investments by NASA, ESA, NSF, the Carnegie Institution, and the University of Zurich have developed increasingly capable airborne instruments and built robust algorithms for quantifying a growing number of functional diversity attributes. The <u>additional investment</u> required in the upcoming Decadal Survey era is a robust, relatively long duration mission providing global coverage and meeting the spectral measurement requirements defined in the literature for accurate and precise retrievals.

How will space-based observations be linked with other observations to increase the value of data for addressing key scientific questions and societal needs?

Space-based data alleviate the inherent spatial sampling bias and sparsity of biodiversity data in remote regions, but require careful calibration and validation. Assembling networks and data sets *post hoc* carries with it the near-certainty of biases: for global models where calculating the correct integral or average value is critical this is a particularly serious issue[32,33]. Remote observations, contain bias and uncertainty of their own and so require careful evaluation against a well-designed *in situ* calibration/validation program. Not all variables can be sensed remotely, however. Using spectroscopic remote sensing for key properties of the biosphere may allow redirection of *in situ* emphasis to equally-important measurements and experiments, on soil properties, microbial processes, genomics, and trophic processes. In some cases, recent advances in ecological theory and further investments in ground data and modeling will enable linking spectral information to these as well as other plant traits that cannot be sensed remotely but that are equally important to Earth system prediction.

What are the anticipated scientific and societal benefits?

Global knowledge of functional diversity is required for a new generation of Earth System Models[15–20]. While current models emphasize simulation of processes such as evapotranspiration and photosynthesis, long-term ecosystem change is driven more by changes to the distribution or types of organisms, which include gross changes mediated by differences in function such as from forest to grassland, and subtler changes such as replacement of current species by more drought-or-fire tolerant species. These functional changes directly affect the global climate and carbon systems, and also lead directly to societal benefits, as the functional properties of species and the structure of the resultant ecosystems influence the potential for the production of food and fiber, clean water, and the spread of human and plant pests and pathogens. There are few cases where the current coarse abstraction of plant types (typically less than 20 in global models) provides direct insight into the full spectrum of ecosystem services and societal benefits. As species and consequent functional properties change more and more rapidly, exploiting the proven spectral techniques to track these changes will provide an ever-widening spectrum of benefits to humanity.

Regular, timely global biodiversity data has been identified as essential for monitoring and enabling progress towards meeting the Aichi targets for averting dangerous biodiversity loss set forth by the Convention on Biological Diversity[34–36]. These data will be used by the International Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), an analogue to IPCC, national and regional policy makers, land and wildlife managers, non-governmental organizations, and citizen-science communities.

The science communities that would be involved.

Spectroscopic missions, with data products designed to support the understanding of global plant functional diversity, will add a new dimension to Earth System Science, bringing biodiversity and the functional variations between species, squarely into the center of long term Earth System monitoring and prediction, with benefits to ecological science and management, and with concurrent benefits to atmospheric science, hydrology, health and disease, and agronomy. It would require strengthening the growing ties between the remote sensing science and biological communities. This would build on very large scientific communities not currently deeply involved with remote sensing and Earth System Science: for example the Ecological Society of America has over 10,000 members in basic and applied ecology, and the Biogeosciences section of the American Geophysical Union is one of the fastest-growing components of that society. Producing global, repeated observations of plant functional diversity with appropriate cal/val and uncertainty would produce a user community on a par with the MODIS-Land user community and would include many research areas that are not currently well-supported by remote observations.

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