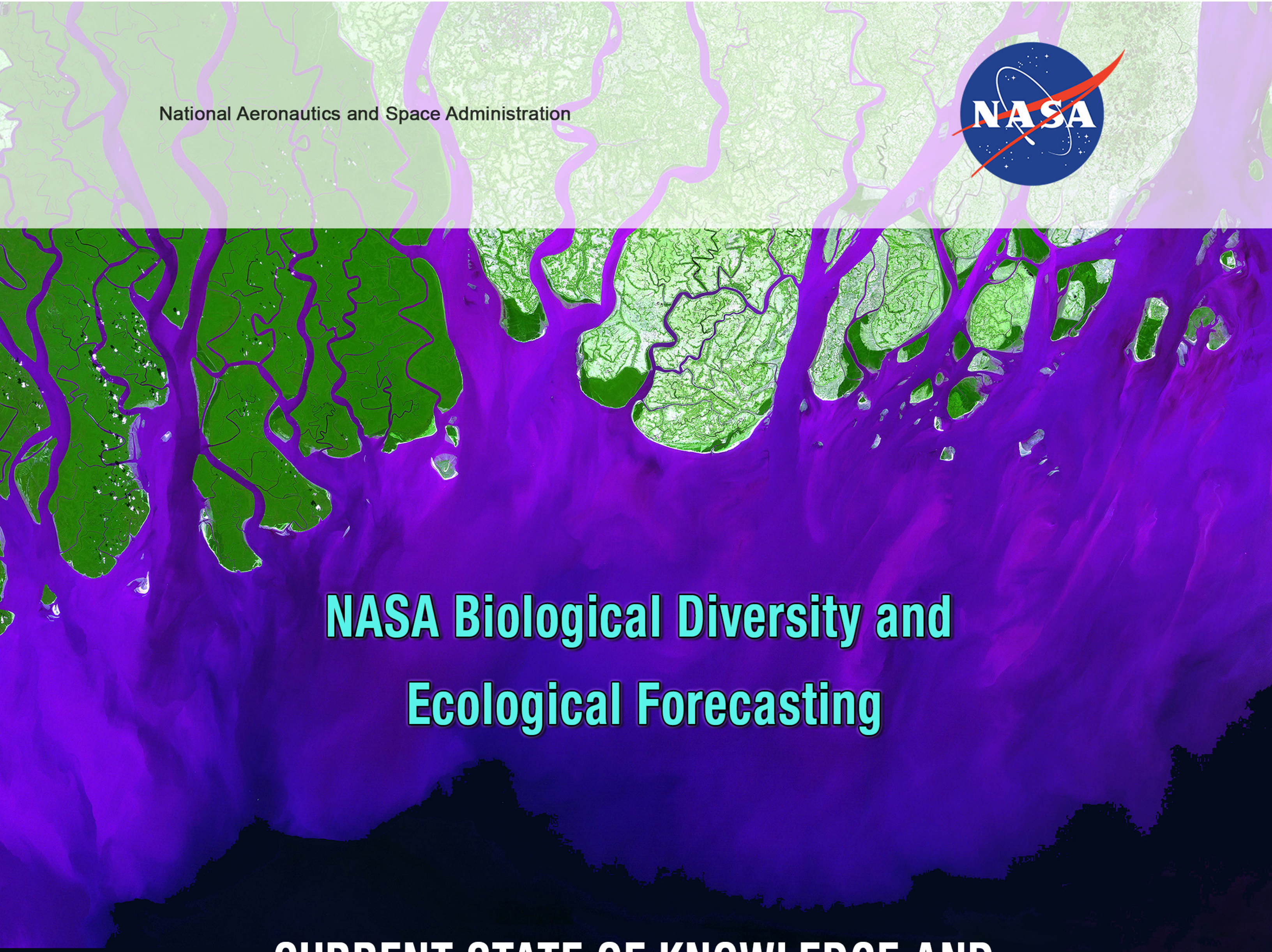

National Aeronautics and Space Administration

# NASA Biological Diversity and Ecological Forecasting

## CURRENT STATE OF KNOWLEDGE AND CONSIDERATIONS FOR THE NEXT DECADE

BIOLOGICAL DIVERSITY
& ECOLOGICAL FORECASTING

cce.nasa.gov/biodiversity

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This image of the Sundarbans in the Ganges River delta was acquired by Landsat 7's Enhanced Thematic Mapper plus (ETM+) on 28 February 2000.

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# PREFACE

Understanding and saving life on Earth: this is the immodest commitment of the Biological Diversity and Ecological Forecasting program elements in the NASA Earth Science Division. Program commitments are important. They provide a North Star, a focus for the day-to-day work of managing grants-based research and applications programs within the U.S. Government.

Earth is a living planet. The only one we know of—so far—in the entire Universe. A fundamental characteristic of life on Earth is its stunning variety. We are still getting our collective head around this marvelous diversity of life. It is only in the last decade or so that we have begun to have reasonable estimates, within an order of magnitude, of the number of species on Earth. Despite our brains, brawn, technologies, and seeming preeminence amongst our fellow species, we are mightily dependent on other species for manifold goods and services without which humanity cannot survive. Our technology, while powerful, is nowhere near sufficient to allow us to engineer our independence from the other species around us—even if we could stand the moral, emotional, and aesthetic loneliness of doing so. Human preeminence is illusory.

Our use of Earth's resources is undermining its vital biological diversity. Our actions, often taken in ignorance, are removing stems and entire branches of the tree of life. We are essentially removing rivets and panels from Spaceship Earth as it travels through the solar system at 67,000 mph. There is a race underway between our ability to learn about our planet, including the variety that underpins its functioning, and our need to utilize its resources to ensure our near-term survival. Time is not on our side. We must both increase our understanding of life on this planet and implement immediately what we learn. This will enable us to save as much life as possible, including the human species. We can do this! But more understanding through regular monitoring of biodiversity will be key.

NASA is truly fortunate to look at Earth from the vantage point of space. Space gives a planetary perspective, bringing the whole into focus and providing the broad context for life. The NASA Biological Diversity program element seeks to increase our understanding of biodiversity with the satellite tools at NASA's disposal, in concert with a plethora of in situ observations, models, and techniques. Given, as Chapter 5 of this document tells us, the spatial scales of biodiversity range across sixteen orders of magnitude from $10^{-9}$ m to $10^{6}$ m and its time scales across twenty orders of magnitude from $10^{-12}$ seconds to $10^{11\text{-}13}$ seconds, satellite remote sensing can never be the sole road to biodiversity understanding. It must be used in tandem with observations across the range of scales at which biodiversity is manifest. That said, as technologies improve, satellites are increasingly capable of detecting and monitoring life at ever finer scales.

In parallel, the NASA Ecological Forecasting program element uses the understanding gained from the Biological Diversity program element and other NASA programs to implement biodiversity conservation. It does so by supporting the development of publicly available tools for decision making and management using satellite products and associated models. It is the NASA program element committed to saving life on this planet.

When these two NASA activities started in the mid 2000s, researching biological diversity and providing managers with satellite-based conservation tools was a stretch. Options for satellite imagery were far more limited. There was Landsat. There was AVHRR. MODIS was only just getting up to speed. There were limited radar data along with products from a scattering of other orbiters. The high-resolution commercial satellite industry was nascent.

In contrast, a wide array of space sensors and technologies are now available, with even more planned. As important, government data policies around the globe are making taxpayer-funded satellite data free and open to the general public. Combine these changes with advances in computation and we find ourselves living in a time of unprecedented access to satellite data products. At the same time, in situ observation systems have made comparable advances over the last two decades. Clearly, we are riding a rising tide of biodiversity observations of very many types—just what is necessary for greater understanding and more effective biodiversity conservation.

The Biological Diversity and Ecological Forecasting program elements had been underway for about fifteen years when their management decided it was time (actually past time) to take stock. We asked fifteen NASA-funded investigators from across the two programs, and other NASA programs, to help us do so. This group became the authors of this text. The goal was to provide an overview of the current state of knowledge in key programmatic areas and to help NASA see opportunities and considerations for the next decade and beyond.

The fifteen recruited authors put hours and hours of work into this report. Their commitment to the two NASA program elements and belief in their programmatic potential are deeply humbling. It has been a high point of a NASA career to work with them. They brought knowledge, enthusiasm, creativity, and brilliance to this effort.

Gary Geller of the Jet Propulsion Laboratory receives credit and our sincere thanks for stepping into the breach to serve as an overall editor for the document. He brought it (and us) over the finish line when the energy of all involved was beginning to flag at the end of a long process.

We live in a challenging time for life on Earth. We also live in an amazing time in which we as a people are developing the very tools we need to reverse the challenges our species has thrown in the path of our fellow planetary voyageurs. The purpose of this report is to show us how we might use these tools.

Enjoy and move out.

Woody Turner and Keith Gaddis
NASA Headquarters

# EXECUTIVE SUMMARY

This report explores NASA's role in observing, understanding, and forecasting life on Earth as part of NASA's Mission and its Strategic Plan. The work is led and carried out through NASA's Biological Diversity and Ecological Forecasting program elements, and the report explores topics of particular relevance to these two program elements. This, in turn, provides a context for identifying opportunities for NASA to consider as it plans for the next decade. Consequently, a key output of the report is a collection of Considerations for NASA developed by the authors—these are discussed in Chapter 8 and listed in full in Appendix C. The information presented is particularly timely as thinking begins for the next National Academies' Earth Science Decadal Survey and as the Convention on Biological Diversity's nascent Post-2020 Global Biodiversity Framework evolves.

Biodiversity is the variety of life on Earth at all levels of biological organization–ecosystems, species, and genes; it is a fundamental characteristic of the planet. However, the Earth's natural systems are changing rapidly, and this has important implications for its biodiversity and the benefits humans receive from it. NASA's Biological Diversity and Ecological Forecasting program elements study Earth from space to understand that biodiversity, how and why it is changing, how it may change in the future, and to provide information to decision makers. Chapters 2–7 explore six broad topics central to the work of these program elements, including its relevance, current state of knowledge, and potential role for NASA in filling knowledge gaps as it plans for the next decade. This report demonstrates the value of remote sensing for understanding and monitoring biodiversity and for supporting policy and decision-making. Some key points explored within include:

- **Biodiversity and its distribution are the result of a complex web of interacting factors that is not fully understood.**
- **Humans derive and are dependent upon benefits from nature, but also affect it in many ways.**
- **Spatiotemporal scale affects the detection and understanding of biodiversity and thus the role of remote sensing for monitoring.**
- **Ecosystem resilience affects the timing and availability of ecosystem services and is particularly important in a changing world.**
- **Ecological forecasts are essential for planning and responding to change.**

## Chapter 1: Introduction and Program Element Overview

NASA's Biological Diversity and Ecological Forecasting program elements study the variety, distribution, and abundance of life on Earth from space to improve our scientific understanding of biodiversity and apply that understanding to management decisions. These program elements are complementary, with the scientific outcomes from Biological Diversity supporting applications in Ecological Forecasting, and the applied needs identified there helping to guide and prioritize research activities. These two program elements are part of NASA's Earth Science Division, supporting the Research and Analysis and Applied Sciences Programs, respectively.

## Chapter 2: Biodiversity

*What is biodiversity and why is it important?*

Biodiversity is the variety of life on Earth at all levels of biological organization–including ecosystems, species, and genes. That variety underpins the structure, function, and composition of ecosystems and leads to complex interactions and interdependencies among biodiversity, humans, and the environment. Understanding the drivers behind biodiversity and how biodiversity's many components interact with each other and the environment is essential for sustainable management of biological resources. Remote sensing has a key role to play in biodiversity research, monitoring, and its associated applications areas due to its ability to regularly observe wide geographic expanses.

## Chapter 3: Drivers of Biodiversity

*What determines the world's biodiversity and how are these drivers changing?*

The world's biodiversity results from a complex suite of factors, including environmental and historical influences on evolution, as well as human activity. Understanding these drivers helps explain the biodiversity observed today, as well as in the fossil record, and is essential for understanding why biodiversity is changing and how it is likely to change in the future. This knowledge is important for making good policy and management decisions.

## Chapter 4: People, Biodiversity, and Ecosystem Services

*How do humans, biodiversity, and the environment affect each other?*

The relationship between humans, biodiversity, and the environment is intimate and complex. Biodiversity benefits society in many ways but this is complicated by the impact humans have on biodiversity, on its benefits, and on the environment. These relationships are strongly dependent on the distribution and abundance of species and how these are changing. Consequently, understanding this dynamic relationship requires regular observations of nature, as well as information about human activities, which, in turn, call for novel approaches for the integration of Earth observations with socioeconomic data.

## Chapter 5: Scales of Biodiversity

> *How do processes occurring at different scales of space, time, and biological organization interact?*

Biological scaling is important but challenging–it affects how biodiversity is measured, described, and understood–and can complicate the study and management of biodiversity in a variety of ways. Major elements of scale–spatial, temporal, functional, and phylogenetic–have special relevance to biodiversity and its observation and monitoring. These elements of scale also have important implications in using observations and models for decision-making.

## Chapter 6: Biodiversity and Ecosystem Resilience

> *Does biodiversity increase ecosystem resilience to environmental change?*

Ecosystem resilience is the ability of an ecosystem to resist or recover from disturbance. Understanding which ecosystem characteristics underlie resilience is essential for assessing or modeling the consequences of a disturbance and is increasingly important as human activity continues to impact the natural world. Because nature provides many benefits to humans, understanding resilience in the context of these impacts is particularly relevant to society and has implications for monitoring and management.

## Chapter 7: Predicting and Projecting Changes in Biodiversity and Ecosystem Services

> *What is needed to predict changes in biodiversity and ecosystem services, and to provide managers, stakeholders, and the public with the best possible information and tools with which to make environmental decisions?*

The discipline of ecological forecasting uses models and observations to predict the consequences of a change in ecosystem characteristics, including the services provided to humans. Natural resource managers need forecasts to help them evaluate various management options and to plan for and respond to changes in climate, land use, and other aspects of the natural world. Periodic, space-based observations are a key input to ecological forecasting models.

## Chapter 8: Considerations for NASA

Chapters 2–7 provide lists of Considerations for NASA that should be useful to these programs for planning over the next decade. The 45 Considerations for NASA are discussed in Chapter 8 and summarized below; the complete list is provided in Appendix C.

### Partnership and Collaboration on Biodiversity Activities

> *Seek out and support complementary partnerships and collaborative activities to advance utilization of remote sensing for biodiversity research and its application for societal benefit*

Understanding and protecting Earth's complex web of biodiversity and how humans interact with it requires expertise and activities in a wide range of areas. Complementary partnerships and collaborations, perhaps particularly with the social sciences, can effectively expand program reach and increase impact. NASA can consider ideas such as the following, many of which are related:

- Support collaborative problem solving with multidisciplinary project teams
- Encourage and support more international collaboration
- Foster integration across terrestrial, marine, and freshwater realms
- Develop closer ties to end-user organizations

### Biodiversity Observations from Space

> *Ensure the continued availability of biodiversity, relevant observations from space*

The use and importance of observations from space to understand biodiversity, how it is changing, and possible response options requires continuity as well as enhanced sensors and products. The following areas are particularly important:

- Enhance observational capabilities with new technology
- Coordinate and support international collaboration
- Support open access to data, technologies, and scientific knowledge
- Leverage private industry partnerships

- Promote novel integration of Earth observations with socioeconomic datasets
- Understand and communicate the value of remote sensing to society

### Biodiversity Observations *in situ*

> *Improve* in situ *observations so they can better support understanding biodiversity from space*

It is hard to overstate the importance of *in situ* observations to NASA's Biological Diversity and Ecological Forecasting program elements and there are significant benefits to enhancing their variety, resolution, scope, quantity, and quality. The focus should be on species diversity, abundance, and distribution, ecosystem physical structure and function, and human activity and values. Pathways for NASA to consider include:

- Develop new and enhance existing partnerships with *in situ* data providers
- Encourage wider use of standards, protocols, and formats to increase data access and usability
- Use NASA's technology expertise to develop new *in situ* observation technologies and integrate them with satellite imagery

### Biodiversity Data Products

> *Provide more higher-level data products, increase their breadth, and enhance their discoverability and usability*

Many of the higher-level data products biodiversity users need are not available because missions often stop processing at Level 2 (MODIS is an exception). More broadly, although tools used to find and access data products have improved, their ease of use often remains limited, thus preventing extraction of the full value inherent in NASA's observations. Steps to consider include:

- Provide more Level 3 and Level 4 Landsat products ("MODISify" Landsat)
- Develop more higher-level algorithms and move more products from research to operations
- Provide data products in more formats and as Analysis Ready Data
- Promote, and perhaps enforce, data product standards
- Develop more multi-source data products by integrating data from multiple sensor types

### Biodiversity and Ecological Modeling and Forecasting

*Enhance and utilize models to forecast biodiversity change and its impacts, guide decisions and policies, and facilitate research*

Models and forecasts are essential to decisions and policy-making. For example, forecasts can paint a picture of the future trajectory of climate and land use change and their impacts on life. Models also have a key role in research, such as in understanding ecosystem assembly or function. NASA can help enhance modeling and forecasting capabilities in a variety of ways, including:

- Support for community-scale cyberinfrastructure
- Develop and support forecast output standards to enhance reuse
- Improve uncertainty quantification of NASA observational products
- Support uncertainty quantification of model outputs to enhance use by decision-makers

### Capacity for Biodiversity Research, Applications, and Monitoring

*Support capacity development to increase utilization of NASA observations and biodiversity, relevant products*

Remote sensing largely remains an area of specialization that is outside the repertoire of many potential users, limiting the value extracted from NASA's data and, ultimately, its impact. NASA can address this challenge in a variety of ways, including:

- Provide training to enhance end user ability to utilize NASA data
- Support development of early career scientists
- Engage undergraduate and graduate students with support for research
- Inspire students at all levels to use NASA data to address societal problems

These Considerations for NASA, as well as the broader discussion of the key questions posed in Chapters 2–7, will help NASA's Biological Diversity and Ecological Forecasting program elements plan for the next decade. This, in turn, will enable these program elements, and NASA as a whole, to maximize the impact of their activities and continue providing key information to society for sustainably using biodiversity, defining and monitoring biodiversity's role in providing societal benefits, and preserving life on Earth.

1

# INTRODUCTION AND PROGRAM ELEMENT OVERVIEW

## Key Points

- Biodiversity is the variety of life on Earth at all levels of organization, from genes to ecosystems, and across all ecological realms, including freshwater, marine, and terrestrial.
- In this report, we construe biodiversity quite broadly, including its genetic, taxonomic, phylogenetic, ecosystem, functional, and trait diversity components, as well as across the ecological scales of alpha, beta, and gamma diversity.
- Biodiversity loss continues, threatening the services it provides to society and on which humans depend and vastly altering the future trajectory of all life on this planet.
- Satellite remote sensing provides essential information on understanding biodiversity, as well as monitoring and assessing the implications of biodiversity change.
- NASA's unique role includes observations, modeling, capacity building, partnerships, and field campaigns and their use in science and applications.
- This report, authored by an expert working group, explores six key areas for which remote sensing contributes value for research and societal applications.
- Within each area, the authors suggest ways the NASA Biological Diversity and Ecological Forecasting program elements can increase their impact over the next decade.

*"The truth is: the natural world is changing. And we are totally dependent on that world.*
*It provides our food, water and air. It is the most precious thing we have and we need to defend it."*

*— Sir David Attenborough*

Indeed, the natural world is changing rapidly. Yet society's dependence on it, much of which is hard to perceive, remains. Key among these changes is loss of biodiversity in all its forms. This loss, and many of its impacts on society, are extensively documented in the recent Global Assessment published by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES 2019). Authored by hundreds of experts in a range of disciplines, the assessment is based on more than 15,000 published studies. From a different perspective, the World Economic Forum's annual Global Risk Report (WEF 2020, 2021, 2022) includes biodiversity loss in the top five risks to society in terms of likelihood and impact for the next decade. Clearly, Sir David Attenborough is right, and there is an increasing sense of urgency for additional societal response.

At the same time, advances in science and technology provide opportunities for monitoring and understanding the implications of biodiversity loss while also offering societal response options. With the challenges and opportunities in mind, this report explores six topical areas central to the NASA Biological Diversity and Ecological Forecasting program elements. Each of these areas focuses on a key question central to understanding and monitoring biodiversity and how it is changing and explores ideas that have the potential to increase the impact of these NASA program elements over the next decade. That decade largely coincides with the time period for the Earth Science Decadal Survey (National Academies of Sciences, Engineering, and Medicine 2018), the next set of targets and goals for the UN Convention on Biological Diversity (CBD), most targets for the UN Sustainable Development Goals, and other international agreements. This is an active and very important decade for the natural world and society.

The purpose of this report is manifold. First, by exploring the topics discussed in each chapter it demonstrates the essential role satellite remote sensing plays in understanding and responding to changes in the natural world and the biodiversity it contains. That discussion is intended to facilitate exploration of new ideas to further the development and impact of the NASA Biological Diversity and Ecological Forecasting program elements. As such, it constitutes crucial programmatic input by posing key questions, identifying challenges, and pointing out opportunities for the next decade. The report's primary audience is NASA program managers and others in the agency, as well as those providing support to the agency at the Federal level, but it is also intended to be valuable to a broad audience including researchers, private industry, policy makers, other space agencies, and natural resource managers.

This report results from a multi-year process involving the communities served by NASA's Biological Diversity and Ecological Forecasting program elements. After assembling a working group of 16 researchers with expertise across the research and operations continuum, a request (Appendix A) was widely circulated to our research and applications communities soliciting short white papers on the questions, challenges, and opportunities for these programs over the next decade. The working group received 130 responses, which it sorted into thematic areas and synthesized into five questions and one cross-cutting topic. Each was then used as the basis for a chapter in this report, written by the working group members listed as chapter authors.

## 1. BIOLOGICAL DIVERSITY

> *Biological diversity is the variability among living organisms from all sources including inter alia, terrestrial, marine and other aquatic ecosystems, and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems (Convention on Biological Diversity 1992; Article 2)*

This definition, used by the CBD, encompasses the richness and abundance of species and other taxonomic hierarchies (taxonomic diversity), the presence of different evolutionary lineages (phylogenetic diversity), and a variety of growth forms and resource use strategies for living (functional diversity). Biodiversity is a planetary-level phenomenon that reflects billions of years of evolution. As discussed in the following chapters, the distribution and abundance of that biological diversity across the globe reflects evolutionary processes, regional natural histories, and the contemporary ecological relationships between life and its surroundings operating together as a single process. Human society and economy have developed within the context of that diversity and, thus, are intertwined with it in complex ways that are not completely understood. This intertwining has created dependencies, many of which can be difficult to perceive and hard to measure, arising from the human benefits that biodiversity provides. Only with systematic means of tracking changes in global biodiversity and informed decision support for conservation action can we hope to combat continued biodiversity loss.

### Monitoring Biodiversity

Changes in biodiversity are a global issue resulting largely from the aggregation of actions taken at the local level, with global, regional, and local impacts that we need to understand for society's well-being. Monitoring helps us understand what, where, and why biodiversity is changing and enables governments, other organizations, and the general public to respond in an informed manner. A complete biodiversity monitoring program would acquire multiple observations across many platforms at a range of spatial and temporal scales. These observations would then be processed to offer a combination of global coverage and a variety of spatial and temporal grain or pixel-size resolutions. Coarser-grained products can support global assessments and provide contextual information for finer-grained products that offer local insight. It is important to integrate satellite imagery with finer-scale observation, such as *in situ* instruments and other field observations. These may be difficult to acquire in a systematic and periodic manner; however, we are fortunate that humans have been observing and collecting elements of the natural world for centuries, thereby providing a grand heritage and deep foundation in museums, research papers, popular articles, biological databases, and elsewhere for satellite observations to build upon and add to. Indeed, this integration of different observations across platforms and with varying spatial and temporal resolutions is itself a fundamental challenge for monitoring biodiversity.

# 2. THE BIOLOGICAL DIVERSITY AND ECOLOGICAL FORECASTING PROGRAM ELEMENTS

While the Biological Diversity and the Ecological Forecasting program elements utilize NASA observations, techniques, and data products, as well as those from other organizations, they play different but complementary roles along a continuum—from basic research through operational applications. This complementarity works both ways, with new knowledge gained through research offering novel management solutions and day-to-day management challenges informing original research questions. Because these complementary roles are bound by their *shared programmatic goals of understanding and protecting life on Earth,* many of the topics raised in this report are relevant to both program elements.

## Biological Diversity

The Biological Diversity program element promotes basic research under the auspices of the Research and Analysis Program within NASA's Earth Science Division (ESD). It seeks to advance fundamental knowledge about life on Earth and helps identify, design, and implement NASA activities that provide the satellite observations and models to improve our basic understanding of biological diversity, how and why it is changing, and its effects on and interactions with the wider Earth system. Patterns and processes of biological diversity across land, water, and air are explored using observations from satellites, airborne and seaborne platforms, and *in situ* approaches, while understanding is also generated through conceptual and numerical models. The primary output is knowledge about the diversity of life and its relationship with the Earth system. This knowledge is made available through publications in the peer-reviewed literature and other media.

Biological Diversity is one of a number of program elements in the NASA Research and Analysis Program, which also includes Terrestrial Ecology, Ocean Biology and Biogeochemistry, and Land Cover and Land Use Change. Biological Diversity overlaps with these three elements in its support for projects seeking to advance understanding of terrestrial and marine ecosystems and their drivers of change. However, it is unique in its overarching focus on the diversity of living organisms within these ecosystems (sometimes described as the biotic composition of these ecosystems) and how this diversity is changing over time.

As NASA's primary research response to the global crisis of biodiversity loss, the Biological Diversity program element has promoted the use of satellite remote sensing, and this is now a key tool used by researchers to understand the diversity of life on Earth and how it is changing over time. It continues to inform our approach to biogeographical and macroecological questions at spatial scales ranging from the biome to specific landscapes and seascapes. These questions are often broadly focused on place and number: why something lives where it does and why there are so few or so many of them there. Remote sensing can detect these patterns, which are the result of a mixture of Earth's many processes. Understanding them typically requires a combination of models, satellite remote sensing, and *in situ* observations, all of which are supported by the program.

## Ecological Forecasting

The Ecological Forecasting program element applies knowledge gained from the Biological Diversity and other NASA research program elements, along with a wide variety of data from many national and international sources, to inform decision-making. Supported projects address societal issues, including wildlife conservation and sustainable ecosystem development. This program element develops applications under the auspices of the ESD Applied Sciences Program. These applications employ satellite observations and associated models to analyze and forecast changes to living systems with an eye toward improving management tools and decision support systems. The result is novel predictive approaches for understanding ecosystems and how they change over time—but with a primary focus on addressing end-user needs. Thus, the program element is a practical, management-driven activity focusing on improving decision-making through deep engagement with end-user partners and clearly defined user needs. Often, these end-users are responsible for long-term operational monitoring of ecosystems to meet their management goals. Successful projects funded by this program element are typically those that achieve a transition of the tool, decision support system, or product funded by NASA to the end-user organization for sustained operation beyond the conclusion of the NASA funding support. This program element represents NASA's primary applied response to the global crisis of biodiversity loss and the resulting need for improved conservation solutions.

Ecological Forecasting is one among several program elements in the NASA Applied Sciences Program. Related program elements are Disasters, Food Security and Agriculture, Health and Air Quality, and Water Resources. Ecological Forecasting overlaps with these in its biological focus but is unique in the primacy it gives to the conservation of natural ecosystems and their biotic components (e.g., protected area management, management of threatened and invasive species, and sustainable fisheries management). In addition, the Applied Sciences Program has a Capacity Building element charged with training U.S. and international users in the art of applying satellite remote sensing to real-world problems. This capacity-building work strengthens the Ecological Forecasting program element's efforts by enhancing end-user capabilities to use the satellite-based tools and decision support systems developed by Ecological Forecasting projects.

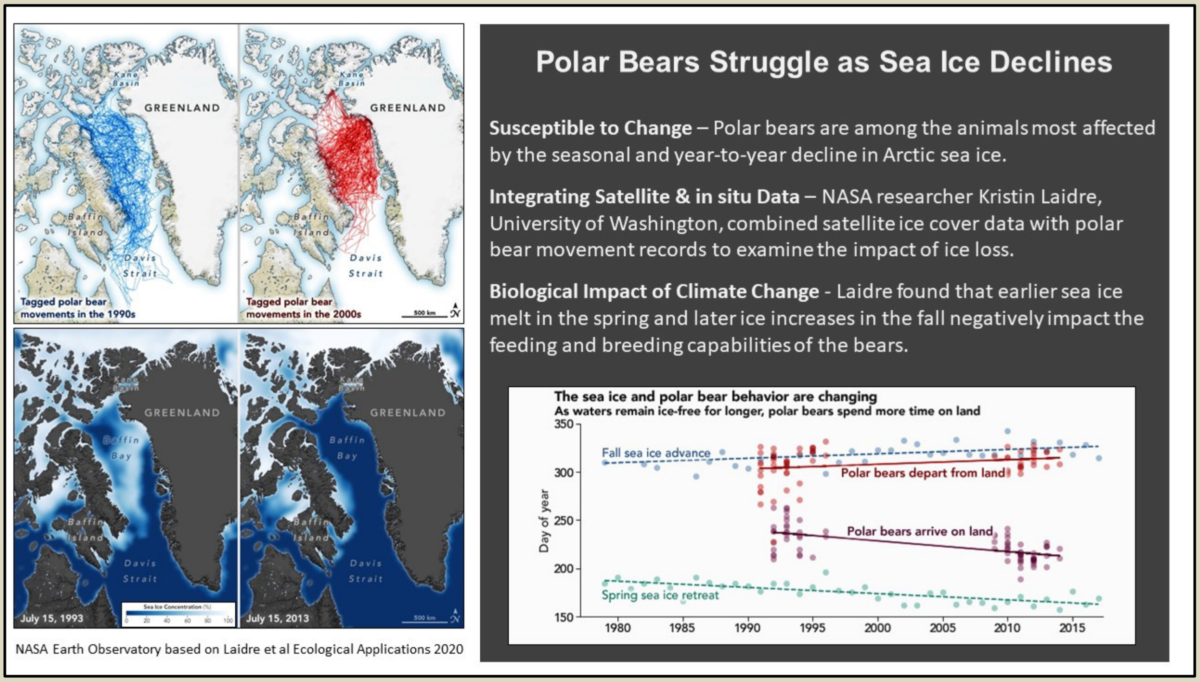
NASA Ecological Forecasting has pioneered the practice of combining observations and models to produce forecasts of how living systems might change in response to human action and inaction. It has generated dozens of remote sensing solutions used to this day by resource managers to conserve and better manage the natural world, including: more sustainable fisheries, protection of endangered species, detecting and targeting harmful invasive species, and developing systems for ascribing economic values to ecosystems that are often undervalued. Ecological forecasting continues to improve decision-making around the world, providing the top-down space-based perspective for management challenges across many disciplines and spatial grains.

Together, the Biological Diversity and Ecological Forecasting program elements have grown over the past decade and a half, supporting and managing over 250 projects during that time. Most of these projects have arisen through funded awards resulting from proposals to NASA solicitations. There have been many successes along the way, some shared across program elements, while others have been specific to an individual element; **Box 1-1** provides an example from each of these elements. Both program elements have helped private and public sectors across the globe meet their domestic and international obligations under a wide array of regulations, laws, commitments, and treaties. And each has increased the U.S. research and applications workforce through grants and other awards that offer training and experience to hundreds of students and postdocs.

After more than 15 years of supporting cutting edge research and infusing NASA data and models into applied, operational systems, it is time for NASA's Biological Diversity and

Ecological Forecasting program elements to assess where they are and where they need to go over the next decade.

**Box 1-1:** Example projects supported by the Biological Diversity (top) and Ecological Forecasting (bottom) program elements.




NASA Earth Observatory based on Laidre et al Ecological Applications 2020


Photo credit: Heather Lynch

Photo credit: Heather Lynch

NASA Visible Earth

## 3. NASA'S UNIQUE ROLE

The NASA Biological Diversity and Ecological Forecasting program elements are central to NASA's core mission. They drive advances in science, technology, aeronautics, and space exploration to enhance knowledge, education, innovation, economic vitality, and stewardship of Earth. All of this is fueled by NASA's exceptional ability to pair scientists and engineers to accomplish goals neither could achieve without the other. This partnership drives innovation in the capabilities of sensors used to observe biodiversity patterns on Earth. NASA designs instruments operating from the lower troposphere to outer space and capturing imagery at global scales to local grain sizes. The knowledge gained from these program elements fosters Earth stewardship and economic vitality for all people, while also informing NASA's search for life on other worlds.

Because NASA designs and implements science, engineering, and technologies to observe the Earth at a planetary scale, it is well positioned to detect, understand, and predict biological diversity patterns. The whole-Earth vantage point from space is ideally suited, even required, to address global challenges and promulgate a common language to communicate environmental change through synoptic-scale knowledge, visualizations, and iterative forecasting. NASA's "Earth as a system" approach incorporates a wide array of environmental variables that directly, or indirectly, affect biology. NASA ESD develops technology, builds, and operates dozens of space-based, airborne, and land/water-based instruments, and processes and stores the massive amount of data collected so it is available

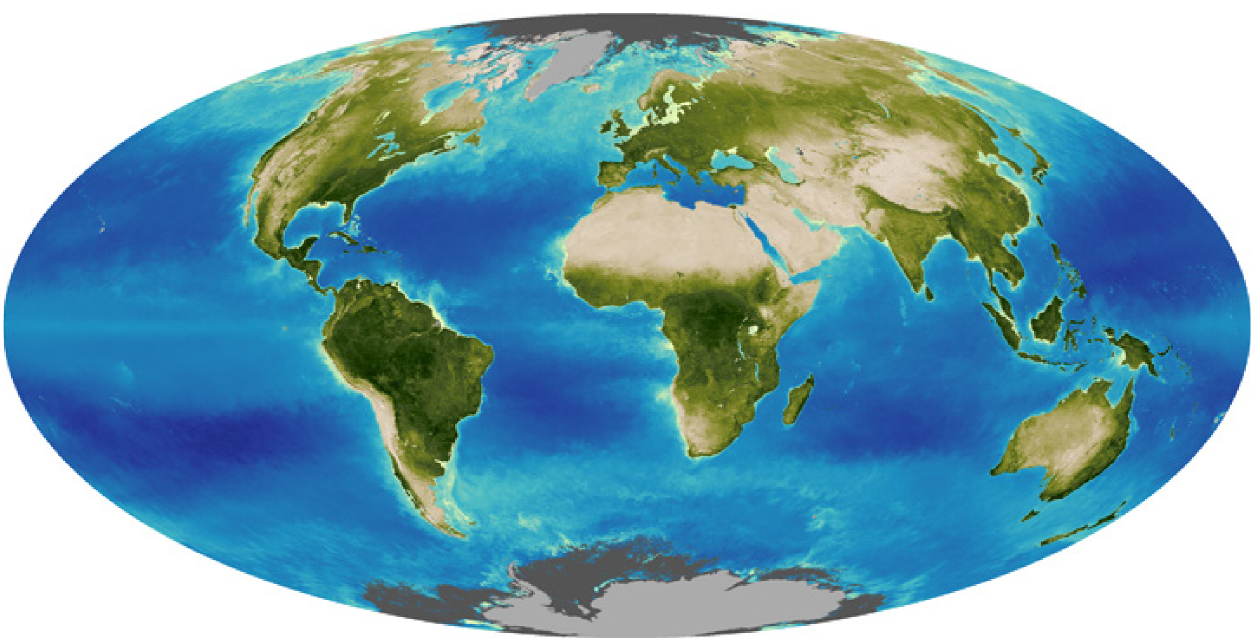


**Figure 1-1.** NASA provides critical observations at the scale of the global biosphere (*NASA Visible Earth*).

to scientists, governments, the private sector, and the general public at no cost. These data document changes in weather, ice cover, geologic and biophysical properties of the Earth's surface, and the movement and functioning of freshwater and marine systems. NASA integrates observations, analysis, capacity building, and field studies to capture the overall pulse of life on our planet.

Understanding biodiversity and sustainably managing ecosystems are priorities for the U.S. Government and humanity in general. For example, monitoring biodiversity and protecting coastal ecosystems are part of the U.S. decadal vision to promote American security and prosperity (NSTC 2018; NAS 2019). The 2018 decadal strategy for Earth observation from space specifically calls upon NASA to address the question: What are the structure, function, and biodiversity of Earth's ecosystems, and how and why are they changing in time and space (National Academies of Sciences, Engineering, and Medicine, 2018)? Similar needs are also expressed in international agreements, such as the CBD, the United Nation's (UN) Sustainable Development Goals, and the Ramsar Convention on Wetlands, and are in accord with assessments by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). The CBD post-2020 Global Biodiversity Framework (CBD post-2020) and UN Sustainable Development Goals (SDGs; UN 2015) depend on information and indicators that, at present, are not fully available. Meeting these international needs forms part of the motivation and strategic planning for the Group on Earth Observations (GEO), Future Earth, Global Ocean Observing System (GOOS), and many other nongovernmental and intergovernmental organizations.

## Observations

**Breadth.** NASA data capture a broad suite of measurements, leveraging multiple sensor technologies at various spatial and temporal scales relevant to understanding Earth's biological diversity and its role in Earth system processes. These observations are unique in terms of the breadth of the electromagnetic spectrum utilized, collecting imagery from the ultraviolet through the visible, near-infrared, shortwave infrared, thermal infrared, and microwave portions of the spectrum. Measurements are collected from the top of the atmosphere to tens of meters below the surface of the oceans and centimeters deep into the soils—and everything in between. Tremendous scientific and technical advancements have been made since the launch of the first scientific Earth Resources Technology Satellite (Landsat 1; launched in 1972). There has been a continual progression in our ability to monitor and understand the Earth system.

**New Technologies.** Technological advances are rapidly expanding the scope of what it is possible to detect from space. For example, over the past generation, biological observations from space, both terrestrial and marine, have largely focused on the environmental parameter of greenness. Whether looking at one of a number of vegetation indices on land or chlorophyll-a-denominated ocean color products from surface waters, greenness has been the parameter of choice underlying many biological data products. Relatively new types of sensors better characterize the composition, structure, and functioning of ecosystems. This revolution is being driven by a combination of technologies; these include hyperspectral imaging spectroscopy with its high dimensionality achieved through many narrow and contiguous bands; light detection and ranging instruments (Lidars) shooting lasers of various wavelengths at the Earth's surface and reading the returning backscatter; radars emitting microwaves and then recording their complex return signals from the surface; thermal imagers measuring emissions from the Earth in the infrared portion of the spectrum; and lights-at-night data critical for directly sensing human activities (e.g., tracking our use of energy as a proxy for the breadth and depth of the human footprint). The NASA Earth Science Technology Office (ESTO) has been instrumental in the development of new observational technologies, as well as the capacity to process and integrate these data with information technology, including data platforms, big data analysis, model-data fusion, and the application of machine learning and other forms of artificial intelligence (AI).

**Data Continuity.** NASA's continuity of remote sensing observations over five decades makes its data archive uniquely valuable for tracking long-term biological processes. Optical records from the Landsat archive (operated by the U.S. Geological Survey) contain nearly 50 years of spaceborne observations. Since 2000, Moderate Resolution Imaging Spectroradiometer (MODIS) data have provided global daily coverage and can be aligned with Advanced Very High Resolution Radiometer (AVHRR) data dating back to the 1980s and Coastal Zone Color Scanner (CZCS) imagery from 1978 to 1986. This series of observations is now carried forward through the Visible Infrared Imaging Radiometer Suite (VIIRS). NASA's non-optical records have also reached decades of continuity. The Gravity Recovery and Climate Experiment (GRACE) missions provide nearly two decades of groundwater, soil moisture, surface water, and snow and ice measurements. The two ICESat missions have a combined ten years of records characterizing ice mass, cloud height, topography, and vegetation characteristics. The Global Precipitation Measurement mission (GPM) now has eight years of hourly precipitation records; combining these with more than 17 years of Tropical Rainfall Measurement Mission (TRMM) data provides a multi-decade view of rainfall. In concert, these data comprise a one-of-a-kind archive for examining relationships between the biotic and abiotic elements of the Earth.

All of these data are publicly available at no cost through the Earth Science Data Systems (ESDS) Program, which operates the massive archives holding NASA data.

Maintaining continuity in these observations to establish long term records of biodiversity and ecosystem function is critical. Archiving more than 30 petabytes today, the NASA archive is expected to grow to 246 petabytes by 2025.

## Modeling

Modeling is an essential element of NASA's ability to understand the Earth as a system. In general, NASA science programs search for patterns large and small; in some cases, the processes driving these patterns are directly observable by satellite or aircraft, in other cases they are not. NASA often uses mathematical models of components of the Earth system to determine whether these components and their interactions are sufficiently understood to predict the physical and biological outcomes seen in NASA imagery. As with hypothesis testing, prediction of future biological and ecological phenomena constitutes the gold standard for demonstrating understanding of Earth system processes. Accurate predictions are also the applied results most desired by decision-makers seeking better solutions to management challenges.

Advances in analytics and in our ability to manage very large data volumes have led to an expansion in the capability and accuracy of ecological models. Rapid data access has enabled continued validation and calibration of short-term models and holds the promise of data assimilation for future ecosystem modeling. Recent advances in observations have raised estimates of ecological data volumes to be on par with those seen in other Earth system realms (e.g., weather data). Development of alternative models of future states for single Earth system variables allows for informed projections of biological response to natural environmental change and human actions. Combined, these capabilities improve our forecasts of ecological change. Efforts to build reanalysis products or harmonize disparate Earth system variables in common, open, and easily usable platforms have allowed broader adoption and use of NASA data.

## Capacity Building

Through substantial investment in training and stakeholder engagement, NASA ESD has expanded the use of Earth observations domestically and internationally. The NASA Applied Remote Sensing Training (ARSET) program produces webinars on the use of NASA data for research and applications. The NASA DEVELOP program offers ten-week internships at NASA field Centers. In the DEVELOP program, participants from undergraduates to career professionals apply NASA Earth observations to community concerns around the globe. NASA's Future Investigators in NASA Earth and Space Science and Technology (FINESST) solicitations support graduate student-designed research projects with funding for up to three years. In addition, many graduate students are supported by and engaged with NASA-funded research projects awarded to more senior investigators. NASA SERVIR is a joint venture with the U.S. Agency for International Development, employing state-of-the-art, satellite-based Earth monitoring data along with other geospatial information and tools to improve environmental decision-making within developing nations around the world.

## Partnerships

NASA's leadership in space research and development has positioned it to build global partnerships and communities of practice focused on understanding and preserving biological diversity. For example, NASA maintains several key positions within the biodiversity arm of the Group on Earth Observations (GEO), the GEO Biodiversity Observation Network (GEO BON). GEO BON's mission is to "Improve the acquisition, coordination and delivery of biodiversity observations and related services to users including decision makers and the scientific community." One GEO BON focus area is development and implementation of key biological parameters, called Essential Biodiversity Variables (EBVs), which guide observation collection and are needed to monitor and help understand biodiversity change. Another is to facilitate development of national, regional, and thematic biodiversity observation networks (BONs), with the long-term goal of an interconnected global monitoring system. NASA also co-leads the Biodiversity Activity within the Committee on Earth Observation Satellites (CEOS). NASA has long supported collaboration with the commercial and NGO sectors to understand the Earth as an integrated system and to enable societal benefit by leveraging the expertise of NASA and its partners to achieve together what neither could alone. This includes an official partnership with Conservation International combining NASA's observational and analytic capabilities with Conservation International's leadership in protecting Earth's natural systems and knowledge of on-the-ground needs and ecological processes. This partnership has a special focus on using Earth observations to support the growing field of ecosystem accounting. The NASA Applied Sciences Program largely acts through partnerships with end-user organizations in which NASA is seeking to provide a remote sensing solution to an end user's problem. Such partnerships require early and frequent engagement between NASA and the end user.

## Field Campaigns and Experiments

Field campaigns and experiments have been important in the NASA toolkit since the agency's earliest days. Often framed as "process studies," these *in situ* efforts commonly unite fine-scale, high-resolution observations on the ground and in the water with airborne and spaceborne imagery. Essentially, field campaigns allow NASA to climb a ladder of observations and understanding all the way up to space-based observations. They enable "unmixing" of coarser resolution pixels captured on orbit and expose the processes underlying and causing the patterns detected by satellites. These activities have led the way in demonstrating how NASA must integrate observations across spatial scales within modeling frameworks to increase our knowledge of the Earth system. Field campaigns typically require collaboration with other U.S. Government agencies (e.g., NSF, NOAA, DOE) and foreign governments, as well as other institutions across all sectors. These campaigns constitute another approach to conducting science, contrasting in-depth, short time frame studies addressing specific process questions with the long-term observations of larger spatial scale patterns obtained by on-orbit satellites. Previous NASA field campaigns serve as models for how the Biological Diversity and Ecological Forecasting program elements can bring NASA satellite data down to the Earth's surface for pattern interpretation and process knowledge.

## 4. REPORT STRUCTURE

The next six chapters in this report explore some of the most important questions relevant to understanding how the Earth system is changing, the implications of these changes for biodiversity and society, and how NASA can best contribute to that understanding. Each chapter has four main sections:

1. **Importance**: Explains the relevance of the topic to biodiversity science, applications, and society
2. **Current State of Knowledge**: Summarizes the current knowledge level of the chapter topic, including key areas for which there are still knowledge gaps
3. **What is Needed**: Discusses the various types of information and activities, within the scope of NASA's mission, that would help address the knowledge gaps, usually mapped into several timeframes
4. **Considerations for NASA**: Suggests directions for NASA to pursue to have the greatest impact in addressing the chapter's topic

**Chapter 2: Biodiversity** places biodiversity in its larger context and focuses on why it is important—to proper ecosystem functioning, to people, for ecosystem resilience, for evolutionary processes, and for the structure of ecosystems and how energy flows through them.

**Chapter 3: Drivers of Biodiversity** discusses drivers that lead to biodiversity—environmental, such as temperature and precipitation; biological, including interactions among species or genetic mutations; and anthropogenic, such as land use change—and the observations needed to track them. It also discusses the evolutionary processes that have occurred over Earth's history that have led to the biodiversity we see today and that will influence how biodiversity changes in the future.

**Chapter 4: People, Biodiversity, and Ecosystem Services** addresses the relationship between humans, biodiversity, and the broader environment, and also identifies key observations needed to monitor ecosystem services—the benefits that humans derive from ecosystems and other elements of biodiversity.

**Chapter 5: Scales of Biodiversity** tackles the importance of scale and investigates the observations and methods needed to understand its implications and its relevance to addressing biodiversity change.

**Chapter 6: Biodiversity and Ecosystem Resilience** explores ecosystem resilience, which becomes increasingly important as humans rapidly alter the natural world.

**Chapter 7: Predicting and Projecting Changes in Biodiversity and Ecosystem Services** goes beyond monitoring change to predicting it and exploring how observations can be combined with models to forecast changes so decision-makers have access to the best possible information.

Finally, **Chapter 8: Considerations for NASA** consolidates the recommendations provided in each of the previous six chapters into overall themes.

Human society and our prosperity depend on understanding the impact we have on the natural world upon which we depend. This understanding starts with an accounting of the composition of life on Earth (i.e., knowing the pieces and how they fit together) and extends into how these many pieces interact with the abiotic world to form the ecosystems that make up humanity's life support system—which we are rapidly altering. NASA's Biological Diversity and Ecological Forecasting program elements—the focus of this report—work to better understand these pieces, their interactions, and how they are changing. Together, they constitute NASA's primary effort to understand and preserve life on Earth and its tremendous value to humans.

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# 2

# BIODIVERSITY

## *What is biodiversity and why is it important?*

### Key Points

- Biodiversity is the framework for ecosystem function, the flow of energy and materials through the biotic and abiotic components of an ecosystem. Increasing the number of some species may increase ecosystem function and services (the capacity of ecosystems to facilitate or enable other life, and particularly to enable human development) but increasing the diversity of certain groups of organisms may not lead to our desired ecosystem services or create ecosystem resilience.
- Biodiversity and related ecosystem functions provide ecosystem services that enhance societal benefits, including health and economic value.
- Some species or groups of species have ecosystem function roles not simply related to abundance. Identifying such keystone species is important to understanding and forecasting changes in community and ecosystem structure and function.
- Feedback between humans and ecosystem function takes many forms. These are relevant, as they may affect the status of specific species populations, communities, and the process of evolution, and may carry social and economic implications.
- Advances in understanding the diversity of life, evolution, and how life interacts with the environment and forecasting ecosystem function and services requires a significant increase in environmental and biological observations collected simultaneously, using common methods and standardized data management strategies, over timeframes spanning seconds to decades and across spatial scales spanning millimeters to global. It also requires experimentation and improvements in models.

- NASA should support the integration of observations from different sensors and platforms, from the ground and aquatic areas to space, and operating across many spatial and temporal scales.
- NASA should ensure continued access to space to deploy the necessary sensors and data communications infrastructure for biodiversity and ecological forecasting research and applications. Such access enables fundamental science that requires repeat observations to understand processes such as connectivity, productivity, and phenology of species populations.

## 1. IMPORTANCE

Biodiversity is a fundamental characteristic of our planet—from genes, cells, and organs to organisms and communities. There is an interdependence between the diversity of life and many of the drivers of biodiversity through numerous types of feedback, many of which we do not fully understand. Our health and nutrition, and that of all organisms, depend on a variety of foods, on the chemical and geological changes and microclimates created by different organisms in and on the soil, and on the status and availability of good quality air and water. Indeed, changes in biodiversity can change ecosystem function and structure and biogeochemical processes at Earth system scales (Norris et al. 2020).

The relationship between an organism's physical and chemical characteristics, their functions, the role that organism plays in an ecosystem, and how these all change over time have been topics of discussion among philosophers and observers of nature since at least 600 Before the Common Era (BCE). Plato, Aristotle, and many others recognized that such knowledge is relevant to human well-being (Boylan 2005). In the late 1700s and through the mid-1800s, the work of Thomas Robert Malthus, Jean-Baptiste Lamarck, Charles Darwin, Alfred Russel Wallace, and Alexander von Humboldt restructured the foundations of biology, advanced the theory of evolution, and established the field of biogeography. In 1916, Arthur Harris used the concept of "biological diversity" to describe the "heterogeneity, variability, contrast" of the Desert Botanical Laboratory, located in Arizona. The concept was used more frequently by different authors starting in the 1960s. They all converged on the concept that a diversity of biological forms and functions are a result of environmental change, and that gradual and abrupt environmental changes, extreme conditions, and resource limitations can drive entire biological communities to extinction. These revolutionary conclusions came about because these authors had access to extensive concurrent environmental and biological observations, including taxonomic and morphological records from around the world collected by explorers and curated by museums.

NASA has made significant contributions to advancing understanding of life and biogeochemistry since the 1970s, with missions like Landsat, Coastal Zone Color Scanner, and subsequent missions that increasingly have provided regional to global monitoring using high quality scientific observations, using active and passive single-band and multi-spectral measurements in the visible, infrared, and microwave parts of the electromagnetic spectrum. Today we are undergoing a new leap in our knowledge of the diversity of life and how we depend on this biodiversity due to advances in sensor technologies, molecular techniques, and computational improvements. But to achieve this will require a significant increase in the number of observations of different aspects of the diversity of life, as well as experimentation and models that help us understand and quantify the interactions between different organisms and the environment. It requires partnerships between different science disciplines, government, and industry. This will further clarify how biological changes affect and are affected by the environment and enable new ways to organize, examine, and utilize massive amounts of observations.

The motivation for understanding biodiversity is all around us. There is a plethora of evidence in our everyday lives about the importance of biological diversity. Many sectors of society require information about biodiversity because of our dependence on life and its diversity. The public sector uses such information for formulating policy options, making decisions, and planning and reporting at national and international levels. This includes developing assessments of the status of biodiversity by the United Nations Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). It also includes tracking progress toward targets of international conventions (UNCCD, CBD, UNFCCC). The private sector needs information to plan for production and investments and to manage risks and opportunities in sectors as diverse as agriculture, aquaculture, fisheries, tourism, and conservation and restoration. The scientific community gains insights from biodiversity measures that help answer questions about life and many questions posed in Earth and Planetary system science, such as biogeochemistry, hydrology, geology, and physics—the data generated in the process are the foundation of solutions to the information needs of public and private sectors. The public in general, and specific stakeholders such as conservation groups, use such information for planning and prioritization; land managers and urban planners use biodiversity information to increase productivity and the health of human societies; indigenous peoples use such information to sustain their customs and practices. Each of these groups needs current and accurate information to ensure progress and their own well-being, and, ultimately, to ensure the survival of humanity.

This chapter summarizes the role of biodiversity in ecosystem functioning, ecosystem structure, and evolutionary processes. Subsequent chapters address drivers of biodiversity, how biodiversity is important to people, ecosystem resilience, ecological forecasting, and the complications of time and space scales when studying biodiversity. Ultimately, society needs to understand and to forecast how ecosystems function. It needs to understand the role of biodiversity in the ecosystem services that benefit people in different locations and at different times.

NASA programs enable repeated observations of the characteristics of life on Earth over local, regional, and global scales. The science and technology enabled through NASA programs help evaluate the patterns and changes in biodiversity that underpin ecosystem functions and services. NASA also works with other agencies to advance national and international partnerships that advance science, engineering, industry, and applications to promote societal benefit. By making biodiversity observations simultaneously with measurements of the physical and chemical characteristics of the air, land, and water, we can develop robust theories and models to improve our ability to plan and manage our critical planetary life support system.

## Importance of Biodiversity to the Functioning of Ecosystems

Biodiversity is, effectively, the diversity within species, between species, and of ecosystems (Margalef 1957; Magurran 2004; Convention of Biological Diversity). It is the framework for "ecosystem function"—the flow of energy and materials through the biotic and abiotic components of an ecosystem, including production of biomass, trophic transfer, and nutrient and water cycling (IPBES). Ecosystem function has also been defined more narrowly as the capacity of ecosystems to directly or indirectly provide goods and services to humans (de Groot et al. 2002). The timing of these functions is also important. For example, when algae and plankton bloom in aquatic environments can define the success or failure of many individual populations at higher trophic levels, such as fishes or birds. The timing of various plants' greening and flowering synchronizes pollinators and initiates animal migrations. Indeed, the life cycles of many species are tightly linked to those of other species. Further, the diversity of bacteria and larger organisms affects how different metals, nutrients, and gasses move through the environment, modulating biogeochemical cycles, Earth surface processes, and the very quality of the air, water, foods, and fibers we depend on.

Ecosystem functions can be grouped into regulation functions (those that regulate essential ecological and life support systems), habitat functions (the formation and maintenance of habitats), production functions (photosynthesis and nutrient cycling that provide genetic material, food, water quality, raw materials, energy), and information functions (opportunities for reflection, spiritual enrichment, cognitive development, recreation, aesthetic experience, and scientific knowledge) (de Groot et al. 2002). In some cases, increasing the number of certain species may increase ecosystem function and services, but increasing the diversity of certain groups of organisms, such as pathogens or weeds, may not lead to desirable ecosystem services. Therefore, stating simply that we need to conserve or increase biodiversity can be misleading.

## Biodiversity in the Context of Community Assembly and Ecosystem Structure

The number and composition of species, the interactions between these species in a community, and the processes that shape these interactions, including biodiversity, are referred to as "community assembly" (Bannar-Martin et al. 2018). The processes of species loss and gain, and the traits and functions of the community composition, is the "community structure." The ecological niche is a convenient way to characterize the position of different species in an ecosystem (Johnson 1910; Grinnell 1917; Whitaker et al. 1973; Kroes 1977; Polechová and Storch 2008). Ecosystem structure is the combination of multiple niches in any one area at a particular time. It features variations in the horizontal and vertical dimensions (biological-physical structure), in the multi-dimensional interactions between organisms (the "food web"), and it changes over time. Biodiversity underpins such ecosystem structure (Chapter 3).

## Importance of Biodiversity to Ecosystem Resilience

Resilience is the capacity of a system to absorb disturbance and change and still retain similar functions and an ecological identity (Chapter 6). Biodiversity is at the core of ecosystem resilience, as resilience depends on the degree of redundancy in the functions that different groups of organisms may perform in an ecosystem. Such functions may allow a larger group of species to recover from a disturbance (Walker 1992; Duffy et al. 2007; Maestre et al. 2012; Midgley 2012). Our understanding of how biodiversity affects resilience through various ecosystem functions comes primarily from local-scale manipulative experiments (Maestre et al. 2012; Grace et al. 2016; Liang et al. 2016; O'Connor et al. 2017). These types of experiments are typically small-scale and done under simplified conditions. Therefore, we still have limited understanding of the role of biodiversity in ecosystem resilience at a range of time and space scales. This is an area where NASA programs can contribute significantly, with repeated observations that scale temporally and spatially from the experiment to the globe and by providing synoptic data that help integrate knowledge gained from more localized ground and laboratory studies.

# 2. CURRENT STATE OF KNOWLEDGE

Today we know that changes in biodiversity over time are regulated by many biological and physical factors. Ecosystems vary in the abundance and composition of their communities, and different populations undergo different behaviors, life cycles, and phenologies, many of which influence those of other populations. Scientists use a variety of models that combine concepts of random mutations, epigenetic inheritance, regulation of transcription and translation, and migration with adaptation to environmental change to further understand evolution and biological diversity (Eldredge and Gould 1972; Benton 2010).

The simple observation that organisms interact with their surroundings steered ecologists in the 1980s to ask how evolution and biodiversity work together to change the environment. Over time, we have discovered that some of the interactions between organisms and the environment cause global-scale changes (Lovelock 1992, 2003; Bagdassarian et al. 2007; Beckerman et al. 2016). Bacteria, phytoplankton, and plants change the composition of the atmosphere, of minerals and rocks, and of aquatic environments over geological time and locally over scales of hours to seasons (Redfield et al. 1963; Sekerci and Petrovskii 2015). Our own human society has repeatedly reworked the landscape, accelerated climate change, and has had major impacts throughout the ocean (Millennium Ecosystem Assessment 2005; Halpern et al. 2008, 2019; IPBES 2019a, 2019b; NAS 2019). Below we explore more deeply what we know about such feedback processes and evaluate the role of NASA in advancing our understanding of biodiversity as part of this introduction to subsequent chapters.

## The Role of Feedback

Feedback is the modification or control of a process or system by its results or effects. A positive feedback may amplify a system response, whereas a negative feedback inhibits the system response. Feedback can lead to spatial variation in biotic interactions (caused by, for example, co-evolution at some common spatial scale), to changes in how population size is regulated in community dynamics, and can facilitate species coexistence (Bagdassarian et al. 2007).

Population density-dependent factors can have positive or negative feedback on species populations and processes like growth, reproduction, predation, disease, mortality, and competition (intra- and inter-specific interactions). For example, a given growth rate and population fitness that increases with population size are examples of positive feedback (the Allee effect). Limits to contacts with mates, vulnerability to predators, and limitations in the size of the gene pool can also cause Allee feedback effects. The International Union for Conservation of Nature (IUCN) considers population levels relative to a particular baseline as one of the factors in designating species as threatened or critically endangered. These processes also depend on the abundance of or access to resources (food, water, or substrate), species composition of the surrounding community, and abiotic forcing.

Feedback mechanisms can also lead organisms to change the environment. Populations and communities of organisms can modify a habitat or lead to a more diverse environment in ways that are favorable to those organisms, which can lead to increased chances of sustaining these populations. Feedback, however, may also cause a decrease in biodiversity or lead to an increase in the diversity and abundance of undesired species. For example, many weed species may modify their environment and make it more favorable to their own survival and persistence by altering sedimentation and erosion rates or nutrient availability or by exuding compounds toxic to other species (a process called allelopathy) (Emery-Butcher et al. 2020). Such feedback effects change the ecology of an area.

Some feedback effects may change the course of evolution, just as some evolutionary changes affect the environment. Feedback processes between humans and ecosystem function are relevant, as they carry social and economic implications (Chapter 4).

## Current Research Directions

Gaps in our knowledge about changes in the diversity, abundance, and distribution of life have limited our options for sustainable development and conservation. A research and resource management challenge of our time is to count and map organisms, populations, species, and their traits to enable detection and understanding of biodiversity and ecological patterns and how they change over time in a variety of locations. Because of the large number of species of organisms, from bacteria to mammals, that may be present in any single habitat on Earth at any particular time, it is impossible to count and monitor all species over all time. Indeed, many species remain to be discovered (Mora et al. 2011). Similarly, efforts to quantify the variety of ecological functions of groups of organisms, by measuring the type and number of traits that define groups of organisms, always focus on a limited number of traits. Thus, methods to quantify biodiversity often deal with specific groups of organisms, using standardized protocols and clear guidelines about the types of organisms to be counted or measured so subsequent metrics of biodiversity are comparable and make sense.

There are many ways to quantify different aspects of biodiversity. These range from simple counts of species or types of organisms to metrics of traits and features of organisms and habitats. This may be enhanced by quantifying population size, productivity, distribution and range, and the variability in environmental parameters that characterize or affect a habitat. Each of these metrics presents significant technological and logistical challenges that are the focus of numerous studies today.

A major scientific goal is to measure how these different elements of biodiversity are changing across different geographies and over time (Jetz et al. 2016). There are a few locations for which time series of biodiversity measurements have been conducted in terrestrial and marine environments for periods long enough to make conclusions about changes beyond seasonal effects (e.g., Dornelas et al. 2014, 2019).

Current evidence suggests that losses of wild habitat due to human development and climate change cause changes in the number of species in terrestrial and aquatic environments (IPBES 2019a, 2019b). This concern has led to international efforts to quantify such losses and develop strategies for conservation and sustainable development.

NASA programs, including suborbital, space-based Earth observations, modeling, and synthesis efforts provide important multidisciplinary environmental context across decades and at the multiple spatial scales needed to understand the drivers of biodiversity. NASA programs across Earth observing and planetary science provide the scientific and engineering potential to obtain observations needed to track indicators of biodiversity at the landscape, regional, and global scales and relevant astrobiology studies contribute to our understanding of the Earth. Such studies help us understand how and why life is organized into particular communities and ecosystems, how they interact, and how these processes change over time. They provide critical data, particularly for remote areas and at the regional and global scales that are impossible to cover otherwise. Field observations and experiments are included in this framework, to conduct measurements not possible from remote platforms, examine particular processes, and calibrate and validate measurements from remote sensors. A better integrated field-remote sensing-modeling framework is required to calibrate remotely sensed data, to understand patterns and processes, and to enable production of practical biodiversity indicators and for ecological forecasting.

NASA has made great strides in developing the science and technology needed to inform ecosystem-based management strategies. These have mainly focused on ecosystem-level integrative measures, such as chlorophyll concentration, leaf area, land cover classes, carbon content, and other indices of biomass for terrestrial and aquatic environments. The emphasis on climate research has led to a major focus on assessing stocks of carbon as a currency in the process of quantifying and monetizing climate change drivers. In policy discussions, much of the dialogue has centered on the value of carbon sinks and sources.

Yet, we know that life is the result of complex processes that are not captured by simple measures of carbon and other nutrients. As mentioned above, the mineral composition of rocks and soil, the concentration and cycling of various nutrients in water, the rate of carbon fixation and release in the environment, and the composition of the atmosphere are mediated differently by different and varying species and the interactions between biological communities. Biodiversity has profound impacts on sources and sinks of carbon and nutrients, and therefore on climate regulation, food and water supply, and on the resilience of ecosystems (e.g., Duffy et al. 2017; IPBES 2019a, 2019b; NAS 2019). Quantifying biological diversity over broad spatial and temporal scales to improve our assessments and forecasting of ecosystem services is an important challenge and a goal for the next decade and beyond.

# 3. WHAT IS NEEDED

This section outlines the challenges and some strategies to address the short term (1–5 years), midterm (5–10 years), and long term (10–25 years) requirements to advance the science, understanding, and applications of knowledge about biodiversity.

## Current Challenges to Quantifying Biodiversity

At present, limited strategies to synergize efforts across the science, government, civil society, and private sectors in the U.S. and internationally, combined with technological limitations, make it difficult to study and understand multiple species across a range of spatial and time scales simultaneously. This has limited the quantitative information we can obtain about biodiversity and our ability to understand the most fundamental Rules of Life (NSF 2017). Major questions remain in ecology (e.g., Sutherland et al. 2006, 2013), such as:

- How does biodiversity change across spatial gradients? Over time? How do such changes affect the physical, chemical, hydrological, and geological processes that we depend on?
- What feedback effects between life and the environment lead to evolution, changes in biodiversity, and a restructuring of Earth System processes? Over what timescales do they act? How are the feedback processes between evolution and biodiversity changing in different places and why?
- How do the ecological functions of different communities vary from place to place, how does this change over time, and why? What are the impacts of these changes (such as population loss, mass mortalities and bleaching due to diseases,

heat stress, acidification, deoxygenation, pollution, etc.) on biological communities, ecosystem functioning, and on society?

- How do terrestrial, freshwater, and marine systems influence each other's biodiversity? If organization and Rules of Life are different in these systems, what rules govern the interface of these systems?
- What feedback exists between biodiversity changes and human uses of the ocean? Is it the same as terrestrial systems?
- What is the potential for populations and ecosystems to recover after disturbance or change, and from multiple, persistent, large-scale stressors? If populations and ecosystems do not recover, can we predict their change?
- How are intrinsic measures of diversity at the molecular level related to biodiversity across landscapes?
- What are basic and high priority indicators of ecosystem services and how and why are they changing?
- What are the effects of biodiversity change on human society?
- Can we predict biodiversity and its effects on ecosystem function across different spatial scales? Are the functions different as we observe from small scales to larger scales?

Specific to the capabilities deployed to date by NASA, these are examples of questions that need to be addressed:

- What is the best way to measure biodiversity using remote sensing, given that it often measures only the dominant (or most abundant) organisms, leaving many animals and micro-organisms undetected?
- What are fit-for-purpose approaches to evaluate diversity, given that remote sensing always confounds signals related to biodiversity (due to averaging over time, spectra, space, or due to other radiometric issues of particular sensors)?
- How can remote sensing and complementary methods trained with field data identify ecosystem structure (e.g., depth or height, time, etc.)?

Among the grand challenges we face is the need to streamline the collection, management, and distribution of biodiversity information. To put some order to data and enable comparisons and synthesis, communities of researchers and practitioners should use best practices that generate interoperable observations. This will allow the integration of information about biodiversity across system types, spatial and temporal scales, and levels of biological organization (e.g., Miloslavich et al. 2018). This is a requirement to advance our current understanding and forecasting of life.

In particular, to facilitate research of changes over large spatial scales, long temporal scales, and enable comparative studies, observers need interoperable data. This requires common and standardized methods and data formats and accessible data. Examples that should be promoted and used by the community are the Darwin Core standard data format and publication of data via the Global Biodiversity Information Facility (GBIF) and Ocean Biodiversity Information System (OBIS). In a similar way, standards and common, interoperable, and linked repositories are required for acoustics, imaging, and *omics data, and these should in turn be linked to databases of environmental observations (physical, biogeochemical, geological, observations) and socio-economic information.

There is also a need to translate knowledge about how biodiversity affects a range of ecosystem services into information that decision-makers, managers, stakeholders, and the public can use. This knowledge helps to define scenarios and forecast desired outcomes of ecosystem function and ecosystem services (Chapter 7).

We need to develop a better and more practical understanding of the causes of disease and the relationship between resilience of particular ecosystems and of human communities. The COVID-19 pandemic that started in 2019, previous pandemics, and other human health issues have repeatedly highlighted the importance of understanding the role of biodiversity in the risk of disease and transmission within and between species. The link between human and ecosystem health is an area of debate and in need of focused research. While there may not be a universal answer on how to prevent disease, information about situations when biodiversity enhances transmission of disease between different species of organisms and viruses is critical to dealing with disease outbreaks, epidemics, and pandemics (Wood and Lafferty 2013; Banerjee et al. 2019; Vidal 2020).

Approaches are needed to provide repeated, frequent, and long-term observations of different dimensions of biodiversity over large geographic areas to allow assessment of the status and trends of various populations, habitat integrity or structure, and of socio-economic implications of change. High-quality, repeat observations will provide measures of uncertainty, variability in processes, and of the causes and consequences of change. Developing best practices and defining standard methods is fundamental to allowing comparisons of data from one location to another, understanding change over larger regions and the globe, and characterizing what may be causing change. An example of an evolving repository of methods is the Ocean Best Practices System sponsored by the Intergovernmental Oceanographic Commission.

There are emerging field technologies designed specifically to better quantify and understand biological diversity in terrestrial, aquatic, and atmospheric environments. These methods include imaging technologies, such as digital photography, automated counting of species and their abundance by artificial intelligence, and other image processing methods. They include specific measures of traits, such as length, weight, color (visible light spectra), and other morphological features. Some measures examine the phenology of different life cycle stages, sound, and behavior. Imaging spectroscopy has been used to characterize the chemical composition of groups of organisms, including the pigment composition and specific marker compounds, and is an effective approach to evaluating the diversity of many organisms, such as bacteria, algae, and land vegetation. The field of molecular biology, or *omics, is extremely active in improving the amount and types of organisms that can be identified, including through methods such as analysis of environmental DNA (eDNA; Goodwin et al. 2019).

Remote sensing is an important tool in evaluating biological diversity over larger areas. The spectral reflectance, texture, temperature, moisture content, biomass, and other characteristics of communities and of their habitats can be measured using multiple types of remote sensing technologies nearly simultaneously. Repeated multimodal measurements are required to build a record of change over short and long timeframes and to characterize, monitor, and understand the phenology of organisms and communities. Remote sensing can detect some species directly, such as particular types of plants on land and phytoplankton in the ocean, and it can be used to monitor drivers and proxies of biodiversity over large scales. For example, the spectral diversity of aquatic or terrestrial communities of primary producers may be monitored for ecosystem productivity and phenology changes (e.g., Muller-Karger et al. 2018a; Schweiger et al. 2018). Remote sensing is a valuable tool to quantify patterns in aquatic and terrestrial biogeography, including the dynamics of ecosystems from local to global scales (Tuanmu and Jetz 2015; Kavanaugh et al. 2016; Cavender Bares et al. 2020). Remote sensing observations are essential to quantify the uncertainty of variables, provide inputs, and validate models of species distributions and diversity.

Short-, mid-, and long-term priorities in biodiversity and ecology research to promote synthesis, new knowledge, and applications of ecological and societal relevance are outlined below.

## Today (0–5 years): Focus on Building Observing Systems

- **Improve links between biodiversity science, public sector decision-makers (state, federal, indigenous, international), civil society, and the private**

**sector** to build, support, and advance research into the drivers of biodiversity and its change. Broadening the linkages between academic groups, government, and the private sector in biodiversity science should focus on research advancements, development of applications workforce and new jobs, as well as sensor and technology development focused on bringing down the cost of technologies. While some important efforts are already underway, the science community needs help in understanding its role and to make such connections with other sectors of society.

- **Sponsor and enable the community of practice that is developing and implementing best practices.** A high priority is to further develop a "community of practice" that is diverse and inclusive as well as fully engaged in quantifying "essential" metrics about the diversity of life in different environments in a way that is comparable across land, water, and air habitats, that allows quantification of uncertainties in biodiversity metrics, and therefore enables detection of change over time. Methods to better quantify biodiversity, phenology, and energy and material flows in the context of the value of ecosystem function and services can be shared by different groups and applied more broadly.

  Best practices in the observation and data processing pipeline include defining requirements for observing biodiversity, designing the collection of data, incorporating information technologies for interoperability, curation, and dissemination of data, generation of information, use and applications of data, and feeding back information into observation requirements. The National Ecological Observatory Network (NEON) represents a step in this direction. These efforts should be linked to the Integrated Ocean Observing System, Ocean Observatory Initiative, Global Ocean Observing System, the many Biodiversity Observation Networks under the Group on Earth Observations, Long-Term Ecological Research (LTER) projects, and other similar initiatives around the world, and coordinated with global fisheries and silviculture and aquaculture management efforts, among many possibilities.

- **Observe species composition, distribution, and traits.** Multiple and multidisciplinary communities collaborate to provide a biodiversity observing system that includes comprehensive measurements of species composition, distribution, their traits, and their physical structure of biological communities on the ground and in the water. A current fundamental capability is the ability to map the presence and abundance of primary producers at large spatial scales.

Planning for full implementation of hyperspectral sensors needs to be a community activity to complement this information with observations of the composition and spatial structure. Because it takes many years to develop missions, planning must begin immediately. Mission requirements should address spatial, temporal, and spectral resolution and radiometric quality to allow identification of community composition, species traits, and biomass composition on land and in the oceans (Ustin et al. 2009; Muller-Karger et al. 2018a; Jacquemoud and Ustin 2019). Planning should include comprehensive spectral libraries for species, lineages, and community types. Lidar, Synthetic Aperture Radar (SAR), Interferometric Synthetic Aperture Radar (InSAR), tomographic SAR, and stereophotogrammetry are necessary to provide understanding of three-dimensional (3D) distribution and biomass, identifying microhabitats and the abiotic topographic, bathymetric, and water-column volumetric conditions associated with them. Rapid maturation of standardized products and increased validation are needed to improve the utility of 3D information in biodiversity observing systems. Space-based Lidars and polarimeters should be developed strategically to help resolve the 3D structure of plankton and particles in the upper ocean.

More research is needed to identify and verify new EBVs. Most of what is used today addresses bulk habitat characteristics (biomass, productivity), often not linked to a specific biodiversity metric. There needs to be an emphasis on characterizing diversity in ecosystems using hybrid multisensory measurements (e.g., combining hyperspectral, radar/Lidar, and thermal for a composite measure of diversity).

- **Develop new sensors and space platforms for Earth observations.** The ability to develop a 4D (3D + time) satellite capability is the critical next step for NASA's effort to understand surface and subsurface (soil, aquatic habitat) biodiversity.
- **Perform experiments to improve our understanding of feedback processes and advance ecological forecasting.** Experiments to advance ecological forecasting (Chapter 7) are needed immediately to build the foundation for more complex projects implemented in the next 5–10 years that will study the interactions and feedback between Earth system processes, human activities, and biodiversity. In many cases, feedback mechanisms may show a lag between a biotic variable or an environmental variable. Detecting types of feedback requires coverage over large scales and a range of periods from short to very long to understand impacts at climate change scales. Experimental

approaches may need to combine field, remote sensing, and simulations (models) to address specific questions and various elements of complex feedback processes. This should include the effects of changes in biodiversity and ecosystem services on human society.

- **More studies using high-resolution commercial observations (visible, infrared, microwave).** Sub-meter resolution imagery can be used to track anthropogenic activities on land and in the oceans, such as cropping patterns, parklands and conservation areas, pollution, shipping, and fishing. More studies taking advantage of high-resolution data represents an opportunity for future growth in the use of satellite imagery for understanding biodiversity and its drivers. This capability has been demonstrated by studies using very-high resolution commercial sensors (e.g., Fretwell et al. 2012; Lynch et al. 2012; Neigh et al. 2018; Lelong et al. 2020; McCarthy et al. 2020). Advancing the science that can be done in the next 10-20 years requires investment today to support researchers planning such studies and taking current data to their limits in coordination with other agencies and multidisciplinary teams.
- **Maintain repeated measurements and planning for long-term observations.** Repeated *in situ* and remote sensing measurements are needed for change detection. Time series have been typically difficult to justify, and yet detecting, understanding, and forecasting change requires a time series of observations. At minimum, existing time series need to be maintained. New time series need to be planned to understand changes in distribution, abundance, and diversity, especially in key locations. While some processes occur on very short time scales that require repeat intervals on the order of hours to days (e.g., phytoplankton blooms, grazing by secondary producers in aquatic ecosystems), some biodiversity processes occur on slower time scales (e.g., herbivory, forest growth, succession, and disease in terrestrial ecosystems). All require consistent observations over a long enough period of time to reliably detect fluctuations and trends in populations (Chapter 5, Chapter 6). Coordination between long term *in situ* monitoring programs and remote sensing programs is needed today to maintain and expand ongoing data collection efforts. This will ensure the statistical power needed to detect change into the future.
- **Convergence of observation frameworks.** There are current opportunities for collaboration between the terrestrial and aquatic research communities in defining joint theoretical and practical research using the Essential Variables frameworks. Several international observing frameworks, including the Essential Climate Variables (ECV), Essential Biodiversity Variables (EBV), and Essential

Ocean Variables (EOV), can help advance the scientific goals of a community of practice focused on providing information about biodiversity.

The Group on Earth Observations Biodiversity Observation Network (GEO BON), a Flagship Program of the Group on Earth Observations, helps organize the global research and operational communities to improve and augment collection of biodiversity data. GEO BON serves as a pathway to link biodiversity data and metadata to the Global Earth Observation System of Systems (GEOSS). GEO BON proposed the concept of Essential Biodiversity Variables (EBVs; Pereira et al. 2013) to focus scientific research on the state and changes of life over time and as a basis to develop indicators to support reporting for international conventions and treaties. The theme of EBVs has taken root within wide segments of the theoretical and applied ecology communities (e.g., Geijzendorfer et al. 2016; Pettorelli et al. 2016; Turak et al. 2016; Kissling et al. 2017; Muller-karger et al. 2018b) (see https://geobon.org/ebvs/what-are-ebvs/, updated from Pereira et al. 2013.). Among the users of information on strategies and frameworks promoted by GEO BON are researchers and national governments responsible for reporting the status and trends in ecosystems and the biodiversity they support to meet their national mandates (e.g., national biodiversity plans, recovering species at risk, sustaining ecosystem services) and international obligations (e.g., Convention on Biological Diversity, Ramsar Convention, Convention on Migratory Species, etc.).

The climate science community developed the concept of essential variables in the late 1990s. This focused resources on the collection of minimal sets of "key variables" for which data records were necessary to understand the status and trends in climate variability (Bojinski et al. 2014). An initial set of ECVs was the result of an evaluation of readiness, feasibility, and impact to address societal needs, and these remain the criteria to incorporate new variables that then become focal points of operational agencies and research concerned with climate assessments and prediction. The ECVs remain fundamental to informing negotiations under the United Nations Framework Convention on Climate Change (UNFCCC) and Intergovernmental Panel on Climate Change (IPCC). Biology is an important theme in such discussions and new ECVs include biological quantities for terrestrial and aquatic observations.

The Framework for Ocean Observing (FOO; Lindstrom et al. 2012) was proposed more or less simultaneously with the EBVs to guide development of the Global Ocean Observing System (GOOS), sponsored by the Intergovernmental Oceanographic Commission (IOC) of UNESCO. The FOO outlines the Essential

Ocean Variables (EOVs), which includes physical, biogeochemical, and biological-ecological variables (Miloslavich et al. 2018). EOVs are complementary to ECVs and EBVs (Muller-Karger et al. 2018b) (https://www.goosocean.org/index.php?option=com_content&view=article&id=11&Itemid=111, updated from Lindstrom et al. 2012).

Convergence and agreement between the different observing frameworks (EBVs, EOVs, ECVs) is required to provide clear direction to existing and new biodiversity observation programs. In the marine space, such convergence is now occurring under guidance of the Global Climate Observing System (GCOS), which is evaluating which of these essential variables to include into ECVs. But this work must be expanded across the sea, land, and air domains. Many EBVs and EOVs are the basis for the new ECVs for terrestrial and aquatic biological assessments.

These natural science frameworks also need to be combined with social science studies to understand and predict ecosystem function and ecosystem services (Chapters 3 and 6).

- **Data and information management.** There is a need to establish a reliable, interoperable, interdisciplinary, and interlinked large-scale infrastructure for handling the staggering quantities of data that exist now and that will be generated at increasingly larger volumes through remote sensing, *omics, video and imaging, acoustics, etc., as the global biodiversity observing capacity grows. This requires FAIR approaches (Wilkinson et al. 2016).

- **Capacity development.** Advancing the science, technology, and applications of biodiversity requires new human capacity. Capacity development is a broad category of activities that cuts across science, engineering, use, and application of information, as well as engaging the public of all ages everywhere about the role of biodiversity and how each of us benefits from it and can help sustain ecosystem services. There are concrete actions that NASA can take to help coordinate capacity development efforts locally, nationally, and internationally. There is a need to coordinate and plan to inform stakeholders and future scientists about the value chain of observing biodiversity in different environments to ensure a sufficient, motivated, and prepared workforce to address the challenges laid out in this report. Workforce motivation and development efforts should aim to achieve a high degree of diversity reflective of the population of the United States.

  Capacity development also provides significant opportunities for U.S. global leadership and for science diplomacy. There is significant opportunity to help address sustainable development and conservation in developing nations, helping governments and the private sector better direct and sponsor capacity-building efforts in biodiversity research and monitoring, so trainees connect with jobs. This is fundamental in the overall framework of national security for the U.S. and for developing nations engaged in this process.

A fundamental need is to develop human capacity to access and effectively use the data and products derived from NASA efforts. This can be combined with formulating and implementing strategies that focus on improving the link between science and engineering communities that design observing and applications systems. Intrinsic to this effort is development and promotion of open data and open software methodologies. Current interactions between these communities are piecemeal. Greater cross-disciplinary education and training efforts should focus on improving discipline-specific competencies across both fields, imparting knowledge to both communities about contemporary issues and improving understanding of the science requirements for engineering solutions and impact of engineering solutions on advancing the science.

Capacity development also includes strengthening and integrating traditional knowledge with new areas in science. Traditional knowledge includes the ways Indigenous Peoples and Local Communities (IPLC) acquire and use information, in addition to knowledge seasoned in antiquity. There is great interest in contributions that traditional knowledge can make to sustainable development and the access IPLC have to genetic data and other resources. However, there is a need to facilitate sharing of experiences and traditional knowledge among these communities, and to understand how their knowledge of change matches that which can be measured through Earth observations. Developing a working relationship with IPLC is a process that takes time and there is a need in the science community to respect and understand the IPLC process of developing knowledge and managing their resources.

There is a need to cultivate and sustain experts in taxonomy. Few researchers today focus on identification of organisms using traditional microscopy. Instead, molecular biology, chemistry, and remote sensing provide new ways to assess genetic composition, presence of particular species, population size, phenology, and to evaluate how and why the traits and functions of organisms change over time. Yet, there remains a need for the traditional taxonomist to provide fundamental observations to support these new methods and to participate in developing advanced and interoperable data management approaches.

A fundamental need is to further develop the capacity to collect, manage, and disseminate (share) big data in an interoperable manner for operational and research uses. There needs to be a renewed effort to partner among nations to conduct data archaeology and rescue efforts.

Increasingly, there is also a need for real and practical linkages between the natural and social sciences and the people in the private sector, civil society, the public, and governments that need the knowledge to conduct their business and live their lives. The concepts of "co-development" and "co-delivery" of solutions require that natural science researchers, engineers, and technologists understand requirements of society, policy-makers, and institutions that help promote economic and social well-being. It requires any science-based and technological solutions to generate products that can be used by these broader segments of society and exercise a feedback mechanism so products may be refined in an iterative way. Mechanisms to promote such multidisciplinary work should start today.

While capacity development activities must begin today, investments and further capacity development must occur to ensure they continue through tomorrow and the future. The investment in today and tomorrow underpins the advances of the future.

## Tomorrow (5–10 years): Implementing Big Biodiversity Science

- **Improve links between biodiversity science, public sector decision-makers (state, federal, indigenous, international), civil society, and the private sector.** Partnerships will help break down barriers between disciplines that make it difficult to work across departments, communities, and cultures to address interdisciplinary challenges, to develop new technologies, and to manage, distribute, and synthesize observations.
- **Promote and expand multidisciplinary research and applications.** Specific focus should be on linking species distribution models using *in situ* and remotely sensed observations to observations made from multiple methods, as well as building cross-sensor teams (e.g., multi-model remote sensing teams combining SAR and hyperspectral) for multidisciplinary biodiversity observations. This includes implementation of a comprehensive strategy for combined ground observations from drone-based aerial, water surface and submarine surveys, camera traps, acoustic instruments, eDNA, and other modalities with information from satellites and models. Multidisciplinary efforts should focus on contributing

to the development of scientifically sound, useful, and interoperable Essential Biodiversity Variables and indicators and documenting the linkages between EBVs and Essential Ecosystem Service Variables (EESVs). Work should continue to promote and develop EBVs, building on the foundation of EOVs and ECVs, and toward bringing EBV products to the same high quality as ECVs. This should occur in partnership with IPCC, GCOS, GEO BON, GOOS, and other partners.

- **Standardize EBVs and indicators.** Multidisciplinary work to develop ECV-level quality EBVs will require standardization of products and rigorous QA/QC to time series of specific building blocks of EBVs (i.e., observations of EOVs and ECVs and models). All derived biodiversity indicator products (phenology, productivity, ecosystem structure, etc.) should follow common mapping, compositing, data formatting, and unit standards. Interoperability and open access of key observations should be promoted by sponsored programs.
- **Greater capacity and workforce development** are needed, with a focus on the future of work in multi-disciplinary science and engineering and in connecting natural and social sciences. Investments should be targeted across academics, applications training, and activities to inspire and motivate a diverse and well-prepared workforce.

## Beyond (10+ years): Sustaining Development and Conservation through Innovation

- **Each of the previous priorities, demonstrated to be best practices,** should be promoted, incorporated into long-term planning, and continually reviewed for updating and defining actions.
- **Sustaining key time series of ground- and space-based observations** is a top priority for the long term. Concurrent with this effort is enabling comprehensive data collection, archival, and sharing protocols at key locations to address specific research and applications problems.
- **Focused technology development** for better characterization of biodiversity, including sensors, platforms, networks, and interoperable information and technologies and knowledge management.
- **Partnerships between the academic, government, civil society, and private sectors should continue to be fostered, built on, and improved.** Partnerships at the regional level help link expertise, infrastructure, and resources between these sectors, building on the strengths of the partners and creating

opportunities to address problems and create new markets and jobs. New partnerships are required to connect populations that have been traditionally underrepresented and underserved and improve local ecosystem services.

- **More multidisciplinary research is needed.** In particular, better links between the land, ocean, and atmospheric research communities must be made, which will support improved Earth System modeling and forecasting that explicitly accounts for the processes of life on Earth as an underpinning driver and outcome of the Earth System. Sponsorship of solutions through co-development with the public and private sectors, in partnership with the social sciences, should be a core element of any long-term planning.
- **Continue capacity development,** with investments targeted across academics, applications training, and activities to inspire and motivate a diverse and well-prepared workforce. NASA should expand the partnerships that help advance graduate STEM training that focuses on the challenges outlined in this report.

## 4. CONSIDERATIONS FOR NASA

NASA is in a unique position to lead and serve as a catalyst for innovation in the observation, forecasting, and application of biodiversity information. NASA plays a singular role as a pioneer and leader in addressing fundamental science about life on Earth and elsewhere and developing new applications of societal relevance. NASA technologies have consistently provided the highest quality observations required to detect small and large critical changes on the Earth's environment and biological characteristics. A critical role NASA can fulfill is one of incentivizing partnerships between national and international groups, agencies, and the private sector engaged in large-scale observation programs, technology development, and formulation and implementation of applications for the benefit of the nation and of humanity.

NASA's technologies enable a unique "big picture" of life on our planet. They can detect environmental events and long-term environmental change at small to global scales, all which can have acute or chronic, beneficial or harmful impacts on organisms. The NASA research community can lead and develop the technology needed to detect events and long-term changes in population structure, community and ecosystem composition, and quantify diversity using new methods across very large areas. It can evaluate the role of changing environmental factors and characterize the feedback between biotic and abiotic processes. In many, if not in most instances, measurements of the Earth are made to understand impacts on and of life, including human life.

Based on the points highlighted in the "What is Needed" section above, the NASA Biodiversity Program and Ecological Forecasting Program should consider these opportunities as it plans for the future:

- **Identify science and technological means needed to better quantify biodiversity, phenology, energy, and materials flow related to ecosystem function and services.** This is a necessary step for NASA to lead development of the technology to observe, analyze, and apply information about changes in ecosystem structure and services that result from aggregate niche characteristics. This includes means of identifying reliable indicators of changes in community traits due to a diversity of species populations that are present in an area, their differing phenologies at different life cycle stages, and environmental change. Because these aggregate community and ecosystem changes occur over large spatial scales, they can only be effectively detected from space and sub-orbital observations combined with distributed ground measurements and models. NASA has unique capacities and equipment to address the science of biodiversity. Close partnership between NASA, other agencies, and the private sector may accomplish what no single entity can do on its own.
- **Stimulate the convergence of observing frameworks (ECV, EBV, EOV, EESV, etc.),** while also providing incentives to partners and NASA PIs to follow standard protocols and best practices. These are critical, time-sensitive activities that will ultimately enable NASA and society to improve the design of observing systems to incorporate best practices identified by the community and focus on essential variables, including assessing community composition, traits, and physical structure around the world.
- **Integrate observing systems.** Observing system designs should explicitly consider and incorporate links between *in situ* and remote sensing systems.
- **Define joint theoretical and practical research opportunities that foster collaboration between terrestrial, aquatic, and atmospheric research communities.** Building multidisciplinary teams that span expertise in multi-modal remote sensing technologies and other observation techniques will progress the state of biodiversity science.
- **Link the socio-economic needs of the general public and specific stakeholder requirements with biodiversity research and ecological forecasting.** This includes leading multidisciplinary investments in defining strategies for sustainable development and biological conservation.

- **Focus on Grand Science Questions and the needs of society.** Grand Science Questions pose fundamental questions and hypotheses about problems that remain unsolved and that require unique technology development and a network-of-networks approach to bring together a community that works across national and international boundaries and across disciplines. These should be used as a framework for building mission teams with an express focus on life on Earth and biodiversity and include elements of applied science that address ecosystem function and services. Currently, the outcome of many NASA solicitations is a selection of many disparate, individual studies that were never designed to work together, and thus are not fully capable of solving large-scale or grand problems associated with the challenges around the study of biodiversity and life on Earth.
- **Foster collaborations across NASA science programs.** The Biological Diversity and Ecological Forecasting programs should work within the Earth Science Division to foster collaboration across programs–which all intersect with biodiversity, as described in this chapter. Furthermore, these programs should engage and explore joint mission concepts with the Astrobiology and Planetary Science program, as important scientific connections about life must begin to be made.
- **Ensure access to space to deploy the necessary sensors and data communications infrastructure for biodiversity and ecological forecasting research and applications.** NASA should focus on access to space to address fundamental science that requires repeat observations to understand processes such as distribution, connectivity, productivity, and phenology of species populations. NASA should continue to advocate for low-cost access to space and promote the evaluation of new opportunities to reduce the overall cost of all missions through improvement in processes, such as efficiencies that may be gained through streamlined review processes. Low-cost opportunities for access to space can promote many measurements relevant to many decadal survey priorities, including biodiversity, connectivity, biogeochemical flows, and applications. This includes planning for an operational research constellation of high quality hyperspectral, higher temporal frequency observations that provide global high spatial resolution across the land and coasts and low-to-moderate spatial resolution of the oceans. Long term planning for missions should include multi-modal constellations that combine hyperspectral measurements with Lidar, radar, polarimetry, and other microwave observing systems. Drone and other autonomous networks and swarms should be incorporated as part of a ground-

air-space observing system. NASA should plan for improved global, science-quality data (high spectral, high spatial, higher temporal resolution VIS-SWIR-TIR, multi-band Lidar, and microwave and other modalities) that characterize habitat structure from space. NASA should continue to develop partnerships across the U.S. government, academia, and with the private sector to further secure means for the science community to place sensors in space. A fundamental strategy is to build on international partnerships and consider the value of specific, targeted science diplomacy efforts, as the U.S. has done with specific countries throughout the twentieth century.

- **Expand capacity development opportunities.** NASA should improve the diversity of the scientific and engineering research community. It needs to build equity across the U.S. to improve access and use of NASA products. It should further expand capacity development opportunities focused on biodiversity observation at the regional to planetary levels. Many of these strategies should be developed as integral elements of the Applied Sciences Program, which houses the Ecological Forecasting program. NASA should:
  - Develop, sponsor, and promote opportunities to engage under-represented minority communities in planning and implementing research programs, missions, and applications. For example, promoting and enabling underrepresented minority PI-led missions and programs.
  - Assess and address gaps and needs in the nation's scientific and engineering workforce; for NASA, this includes research and applications on biological diversity and ecology, technologies including new sensors, and data analysis including big data, image analysis, interoperability, and forecasting problems.
  - Develop promotional and educational communications materials targeted at K–14 programs and the general public, including local, state, tribal, and federal representatives.
  - Promote K–14 and undergraduate research opportunities, graduate research, and engineering programs.
  - Invest in capacity building, training, and workforce development in the use and application of biodiversity data in government, academic, and the private sector.
  - Link to national NASA outreach efforts, such as the Space Grant, Challenger Schools, and University Research Centers.

- Promote national prestigious prizes for NASA-derived sustainable development and biological conservation activities and outcomes.
- Invest in developing a national awareness and sense of pride for research about biodiversity, similar to the sense of pride of human exploration of space.
- Consider expanding Fellowship programs, like the Future Investigators in NASA Earth and Space Science Technology (FINESST) and Early Career New Investigator Program (NIP), as well as the OSE Fellowship program, to become more diverse and inclusive and address national needs, such as biodiversity research.
- Consider alternate fellowship and honors programs for early career professionals, including awards related to addressing each of the items listed under 'What is Needed'.
- Develop a proactive and far-reaching science diplomacy program with extensions and outreach to developing nations.

• **Implement strategies to foster the success of multidisciplinary teams.** NASA should implement strategies for the next decade to improve the networking of research groups, develop best practices and defining standards in observing, data, and information management and analysis, and for the distribution and practical application of complex biological data. These are areas where the biological sciences have allowed substantial divergence to develop between groups and disciplines, yet the research of complex biodiversity dynamics over regional to global scales now requires new interoperability paradigms, large-scale observing strategies, and partnerships. The strategy should incorporate incentives for multi- and transdisciplinary work, including meaningful collaborations between the natural and social sciences, technologists, and engineers. NASA should formalize a requirement to release all relevant biological, biodiversity, and environmental observations openly and define caveats related to national security and conservation.

• **Require combined remote sensing observations to follow standard protocols.** Basic products (e.g., radiance, reflectance, emissivity, scattering) should have common units. For example, DESIS (DLR and Teledyne) data and other reflectance products procured under NASA Data Buy programs and other tools should have the same units, formats, and documentation requirements as, for example, a NASA MODIS VNIR reflectance product. NASA should also promote easy and more practical access to Earth observation data and derived products. NASA has recently made notable improvements in this area (e.g., the EarthData Pathfinders), which should be expanded: biodiversity products should span the globe—wherever life is found, across land, air, and water—and should integrate vertical data for oceans, soil, and other critical areas. This is consistent with the strategy to develop EBVs. Specific suggestions include:

- Biodiversity products that include coherent calibrated reflectance, scattering, and emittance/emissivity products from a virtual multidisciplinary constellation preserving the highest spatial, temporal, and spectral resolution of each sensor (e.g., same reflectance units for sensors in the same family, same file format).
- A family of L2B-L3-L4 products built from one or multiple sensors (e.g., EBVs, seascapes/landscapes, environmental forcing variables) should be harmonized and follow the same file format.
- A toolbox of open source models for scenarios and results, such as ocean/atmosphere circulation, species distribution, habitat suitability, primary productivity, and biodiversity indicators. All results should be generated in a family of accessible file formats, fundamental to enabling "digital twins" of biodiversity characteristics and ecology processes. It should also enable the community to easily link to current Committee on Earth Observation Satellites (CEOS) and other projects, such as the COVERAGE/virtual ocean observation constellation or virtual constellation for land surface imaging, to derive full Earth surface EBV products.
- Basic tools to run the above toolbox, including to extract data and products from multiple sensors at their highest resolution or collapsed to a common resolution. Tools should include the facility to calculate basic statistics.

• **Continue to engage in and grow partnerships, including with the private sector.** This includes continuing to work with partners for multi-agency announcements like the National Ocean Partnership Program announcements for the Marine Biodiversity Observation Network (MBON). There is an opportunity to develop an international equivalent to the National Ocean Partnership Program, perhaps under CEOS, focused on coordinating large-scale research funding to address biodiversity on Earth and not just within narrow themes. NASA should partner with GEO BON as an implementing mechanism for a large-scale program. Working with the private sector could follow the approach used for ISS National Laboratory management by the Center for the Advancement of Science in Space

(CASIS) or management of the NSF's National Ecological Observation Network (NEON). Other commercial opportunities include partnerships with commercial satellite data providers.

- **Play a leading role nationally and internationally in promoting research, partnerships, and new technology development to enhance regional and global biodiversity observations.** All these activities must be continuously re-assessed and refocused to continue to advance our knowledge about biological systems.

Through strategic research community networking around common fundamental questions and by fostering the use of best practices and standards, advancing technology, and supporting application of what is learned, NASA will advance human knowledge and facilitate sustainable development and wise conservation strategies.

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# DRIVERS OF BIODIVERSITY

## *What determines the world's biodiversity and how are these drivers changing?*

### Key Points

- A combination of drivers has led to the biodiversity patterns now observed globally. These drivers include physical, chemical, biotic, and evolutionary processes that have occurred over Earth's history.
- Climate variations on millennial to interannual time scales affect many of these drivers and have resulted in important temporal and spatial shifts in biodiversity.
- Anthropogenic forces are increasingly modifying these drivers directly (e.g., habitat destruction, pollution, exploitation) and indirectly (i.e., via changes in climate), leading to rapid changes in species composition and biodiversity loss.
- Anthropogenically driven changes in biodiversity feed back to the physical and chemical drivers (e.g., leading to increases in temperature, changes in precipitation patterns) that further exacerbate changes in biodiversity.
- Physical and chemical drivers of biodiversity change are relatively well measured, in sharp contrast to biotic drivers, which are not. How physical, chemical, and biotic drivers interact to cause biodiversity change is poorly understood and difficult to model.
- Observations of drivers and biodiversity change during large-scale climate (e.g., El Niño) and extreme (e.g., volcanic eruptions, pandemics) events can help elucidate how drivers interact to influence biodiversity and can be useful for improving model parameterizations.
- NASA's current strength lies in measuring variations in physical and chemical drivers of biodiversity at a global scale. NASA can also measure critical aspects of

global terrestrial biodiversity and biotic drivers and this capacity is increasing with planned missions.

- NASA should enhance collection of biotic and abiotic *in situ* information because these are essential for understanding and monitoring biodiversity from space. To further this, NASA should develop partnerships with other organizations, invest in process and field campaigns, and develop autonomous *in situ* data collection systems.
- NASA should support development and improvement of models that relate driver variability to biodiversity.
- NASA should promote new concepts and approaches to observe aspects of biodiversity and drivers not presently observable from space.

## 1. IMPORTANCE

Life on Earth spans biodiversity at all levels—from genes to biomes—and is distributed from the deep ocean to terrestrial mountain tops, in the atmosphere, and across all latitudes from pole to pole. To understand the drivers that led to this biodiversity, it is useful to look back in time to when life on Earth first evolved, roughly 3.8 billion years ago.

Life as we know it today consists of unicellular or multicellular organisms that contain nucleic acids and use this material to control metabolic processes and to self-replicate. The details of how these organisms formed are uncertain but they first occurred in the absence of free oxygen and used light, heat, or chemical energy to convert inorganic elements to organic molecules. Early life thus consisted of anaerobic cells, and these remain an important part of the conglomerate of life we find today. Photosynthetic organisms, such as cyanobacteria, evolved later, and the oxygen released as part of the photosynthetic process profoundly changed Earth's atmosphere and, in turn, how life evolved. Oxygen then was a key driver of the biodiversity we see today because it enabled development of more complex and efficient organisms.

Some of these new organisms developed a "nucleus" (eukaryotes) and were capable of oxidative metabolic processes. Eventually, individual cells "aggregated" into multicellular organisms that are the most visible component of the broad diversity of life found on Earth today. The major lineages—including archaea, bacteria, and eukaryotic plants, animals, and fungi—evolved and expanded over millennia, and the evolutionary paths these lineages took is captured in what is known as the tree of life (Figure 3-1). The tree of life is estimated to encompass about 8.7 million species on land and in the oceans (6.5 million species on land and 2.2 million in oceans) (Mora et al. 2011), greater than 85% of which remain undiscovered.

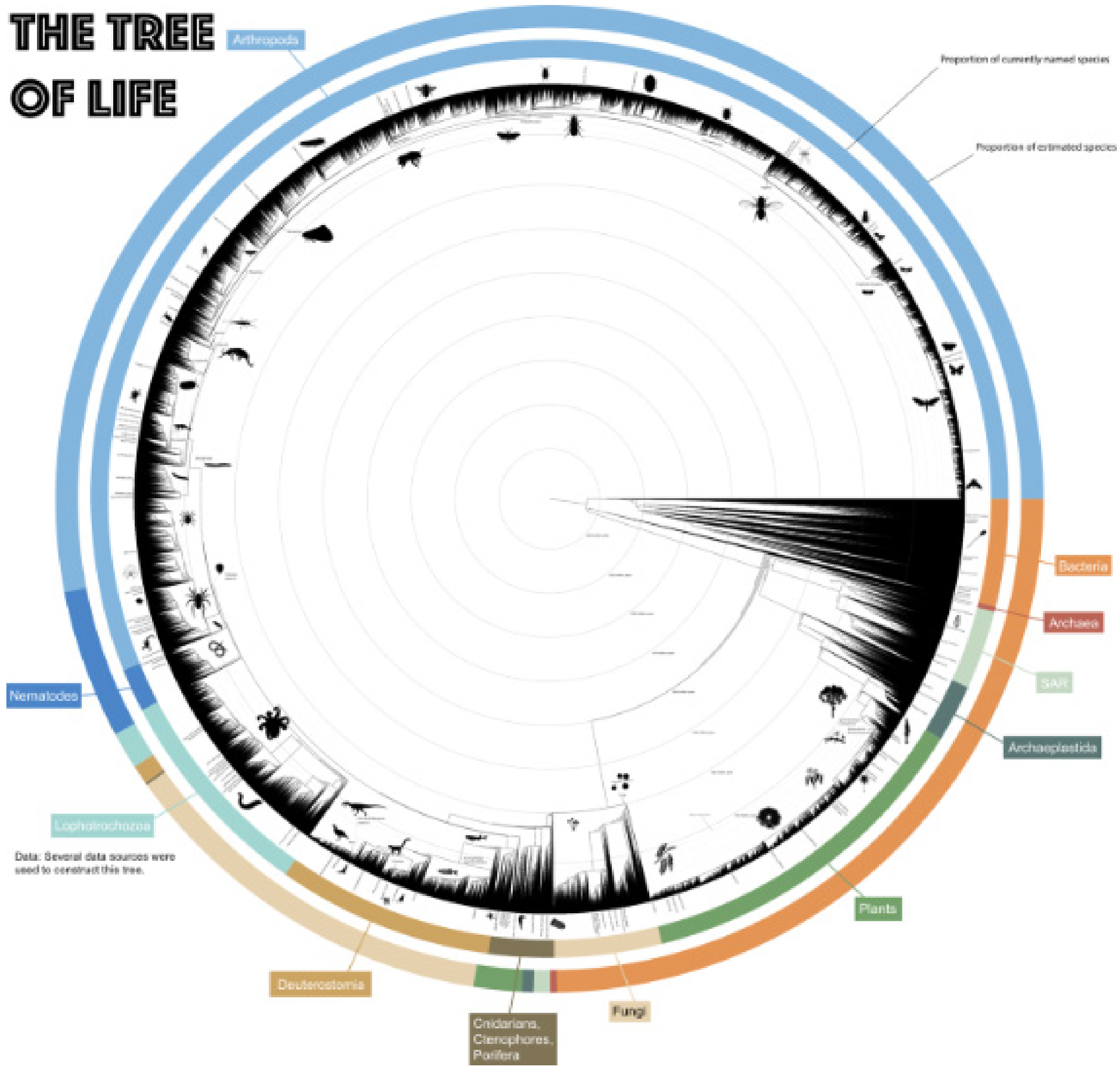


**Figure 3-1.** Biodiversity has evolved over millennia to produce the lineages of organisms across the evolutionary "tree of life." The tree of life shown here represents a small subset of the total species on Earth and illustrates how species are related to each other. Generation of the tree of life through phylogenetic inference has only been possible to assemble in recent years due to transformative advances in DNA technology and computational power. The hierarchical organization of life, in which species are nested within lineages of larger and larger size, reflects evolutionary diversification and extinction processes and the accumulation of novel genes and characteristics over time. All members within a lineage share a common ancestor and many of the accumulated genes and characters of that ancestor, such that all species in any given lineage share commonalities in their genetic, structural, and functional characteristics.

*"The Tree of Life" reproduced with permission from Stephen A. Smith using data from Hinchliff et al., 2015, "Synthesis of Phylogeny and Taxonomy into a Comprehensive Tree of Life," Proceedings of the National Academy of Sciences, 112 (41): 12764–12769.*

Biodiversity, however, is not distributed uniformly. Spatial variability in environmental and biotic conditions means evolutionary drivers vary from place to place, and these varying conditions directly affect the characteristics needed for an organism to survive and reproduce in any location. Further understanding requires exploration of two functional biodiversity elements:

1. Primary producers, those that use light or some form of chemical energy to convert inorganic elements to organic molecules (e.g., plants).
2. Heterotrophs (consumers), those that require previously processed organic molecules to grow and replicate (e.g., humans and other animals).

Environmental conditions determine the quantity and composition of primary producers and, consequently, the heterotrophs that depend on them. In aquatic systems, the amount of light and inorganic nutrients are determinants of the characteristic biodiversity of a region. In terrestrial ecosystems, water availability and temperature–in addition to nutrients–are also critical determinants of biodiversity. Under high levels of light and nutrients, photosynthetic organisms capable of self-replicating faster are favored, whereas under low levels, more specialized and slower-growing primary producers evolve. In all living systems, temperature is important in regulating rates of growth and influences the resulting biodiversity patterns. In many cases, interactions among organisms, such as grazing or the production of chemicals, can stimulate or inhibit the growth, production, and evolutionary processes of species. The combination of physical, chemical, and biological conditions determines the characteristic biodiversity of a particular geographic region, with clear spatial variations (Figure 3-2). Biodiversity is more than the number of species, shown as species richness in Figure 3-2. It includes all aspects of the variation in life, including the phylogenetic diversity measured from branches across the tree of life (Figure 3-1), functional variation among living organisms, as well as how diversity is distributed in its various dimensions in time and space. This includes the functional trait variation of terrestrial vegetation within and among ecosystems, which can be remotely detected (Cavender-Bares et al. 2022).

The overall spatial distribution of properties regulating life on Earth is relatively well understood for aquatic and terrestrial ecosystems. For example, combined terrestrial and marine global maps of vegetation from remote sensing show regions of high (grasslands/ forests, algal blooms) and low (deserts, oligotrophic gyres) concentrations. The productivity of freshwater bodies can be nil or extremely high. The spatial distribution in terrestrial environments, in particular outside of the polar zones, is closely related to patterns in precipitation and temperature–forests in wet regions and deserts in dry ones. In the same latitudinal bands in marine environments, the patterns are related to the supply of nutrients.

Nutrients may rise to sunlit waters near the surface from below the thermocline by a number of physical forcing factors. Rivers and deposition of nutrients from the atmosphere in rainfall or aerosols are also a fertilization process. Upwelling regions are generally more productive (and less diverse) than the thermally stable oligotrophic gyres.

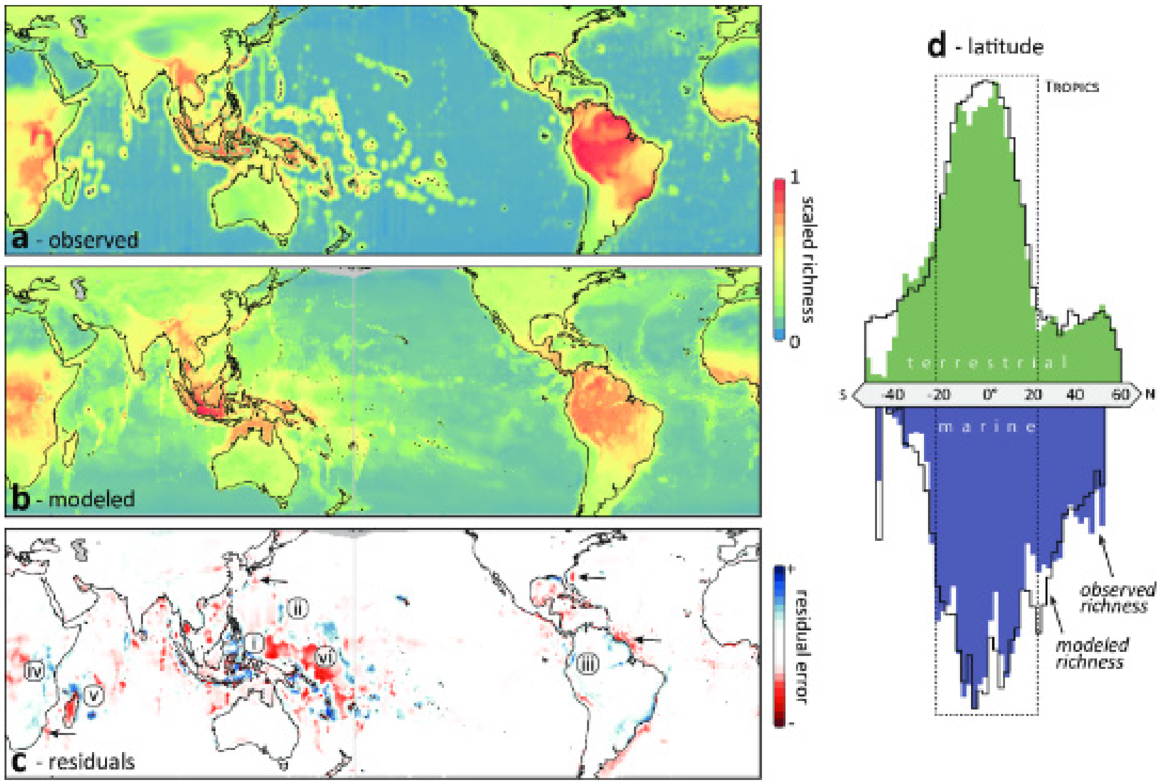


**Figure 3-2.** Global terrestrial and marine biodiversity patterns.Observed species richness derived from the distributions of 44,575 marine and 22,830 terrestrial species. Species richness is ln-transformed and rescaled within each domain (terrestrial and marine) and plotted on a 50 km equal area grid. (b) Artificial neural network model predictions (ANNs) of species richness considering a suite of 29 environmental drivers. (c) Model residuals highlight areas that are particularly species-rich (underpredicted, blue) and species-poor (overpredicted, red) regions relative to the underlying environmental drivers. These highlight locations of exceptional biodiversity, such as reef ecosystems of the (i) Coral Triangle and (ii) Marianas Archipelago and wet forests of the (iii) tropical Andes and (iv) Eastern Arc mountains. It also identifies species-poor settings like isolated islands (v, Madagascar) and major biogeographic boundaries in the ocean (vi, Andesite line). Arrows designate species-poor marine regions with high velocity boundary currents. (d) Latitude does not affect model performance, as there are no systematic meridional differences between observed and modeled richness. The northern-hemisphere bias of land, and the corresponding abundance of shallow ocean environments, generates a similar imbalance of marine species richness. The chart represents average species richness, zonally, in 2° latitude bins (Gagné et al. 2020).

These predictable and highly seasonal spatial patterns are modulated year-to-year by weather and climate.

Climate then determines the characteristic biodiversity of a region via a series of drivers (e.g., temperature, light, precipitation; Table 3-1). Figure 3-2 displays latitudinal variations in species richness in marine and terrestrial environments resulting from these drivers. However, climate and its driving forces vary on millennial to interannual time scales, resulting in important temporal and spatial shifts in biodiversity. In addition to climate, evolutionary history, biotic processes (e.g., competition, predation, symbiosis), and historical biogeography influence a region's characteristic biodiversity. Biodiversity is also a consequence of total habitat area (Rosenzweig 1995), the time and area a biome has

Table 3-1. Physical, chemical, and biotic drivers—direct and indirect—of biodiversity and its change through time and space. Examples of the mechanisms, impacts, measurement methods (or data sources) and remote sensing techniques are given along with the likely lead and partnering agencies/institutions in the United States.

| Driver | Mechanism | Impact | Measurement Method | Remote Sensing Technique | Org |
|---|---|---|---|---|---|
| **Direct Drivers of Biodiversity Change** | | | | | |
| **Climate Variability** | • Changes in climate variability influence micro and macro-evolutionary processes<br>• Temperature and freshwater influence nutrient supply in the ocean through stratification<br>• Changes in temperature and precipitation regimes influence organismal function, biorhythms, and phenology as well as species interactions, survival, and distributions<br>• Influence biotic interactions (e.g., intensity, predator-prey cycles, degree of competition) | Extinction, migration, species distributions, ecosystem composition and diversity, changes in primary productivity | Remote Sensing, *in situ* measurements | Spectral imaging, thermal imaging, Radar, SIF/ chlorophyll fluorescence | NASA, NOAA, NEON, LTER, NSF |

| Driver | Mechanism | Impact | Measurement Method | Remote Sensing Technique | Org |
|---|---|---|---|---|---|
| **Temperature** | Influences metabolic rates, nutrient supply rates in aquatic systems, etc. | Organisms adapted to a specific temperature range will not survive changes outside the range | Remote sensing, *in situ* measurements | Thermal Imaging/ radiometers | NASA, NOAA, NEON, LTER |
| **Depth and Elevation** | Influence nutrient cycling, food availability, temperature, and access to light | Both limit species distributions and interact with environmental change (e.g., high altitude species may get pushed to extinction as climate warms) | Remote Sensing/ *in situ* measurements of depth, elevation, or pressure | Synthetic aperture Radar Interferometry, Lidar, stereo-photogrammetry, optical depth measurements, Lidar bathymetry | NASA, USGS |
| **Biotic Interactions** | Competition, predation, or absence of mutualists, dispersers, and pollinators may limit where species can grow and reproduce | Changes species distributions, composition, and diversity | Occupancy and abundance of species, intra- and interspecific variation in traits, changes through time in vegetation structure | Hyper and multispectral imaging, Lidar | NASA, GBIF/ iDigBio, NEON, LTER, LTAR, Forest-GEO |
| **Nutrients (including Oxygen)** | Critical to photosynthesis, growth, metabolism, ability to withstand stress and survival | Controls biological productivity; influences species distributions | Depth of nutricline, soil sampling | Hyperspectral/ Multispectral imaging | NEON, LTER, LTAR, CZO |
| **Light Availability and Quality (Spectral)** | Influences photosynthetic rates, light harvesting, light stress, plant responses to neighbors | Controls biological productivity; influences species distributions | Remote Sensing of Light profiles in vegetation | Lidar and spectral imaging | NASA, NEON, NSF |
| **Primary Production** | Fixation of carbon through plant photosynthesis providing energy base for all other trophic levels | Changes in productivity that limit growth and abundance of heterotrophic organisms | Remote Sensing, *in situ* measurements | Multispectral imaging/Synthetic aperture radar, SIF/ chlorophyll fluorescence, timeseries | NASA, LTER, NEON, LTAR |
| **Precipitation/ Water Availability** | Terrestrial organisms require water for metabolic function, nutrient and carbon transport, maintenance of cell function, stress tolerance | Changes in species distributions and ecosystem composition and productivity | Remote Sensing, *in situ* measurements (Daily or subdaily measurements of precipitation amount and type (snow vs rain)) | Precipitation Radar/Microwave Radiometer | NASA, NEON, LTER |

| Driver | Mechanism | Impact | Measurement Method | Remote Sensing Technique | Org |
|---|---|---|---|---|---|
| **Habitat Heterogeneity** | Leads to speciation; promotes niche partitioning | Influences the variety and composition of species that occur in an area; maintains diversity | Remote Sensing, *in situ* measurements, UAVs, and SfM | Lidar, radar, and spectral imaging | NASA, NEON, USGS |
| **Geodiversity** | Diversity of abiotic landscape features that influences water, nutrient, and carbon supply (via light availability) as well as temperature, landscape connectivity, movement | Influences the diversity and distribution of species | Remote Sensing | Lidar, radar, and spectral imaging, stereophotogrammetry, optical depth measurements | NASA, USGS |
| **Fire** | Destroys biomass; promotes fire dependent and fire tolerant species at the expense of others | Changes in biomass, primary productivity, and species composition | Remote Sensing (near real-time imaging, changes in structure) | Hyper and Multispectral, thermal imaging, Lidar | NASA |
| **Historical Biogeography** | Long-term historical processes that influence which species, lineages and biomes occur where | Continental scale distributions of species | Fossil data, phylogenetic reconstruction using DNA | (Not applicable) | Neotoma, NSF |
| **Diversification, Speciation, Extinction** | Macroevolutionary processes that generate or eliminate species and lineages | Changes in the regional species pool and adaptations of organisms to environment | Fossil data, phylogenetic reconstruction using DNA sequences | (Not applicable) | Neotoma, Genbank, NSF |
| **Indirect Drivers of Recent Biodiversity Change** | | | | | |
| **Anthropogenic Climate Change** | Alteration of ecological niches, changes in timing and rates of metabolic processes | Changes in species distributions outside abiotic tolerances and competitive abilities, shifts in phenology, uncoupling of co-evolved biological processes (e.g., dispersal and pollination syndromes), change in temporal patterns of ecosystem function | Remote Sensing, *in situ* measurements | Lidar, radar, thermal, hyper and multispectral imaging, SIF/ chlorophyll fluorescence, and change detection | NASA, NEON, LTER, Forest-GEO, NSF |
| **Land/Sea Use Change** | Habitat availability | Habitat loss, extinction | Remote Sensing, *in situ* measurements | Multispectral/ SAR imaging, and change detection | NASA, LTER |

| Driver | Mechanism | Impact | Measurement Method | Remote Sensing Technique | Org |
|---|---|---|---|---|---|
| **Pollution** | Toxicity, nutrient addition | Increased mortality, decreased fertility, extinction | Remote Sensing | Multispectral, hyperspectral/ SAR imaging, and change detection | NASA, EPA |
| **Exploitation** | Removal of organisms from land and water | Population declines; disruption of food webs, extinction | Remote Sensing, *in situ* measurements | Multispectral, hyperspectral/ SAR imaging, and change detection | NASA |
| **Invasive and Alien Species** | Competition, homogenization of ecological communities, spread of pests and pathogens | Habitat loss, changes in organic inputs into ecosystems; disruption of food webs, extinction; change in composition, diversity and productivity of organisms and ecosystems | Remote Sensing, *in situ* measurements, UAVs, SfM | Multispectral, hyperspectral/ SAR imaging, and change detection | NASA, GBIF/ iDigBio, LTER, NEON, Forest-GEO, USDA |

occupied through time (Fine and Ree 2006), habitat diversity and heterogeneity (Kerr and Packer 1997; Kerr et al. 2001; Tews et al. 2004), the niche breadth of species (Tilman 1982), ecosystem productivity (Waide et al. 1999), and biogeographical and historical contingencies (Latham and Ricklefs et al. 1999; Wiens and Donoghue 2004). These factors influence the generation of biodiversity, as well as how it changes through time. Increasingly, diverse assemblages of organisms have evolved in regions with warmer climates, abundant resource availability, high habitat heterogeneity, and long-term climate stability, resulting in major latitudinal gradients in diversity (Figure 3-2).

These are general trends in the distribution of life on Earth, but there is growing evidence that the characteristic biodiversity in terrestrial, freshwater, and marine ecosystems not only fluctuates but is changing relative to the historical record (McRae et al. 2017). Many changes can be related to variations in climate, with ice ages being the most dramatic on centennial to millennial time scales. On time scales relevant to humans today, phenomena such as El Niño are notable and drive significant year to year changes in biodiversity, typically in a see-saw pattern moving from one characteristic state to another.

Increasingly, humans are changing or adding to the drivers behind biodiversity. For example, anthropogenic climate impacts may be changing the see-saw patterns in biodiversity mentioned above, and a warmer world may be driving 1) larger swings in natural climate variations, 2) new phenomena, or 3) stepwise changes in ecosystems (Chavez et al. 2017). Anthropogenic impacts and drivers also directly modify natural land or seascapes (agriculture and other land-use activities, fisheries, etc.), leading to changes in "provisioning" services of ecosystems. For example, as native species are replaced with new mixtures of organisms planted for agricultural or aquaculture purposes, there may be an increase in "provisioning" services, but a decrease in species diversity. Human activities also result in an increasing number of introduced, and perhaps invasive, species that change the biotic environment in addition to having a direct effect on overall biodiversity. Often there are many consequences from these perturbations on biodiversity and their services that are less obvious or immediately apparent.

# 2. CURRENT STATE OF KNOWLEDGE

## Historical Drivers of Patterns of Biodiversity and Change

The geographic biodiversity patterns observed today (Figure 3-2) are maintained via interactions of a wide suite of physical, chemical, and biotic drivers (Table 3-1) that operate at different temporal and spatial scales (Chapter 5). Some of the critical processes responsible for year-to-year changes in biodiversity patterns are climate variability and change, as well as human movement and disturbance and their interactions (IPBES 2019). Climate variability is defined here as those variations relative to the mean as determined from historical records where anthropogenic forcing was limited. Climate change is related to variations that can be associated with anthropogenic forcing. These two modes are difficult to separate today and for the purposes of this report are treated together.

The ocean and atmosphere are two intimately related fluids that form the most important components of a large heat engine that determines the fluctuations in our climate. Because of its heat capacity, climate variations are best resolved by measuring the ocean and its impact on atmospheric pressure systems. Variations in climate are typically measured by changes in temperature, atmospheric pressure, sea level, and precipitation. Multiple modes of interannual to multidecadal climate variability have been identified from the recent instrumental record (100+ years) and centennial to millennial proxy time series (e.g., marine sediments, ice cores, tree rings). These are described briefly below. Predictions of these variations are improving but significant work remains; in particular, on how to predict changes in biodiversity. Given that this report looks 25 years forward, the focus is on variation trends with periods of centuries, while noting longer term phenomena.

The interannual (every 3–7 years) El Niño Southern Oscillation (ENSO) phenomenon explains the greatest proportion of variance in the marine instrumental record (Messie and Chavez 2011). Peruvian fishermen coined the term El Niño because the unusual ocean warming appeared around Christmas. Its influence on the global atmosphere has been well documented (Rasmusson and Wallace 1983). Walker (1924) described the Southern

Oscillation (SO) as "when there is high pressure over the south Pacific there is low pressure over the Indian Ocean." Today the SO is measured as the difference in barometric pressure between Tahiti and Darwin, Australia and El Niño as the sea surface temperature (SST) anomaly in the central equatorial Pacific. These measures are used for seasonal weather prediction globally. The strongest drivers of change in biodiversity for ENSO are precipitation and temperature for terrestrial environments (Rasmusson and Wallace 1983). In marine environments, there are significant changes in the productivity of ecosystems and dramatic redistributions of highly migratory species. The impacts are related to changing physical conditions (sea level, depth of the thermocline) impacting nutrient ($NO_3$, $PO_4$) supply and phytoplankton production (Barber and Chavez 1983).

The second mode of global ocean temperature variability is the Atlantic Meridional Oscillation (AMO), which has a 50+ year periodicity. It has only recently been recognized given that our instrumental record is just over a century, but clear impacts on biodiversity are now being documented. The third mode of climate variability is the Pacific Decadal Oscillation (PDO). It is also aperiodic, with a cool or a warm phase lasting 20–40 years. PDO influence on marine environments, where it was first discovered, is most notable in the abundance and distribution of fish (Mantua et al. 1997; Chavez et al. 2003). It is also well recognized in the annual rings of long-lived trees. A new phenomenon, the North Pacific Gyre Oscillation (NPGO), has recently been identified because its variations have increased in amplitude. It has been linked to recent marine heatwaves originating in the Alaska Gyre (nicknamed "the blob"). Recent marine heatwaves are becoming associated with anthropogenic influences on the climate system and appear to be increasing in frequency. We only have a cursory understanding of how these variations impact biodiversity, but the few available observations indicate they are substantial.

Glacial to interglacial cycles are major centennial to millennial climate variations. Ice ages show dramatic changes in temperature, atmospheric carbon dioxide, and in biodiversity. Dramatic changes in diversity have been recorded in deep-sea sediments (Gutierrez et al. 2009). Polar regions expand and contract notably, with shifts in high- and low-pressure systems and substantial differences noted during glacial periods than those observed today. During warm or interglacial conditions, tropical regions expand and polar regions shrink, and biodiversity responds accordingly, with tropical species expanding toward the poles. The inverse happens during the cool ice ages. Following patterns for glacial to interglacial transitions, the observed present day century-scale warming has been accompanied by expansion of tropical and temperate species poleward (Chavez et al. 2017). Global warming has already led to abrupt and unpredictable changes in the ecosystem state, dramatically impacting biodiversity. This is the case in many tropical, shallow-water coral reefs, but also various Arctic habitats. The geological record contains several examples of abrupt biodiversity changes on Earth; for example, the demise of the dinosaurs, which is attributed to the impact of a large meteor, comet, or asteroid. There is concern the steady global warming we are experiencing today may lead to unpredictable, large, sudden shifts in biodiversity.

## Anthropogenic Drivers of Recent Biodiversity Change

The environmental factors that set the stage for the evolution and ecological organization of global biodiversity patterns only partially account for the current changes in biodiversity and the ongoing rapid loss of biodiversity. In the current era, human activities are the primary drivers of change. Anthropogenic forces are currently modifying the drivers directly (e.g., habitat destruction, pollution, exploitation) or indirectly (via human-mediated changes in climate) resulting in rapid changes in biodiversity relative to the historical record (Chapter 4).

As established by the global and regional assessments of IPBES, recent losses of biodiversity have occurred at an unprecedented rate in human history and are largely a consequence of anthropogenic factors. Changes in land/sea use, direct exploitation of biodiversity, climate change, pollution, and invasive and alien species are considered the major drivers of this biodiversity loss (IPBES 2019). The human population has been growing globally, increasing 1.56 times since 1980, with implications for environmental degradation (IPBES 2019). The high human population densities in cities affect spatial patterns of land use, and consequently, diversity patterns. Changes in agricultural productivity through greater application of irrigation, fertilizers, and machinery associated with the Green Revolution have benefited food yields and national economies but have also drastically altered land use, along with biogeochemical cycling, and have contributed to biodiversity loss. Currently, more than one-third of the world's land surface and approximately 75% of freshwater resources are devoted to agropastoral production. Grazing occurs on approximately 50% of agricultural lands and 70% of drylands. In the sea, industrial fishing has had an even greater impact on biodiversity than terrestrial agriculture (IPBES 2019). At least 55% of the oceans are fished by the 70,000+ reported industrial fishing vessels, including hotspots in the northeast Atlantic, northwest Pacific, and upwelling regions off South America and West Africa. Reductions in total forest cover during 1990 to 2015 totaled 290 million ha (~6%), due to the production of industrial roundwood and fuelwood, even as the areas of planted forests rose by 110 million ha.

We have a solid understanding of individual physical and chemical factors (natural and anthropogenic) associated with biodiversity patterns and changes in biodiversity in well-studied regions. However, there are major gaps in our understanding of how biodiversity is changing in many regions of the planet due to the sparse nature of observations that allow estimates of biodiversity in terrestrial and aquatic habitats. So, while the physical and chemical drivers are relatively well measured globally, the biotic drivers (such as species numbers, species interactions, dispersal, etc.) are poorly measured, even while they are understood reasonably well for many ecosystems in some regions, particularly temperate terrestrial environments in the northern hemisphere. Some biomes, including wet and dry tropical regions and the majority of the ocean, remain undersampled and understudied. Similarly, how natural and anthropogenic drivers interact to cause biodiversity change is poorly understood, and hence our ability to model and predict changes into the future is compromised. Large-scale perturbations (like the COVID-19 pandemic, atmospheric $CO_2$ increase, and ocean acidification) and major regional changes (landcover change in tropical regions, wildfire increases in regions experiencing increased drought) can be used to elucidate how drivers interact and improve model parameterizations.

## 3. WHAT IS NEEDED

A significant body of evidence and existing understanding of the basic tenets of biogeography point to the fundamental abiotic (physical and chemical) drivers of biodiversity. Global measurement of these drivers is well covered by remote sensing instruments and international programs (i.e., GOA-ON, $GO_2NE$, etc.). The biotic drivers—such as primary production, competition, predation, food web structure and dynamics, evolution, or speciation—are understood, in the sense that we know they occur and are important determinants of biodiversity. However, they have yet to be measured at the same spatial and temporal scales as the physical and chemical drivers. The same poor temporal and spatial coverage is true regarding biodiversity itself. In addition, biodiversity observations from space suffer from poor taxonomic resolution, as well as not being able to penetrate to depth in the ocean or through canopies or sediments in terrestrial systems.

NASA plays a fundamental role in measuring and modeling variables associated with weather and climate variability, longer-term change (precipitation, temperature, salinity, atmospheric carbon dioxide, etc.), as well as aspects of the biodiversity response (vegetation biomass, chlorophyll, phenology of traits, animal movement, etc.). However, while we have good understanding and measurement of the abiotic correlates and drivers of diversity, we have poor understanding of how these interact with each other and with anthropogenic drivers to determine biodiversity change. This means our current ability to predict or forecast biodiversity into the future is rudimentary.

New technologies to observe biodiversity—such as hyperspectral remote sensing and environmental DNA—have only started to allow for large-scale monitoring and assessments of the entire food web so that abiotic and biotic drivers can be more clearly elucidated. While new technologies provide a glimpse of how drivers and biodiversity interact, we have yet to gather sufficient data over the spatial and temporal scales needed to achieve predictive understanding. For marine environments, broad deployment of autonomous systems capable of measuring biodiversity will be required. In terrestrial systems, integration of remote sensing and *in situ* operations are essential. The following section discusses what the community needs over timeframes of 0–5, 5–10, and 10 years and beyond.

## Observations

### Today (0–5 years)

Continuing the long-term time series of observations from space relevant to biodiversity change and its biotic and abiotic drivers is critical; this time series started with the launch of the first Landsat in 1972. Routine observations of biodiversity and the factors that regulate the abundance and distribution of life on Earth are required to monitor and respond to the ongoing changes to the Earth system.

Space-based observations must be complemented with *in situ* observations of biodiversity and the abiotic environment, but additional *in situ* measurements that extend and validate those from space are urgently needed. Such expansion could take multiple paths, including: 1) developing partnerships with other organizations, 2) investing in process and field campaigns, and 3) developing autonomous collection systems. Continued and expanded partnerships with other U.S. and international agencies, academia, and the private sector will be required to fully document and understand how biodiversity is responding to climate variability and change. Terrestrial and marine biodiversity observation networks (BONs) are natural partners. In the U.S., multiple agencies are involved in biodiversity studies; for example, the National Ecological Observatory Network (NEON) is well poised to partner on drivers of terrestrial and aquatic biodiversity in North America.

Partnerships should include organizations involved in animal tagging or bio-logging, networks of camera traps and acoustic sensors, environmental DNA, citizen science (e.g., eBird, Breeding Bird Survey, iNaturalist), integration of data sources for species distribution and species population EBV development (e.g., Map of Life), as well as those managing and tracking the distribution and abundance of living resources. Animal/organism tags can also collect environmental data that can be used to interpret variation, identify drivers, and train models. Additionally, collection of this *in situ* information should be globally coordinated under the auspices of programs such as the Global Ocean Observing System (GOOS), Global Climate Observing System (GCOS), and Group on Earth Observations Biodiversity

Observation Network (GEON BON). Large biodiversity networks are in place for ground-based biodiversity research, including the Smithsonian's ForestGEO and MarineGEO and programs run by NatureServe, Conservation International, and WWF, among others. The NSF Rules of Life program, natural history collections aggregated through the Global Biodiversity Information Facility (GBIF), and Biology Integration Institutes are important partnerships for discovery and integration of biodiversity with spaceborne measurements.

Although remote sensing and *in situ* observations are critical, it is equally important to process these data into useful products. New and continued suites of high to medium resolution data products, from existing and upcoming mission data, akin to the existing MODIS/VIIRS products, will be needed. High to medium resolution (1 to 100 m) products that help characterize biodiversity drivers should be generated from existing Earth observation data—this is one of the largest gaps in terms of drivers of biodiversity on the terrestrial side. The current constellation of two Landsat and two Sentinel-2 sensors provides a huge opportunity for highly accurate 30-m data products, for example. Furthermore, the recent launch of Landsat 9 provides a great incentive to create such products, as do other current and likely future missions, such as ICESat-2, GEDI, NISAR, SBG, PACE, and more. Examples of products needed on the terrestrial side include 10 to 30 m land cover and use, snow, NDVI/EVI, vegetation continuous field, biomass, canopy height, surface topography, evapotranspiration, and burned area. Examples also include products from airborne instruments, such LVIS, G-LiHT, UAVSAR, AVIRIS-NG, and more. Algorithms, as well as missions to create these products, already exist (Jetz et al. 2019; Pinto-Ledezma and Cavender-Bares 2021). To ensure these products can easily flow to and be utilized by users, harmonized analysis-ready and application-ready data with uncertainties and recommendations on how to compare data is crucial.

## Tomorrow (5–10 years)

New concepts and approaches to observe aspects of biodiversity and its drivers from space are needed because a significant portion of Earth's biodiversity is not currently measurable from space (though some is inferable through instrumentation mounted on aircraft or boats). This includes biodiversity located where we cannot yet remotely sense (e.g., at depth in the ocean and in freshwater bodies, under forest canopies, in soils/ sediments) and organisms too small or mobile to be measured with current spaceborne capabilities. New concepts to observe these should be developed. For example, techniques like airborne and spaceborne Lidar scanning and SAR tomography can measure sub-canopy structure and volume, and multispectral data, particularly at high resolution (e.g., <1 m), can better discriminate species and provide information on traits that can relate biodiversity to drivers.

## Beyond (10+ years)

New approaches to characterizing biotic drivers of biodiversity that leverage remote sensing, but also take advantage of growing *in situ* capabilities, will be needed. Collection of *in situ* information using traditional human intensive and expensive methods will need to transition to one where autonomous systems make the required observations. There are currently only a few concerted efforts to develop and field multiple autonomous systems (AUVs, ASVs, UAVs, etc.) for the combined collection of environmental and biodiversity information. Continued support from NASA for the development of the platforms and required sensors will accelerate this transition. Determining the few, optimized sets of measurements that should be measured globally will require intensive process-oriented studies where land or ocean is observed at high spatial and temporal frequency using a wide variety of techniques/instrumentation.

As climate and land use change continue, radically different remote sensing approaches used to observe biodiversity changes in relation to driver variability will be of increasing need. Although environmental drivers of biodiversity are well measured globally, there are multiple components of biodiversity and its biotic drivers that we currently are not able to adequately measure by remote sensing. In the future, it might be possible to remotely sense DNA directly, for example. Evolving technologies (i.e., environmental DNA, autonomous systems, hyperspectral imaging, multispectral Lidars) will be required for integration with *in situ* biological information and predictive models to enable accurate interpretation.

## Modeling

Nested modeling capabilities that link biodiversity change to biotic and abiotic driver variability are needed now and into the foreseeable future. Models that incorporate basic ecosystem rules, developed from observations, at multiple temporal and spatial scales, are required so forecasts are available; predictive modeling of changes in biodiversity under a range of scenarios is recognized as an important frontier by GEO BON, IPBES, and the Convention on Biodiversity. Models that forecast changes in biodiversity based on scenarios of change require clear causal linkages between biodiversity and their abiotic and biotic drivers and can directly address monitoring needs within the post-2020 Global Biodiversity Framework (Hansen et al. 2020). Forecasts with iterative validation will provide information on important processes and mechanisms (Dietze et al. 2018). These, in combination with the advancement of species distribution models (SDMs, also called environmental niche models, ENM), which can be enhanced through the use of remotely sensed data products (Jetz et al. 2019; Randin et al. 2020; Pinto-Ledezma and Cavender-Bares 2021), will help understand biodiversity change. SDMs are correlative but have the capacity to accurately predict metrics of taxonomic, functional, and phylogenetic diversity, in addition to the distributions of individual species (Paz et al. 2020). Even with increasing capability of accurately detecting some groups of species (e.g., trees), SDMs will remain important in constraining which species are likely to occur in a region (Meireles et al. 2020) in combination with modeling of processes, mechanisms, and dynamics (Jetz et al. 2019).

Integration of *in situ* and remote sensing observations through species distribution models (SDMs) and other modeling approaches will contribute to biodiversity monitoring systems and inform scalable biodiversity change indicators for management programs and policy targets (Navarro et al. 2017; Jetz et al. 2019).

Some key areas where forecasts (and observations) are particularly important include:

- Expansion of tropical ecosystems as the Earth warms and tropical species shift their distribution poleward.
- Fluctuations in interannual to centennial variability, leading to more and greater boom and bust changes in marine and terrestrial communities.
- Human footprint, such as for agriculture and urban needs, especially as human populations increase, leading to a larger spatial footprint and greater food production.
- Sudden shifts in biodiversity abundance and composition as thresholds are reached by steady unidirectional changes (i.e., from temperature and habitat reduction). These are currently unpredictable but can be catastrophic and are of great concern.

## Research

Research with an evolutionary perspective is an area that needs additional emphasis because it is closely related to the drivers behind biological evolution. One pathway could be for NASA's Biological Diversity and Ecological Forecasting program elements to provide joint funding or undertake collaborative projects with the NSF Dimensions of Biodiversity program or the Biology Integration Institutes. NSF's Understanding the Rules of Life initiative, which has ties to models and forecasting, and its emphasis on AI would link well. Another useful research area lies in improving understanding of intra-annual drivers of biodiversity and their implications for biodiversity itself. This may have particular relevance for invasive species.

## 4. CONSIDERATIONS FOR NASA

Recommendations in this section follow items identified in the "What is Needed" section above. Some of these focus on continuing existing Earth observation measurements, partnering with other remote sensing agencies, existing *in situ* networks, and analyzing currently available remotely sensed data from spaceborne and airborne platforms. Others are focused on developing new concepts and partnerships, scaling existing airborne and *in situ* technology to spaceborne concepts and missions, or the implementation of new techniques, models, and spaceborne concepts.

- **Continue and enhance long-term time series of biodiversity change and biotic and abiotic drivers from space.** Routine observations from space provided by NASA, in partnership with other space agencies, should continue to support monitoring of biodiversity and the drivers of change in the abundance, composition, and distribution of life on Earth. Marine biodiversity observations are in particular need of enhancement.
- **Enhance collection of biotic and abiotic *in situ* information by investing in process and field campaigns and deploying autonomous *in situ* or animal tracking measurement systems.** *In situ* data coupled to remote sensing are necessary to: 1) develop and validate remote sensing algorithms and models, 2) improve understanding of the mechanisms by which physical, chemical, and biotic drivers interact to cause biodiversity change, including the importance of historical evolutionary and biogeographic processes in deep time as well as ongoing Earth system changes, 3) understand the mechanisms by which biodiversity influences ecosystem processes across scales, and 4) provide information for areas not currently accessible by remote sensing (i.e., the deep ocean, areas under canopies, etc.). Autonomous systems can contribute to the latter. Collaborations with those exploring space in search of life should be encouraged, given that similar methods are needed for remote and difficult to access regions on Earth.
- **Enhance and establish partnerships with other U.S. federal and state agencies, philanthropic organizations, and biodiversity observation networks.** To achieve this, NASA Biological Diversity and Ecological Forecasting programs should partner with other NASA programs, missions, and projects to develop analysis-ready data of biodiversity drivers. Examples include the National Ecological Observatory Network (NEON) developed by NSF, citizen science initiatives (e.g., eBird, Breeding Bird Survey, iNaturalist), Smithsonian ForestGEO

and MarineGEO, NatureServe, Global Ocean Observing System (GOOS), Global Climate Observing System (GCOS), Group on Earth Observations Biodiversity Observation Network (GEO BON), Global Biodiversity Information Facility (GBIF) and iDigBio, Map of Life, and NSF Biology Integration Institutes.

- **Enhance modeling capabilities that link biodiversity change to biotic and abiotic driver variability and generate forecasts.** This will require more nested modeling capability, where multiple models are linked, as well as empirical and mechanistic modeling approaches; mechanistic models that link environmental drivers to biodiversity change are particularly needed. NASA should partner with other U.S. and international agencies and the academic community to achieve these challenging modeling goals.
- **Produce high to medium resolution (1 to 100 m) analysis-ready data of biodiversity drivers from existing Earth observation data.** NASA is well-known for producing routine remote sensing products. NASA's Biological Diversity and Ecological Forecasting program elements should partner with existing NASA programs, missions, and projects, as well as other space agencies, to extend standard products to higher-resolution analysis-ready data of biodiversity drivers.
- **Encourage research with an evolutionary perspective that incorporates the tree of life, genetic, genomic, and metabolomic data (*omics, etc.), traits, and communities.** Static remote sensing information can be linked to paleo records to better understand and predict long term changes in biodiversity, but this will require partnerships with organizations (i.e., U.S. National Science Foundation) supporting evolutionary-focused research.
- **Promote new concepts and approaches to estimate biodiversity and its drivers that are not currently observable from space.** A lack of *in situ* data, especially in areas below forest canopies, at depth in the ocean and sediments, can limit the use of remote sensing data for understanding biodiversity change. Enhanced ground-based approaches for measuring physical, chemical drivers of biodiversity, as well as biodiversity itself, would dramatically increase our understanding of biodiversity change.
- **Improve *in situ* capabilities with multidimensional assessment of data gaps, new approaches, and a prioritization of measurements that maximize the biodiversity relevance of remote sensing data.** Availability of *in situ* data, particularly in some high biodiversity or remote areas like the open

ocean, is a limiting factor to monitoring biodiversity from space. Autonomous systems can help fill that gap, especially in marine systems. Determining the few, optimized sets of measurements that should be measured globally will require intensive process-oriented studies.

- **Explore radically different remote sensing approaches to observe biodiversity change in relation to driver variability.** A significant portion of the world's biodiversity is not currently measurable from space or aircraft, for example at depth in the ocean and in freshwater bodies, under forest canopies, or in soils/sediments. Examples of new approaches include techniques, such as spaceborne imaging Lidar scanning, SAR tomography, molecular sensors on autonomous systems, and animal-borne sensors (biologging). Hyperspectral sensors and high spatial resolution multispectral sensors (<1 m pixel spacing) are needed.

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4

# PEOPLE, BIODIVERSITY, AND ECOSYSTEM SERVICES

## *How do humans, biodiversity, and the environment affect each other?*

## Key Points

- People are part of the Earth system and inextricably linked to biodiversity-depending on and affecting it.
- Many decisions require monitoring and understanding 1) nature's benefits to people, 2) how people affect biodiversity, and 3) how and where benefits will change due to these effects.
- Satellite observations are essential to assessing the benefits that humans derive from nature and the effects of human activities on those benefits.
- While existing observational capacity is useful, particularly for land cover and land use change, substantial gaps in Earth observations remain for identifying human activities, vulnerabilities, and the relationships between biodiversity and ecosystem services.
- There are great potential benefits for fusing satellite observations with social science datasets that remain untapped.
- Readily available medium-resolution (10–30 m) Level 3 and 4 products (e.g., land use and land cover), would greatly facilitate assessments of human-environment interactions and have large societal benefits.
- The lack of coarse to medium resolution datasets of species distributions and other biodiversity metrics is a major limitation for research on human-environment interactions and for sustainable land management.
- NASA should expand the capabilities for integrating ecological and social variables.

- NASA should develop inter-agency partnerships (e.g., joint funding of research with NSF, partnership with USDA, USAID, etc.) to enable creation of new spatially explicit social datasets.
- NASA should foster formation of diverse and interdisciplinary teams to tackle research problems on human-environment interactions.

# 1. IMPORTANCE

Human actions are rapidly changing the environment, and changing environments, in turn, have major consequences for people, their cultures, well-being, and livelihoods, and ultimately for all of life on Earth. Two questions are thus inextricably linked: how do people affect biodiversity and what benefits do people derive from biodiversity? There is urgency to understand the feedback between humans and natural systems to make wise policy and management decisions affecting nature and people. People affect biodiversity and the environment positively, through conservation, restoration, rehabilitation, regeneration, and cultural practices, and negatively, through overuse, pollution, habitat conversion, climate change, and introduction of invasive species. Informing decisions about nature requires predictions of both types of effects. For example, demonstrating the effectiveness of human actions to restore and protect the environment can provide justification for more of such actions. Similarly, understanding how biodiversity benefits people allows prioritization of where to invest in nature-based solutions. More generally, the quantification of nature's contributions to people, and their importance relative to anthropogenic capitals, allows selection of management options for land- and seascapes that maximize benefits from ecosystem services while minimizing costs. Improving the accuracy of predictions, anticipating the consequences of policy and management decisions, and identifying where and when benefits of and impacts to biodiversity will occur will result in more sustainable development and more effective conservation, restoration, and management actions.

## Audience for Information about Human Effects on and Benefits from Biodiversity and the Environment

The audience in need of better information and measures of how humans are affecting and benefitting from biodiversity and the environment includes at least three decision-making groups. The first group includes those who take action: landowners deciding upon the use of their properties, managers of companies deciding where and how to invest, consumers deciding which goods to purchase, resource managers deciding how to manage public lands and environmental resources, indigenous and local communities that consider the preservation of nature and biodiversity as sacred and manage their lands accordingly, and conservation organizations and other NGOs deciding where to secure protected areas or restore habitat. The second group includes those who influence those who take action, including regulators and legislators who direct human actions either with restrictive regulations or with tax incentives and subsidies, and NGOs or other groups that work with landowners to change their management or provide easier access to information to guide management. The third group includes natural and social scientists who use and generate biodiversity data: natural scientists generally focus on the diversity of life and the environment and social scientists typically focus on the diversity of cultures, peoples, and social structures that are intricately linked to the diversity of other organisms and the environment. Increasingly, these two scientific disciplines are working together to improve understanding about the interaction between people, biodiversity, and the environment.

The user and beneficiary group for information on the relationships between people and nature is broader than that for biodiversity alone because it also includes audiences taking a more human-centric approach. For example, while status and trends of biodiversity are of strong interest to conservation organizations and environmental ministries, finance and business sectors are increasingly concerned about the risks posed to their investments and supply chains by degradation of the ecosystem services upon which they rely.

The extent to which biodiversity supports human well-being and livelihoods is of concern to national, tribal, and local governments, human development agencies, and multilateral development banks. Countries ranging from China to Costa Rica to the UK have conducted national ecosystem service assessments to guide their development planning (Mandle et al. 2019). The Natural Capital Declaration, a finance-led initiative resulting from the Rio+20 Summit in 2012, greatly helped to integrate natural capital considerations into loans and public and private equity (The Natural Capital Declaration 2012). The Natural Capital Protocol, following suit in 2016 for the rest of the private sector, provides a road map for companies to connect natural assets to their accounting and understand the risks and opportunities therein (Natural Capital Protocol). Now, the UN System of Environmental Economic Accounts (SEEA) has developed a set of Ecosystem Accounts that provide internationally accepted statistical standards for countries interested in evaluating ecosystem services and their contribution to the economy within their national accounting framework (United Nations). Multilateral development banks consider natural capital and/or ecosystem services in their performance standards and programs, such as the World Bank's WAVES program (Wealth Accounting and the Valuation of Ecosystem Services). This diverse set of decision makers obviously have a broad range of decision-support needs but could all benefit from a common set of information for measuring and modeling the state of nature and its benefits to people.

## The Need for Globally Available Trans-boundary Information

Government, private sector, and research efforts to better account for nature in decision-making are often limited by what information is readily available. Many of these efforts involve pilot- and case-studies that demonstrate what is possible and how beneficial certain actions can be, but case studies can only be generalized or repeated elsewhere if the necessary data to do so exist. There is a critical need for data on nature's benefits to people—including its contribution to financial or social returns—that have global coverage yet are of fine enough resolution to be locally relevant, as well as standardized, interoperable, and replicable. Several efforts NASA is already championing are valuable in this regard, including the development of data standards and common frameworks for developing data products for human-environment interactions. The Group on Earth Observations Biodiversity Observation Network (GEO BON) has frameworks, though not yet readily available data products, to characterize the state of biodiversity and nature's benefits. The Earth Observations for Ecosystem Accounts (EO4EA) initiative supporting the UN SEEA's Ecosystem Accounts is supporting development of "account-ready datasets" to facilitate national accounting that integrates human-environment interactions. NASA is uniquely positioned to meet the need for this type of information through its space assets (Appendix B), the research it conducts, and the scientific community it supports. In doing so, NASA can shed light on how humans are affecting their environment and biodiversity, and vice versa. This chapter provides an overview of how current NASA assets are already contributing to that goal and what is possible in the future.

# 2. CURRENT STATE OF KNOWLEDGE

## What We Know

### Human Benefits from Biodiversity and Ecosystems

Nature's benefits to people were articulated as "ecosystem services" in the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005). The Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services (IPBES) recently introduced the term "nature's contributions to people" to include a broader definition of the relationship between people and nature and to re-emphasize the importance of people in the equation (Pascual et al. 2017; Diaz et al. 2018). Nature's Contributions to People is inclusive of ecosystem services, and measurements should consider the ecological supply side, through assessment of the diversity and stocks of natural resources that perform specific functions, and the human demand side, through assessment of the needs, preferences, and vulnerabilities of different populations, so the flow of benefits is quantified for specific beneficiaries. The ecological supply of a given service is based on the structure and function of ecosystems and is an area where NASA data have been used and could continue to be improved. A new area of opportunity for NASA is to identify who exactly benefits from different ecosystem services and to highlight tradeoffs between those services. Enabling research on ecosystem service beneficiaries fosters the development of policy options, can provide information to address equity implications, and facilitates more sustainable and just outcomes of decisions.

Biodiversity is the underpinnings and a regulator of ecosystem processes but can also be thought of as an ecosystem service in itself, serving as an indicator of a variety of benefits that support human health and broad aspects of the economy (Mace et al. 2012). Identifying the relationship between biodiversity and other ecosystem services—especially the extent to which provisioning and regulating ecosystem services are supported by a greater diversity of species, genes, or ecosystems—is an important scientific question. A review of 530 studies found that species richness, abundance, and diversity are positively related to many services, including atmospheric regulation, pest regulation, and pollination (Harrison et al. 2014). Species abundance is particularly important for pest regulation, pollination, and recreation (especially when populations fall below functional densities), while species richness has positive effects on timber production and fisheries. Freshwater regulation, water purification, and water flow regulation are most frequently linked with ecosystem area, but also ecosystem structure and age. Similarly, the number of species utilized by local communities correlates with overall species richness. Higher levels of biodiversity may also increase the stability of ecosystem services through time (Chapter 6).

Situations where biodiversity negatively affects ecosystem services are rare, but part of the shift in the language from "ecosystem services" to "nature's contributions to people" was motivated by the recognition that nature can also affect people negatively. Examples include freshwater provisioning, where humans are often competing with natural communities for limited water resources, for human-wildlife interactions, such as livestock predation, and for wildfire risk. Increasing abundance or numbers of species deemed undesirable by people (e.g., invasive weedy plants, agricultural pests, harmful bacteria, parasites) can also be problematic, although species richness of plant and host species also provides some pest and disease control function (Ostfeld and Keesing 2012).

The effects of loss of biodiversity levels on ecosystem processes are often nonlinear (Cardinale et al. 2012). Measuring, monitoring, and modeling biodiversity, ecosystem services, human benefits, and the feedbacks between them are all essential to decision-support for sustainable development.

### Human Effects on Biodiversity and Ecosystems

Humans have altered patterns of biodiversity in many ways and for millennia. Among the more notable alterations in the modern age are the clearing of land for housing, agricultural, and mining practices, including clearing of tropical forests (IPBES 2019). Large animals have been greatly reduced in numbers by hunting and replaced with livestock, along with agriculture, to feed a growing human population. In aquatic systems, overfishing, excessive inputs (i.e., pollution), and dredging lead to parallel changes in the diversity of organisms, often linked to changes in terrestrial land use and increasing demands for aquatic resources. Humans are also modifying the environment that sustains life on Earth through greenhouse gasses and other pollution.

The feedback processes between biodiversity, humans, and climate are an important area of research, and one to which NASA has made crucial contributions, with the ultimate goal of long-term forecasting of ecosystem services. This includes the effects of fossil fuels and other pollutant inputs into the atmosphere, ocean, freshwater, and terrestrial systems causing major changes in weather, sea level, sea surface temperature, and sea chemistry, and into more subtle biogeochemical processes that affect biodiversity.

## What We Don’t Know

### Effects of Changing Biodiversity on Ecosystem Services

Some of the most fundamental research questions that remain open concern the relationships between biodiversity and ecosystem services, for different aspects of biodiversity, different ecosystem services, and at different scales. Field experiments of species richness and ecosystem functions, such as productivity or nutrient cycling, suggest that relationship is nonlinear (Chapter 5) (Tillman et al. 2014; Isbel et al. 2017). However, there is a need for a systematic mapping of the relationship between genetic, species, ecosystem, and functional diversity and the delivery of ecosystem services at landscape scales. Even with the increasing availability of hyperspectral data, which can map biodiversity and ecosystem function with better fidelity, our understanding is limited because most ecosystem services are modeled, not directly measured, and the models do not typically represent the service of interest as a function of biodiversity. However, the benefits of biodiversity to people, whether use is direct or indirect, depend in all likelihood on the condition of biodiversity and overall ecosystem functioning. Testing this assumption requires more empirical (not modeled) measurements of the benefits themselves at the point of use, such as water quality, flooded area extent, crop pollination and pest control and resulting crop production, nature visitation, harvest of wild plants and bushmeat, and fisheries.

Another open question is how much biodiversity is sufficient to sustain the natural processes underpinning human well-being. Declines in service provision may not always be immediately apparent if there is a threshold beyond which further biodiversity declines will lead to an abrupt loss in ecosystem service provision. In other words, how resilient are ecosystem services when biodiversity declines (Chapter 6)? Management decisions often aim to maintain the sustainable provision of several ecosystem services and to minimize trade-offs between them, especially when attempting to balance the long-term maintenance of biodiversity conflicts with short-term maximization of certain services, such as crop production, fish production, and the harvest of wild plants and meat.

## Effects of Humans on Biodiversity

A third major question is how different human actions affect biodiversity (Chapter 3). While specific human actions, such as land use change, can be mapped, the same actions often have different effects on biodiversity in different parts of the world. For example, in the western U.S., effects on birds of forest fragmentation caused by logging are much weaker than in the eastern U.S., most likely because western forests are naturally often fragmented, whereas eastern forests are not, so birds are not adapted to fragmentation there. Understanding changes in freshwater and marine biodiversity, and pinpointing causality due to human or natural causes, is also an exciting area for future research. For example, while overfishing is one of the greatest causes of ocean biodiversity decline, changes in coastal land use are likely just as important a contributor but include indirect effects that are difficult to quantify over time.

A final line of inquiry concerns how outcomes of human actions designed to limit biodiversity loss, as well as actions designed to safeguard ecosystem services, vary spatially. For example, the effectiveness of protected areas on land and in the ocean varies greatly depending on the species of concern, historical range of variability, broader landscape context, novelty of environmental conditions, and level of enforcement. This makes it difficult to assess the net gain due to protection or habitat restoration, and yet there is now a $25 billion USD annual domestic ecological restoration industry (BenDor et al. 2015). Over the past two decades, the USDA alone has spent >$4.2 billion on wetland restoration and protection. However, outcomes of restoration projects vary dramatically, and some fail, often due to incomplete ecosystem assessment (Zhao et al. 2016). Furthermore, restoration project success is typically assessed in terms of area planted, change in forest cover, or simply extent of protected area as in marine cases, without necessarily tracking biodiversity. More broadly, the effects of disturbance and protection alike on biodiversity are typically assessed via space-for-time substitution, occasionally via natural experiments. The inference that can be drawn from such assessments is weak; impact evaluations based on quasi-experimental approaches are stronger and are a great area of opportunity for NASA research programs (Butsic et al. 2017).

At present, a reliable, globally consistent process to define areas of conservation and mitigation, monitor biodiversity and ecosystem services derived from these areas, and assess human effects on biodiversity in these areas, is lacking but the necessary datasets and approaches are available to fill this gap.

## 3. WHAT IS NEEDED

To monitor human effects on nature and nature's benefits to people, it is necessary to observe the state of nature and patterns of human activities. Current observational capabilities are very valuable, but also insufficient.

### Observations

#### Today (0–5 years)

- **Biophysical information for modeling the "supply side" of ecosystem service and tracking environmental change.** Satellite observations are key to assessments of the benefits that humans derive from nature. While land-cover maps and NDVI continue to be the most-commonly used remote sensing data products, there is a much larger array of Earth observations that capture nature's benefits and human effects on nature (Appendix B). Numerous Earth observation products are used in ecosystem services models and many of the same products that delineate human use of or need for nature also provide estimates of the effects of human actions. For example, land cover maps, as well as coastal or marine habitat maps, form the basis for many ecosystems service models, with different model coefficients set for different land cover types, as well as estimates of habitat fragmentation, which has negative consequences for many animal and plant species. Digital elevation models (DEM) derived from radar, Lidar, or stereoscopic optical data are important inputs for hydrologic service models (water purification, erosion regulation, flood risk mitigation, etc.), with higher resolution products preferable for accurate routing of water through the watershed. DEMs are also important in species distribution models, which in turn feed into ecosystem service models and coastal inundation and erosion modeling. Remotely sensed climate data are inputs for many terrestrial and aquatic ecosystem service models, for example, precipitation to hydrologic models and temperature and precipitation to biomass production models, habitat suitability, and species distribution models. Soil moisture is an input to biomass production and some hydrologic models. Although currently these data are typically from modeled sources, such as ISRIC, active sensors such as SMAP could likely improve the accuracy of these models. It is also possible to predict biomass with regression models using MODIS, VIIRS, Landsat, or Lidar data as predictor variables (Avitabile et al. 2016; Baccini et al. 2017). Biomass is a stock indicating the important ecosystem service of carbon storage and sequestration for climate regulation, and, along with other satellite-derived metrics such as LAI, PAR, and GPP, provides a proxy for energy availability in food networks, making it a great predictor of species richness (Radeloff et al. 2019). Likewise, water quality, including Total Suspended Solids (TSS) and algal blooms, can be detected from hyperspectral imagery and assist in calibration or validation of hydrologic ecosystem service models (Hestir et al. 2015; Lymburner et al. 2016; Ho et al. 2019).

- **Social information on human activities and infrastructure.** To attribute environmental change to human impact, social data are needed to model the "demand side" of ecosystem services and to correlate with biophysical information. Satellite observations are essential to monitoring human activities. Such assessments, which include people affecting nature and people using nature, have improved greatly in the last decade. In terms of Landsat data analysis, "freeing" the USGS archive in 2008, the current constellation of two Landsat and two Sentinel-2 satellite that provide frequent 10–30 m observations, and commercial satellite imagery, combined with steep reductions in processing costs and cloud computing (including Google Earth Engine), has led to an explosion of new algorithms and datasets capturing how people affect nature. A great example is the 30-m data on global forest dynamics by the GLAD group at the University of Maryland, which captures forest loss annually at unprecedented spatial resolution (Forest Monitoring Designed for Action). Road network detection can map threats to wildlife populations and movement and can also be used to model potential future ecosystem change, but also access to nature by humans for cultural or provisioning services. Together, DEMs, land-use, river networks, and road networks can create "friction surfaces" used to model people's travel, providing a proxy for demand for, or accessibility of, place-based ecosystem services, such as gathering of plant or animal products and recreation (Weiss et al. 2018). Impervious surface maps serve as an input for many hydrologic models, especially those focused on flood risk mitigation and water regulation, and as a proxy for human disturbance affecting wildlife populations. High-resolution imagery processed with machine-learning neural networks can map each house across entire continents, which can then be combined with census-level population data to extrapolate population density at much finer resolution than previously possible (Facebook Connectivity Lab and Center for International Earth Science Information Network 2019). Nighttime lights can help map poverty, both globally and regionally, providing important proxies for substitutability for ecosystem services (Elvidge et al. 2009; Jean et al. 2016). Furthermore, population density and poverty mapping locate ecosystem service beneficiaries, and social media and other mobile data have great potential to differentiate between different types of beneficiaries. Satellite tracking of marine vessels and the Global Fishing Watch have been used to track fishing vessel activities and identify illegal poaching. Dynamic global satellite seascapes provide a biogeographic framework for understanding the marine food web and linkages to environmental factors.

## Tomorrow (5–10 years)

- **Detection of additional biophysical characteristics and functions.** This will improve understanding and tracking of ecosystem condition and biodiversity. Recently launched sensors, ongoing research, and planned missions will considerably advance the observational capacity to capture human-environmental interactions from 2021–2030. Whereas past observations have focused on plants, and mainly on one aspect of plants (i.e., greenness), new spectral imaging is capable of representing other aspects of plants *and* animals—a whole new picture of life on this planet. An exciting array of sensors are now on the space station, including ICARUS (terrestrial and marine animal movement), GEDI (vegetation height and structure), ECOSTRESS (temperature), OCO-3 (carbon), and DESIS (hyperspectral). Their data greatly improve assessments of human benefits from nature, and threats to it, especially when combined with large-scale ecological data networks. Looking ahead, the planned launch of NISAR, SBG, PACE, and geostationary satellites like GLIMR will provide hyperspectral imagery globally or over large areas and will revolutionize the mapping of biodiversity and of human-environment relationships. For example, with SBG, it will be possible to track the chemical composition of terrestrial plant tissue, including nitrogen (protein) concentration and fiber/lignin, which are determinants of forage quality for livestock grazing—the key ecosystem service of rangelands. Characterization of foliar functional traits will also enable assessment of biodiversity in managed grasslands, which offers an opportunity to alter livestock rotation to maximize diversity (e.g., as functional type composition changes during the course of the growing season). NISAR will improve estimates of forest structure and biomass. PACE, SBG, and GLIMR will provide information on phytoplankton functional groups and better ways to separate phytoplankton from colored dissolved organic matter and other suspended solids in freshwater bodies and in coastal and ocean waters across spatial and temporal scales spanning tens of meters to thousands of kilometers and minutes to years. A challenge for ecosystem service modeling will be to make use of these advances in information about ecosystem condition and biodiversity.

- **Enhanced spatial and temporal resolution of Earth observations.** This is needed to pinpoint human impacts and where and when nature matters most to people. A multitude of sensors will soon provide global satellite data with much better temporal and spatial resolution. Weekly or more frequent 30-m maps of the Earth's land cover and coastal water quality will become the norm in the near future. Surface reflectance datasets are also now available for near-daily global assessments of global land and ocean surfaces (e.g., USGS Landsat Analysis Ready Data (ARD), NASA's Global Harmonized Landsat Sentinel data, global NASA and Copernicus ocean color spectral data). These advances are due to the current constellation of Landsats (7 and 8), MODIS (Terra and Aqua), VIIRS (Suomi-NPP, JPSS-1), and Sentinels (2a and 2b, 3a and 3b). These assets will be complemented with the launch of Landsat 9 in 2021 and Sentinel 2c in 2023, in addition to PACE, SBG, GLIMR, and several other sensors, including DLR's EnMAP, ISS EMIT, and ESA's planned CHIME sensors. There has never been a similar wealth of medium-resolution (10–30 m) satellite data and this will result in another major leap forward in the types of datasets available to capture human impacts in the next decade. Similarly, GEDI Lidar data will spur a wealth of new studies on how humans affect vegetation structure, as will the growing archive of Sentinel-1 radar data and upcoming NISAR launch. These sensors can also provide additional inputs needed for ecosystem service modeling, such as coastal bathymetry constructed with ICESat-2 data, which could improve modeling storm risk reduction by coastal habitat.
- **Improved detection of human activity.** This will enable better representation of the range of ways that people benefit from and affect nature. An important source of information about human activity are night-time images of the Earth (Earth at Night National Aeronautics and Space Administration 2019). Astronauts have for decades marveled at the lights from cities as observed from orbit and have captured them in night-time photographs. The series of Operational Linescan System (OLS) on the Defense Meteorological Satellite Program (DMSP) have provided such data since 1972. A low-light sensor was also included on the

Visible Infrared Imaging Radiometer Suite (VIIRS). The VIIRS Day/Night Band (DNB) can detect very faint light sources, such as from small fires, highway lamps, and individual fishing boats. The future operational VIIRS includes these capabilities and will provide a continuing time series that can help evaluate global human energy use and other activities. These images show how humans have aggregated over time in urban and rural areas, how human settlements are related to the physical geography of the Earth, where commercial and illegal fishing may be occurring, changes in use of energy during emergencies, and socio-economic differences among countries and between cities and rural areas.

- **Creative use of novel datasets.** There is currently a gap between what is observable from remote-sensing and the socio-economic endpoints that matter to people. Assessments of human benefits from biodiversity, and effects of human activities on nature, could greatly benefit from data fusion of biophysical and socio-economic data from ground-based and remotely sensed sources. Many of the key pieces of information needed to characterize or understand human effects on ecosystems, vulnerability of humans and ecosystems, and demand for ecosystem services (e.g., household income source, diet, land tenure, and demographic variables like age, race, and health status) are often available only at coarse administrative scales (U.S. Agency for International Development). These need to be disaggregated to link socio-economic conditions to ecosystem flows at landscape scales, where they occur. Linking to household survey datasets, such as the World Bank's Demographic and Health Surveys (DHS), offers great promise in developing predictive relationships with Earth observations (e.g., Naidoo et al. 2019). Relating such socio-economic variables to different Earth observation products (e.g., night-lights, impervious surfaces, vegetation trends and variability, methane emissions, etc.) through a variety of statistical approaches could provide downscaled estimates that would then have to be ground-truthed. These downscaled estimates have the potential to enhance understanding of how environmental variables are influencing socio-economic variables too. A growing human population will be even more dependent on marine organisms. Enhanced acoustic measurement techniques will enhance our understanding of anthropogenic marine use on species and ecosystems (Estes et al. 2021).
- **New analytical approaches.** These are needed to integrate and make sense of an increasing amount of data emerging from different sources. As improved satellite imagery becomes available, expanding the capacity of current machine-learning approaches for identifying human settlements (e.g., individual houses and other built infrastructure mapped from imagery at 1 m or higher resolution;

CIESEN 2016) and spatially disaggregating poverty is a much needed next step (Jean et al. 2016). These promising approaches need to be scaled up from the 20–30 countries currently mapped to global maps, and such approaches should be automated so products can be made available annually, as is necessary for LULC products, including agricultural crops. Machine-learning methods that map individual dwellings within human settlements could also detect roads, dams, and other infrastructure, either from Lidar or increasingly high-resolution satellite imagery, to determine infrastructures effects on biodiversity and demand for ecosystem services (Weil 2018; Nachmany and Alemohammad 2019; Swan and Griffin 2019). Furthermore, detecting transboundary water transfers via combinations of gravity-based measurements (e.g., Grace FO), radar, and commercial high spatial resolution imagery will improve modeling of beneficiaries of freshwater ecosystem services.

## Beyond (10+ years)

Many future missions in the planning stage will greatly advance observational capabilities of the human condition and relation to ecosystem services. However, many important socio-economic and related ecological questions cannot be sufficiently answered with current and upcoming technologies and data products (**Box 4-1**). There remains an urgent need for new data products, technologies, sensors, and missions to capture human benefits from, and threats to, nature and society at the level necessary for decision-making and to enable sustainable development.

- **Higher resolution derived products.** One key need are data products akin to what is available from MODIS/VIIRS, but at 10–30 m resolution. While MODIS/VIIRS datasets are excellent for global- and continental-scale analyses, their resolution is far too coarse to be relevant for most land management, water quality, aquatic resource management, and conservation decisions. Technologically, many land cover, freshwater, and coastal 10–30 m data products are feasible today. Indeed, the USGS has started to generate some Analysis Ready Data (ARD) products (United States Geological Survey). However, the list of available products remains short, what is provided is largely opportunistic, and products are only available for the United States. A global ARD reflectance product, as a first step, followed by high-level products capturing vegetation indices, water quality indices, land cover, phenology of land and aquatic areas, land surface temperature, burned area, and snow, among others, would be game-changing for assessments of the benefits nature provides for people and of people’s effects on nature, and subsequent social and economic impacts.

- **Coastal habitat mapping.** For coastal habitats, most products are currently limited to land-imaging sensors (Landsat and S2), which are not designed to well-resolve coastal processes spectrally, radiometrically, or temporally. Future missions should advance sensor technology for the coastal zone. SBG is a promising start, but needs to be expanded. Partnership between NASA, USGS, NOAA, and other national and international agencies focused on such efforts could lead to such an array of products, on land and in the ocean.
- **Standardized biodiversity datasets.** Similar to the need for medium-resolution Earth observation data products is the need for consistent, medium-resolution, regularly updated biodiversity maps, such as species distributions, especially of species of conservation concern, and measures of alpha, beta, and functional diversity. A major reason why the form of the relationship of biodiversity and ecosystem services and of human effects on biodiversity remains an open question is the lack of such biodiversity data products. While there are notable efforts to collect biodiversity observations (GBIF, OBIS), assess species ranges (IUCN), and predict biodiversity (Map of Life, Aquamaps, etc.), none currently provide wall-to-wall, standardized biodiversity data that are easily accessible and adequate to predict ecosystem services or the effects of human actions on biodiversity. Initiatives such as GEO BON are designed to develop datasets that capture the Essential Biodiversity Variables (EBVs), but it is not clear such datasets will become available. We emphasize the urgent need for standardized biodiversity datasets to provide the link between satellite observations and indicators of biodiversity status and trends, such as for the EBVs and related Essential Ecosystem Service Variables (EESVs), which remains unmet.
- **Tracking animal movements.** Estimates of grazing benefits and of overgrazing effects, for example, would be much improved if it was possible to see where livestock is located. Airborne FLIR can detect livestock easily, and it would be very exciting if a spaceborne FLIR mission could provide this information globally. In addition to livestock estimates, spaceborne FLIR would allow researchers to track migrations of large herbivores (e.g., caribou, pronghorn antelope, wildebeest) and capture how they adapt their migration routes to human infrastructure and disturbance. ICARUS, which is currently deployed on the ISS, offers exciting opportunities to track animals fitted with transmitters. However, due to the ISS orbit, ICARUS does not provide global coverage; a polar-orbiting successor mission would be highly valuable. Missions like ICARUS will become exponentially more valuable as transmitters become cheaper and lighter and are deployed

using open and interoperable data strategies compatible for aquatic (freshwater, marine) and land operations.

- **Near real-time monitoring of vegetation and disturbance.** Instruments currently deployed on the ISS (e.g., GEDI, DESIS, OCO-3, ECOSTRESS), provide important pathfinder datasets for studying and monitoring global vegetation structure and health. NASA should plan for successor missions that provide truly integrated global data products to help monitor global trends in upcoming decades and at temporal resolution sufficient to detect disturbances and evaluate uncertainties. Disturbances (e.g., fires, floods, pollutant discharge events) pose threats to people and to continued provision of ecosystem services. Current technology is able to capture active fires daily; however, many fires start after the MODIS and VIIRS active fire sensors' morning overpass times, and are therefore missed. High-resolution geostationary satellites, or constellations of low-cost sensors in lower orbits, could enable continuous monitoring of fire and capture fire spread in near-real time, which would benefit fire science, enhance understanding of the relationships between vegetation structure or health and fire likelihood, improve models of fire spread, and be highly valuable for firefighting.
- **Tracking human activity at high resolution.** This information is essential for informing and monitoring management decisions. Knowing where each human dwelling is located on the planet is technically feasible and would be highly beneficial to assessments of human effects on biodiversity given that residential land uses reduce availability of habitat, often introduce light and noise pollution as well as invasive species, and frequently result in human-wildlife conflicts. The location of human dwellings also provides important indicators of benefits from nature, in terms of access to green space, reliance on wild foods and other gathered products, or vulnerability to—and protection from—natural hazards. Technology already exists to map each housing footprint from high-resolution satellite imagery and convolutional neural networks (CNNs), and has been successfully demonstrated for the U.S., Canada, Australia, and East Africa, but there is a need to regularly update these maps for the U.S., and to map housing footprints globally (Microsoft Building Footprints: AI Assisted Mapping 2021). High-resolution satellite data also offer exciting opportunities to map microstructures in agricultural landscapes, such as fruit trees in agroforestry systems, hedgerows that reduce wind erosion and provide habitat for beneficial insects, terracing to reduce soil erosion, and a host of other best-management practices that regulate the flow of ecosystem services to and from agriculture.

High temporal and spatial imagery designed to measure the small changes in light reflected and absorbed in freshwater, coastal, and marine areas provides information critical for water, food, recreation, and other human needs. However, the algorithms to routinely map these phenomena and processes for large areas are lacking, as is an acquisition plan for freely available, high-resolution global satellite data. Current NASA data buys are an important step in this direction.

- **Novel integration of satellite with other big data.** There is a large, mostly untapped potential in the fusion of satellite data with social media datasets, especially in terms of cultural and social values for nature (Schwartz et al. 2019). Many consumer datasets provide valuable information about socio-economic status and behavior. Many of the intangible values of nature have historically been difficult to model and track, but with mood and sentiments increasingly being recorded on social media, along with cellular data tracking human movement, it is possible to connect these psychological and emotional aspects of human well-being with quality and quantity of nature exposure. Mental health depends on access to nature, but the small sample sizes of formal experiments has precluded the development of a dose-response relationship (Frumkin et al. 2017; Bratman et al. 2019). However, such research could be conducted for entire populations using Google Maps or other location-tracking apps and social media, such as Twitter and Facebook. Another example is that consumer purchasing patterns are already traded between companies to develop models with a high degree of accuracy of health conditions diagnosis (Duhigg 2012). If this information was combined with other ecosystem service supply and demand data and tracked over time, new models could be developed relating physical health with a variety of ecosystem services. However, this will require new partnerships with companies and addressing privacy concerns before fully exploring the potential uses of such data. Ultimately, there is great potential to use location and consumer data to better relationships between nature and people; not in aggregate, but in the way nature is experienced by each person. The UN "Global Pulse" group is making progress working with data providers to share and learn from the "data exhaust" left by individuals moving through a digital world (Big Data for Development and Humanitarian Action).

**Box 4-1:** Questions about human benefits from and impacts on nature across a range of sectors can guide future NASA missions and technologies.

**AGRICULTURE/AQUACULTURE**
- What are the yields?
- Which species are grown where (near real-time)?
- What are the inputs (fertilizer, herbicides, irrigation, etc.) used for agriculture and aquaculture?
- Where is soil degraded (erosion, compaction, salinization, etc.)?
- Where is water degraded?

**FORESTRY**
- Which human activities are leading to deforestation?
- What is current tree species composition and how is it changing?
- Where are non-native trees either invading or being planted?
- Which trees are stressed or dead?
- Are current rates of harvest sustainable?

**WILDLIFE (AQUATIC AND TERRESTRIAL)**
- Where does poaching occur?
- Where are migratory herds and birds each day?
- What is the status of insect populations?
- What is the status of aquatic invertebrates?
- When and where are anadromous fishes migrating?

**FISHERIES**
- Where are illegal fishing vessels?
- What is the status of important nursery habitat?
- Where and when do fish migrate?

**RANGELANDS**
- Where is grazing livestock and when (diurnally, annually)?
- What is the potential productivity and carrying capacity for grazing?
- Which areas are overgrazed?

**NON-MATERIAL USE OF "NATURAL" SYSTEMS**
- Where are people visiting nature?
- Where are sacred sites?

**EXTRACTIVES AND INFRASTRUCTURE**
- What is the extent of pollution and erosion due to mining?
- What are the short- and long-term impacts of generation and use of energy (green or gray)?
- Where is water going? Who is dependent on water-related ecosystem services from distant watersheds?
- Where is each dam on the planet (especially small ones) and what are their water-storage capacities?
- Where are all the roads on the planet? Where are roads currently (near-real time) being constructed?

**SETTLEMENTS/URBANIZATION**
- Where is each dwelling on the planet and how densely are they arranged?
- What building construction materials are used?
- Where are the poorest and most vulnerable people?
- Where are extreme urban heat islands degrading quality of life?

**MULTIPLE USE**
- What are the impacts of multiple uses of an area (fishing, energy, recreation, discharge, etc.)?

## Analytical Capabilities to Utilize Satellite Observations

The current analytical capability and approaches to utilize Earth observation products in ecosystem service modeling varies depending on the services in question but tends to fall into one of three broad categories: as inputs to complex process-based models, as predictor variables in regression or machine-learning models, or as proxies for related but more complex underlying trends that so far cannot be modeled directly.

- **Inputs to process-based models.** Many physical variables described in Section 3 (e.g., LULC, soil, slope, and climate, especially for hydrologic models) already fall into this category. However, major improvements could be made when modeling the ecological production of ecosystem services by integrating Earth observations for species and ecosystem level diversity, structure, and function. To make the best use of these Earth observation products, modeling approaches for ecosystem services will need to be adapted to new inputs. The extent to which such Earth observation products can be integrated into process-based ecosystem service models should make them more accurate, easier to run operationally, and better at capturing subtle changes in ecosystem condition resulting from management (Ramirez-Reyes et al. 2019). Almost all current terrestrial ecosystem service models incorporate land cover but could be made more responsive to different characteristics, such as phenological, compositional, and structural diversity of ecosystems. Because diversity affects ecosystem function, it also influences ecosystems' capability to provide services. For example, seasonal variability in productivity or photosynthetic cover determines the retention capacity of vegetation to trap sediment and prevent erosion, and phenological diversity of the natural vegetation surrounding farmland determines the flowering resources available to pollinators and hence their contribution to crop yields (Galbraith et al. 2015; Borrelli et al. 2017; Pechanec et al. 2018). Similarly, monsoonal cycles and seasonal rainfall patterns drive freshwater discharges into coastal areas that affect water quality, create harmful algal blooms, and provide a fertile environment for coral disease (Shore et al. 2019).
- **Predictor variables in empirical models.** Direct detection of ecosystem service supply, such as biomass or water quality, and certain aspects of demand can be represented by fitting models to satellites or airborne observations combined with on-the-ground or field-based data to calibrate and validate model output (Baccini et al. 2017; Forest Monitoring Designed for Action). Ultimately, it is necessary to capture the mechanistic links between proximate drivers (e.g., land use change, uses of ocean spaces including fishing, mining, energy, or recreation,

and broad-scale factors, such as climate change, changes in the range of species, and species introductions) and specific aspects of biodiversity and ecosystem services when modeling human effects and dependencies on biodiversity (Chapter 3). Future human effects or dependencies on biodiversity and the environment can sometimes be assessed through extrapolations of past trends, applications of regression-type relationships in current dataset to output from models (e.g., climate change, human demographics), or scenario modeling. However, to make this information more decision-relevant, much more work is needed to reveal mechanistic links between underlying drivers (e.g., agricultural subsidies, carbon tax, trade) and proximate drivers that affect biodiversity and ecosystem services. Theoretical advances are needed to predict trends in future and underlying drivers and to link this to different scenarios of change in decision-support and ecological forecasting (Chapter 7).

- **Proxies for complex processes.** In many cases, relatively easy-to-measure proxies are used to predict hard-to-measure processes. For example, population density or road access are proxies for ecosystem service demand, vulnerability, or dependency on nature. These proxies also capture pressure or threat to ecosystems, and in this case, satellite products are often combined with government census or point-based data on demographics or costs if economic valuation is desired. Overall, the demand side of ecosystem service modeling is not as fully developed as the supply side and more theory is needed to develop better demand-side models that make use of the available data on human activities (Rieb et al. 2017).

## Capacity Building

Despite a few shining examples that push the research frontiers of how to utilize Earth observations to improve understanding of human benefits, the vast majority of ecosystem service modeling at present does not utilize the full range of available Earth observation products. In 2018–2019, NASA funded a series of workshops to improve use of Earth observations in ecosystem service assessments, bringing together 50+ experts in remote sensing and ecosystem services modeling (Ramirez-Reyes et al. 2019). Representatives from some of the most widely used decision-support tools (InVEST, ARIES, Co$ting Nature) participated, highlighting the challenges, including awareness, processing, and accessibility, ecosystem service researchers and practitioners face in advancing their use of satellite data. Beyond these technical capacity limitations, which could be overcome through expansion of the types of training that NASA supports, it is apparent more opportunities for community interaction and co-learning are also needed.

- **Creating awareness.** Ecosystem services analysts typically have little to no training using Earth observation products and thus have limited awareness of the range of available products or the ability to differentiate among them. Discoverability of new datasets is an ongoing issue (Appendix B). Satellite data products developed for research but not archived in public and easy-to-find repositories are overlooked by ecosystem service analysts.
- **Lifting barriers on computation or data processing.** Ecosystem service assessment models generally demand data that have high temporal frequency and spatial resolution and broad extents, but such datasets tend to be large. In the past, this has required high-speed internet connectivity as well as specialized hardware and software resources, many of which are unavailable to practitioners. As cloud computing becomes more widespread, this barrier can be expected to be somewhat lifted (Earthdata Cloud Evolution, 2020). However, some processes are not available on the more user-friendly cloud computing systems (e.g., hydrological routing is not possible on Google Earth Engine), and setting up virtual machines with all the necessary dependencies to run ecosystem service models requires advanced computing skills. Combining different types of data also presents challenges. For example, modeling how people affect biodiversity requires information on demographics, economics, land use development, and patterns of migration, and socio-economic datasets are often reported for administrative districts—spatial units that are not well aligned with raster datasets on biodiversity and its drivers.
- **Increasing accessibility of data.** Even when ecosystem service analysts can identify and process the satellite data of interest, they may be unable to access it. While some common satellite products, including those from MODIS, Landsat, and Sentinel, are freely accessible, high-resolution data are costly. The development of 10–30 m resolution terrestrial data products, available from a central repository such as the Land Processes Distributed Active Archive Center (LP DAAC), would go a long way to remedying this.
- **Community interactions to build networks of support or communities of practice.** This would allow practitioners to know whom to turn to for advice or input on a project decision or data selection. Inclusion of graduate students, early career researchers, and international perspectives will strengthen and grow collaborations and the research community. Through collaborative workshops, pilot projects, and eventually full proposals, the ecosystem services community would understand limitations (e.g., this data set is not fit for that purpose) and opportunities (e.g., these data would make a good input to an improved model)

for Earth observations. Transdisciplinarity should be promoted through community-engaged research to improve the relevance of satellite data. Such efforts provide opportunities to enhance the diversity of stakeholders engaged in this work by focusing on issues that are immediately affecting the communities and livelihoods of underrepresented groups. Such activities would also help identify areas of synergy for deeper integration and advancement, build stronger collaborations between scientists interested in mapping biodiversity with those studying human activities, and support developing methods for linking datasets across disciplinary divides. Similar capacity-building needs exist among the agencies and conservation organizations focused on human effects on nature. While some of the international conservation organizations have the in-house capacity to process satellite imagery, that capacity has limits, and most smaller conservation organizations lack it altogether. Similarly, some federal land management organizations in the U.S. have remote sensing centers, such as the U.S. Forest Service's Geospatial Technology and Applications Center, but such capacity is often lacking at the state level and below and in developing countries (hence the need for SERVIR). Existing data products are either too coarse to meet management needs (i.e., MODIS/VIIRS data) or difficult to access and process because datasets are scattered and differ in spatial and temporal resolution. None of these are new problems, and past efforts to build capacity in land management agencies and conservation organizations have been valuable and successful, but the need to build capacity still remains.

## Field Studies and Experiments

- **Supporting controlled experiments at larger scales.** The relationship between people, their environment, and biodiversity typically manifests over a range of temporal and spatial scales. This makes it challenging to conduct controlled experiments. In economics, there has been a trend toward more controlled experiments; for example, to measure the effectiveness of protected areas or payments for ecosystem services programs. A push for more controlled experiments could greatly strengthen scientific insight into human-environment relationships.
- **Taking advantage of "natural" experiments.** Much could be learned from opportunistic analyses of natural or unplanned experiments; that is, natural events or human actions that are not designed or controlled experiments but allow researchers to assess, for example, the effects of fires on vegetation or of war on land use. Global change is in many ways the grandest of all experiments,

although it is certainly not controlled, nor well replicated. Novel ecosystems and novel environments, ecosystems, or sets of environmental conditions that did not exist prior to human-caused global change provide rich opportunities to test hypotheses about the relationship of biodiversity and ecosystem services (Radeloff et al. 2015). Similarly, as humans affect ecosystems in ever-new ways, there is much to be learned about the mechanistic links between human actions and biodiversity. Natural experiments require unique analytical tools to conduct rigorous analysis because the "treatment" (i.e., human action, such as deforestation or urban growth) is never randomly applied. In econometrics and in impact analysis, a rich set of "quasi-experiment methods" (e.g., matching analyses, regression discontinuity analysis, difference in difference estimation, instrumental variables) has been developed (Butsic et al. 2017). These quasi-experimental methods are already widely used when quantifying causal mechanisms (Ferraro et al. 2015; Hanauer et al. 2015).

## 4. CONSIDERATIONS FOR NASA

NASA provides theoretical and engineering solutions to observing Earth, including humans and our activities. Incorporating Earth observations into models is important and leveraging detection of human activity with satellite data to improve models of socio-ecological systems is one area where NASA could make a major contribution to advancing the state of science and decision making. The following recommendations would greatly enable research on human-environment interactions that result in actionable, management-relevant information.

- **Expand capabilities for integrating ecological and social variables.** NASA's vision is "to discover and expand knowledge for the benefit of humanity" (NASA 2018 Strategic Plan). Expanding the extent to which Earth observation can represent social variables, or where existing social science datasets can be more fully integrated into NASA Biodiversity studies, are areas where NASA can make important contributions. There are many opportunities for building this into the Biological Diversity and Ecological Forecasting program elements. For the Biological Diversity program specifically, theory establishing the relationship between biodiversity and ecosystem services is needed, and satellite data are key to doing so over broad extents, beyond the plot scale of micro- or mesocosms typical for field experiments. There is much to be learned about mechanisms via which human actions affect individual species, communities, and the different dimensions of biodiversity. For the Ecological Forecasting program, applications projects could be focused on mapping and quantifying human effects and dependencies on biodiversity, developing decision support systems that integrate projections of likely change with scenarios of change resulting from different decisions and optimization or prioritization of resources use.

- **Provide new datasets to facilitate modeling human-environment interactions.** For the Biological Diversity and Ecological Forecasting programs, availability of a suite of Level 3 and 4 10–30 m resolution products akin to the MODIS/VIIRS products would fundamentally change how Landsat-like satellite data can be used. The value of global higher-level products, such as vegetation indices, land cover, deforestation, inland water indices, burned area, coastal sediments, snow cover, etc., at 10–30 m is evidenced by the widespread use of the few products currently available nationwide (e.g., the National Land Cover Dataset) or globally (e.g., global forest dynamics). Developing these datasets would benefit from close collaboration between NASA and the USGS, including its Landsat Science Team. Furthermore, only proxies for biodiversity, such as NDVI, are available globally. Global biodiversity maps derived from range maps are too coarse for management decisions and standardized maps based on species distribution models are not available for most species. Providing operational biodiversity datasets is a major task and needs to be the responsibility of federal agencies, such as NASA, USGS, NOAA, and FWS.
- **Form inter-agency partnerships to enable creation of new, or integration with existing, spatially explicit social datasets.** Understanding human-environment interactions requires the fusion of socio-economic and biodiversity data, satellite and *in situ*, produced by agencies and other organizations not accustomed to working together. Cooperation between public and private generators of data on human activity, employment, consumer behavior, location, demographics, vulnerability, and other characteristics are necessary to leverage the full potential of information. NASA can take a leadership role in convening different audiences with a common interest in improving the relationship between people and nature.
- **Foster the formation of diverse and interdisciplinary teams to tackle research problems on human-environment interactions.** NASA is second-to-none when it comes to building large teams of engineers and scientists working toward a shared goal. The importance of the benefits that nature provides to people and the risk that global change and another looming mass extinction entail, combined with the complexity of human-environment relationships across the planet, require highly diverse teams of social scientists, ecologists,

economists, and remote sensing specialists. The primary goal of such teams should be to integrate knowledge among different fields so pressing questions can be answered, rather than advancing any individual field—in other words, to focus on that which is important to society and the global biosphere instead of merely exploring interesting topics within a single discipline. In particular, NASA could increase the representation of local socio-cultural context by requiring participation of social scientists on project teams through targeted funding calls. The focus of much of this chapter has been on meeting the demand, apparent in many decision contexts and international fora, for standardization and replicability of data at global extents, which is a sweet spot for NASA and global satellite products. However, NASA data can also make great contributions to local studies of human-environment relationships that are too context-dependent to standardize, replicate, or scale up to the globe. Currently, cultural differences are handled fairly shallowly by ecosystem services modeling tools, and perspectives and values held by local communities are not easily described by an ecological production function. However, many of the biodiversity and ecological variables detected or modeled by satellites can provide useful information to complement more normative measures made by social scientists. NASA could engage such communities through funding calls directed toward social scientists to utilize satellite products in work on relational or cultural values of nature, similar to more general recent calls on the economic or health benefits of such information (Grants for Assessing the Benefits of Satellites [GABS]).

- **Create a new thematic area in "Human Benefits and Effects" within the Biological Diversity and Ecological Forecasting program elements and explore partnerships with other funding agencies to achieve joint objectives.** These suggestions could all be achieved through programmatic foundation building, in people and processes. One precedent for this is the NASA LCLUC program, which has a strong track record integrating social science and remote sensing. Similarly, the NASA Interdisciplinary Science Program has funded excellent science bridging disciplines, and IDS calls focused on human benefits from or effects on biodiversity would be an important first step. Another strategy could be a joint call with NSF's Dynamics of Integrated Socio-Environmental Systems (DISES) program, similar to the prior joint calls with NSF's Biocomplexity program that were highly successful and broadened the science community in the Biodiversity and Ecological Forecasting programs noticeably. However, teams funded by a research grant often dissolve at the conclusion of that grant. Interdisciplinary teams need time and opportunities for growth to learn about each other's disciplines, build institutional memory, and discover opportunities for deep integration. A larger institutional commitment within NASA to human-environment interaction research is necessary to fully realize the potential of NASA products to inform decision-making and improve outcomes for people and nature. Collaborative workshops or working groups provide the first opportunities for researchers to learn outside their disciplinary expertise, and together confront challenges, such as Earth observation limitations, model constraints, or stakeholder needs. A natural follow-on to such workshops is putting ideas developed in workshops into practice through small grants, allowing teams to explore new ideas and work together. Creating a pipeline of researchers through such preliminary steps would foster more competitive and truly translational proposals and projects in future grant-making activities.

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# 5

# SCALES OF BIODIVERSITY

## *How do processes occurring at different scales of space, time, and biological organization interact?*

## Key Points

- The issue of scale permeates the diverse biological entities and processes NASA seeks to understand, as well as the tools NASA uses to detect and model biodiversity.
- The multiscale nature of biodiversity requires solutions that can address cross-scale questions and identify and resolve cross-scale phenomena.
- Modeling of biodiversity will allow upscaling-downscaling between observable states. A high-resolution global reanalysis of biodiversity would provide solutions across many scales.
- Sustained multi-faceted investments will be needed to understand how processes occurring at different scales interact to produce observed biodiversity patterns.
- Discovering critical traits that affect biodiversity and their connections across scales is critical to preservation and responsible use of biodiversity resources.
- NASA should strengthen inter-agency and international partnerships, facilitate development of multiscale observation systems combining Earth observing satellites and *in situ* systems, and advance cooperative solutions for up/down scaling and modeling, data standards, and shared platforms.
- NASA should advance existing and develop new remote sensing techniques to meet the challenges facing biodiversity research and applications across micro- to macro-scales in space and time.
- NASA should invest in research that leverages effective data systems and new knowledge into decision making tools.

# 1. IMPORTANCE

The evolution of life on Earth has led to diverse biological entities characterized by variation among genes, species, populations, communities, and ecosystems. The interaction between these entities and abiotic factors across space and time scales increases their complexity and makes them a challenge to study. NASA, with its Earth Observation program, is well positioned to play an important role in biodiversity research. Because the NASA Biological Diversity and Ecological Forecasting programs aim to study and predict biodiversity phenomena on Earth, the effects of scaling on biodiversity have theoretical and practical significance, which leads to considerations for future experiments, missions, and sensor design. For the purposes of this chapter, major dimensions along which biodiversity scaling is relevant to the NASA Biological Diversity and Ecological Forecasting program are taxonomic/phylogenetic, functional, spatial, and temporal. The first two dimensions represent elements of biological scaling, while the last consider the physical spatial-temporal scales over which biodiversity is characterized and affected by a variety of processes. Aspects of biodiversity can be modeled bottom-up, adding the distributions of individual species; top-down, from remote sensing proxies; at a process-level, with models that use environmental drivers and covariates to predict biodiversity; or considering transfer between scales, with allometric approaches. Under any definition, biodiversity measures are statistical summaries, and as such are affected by the grain-size of their individual measurement, as well as the spatiotemporal scope of the whole observation set. Therefore, the issue of scale permeates the diverse biological entities and processes NASA seeks to understand, as well as the tools NASA uses to detect and model biodiversity.

Biological scaling is complex. Phylogenies and the taxa they organize scale hierarchically throughout the tree of life. The granularity of taxonomy is represented primarily by species aggregated together into phylogenetic categories, such as species, genera, families, orders, and domains. The phylogenetic biodiversity dimension can be used to construct biodiversity indexes that link to the spatiotemporal dimension. In this way, alpha, beta, and gamma biodiversity are used to characterize variations within sites/habitats, between sites, and over whole regions or ecosystems (Whittaker et al. 2001). Another dimension of biodiversity characterization is functional, which varies from genes and the molecular reactions they control, to physiological traits, populations, communities, food webs, and biomes. Rather than being hierarchical, the functional dimension of biodiversity can be characterized by complex interconnected networks, with each node representing a species or a guild of traits/species, while ecosystem processes represent connections between one or more nodes (Bascompte and Jordano 2007). A cross-cutting approach for biodiversity characterization is allometry, which intersects phylogenetic hierarchies and functional networks. Characteristics such as metabolic rate, life history, mortality, growth rate, and species diversity scale with factors like environmental temperature and organismal size (Brown et al. 2004).

Processes and patterns that shape biodiversity span vast spatiotemporal scales. For example, biodiversity spatial scales range 16 orders of magnitude, from genetic diversity within microbial communities ($10^{-9}$ m) to global ecosystems ($10^{6}$ m). Similarly, biodiversity time scales span over 20 orders of magnitude. At the high-resolution end, molecular processes, such as photosynthesis, operate and respond to environmental variation on scales as fast as picoseconds ($10^{-12}$ s). At the other extreme, Glacial-Interglacial Cycles that influence global climate, sea-level, ocean circulation, and evolutionary trajectories cycle at approximately 10 K to 10 M years ($10^{11-13}$ s). Different ecosystems and biomes may have different dominant spatial and temporal scales. Stommel diagrams help visualize this broad range in spatiotemporal scales along which different processes and organizational units vary (Haury et al. 1978). These spatiotemporal scale-process relationships could be applied to the units and processes that make up biodiversity, as well as to the biological and physical processes that drive them (Figure 5-1).

An additional scale-related challenge to measurement and modeling of biodiversity is matching the scale of the phenomena that are the targets of observation with the intrinsic scale of the measurement (Metzger et al. 2013; Anderson, 2018). Any observation has a characteristic resolution and extent that may only partially match and overlap with the characteristic scale of spatial autocorrelation of the biological components (Figures 5-1, 5-2, 5-3).

Multiple indices have been developed to quantify and monitor the current state of biodiversity at multiple scales and along different time and space dimensions to detect changes to biodiversity (Pereira et al. 2013; Jetz et al. 2016; Butchart et al. 2010). These biodiversity indices promote consistent global monitoring following common protocols, such as GEO BON (2017).

Biodiversity conservation targets must address the intrinsic value of biodiversity itself, the biological function that it enables, and the socio-cultural connections and implications for humans. Therefore, it may be important to consider biocentric and anthropocentric connections in identifying critical biodiversity nodes. Studying and managing at the “wrong” scales or without appropriately integrating across natural and social scales can lead to incorrect scientific conclusions and poor management decisions based on flawed predictions. Identifying key biodiversity nodes and their relevant scales will promote better decision-making and more strategic data collection (GEO BON 2017).

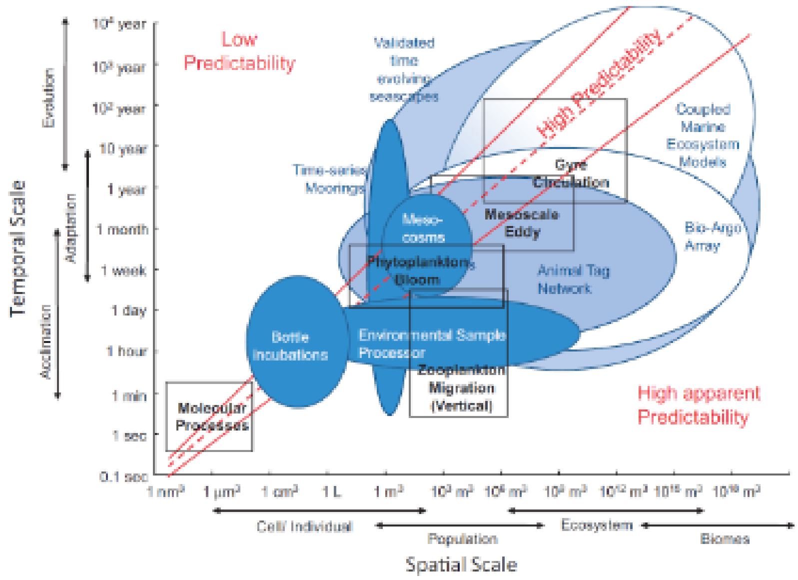




**Figure 5-1.** The temporal and spatial scales of marine biological processes (black rectangles), and the corresponding scales of experimental approaches (blue), observations (light blue), and models (white) that can detect and predict them. (Kavanaugh et al. 2016).

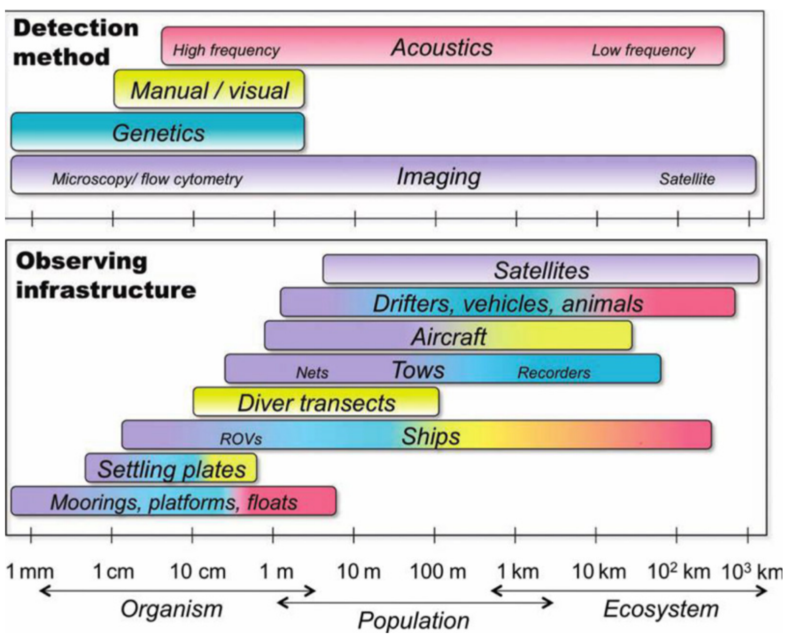




**Figure 5-2.** Observing infrastructure available for measurement of oceanic biological phenomena, their detection method (color key defined in upper panel), and their scale along an axis of biological functional organization. The color scale corresponds to an arbitrary scale of taxonomic resolution, with darker colors denoting increased taxonomic resolution (Duffy et al. 2013).

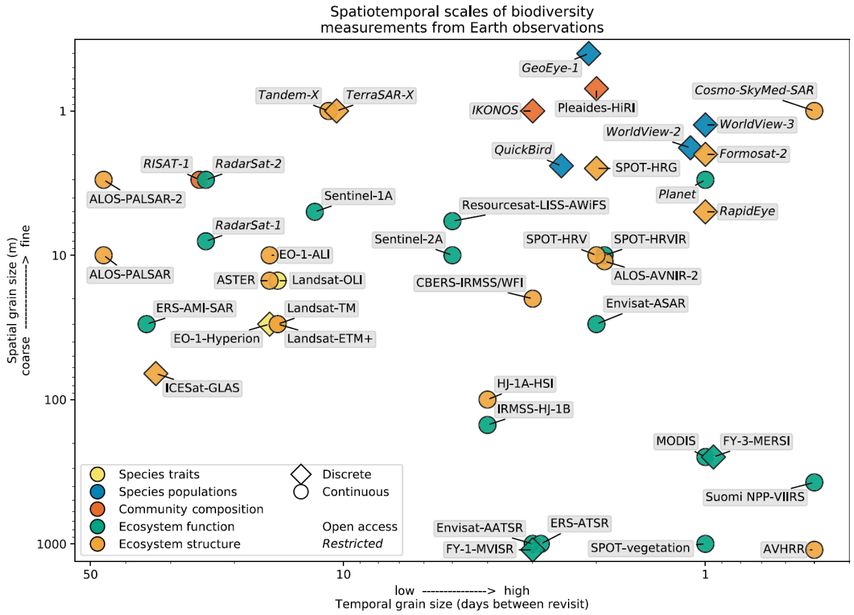


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**Figure 5-3.** Log–log plot of spatial and temporal grain sizes for current and historic satellite Earth observation sensors, colored by biodiversity pattern type. Several sensors have been used to measure multiple biodiversity patterns. The most cited or most novel were selected in these cases (Anderson 2018).

The resolution required for direct observations of biodiversity varies based on life form and biome. For example, species identification of tropical trees requires ~1-m resolution and high spectral resolution, which are close to being feasible today with the current airborne and satellite platform capabilities available through NASA and other agencies. However, this has not yet been demonstrated over large spatial domains or with regular return intervals.

Earth observations can be used to validate and improve models that predict biodiversity by characterizing the distribution or presence/absence of species and particular functional traits at particular locations. Key questions in the scaling of biodiversity are when and where this additive sum-of-the-parts approach breaks down in biologically meaningful ways. And, once such scale-dependent failures and the processes that cause them are identified, there is a need to understand how to address them through understanding/ theory without having to resort to computationally irreducible approaches (i.e., observe everything everywhere at infinite resolution).

# 2. CURRENT STATE OF KNOWLEDGE

## What We Know

The existence of allometric scaling relationships of size and function across diverse taxa suggest the existence of broad biodiversity scaling rules bounded by physical constraints (Brown et al. 2004). What mechanisms are behind these constraints is still a matter of debate, but they can be a useful starting point for biodiversity predictions and analysis. These analyses can be done along the different dimensions of diversity or combining multiple dimensions. NASA's Earth observation capabilities will be key in tracking Earth's biodiversity over time, identifying changes, and predicting biodiversity under future conditions (Zarnetske et al. 2019).

The phylogenetic dimension of biodiversity can currently be characterized to some limited degree by hyperspectral or multispectral observations. For example, some identification is possible at the species level, particularly in plants, corals, and macroalgae, as well as at aggregated taxonomic levels and/or functional types in plants and plankton (Hochberg et al. 2003; Sathyendranath et al. 2014; Schimel et al. 2015; Wang et al. 2018). Biodiversity models validated using ground-based observations use remotely sensed environmental conditions as predicting variables for species- and community-level phylogenetic biodiversity (Leitão and Santos 2019; Zarnetske et al. 2019). The functional dimension of biodiversity, metabolisms, food webs, and biomass distributions can also be observed by the spectral signatures of specific enzymes and metabolites (e.g., solar-induced fluorescence to estimate photosynthesis).

## What We Don't Know

An emerging approach to linking scales in biodiversity draws from network analysis, in which biodiversity is the emergent property of connected individuals and processes. Metabolisms, food webs, biomass distributions, and phylogenies often approximate complex networks whose connections are power-law distributed (Wang and Chen 2003). This means there are a few biodiversity entities with many connections (e.g., keystone species) and many biodiversity entities with few connections (i.e., individuals or populations with little interactions with others) (Wang and Chen 2003; Bascompte et al. 2006). Disruptions in one of these highly connected nodes can cascade across functional scales (Donadi et al. 2017). The loss or depletion of highly connected species may manifest as thresholds, tipping-points, or trophic cascades, as otherwise stable biodiversity or ecological systems suddenly degrade or switch into another state.

Discovering critical traits that affect biodiversity and their connections across scales is critical to preservation and responsible use of biodiversity resources. Such discoveries address the missions of NASA's Biological Diversity program, which seeks to quantify and detect biodiversity and its spatio-temporal patterns, and NASA's Ecological Forecasting program, which seeks to understand and model those changes by observing their drivers and understanding their underlying processes. If critical processes, species, systems, or habitats can be identified, then humans have the opportunity to preserve and or better manage biodiversity resources. The difficulty in identifying key environmental conditions that affect biodiversity goes beyond the number of cross-scale connections of any particular resource.

As an example, Antarctic krill are among the most numerous animals on the planet, are the primary prey source for most of the Southern Ocean ecosystem, and are considered a keystone species. Without krill, the structure of the Southern Ocean ecosystem would be fundamentally disrupted. Therefore, proposals to expand krill fisheries raise key biodiversity questions. Current methods are insufficient for NASA to be able to provide useful estimates of the spatial and temporal distribution of krill. New technologies need to be developed to characterize biodiversity patterns and quantify the impact of humans on krill in the Southern Ocean ecosystem.

There are also key biogeochemical molecular processes that are fundamental to global biodiversity. For example, the process of nitrogen fixation makes nitrogen available to a trophic web. The importance of this process was illustrated by human effects: before the industrial revolution, nitrogen fixation was primarily performed by prokaryotes. This limited the supply of nitrogen in global ecosystems. After the industrial revolution, humans now use the Haber-Bosch reaction for fertilizer to fix far more gaseous nitrogen than natural biological systems. On average, half the nitrogen in a person's body has been in a Haber-Bosch reactor (Smil 1999). This key biodiversity process has strong ecological and social connections. It is an example of a process that is highly connected to the daily lives of people, yet we do not have a way to monitor the flows of bioavailable nitrogen on global scales. This is an example of a key process that needs further investigation from a biodiversity viewpoint across many orders of magnitude in scale (microbial to global).

NASA Earth observations are already providing important information about a wide range of physical, geographical, hydrological, and meteorological conditions that affect biodiversity and can be used to model and predict it at a wide range of scales and spatiotemporal resolutions. Better understanding is essential for mechanistic modeling of biodiversity. One approach is to examine the impact environmental variables at varying spatial and temporal scales have on the different dimensions of biological diversity. Many studies examine biological diversity simply as the number of species present at a given location (alpha-diversity). However, it is equally important to examine how the composition of these species changes across space and time (beta-diversity) and how those variables relate to the overall number of species contained within a larger region (gamma-diversity). Different scales of environmental change may vary in impact on these levels of biological diversity. For example, in marine and terrestrial ecosystems, plant biomass and primary production are linked together principally by the spatial and temporal distribution of photosynthesis. Photosynthesis is the major process providing organic matter and oxygen to the biosphere and it is sensitive to changes in water, light, and nutrients. This is a central process to most life on Earth, and therefore a critical biodiversity process. Knowledge of the distribution of plant biomass, the oxygen it produces, and the carbon it sequesters is essential to understanding the global ecosystem and the interaction between humans, primary production, land use, water quality, and related drivers of biodiversity.

The multiscale nature of biodiversity requires solutions that can address cross-scale questions and identify cross-scale phenomena (Soranno et al. 2014). While intrinsic to ecosystems, species diversity is a statistical summary metric of many individuals, and its dynamics are influenced by these individuals' responses to environmental conditions through movement, growth, reproduction, and survival at small scales. As described in Chapter 2, organisms can influence environmental conditions, and evolution may occur in tight feedback with environmental processes. However, these small-scale signals and interactions combine to form very large-scale patterns of biodiversity, and the environmental conditions that drive those patterns are often part of large-scale global circulations and climate patterns.

## 3. WHAT IS NEEDED

**Observations** are needed at the full range of scales that interact to impact biodiversity (Figure 5-1). The needed improvement in the scale of observation is multi-dimensional. An important requirement for observations of biodiversity is the capability to observe individual organisms and distinguish species and functional traits of these organisms. As it will never be possible to observe everything everywhere, there is a need to improve **models and analyses** for scaling of biodiversity. For that, we need to compile datasets of **ground-based observations** of biodiversity at multiple scales with which to **validate models**, improve the observations of the environmental conditions that drive biodiversity, and improve the **analytical approaches** and tools with which we can apply allometric rules to predict biodiversity at multiple scales. With **future NASA capacity** for improved remote sensing, compiling ground-based datasets, modeling and data analysis, datasets from observations, models, and re-analyses of biodiversity across the full range of scales from local to global should eventually be available to end users.

## Observations

Today, there is an immediate need to observe small- and large-scale spatiotemporal patterns and changes to biodiversity (Chapters 2 and 3). Near-term investments are needed to advance observational capabilities that will expand our understanding of how biodiversity patterns and changes relate to one another in space and time, through biological processes, individual movements, species composition, and population spread (Figures 5-1, 5-2, 5-3). Over a decadal timeframe, these kinds of advances will promote the capability to detect local- to large-scale patterns and changes in biodiversity, and also understand how cross-scale processes drive biological patterns. On a multi-decadal time horizon, enhanced observational capability, combined with understanding of how biodiversity impacts scale up and down in ecosystems, will promote decision-making that effectively accounts for the influence of scale on biodiversity and ecosystem functions.

The observations that can answer cross-scale biodiversity challenges need to have high spatial, temporal, and spectral resolution to detect changes to distribution, phenology, and demography. In some cases, high spatial resolution is needed to detect individuals, individual-based processes, and identify species (e.g., animal tracking networks) and traits. In other cases, high temporal resolution is needed to track important event-scale processes and their impacts (e.g., storms, river plumes, high-latitude icing events, floods, upwelling, frontal-zone dynamics). Observations should also span long timeframes and cover large geographical regions to be able to observe the full range of movement and spread of individuals, emergent dynamics of populations and ecological communities, and large-scale environmental conditions that affect them. Since it is impractical to observe everything, everywhere, all the time, the challenge is to identify strategies of data collection and scaling that optimize information, promote understanding, and facilitate decision making. This will require access to multi-scale remote sensing systems—consisting of spaceborne, airborne, and UAV-based platforms—that can bridge the gap from site-scale measurements to regional- and global-scale measurements.

One example of how this can play out in marine ecosystems relates to the impacts of plankton biodiversity. Currently, NASA ocean color radiometry, even with the improvements of imaging spectroscopy (e.g., PACE), are largely limited to characterizing phytoplankton. Systematic approaches are lacking to observe zooplankton, the next trophic level up. Going forward, it is critical for satellite remote sensing to be used in conjunction with new techniques (e.g., space and airborne Lidar, *in situ* acoustics, *in situ* imaging) to characterize zooplankton across space and time scales. From there, we can use other devices, including telemetry, to track higher levels of the trophic web. Ultimately, enhanced observational strategies and knowledge gained will enable more comprehensive ecosystem-based management strategies, including protection of endangered and commercially important species.

# Analysis

## Today (0–5 years)

Models that merge data products of environmental drivers of biodiversity across different scales are needed to bridge high-frequency processes and high-resolution species distributions with the coarse, long-term patterns of biodiversity, and the climatic and large-scale processes that control it and drive its changes. Reanalysis models, which assimilate global and local observations with global model predictions, may provide such inter-scale bridges. This is currently the case for scaling weather observations, ocean currents, and ocean surface properties, where long-term reanalysis products exist. Such reanalyses can be used to provide the input variables for models of biodiversity across scales. However, the spatial-resolution of current reanalysis (tens of km) may be too coarse to address local drivers of biodiversity at small-scale hotspots (e.g., wetlands, coastal-zone fronts). Critically missing at present are reanalyses of soil moisture and hydrological states (rivers, wetlands, precipitation), and re-analyses of biological states (composition, structure, and function). These should be developed in the near-term, as the components needed for such re-analyses (observations and models) already exist. Earth system models currently resolve biogeochemical processes aggregated to a biological scale of generic functional types within biomes. Going forward, models that link biogeochemical and physical processes to biodiversity are needed to test hypotheses as to how physical processes affect the biological processes that ultimately shape biodiversity.

## Tomorrow (5–10 years)

Another challenge for reanalysis models is the need for improved data assimilation and model optimization to optimally leverage ground-based data compilations and remotely sensed data (Chapter 7). Such different observation sources typically come at different resolutions and extents and create a need to improve methods that estimate parameter uncertainty given validation data at multiple scales. Focused investment will be needed to meet the challenges inherent in multi-sensor data fusion and model-data fusion. Critical questions must be addressed with future products and research: How does uncertainty of species richness and biological process diversity vary across scales? How should uncertainty at different scales be combined when considering multi-scale observations to parameterize a single model?

Great strides toward modeling biodiversity across scales are currently being made with Artificial Intelligence (AI) tools for supervised and unsupervised methods. With the advance of high-resolution observation products and classification tools, it will become increasingly important to put renewed focus on selecting and making the strategic ground observations needed to train and validate such products and models. Many current ground observations do not provide the species/individual-based information needed to maximize benefits from high resolution observations that span multiple space and time scales.

### Beyond (10+ years)

A continuous reanalysis of biodiversity needs to be undertaken globally, across a long climatic time span, and at sufficiently high resolution, linking aquatic and terrestrial biodiversity below and above ground, and phylogenetic, functional, trait, microbial, plant, and animal biodiversity. Such reanalysis could apply either bottom-up mechanistic models of species distribution and movement or allometric and top-down models of biodiversity to integrate observations and analyses for a global high-resolution dynamic data product of different types of biodiversity in the oceans and terrestrial ecosystems.

## Capacity Building

Today, and through the next few decades, a promising strategy for compiling large-scale observational datasets of small-scale individual and species presence and movement is through collaborative and open data archives. Data sharing platforms are needed to make high-resolution data available, discoverable, and with metadata and observation methods that make it broadly usable and scalable. By sharing many high resolution "point" observations, large scale patterns and long-term trends in the observations may emerge. Current examples, including e-Bird, e-Mammal, Movebank, OBIS, GBIF, Map of Life, GEO BON, LTER/iLTER, MBON, ATN/OTN, and IOOS, enable large-scale and long-term studies by compiling many short-term, small-scale observations into large scale datasets. Networks, such as NCDC, NEON, and Ameriflux, create large-scale datasets from point observations. However, each of these need to be actively and exclusively (to that specific network) updated by users. A key point is the degree to which best practices and standards can be used to ensure observations are comparable across scales and among archives, from one place and group to another, through time, to detect change and evaluate uncertainty.

**Future vision.** Metadata for data sharing will make all biodiversity-related data searchable and discoverable to enable Google-like biodiversity tools. In this context, biodiversity-related data are any observations of individual animals/plants that can be compiled to form local/regional estimates of biodiversity and observations of potential drivers of biodiversity. Continued development of metadata standards that can encapsulate sampling methods and occurrences extending beyond the key ones currently in use (e.g., the Darwin Core), semantics for keywords and tags, and access protocols that respect data ownership and protected data (e.g., for endangered species) are still needed. Such efforts will allow globally discoverable and interoperable archives that could effectively compile global datasets, while individual observations from highly diverse sources will be discoverable. Such a digital ecosystem of biodiversity data sources could bridge across scales from point observations to global datasets and serve as a complementary data source to remote sensing observations that need validation. Flexible infrastructure with increasing storage capacity for long term accumulation of large data must be considered and developed.

## Field Studies and Experiments

### Today (0–5 years)

Field studies and experiments should aim to test hypotheses across multiple scales by nesting high spatial and temporal resolution observations within models informed by regional and global patterns of biodiversity. Models that address multiple scales, from the individual organism to the regional, and span long term at high temporal resolution, should be used to contextualize *in situ* observations to identify and characterize cross-scale biodiversity interactions and evaluate their uncertainty. Large-scale space-for-time and natural experiments that can test the relationships between observable physical drivers and spatio-temporal changes to biodiversity are needed. Development of regional ocean observatory infrastructure and studies that leverage their contextual measurements show promise for being able to test hypotheses that cross biodiversity scales (Manderson et al. 2011; Palamara et al. 2012; Oliver et al. 2013; Mannocci et al. 2017; Scales et al. 2017).

Ground-based observation sites and data networks (e.g., NEON, Ameriflux, Movebank) that enable training and validation of classification tools and high-resolution products are needed to complement observational advances. Currently, many ground-based observations of species occurrence and movement, biological traits, genomes, and biological processes are conducted world-wide. Nonetheless, these observations are rarely compiled to searchable, discoverable, and scalable datasets that could be analyzed and compiled to metrics of biodiversity. NASA could leverage its expertise at data collection, archiving, and distribution, and collaborate with other agencies to compile and curate such datasets. Maintaining continuity of observations with these data networks is needed to detect long-term temporal changes and trends of biodiversity.

### Tomorrow (5–10 years) and Beyond

In the future, approaches must be developed to identify the minimal scale necessary to detect the drivers of biodiversity. Such advances will make it tractable to address important biodiversity scale questions. For example, which conditions at what scales determine the viability of a keystone species? Is it necessary to know the location and taxonomic identity of every coral individual to determine the viability of seastar (a keystone species), or are there some average or emergent characteristics that are informative enough?

Improvement in the ability to predict biodiversity across scales would come from field experiments that elucidate key processes and controls on the scaling of biodiversity. For example, we need to better understand the feedback between very long-term biological processes, such as evolution, and shorter-term biological and environmental processes.

## 4. CONSIDERATIONS FOR NASA

We face myriad challenges to interact with Earth's natural systems in ways that promote healthy ecosystems, enhance sustainability, and adapt appropriately as climate change progresses. A major reason these challenges remain so difficult to meet is the demand for strategies to monitor status and change across many levels of biological organization, from genes to species to ecosystems. Looking ahead to solutions, the importance of NASA's Earth-orbiting satellite platforms cannot be overstated. These platforms, and the diverse sensors they carry, provide access to spatial scales of tens of meters to thousands of km (six orders of magnitude in space) and temporal scales of days to decades (three orders of magnitude in time). NASA excels at measuring environmental drivers that could be used to model biodiversity, including weather and other environmental conditions, and also key characteristics of the ecosystems, such as biomass and photosynthesis, as well as carbon and energy exchange. Climate models allow us to forecast future conditions that influence biodiversity. These unique capabilities make it possible to characterize aspects of biodiversity and habitat variability across a wide range of conditions. Measurements from space can provide direct assessment at relevant scales for some aspects of biodiversity, such as patterns of variability in terrestrial vegetation, land cover, and photosynthetic biomass in aquatic systems. Even aspects of organismal and functional diversity that operate outside the range of directly observable space-time scales can produce emergent properties that are detectable from space. Examples include microbial primary producers in aquatic systems and optical signatures reflecting the effects of photosynthesis.

To meet the challenges we face in addressing biodiversity research and applications across micro- to macro-scales in space and time, NASA should continue advancing existing and developing new remote sensing techniques. Important targets for observation include more direct characterization of biodiversity and enhanced assessment of essential habitat features. Focusing on the advance of individual sensor-platform systems will continue to promote observational capability across a range of scales relevant for biodiversity research. However, an important challenge is to design observing systems from different disciplines that target different environmental processes in synergy, to understand life on Earth, its diversity, and its functions from an applied ecology perspective. Going forward, such an approach can address critical questions that require integration of observations and results across scales. The scaling problems demand a greater emphasis on coordinated design of multi-sensor-platform systems, including constellations of Earth-orbiting sensors and, equally important, strategically sited *in situ* sensors. Further benefits from such strategically designed systems that combine new Earth observing satellites with other agencies (nationally and internationally) and surface-observation networks, could be achieved by integrating advanced adaptive sampling algorithms with smart, ground-based (e.g., camera traps) or on-animal sensors (e.g., ICARUS animal tracking tags, ocean gliders) that communicate through satellites. These will make it possible to derive information about biodiversity at the very small scale and aggregate this local information to large-scale and long-term patterns of observed biodiversity.

Furthermore, NASA should leverage its leadership in generating observations and data archiving and distribution. For example, NASA can partner with other agencies and could lead the effort to coordinate metadata and archiving standards and coordinate efforts for shared platforms for data exchange (e.g., GEO BON) and up/down scaling and modeling (NASA MERRA). Such data systems will promote new knowledge and decision-making tools, especially when combined with advances in data assimilative models that incorporate biodiversity products and processes across scales.

Ultimately, NASA can contribute critical aspects to observations, models, and knowledge required to produce a biodiversity reanalysis, a digital twin of Earth with species composition, structure, function, etc., informed by satellite observations, *in situ* data, and models. This kind of analysis will lead to insights into the ways processes occurring at different scales interact to produce biodiversity patterns and impacts. New mechanistic knowledge will in turn enable more sustainable practices and promote resilient ecosystems, including their human elements.

- **Continue critical investments in Earth-orbiting satellite platforms.** This includes developing a diversity of sensors to provide observations across the vast spatial and temporal scales (six orders of magnitude in space, four orders of magnitude in time) relevant to characterizing aspects of biodiversity and habitat variability. Sustained investments are needed to understand how processes occurring at different scales interact to produce biodiversity patterns and impacts.
- **Advance existing and develop new remote sensing techniques.** Important targets for observation include more direct characterization of biodiversity, from biological individual resolution to global scale, and enhanced assessment of the corresponding essential habitat features.
- **Prioritize coordinated design of multi-sensor-platform systems.** This is essential to address critical questions that require integration of observations and results across scales. Strategically sited *in situ* sensors, surface-based observational networks, and integration of surface-based observations with remote sensing data are as critical as space-based sensors. Investment in improving two-way information exchanges between NASA and local ground-based scientists and the public who collect *in situ* observations and manage biodiversity is also a critical component. NASA should continue to strive toward building multidisciplinary partnerships in solicitations and internal research and operations.
- **Strengthen inter-agency (national, local) and international partnerships.** These connections are essential for coordinating several critical areas, including: 1) facilitating global, strategically designed, multiscale biodiversity observation systems via new Earth observing satellites and *in situ* systems, 2) advancing cooperative solutions for up/down scaling and modeling in biodiversity research, forecasting, and management, and 3) creating metadata and archiving standards and shared or interoperable platforms that enable data exchange, discoverability, and applicability of data from multiple sources and scales for the study of biodiversity and its drivers.
- **Advance and employ methods that combine remote sensing and *in situ* observations.** For example, NASA should provide direct support for adaptive sampling algorithms developed and integrated with *in situ* components, such as smart ground-based sensors and on-animal sensors.
- **Invest in research that leverages data systems and new knowledge into decision making tools.** NASA should focus on tools informed by advances in

data assimilative models that incorporate biodiversity products and processes across scales. This research should specifically address identified policy objectives and targets, particularly the 21 action-oriented targets of the post-2020 Global Biodiversity Framework being negotiated as part of the UN Convention on Biological Diversity (CBD).

- **Participate in and contribute observations, models, and knowledge in support of a "biodiversity reanalysis."** This is a digital twin of Earth with species composition, demography, function, etc., informed by satellite observations, *in situ* data, and models.
- **Play a critical role in meeting the myriad challenges of society.** Supporting multi-scale socio-ecological assessments is key. As part of this effort, NASA should develop information and deliver it to decision-makers to help humanity interact with Earth's natural systems in ways that promote healthy ecosystems, enhance sustainability, consider socio-economic factors, and adapt appropriately as climate change progresses.

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6

# BIODIVERSITY AND ECOSYSTEM RESILIENCE

## *Does biodiversity increase ecosystem resilience to environmental change?*

### Key Points

- "Ecosystem resilience" is the ability of an ecosystem to absorb environmental perturbations, such as wildfire, storms, and other extreme events, while retaining composition, structure, and function.
- Improved understanding of ecological resilience can facilitate management and planning for societal resilience.
- A global perspective of how biodiversity and ecosystem functions and services respond to and recover from environmental perturbation is lacking.
- Sustainable management of natural resources requires a mechanistic understanding of the relationships between biodiversity and ecosystem resilience.
- Long-term, harmonized Earth observation and *in situ* products are necessary to study, understand, and predict resilience.
- NASA should support long-term *in situ* biodiversity monitoring designed for integration with Earth observations.
- NASA should increase support for research into socio-ecological systems, especially in the context of monitoring and managing ecological resilience to environmental variability.
- NASA should facilitate research to improve our ability to forecast ecological responses to perturbation events.

# 1. IMPORTANCE

The Earth system is dynamic across spatial and temporal scales. This includes variation in ecosystem-level properties, such as net ecosystem productivity, community-level variation in species composition (which species are present), and population-level variation of abundance and performance/function. The structure, function, and composition of ecosystems change in response to "internal" processes, such as population dynamics, ecological succession following disturbance, and other biotic interactions, and "external" processes, such as abiotic environmental change. In some cases, these changes result in short and/or long-term ecological shifts, while in other cases ecosystems return to a state similar to that before the perturbation. For example, severe wildfire in a forest typically leads to abrupt and dramatic changes in species composition, abundance, and the resulting ecosystem functions. But over time, a forest with recognizably similar structure, function, and composition can return. The long-term maintenance of function, biodiversity, and services depends on the ability of ecosystems to respond and adapt to continuous environmental change. In many cases, however, severe environmental perturbation results in significant shifts in biodiversity (composition, structure, or function) that do not recover within a timeframe relevant to important ecosystem services. In some ecosystems, there may be multiple ecological states that could persist under similar environmental conditions (such as forest/savannah or oligotrophic/eutrophic lakes) and one ecosystem state could be replaced by another following a perturbation (Holling 1985).

Resilience, as defined by Folke et al. (2010), is the "capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure and feedbacks, and therefore identity, that is, *the capacity to change in order to maintain the same identity.*" Resilience is often considered in the context of social-ecological systems (SES), including human interactions and feedbacks (Chapter 4). A primary focus of the resilience literature has been on human systems, with emphasis on individuals, communities, and society as a whole, while recognizing the importance of adaptation or transformation over return to an earlier state (Folke 2016). Social resilience depends upon (and likewise impacts) ecological resilience, along with many other institutional factors, such as polycentricity (multiple, overlapping jurisdictions) of governance, capacity for learning and experimentation, support for complex adaptive thinking, and breadth of participation (Biggs et al. 2015). We offer a few examples of how NASA can contribute to the study of the social dimensions of resilience; however, these are difficult to measure or even characterize through remote-sensing, and thus are not the focus of this chapter.

In this report, we focus on the **role of biodiversity in ecosystem resilience to environmental change and disturbance** through two perspectives defined by Willis et al. (2018):

1. The ability to **resist** change despite environmental perturbations, and
2. The **recovery rate** following a perturbation.

At least two attributes must be defined to study the resistance or recovery of a system—the "of what" and "to what" (Carpenter et al. 2001). The "of what" refers to the parameter/state of interest, such as the primary productivity of a forest (at a particular baseline level), while the "to what" refers to the potential perturbation, such as climatic variability in that location. These attributes could be defined by many different biodiversity metrics, from the population level (e.g., how resilient is a population of penguins to changes in sea ice?) to the system level (e.g., how resilient are the functions and services of this ecosystem to a change in the wildfire regime?). Therefore, quantification of resilience could include very specific metrics, such as the size of particular populations, or ecosystem-level characteristics, such as primary productivity that can more easily be measured from above with remote sensing.

The primary beneficiaries of this research include natural resource managers and decision-makers. Of particular and immediate relevance are regions that experience wildfires, hurricanes, floods, extreme climate events, or other types of environmental disturbance that affect the underlying biodiversity. Over the longer term, many habitats are expected to change under the combined action of various climate forces and direct human action. Natural resource managers have the difficult task of monitoring and managing ecosystems that vary naturally through time, often balancing human needs, including life and infrastructure, with the maintenance of biodiversity, ecosystem function, and ecosystem goods and services. Resilience is an important topic for land managers and conservation organizations to communicate conservation and sustainable development to the public. For example, the value of local ecosystem stability is easier to understand than the complex relationships between biodiversity and ecosystem function. NASA technologies and research can focus on increasing the capacity to understand and manage ecosystem resilience. Understanding the factors that affect ecological resilience will improve ecological forecasting and address likely outcomes of various management strategies.

# 2. CURRENT STATE OF KNOWLEDGE

## What We Know

Ecological resilience to environmental perturbations has been studied in ecosystems around the world. Often the motivation for the research includes basic questions about system dynamics and applied objectives related to the sustainable and long-term management of natural resources. For example, the U.S. Forest Service is working to improve its understanding of what makes forests resilient to environmental disturbance (Bone et al. 2016). This includes researching management interventions, such as assisted migration and seed selection (M. I. Williams and Dumroese 2013), with the overarching goal of maintaining ecological function and services through environmental change. There is growing interest in the ability of forests to sequester carbon emissions through the coming century. However, resilience is determined by the ability to maintain function through changing frequencies and severities of drought, fire, and other disturbances (Anderegg et al. 2020). Similarly, there are active efforts to understand ocean resilience to uses, including conservation, fishing, recreation, and extraction of natural resources from the coast to the deep sea. Coral reef biologists have argued that transition to a resilience-based management framework would maximize corals' ability to respond to future changes (Mcleod et al. 2019). This could include passive interventions, such as increasing protected areas or reducing exploitation, and active interventions, such as translocating species or even assisted evolution (Oppen et al. 2017). Similarly, Ecosystem-Based Fisheries Management strategies use remote sensing observations to inform decision making and "maintain resilient and productive ecosystems" (Townsend et al. 2019). An improved understanding of the role of biodiversity in ecosystem resilience would guide the sustainable management of these systems.

Assessment of ecological resilience facilitates management and planning for social resilience by anticipating stressors and vulnerabilities in ecosystems. For example, agricultural resilience underpins the cohesion of many rural communities, with erosion of livelihoods and mass migration following the collapse of these systems. During the U.S. "dust bowl" in the 1930s, rapid drying led to the desertification and degradation of agriculture and rangelands. Similarly, recent increases in 'fire weather' (Abatzoglou, Williams, and Barbero 2019) combined with pest outbreaks in the forests of the Western U.S. have resulted in record-breaking fires (Zhang et al. 2020). Of course, all social systems depend on ecological resilience at a fundamental level, since the habitability of the planet is, by definition, critical to our survival. Indeed, the notion of a "safe operating space" for humanity was proposed to help buffer zones of uncertainty with potential thresholds of these critical processes at the global level, or "planetary boundaries" beyond which conditions for human life on Earth would become far less favorable (Rockström et al. 2009). However, localized changes in ecological resilience could still have cascading effects on social resilience for communities or industries disproportionately dependent on natural resource management. As explained in Folke (2016), a "resilience approach would emphasize flexibility and opportunity of diverse pathways and keeping options open to be able to shift between those, in a manner that remains within the safe operating space of the biosphere, and with prosperity and abundance for humans in collaboration with biosphere resilience."

Remote sensing plays an increasingly important role in observing our dynamic Earth and enabling research into how biodiversity and ecosystem function respond to various perturbations. These include observation of abiotic processes, such as weather, fire, and storms, as well as biotic processes related to community composition, ecosystem function, and ecosystem services. We need to improve our understanding of the role of biodiversity in supporting ecosystem resilience to environmental change.

## What We Don't Know

An important and challenging component of resilience-related research is in carefully defining the "of what" and "to what" of the research question. Development of Essential Biodiversity Variables (EBVs) (Pereira et al. 2013; Turak et al. 2017; Muller-Karger et al. 2018) in the remote sensing and biodiversity science community will establish a set of observable metrics that indicate ecological status. A set of EBVs that capture all the essential characteristics of an ecosystem will track and monitor change through time. However, reducing complex systems to a relatively small set of metrics can be misleading.

For example, a single ecosystem-level metric, such as net primary productivity (NPP), may show full "recovery" following disturbance, even with complete species turnover and changes to ecosystem services. Increasing productivity could mean rapid growth or invasion by non-native species, which can reduce resilience in some systems (Chaffin et al. 2016). Increasing spectral diversity following a perturbation could mean biodiversity is recovering or the system is being further fragmented by ongoing impacts. Thus, the selection, calibration, and interpretation of the metrics used to monitor ecosystem resilience is critically important and understudied. In addition, the development of multivariate "resilience" metrics may lead to a more nuanced perspective of ecological change and response to perturbation.

A related challenge to identifying relevant metrics is to understand the reliability of relationships between those metrics of interest and RS observations. Many RS-derived modeled products rely on empirical relationships between what is measured (e.g., radiance at the top of the atmosphere) and a surface property (e.g., NPP). Given that most resilience-related studies will focus on long-term variability, it is critical our observations are well-calibrated, and that the calibration remains sufficiently accurate throughout the temporal domain of the study. For example, the well-known MODIS NPP product (Zhao et al. 2010) relies on lookup tables based on empirical data from various ecosystems. As those ecosystems change in composition, structure, or function, the relationships between NPP and reflectance may also change and affect the estimates of NPP. The calibration drift of RS products may be difficult to detect without ongoing collection of *in situ* observations.

The relevant time scales of observations and the processes that generate them are also important to consider. As discussed in Chapter 5, the timescales of relevant ecological processes (such as succession following disturbance in a forest system with long-lived species) may be orders of magnitude longer than even the longest RS data product (and many orders of magnitude longer than the more recent RS data products). Thus, important internal dynamics of a system may be unobservable, even with decades of satellite observations. These and other "slow" variables, such as nutrient cycling, are critically important yet very difficult to observe without extensive field work and use of *in situ* proxies. This includes historical and paleoecological perspectives that can provide more context on recent observations (Paciorek et al. 2016; Dawson et al. 2019).

Recent and projected change in mean conditions, as well as the frequency of extreme events related to climate (and events including wildfire), are part of anticipated ecosystem variability and change. Some specific mixtures of populations or functional traits are thought to increase ecosystem resilience through varied responses to changing environmental conditions and extremes (Isbell et al. 2015), but this has been hard to evaluate at the ecosystem scale across large domains. This also requires a nuanced and practical definition of biodiversity. The concept that biodiversity underpins resilience is based on several theoretical justifications, such as the "insurance hypothesis," which argues that having more species in a community makes it more resilient because multiple species may provide similar functions and so if one is lost or impacted, the function will continue (Yachi and Loreau 1999). For example, there may be rare species in a community that currently do not provide a significant contribution to the overall ecosystem function (such as NPP). However, the rare species could be more tolerant than a common species to some environmental perturbation and thus critically important to maintaining ecosystem function given future environmental variability. This has been shown for some systems at the community level but lacks good evidence at regional-global scales (Willis, Jeffers, and Tovar 2018).

The ecological concept of "multiple stable states" is also important to understanding ecosystem resilience. The basic idea is that natural ecosystems (and the species they support) can be persistent and yet "susceptible to catastrophic change" (Petraitis 2013). An example is the extraordinarily biodiverse coral reef ecosystem, which may persist for hundreds or thousands of years and then be suddenly replaced with a much less diverse seaweed-dominated system following a significant environmental perturbation (Petraitis 2013). Some ecological changes do not occur gradually, and the possibility of catastrophic change likely increases as we move the planet outside the geophysical boundaries of the past few millennia. This environmental change brings the increasing possibility of "no analogue states" (Williams and Jackson 2007), novel and disappearing climates (Williams, Jackson, and Kutzbach 2007), novel ecosystems (Radeloff et al. 2015; Williams et al. 2019), and tipping points in the Earth system (Hsieh et al. 2005; Drijfhout et al. 2015; Lenton et al. 2019).

Similarly, even process-based models are calibrated and validated using available data and observed relationships, which means they are typically more uncertain when projecting outside of observed bounds. Given the complexity of interactions and feedbacks occurring within any ecosystem, some biological processes will likely remain opaque over the coming decades despite rapid advancements in remote sensing, ecology, and genomics. In other words, our models will never include all relevant processes and states of the biosphere, and thus will not fully capture the system's ability to handle various perturbations. What happens when the system is pushed outside the observed envelope of variability? These unprecedented events may lead us outside the space that is well characterized by models and into uncharted territory without our realizing it. We do not currently have a sufficient understanding of biodiversity and ecosystem dynamics to accurately predict how they will respond to future environmental variability. However, we can use the data collected in the recent past to identify early indicators of state changes in ecological structure and function and how these can be detected over broad spatial scales. We can also ask how, when, and at what rate has biodiversity and ecosystem function recovered from environmental perturbation in the past. The answers to the previous questions may also help us identify management strategies for maximizing ecosystem resilience to environmental perturbations.

Sustainable management of natural resources requires understanding how ecosystems respond to environmental perturbations (such as wildfire, storms, and other extreme events). Studying ecosystem response to disturbance can reveal important elements (species, communities, interactions), their roles in the community, and how this impacts the maintenance of ecosystem function and services. Understanding the relationship between biodiversity and ecosystem resilience will enable improved management and conservation decisions to enhance ecosystem resilience to current and future environmental variability (Chambers, Allen, and Cushman 2019). It is especially critical that decision makers have the best available information about how to manage for ecosystem resilience to maintain biodiversity and ecosystem goods and services.

# 3. WHAT IS NEEDED?

## Observations

Remotely sensed observations and derived products can be used as the "of what," "to what," or as a related variable in ecological resilience studies. Earlier chapters summarized the myriad ways remote sensing can provide valuable observations of various aspects of biodiversity and ecosystem function. The methods described below focus on analysis and interpretation of those observations, particularly on variability through time. New and upcoming technologies will allow us to capture more dimensions of biodiversity and ecosystem function and monitor those various dimensions more effectively. In some cases, the variables of interest (either "of what" or "to what") may be directly observable through existing or future RS platforms, while in other cases we will be limited to proxies or modeled estimates.

### Today (0–5 years)

The majority of existing research on ecosystem resilience using remote sensing has relied on ecologically integrative measures that are relatively easy to observe from space, such as primary productivity (and proxies, such as NDVI/EVI) at spatial resolutions ranging from 1 km to 30 m (e.g., Pettorelli et al. 2005; Liniger, Jucker Riva, and Schwilch 2016; De Keersmaecker et al. 2017; Fang et al. 2018; Gazol et al. 2018; Hantson et al. 2018). Scientists have monitored marine ecosystem variables that influence coral reef resilience and coral reef stressors (e.g., Knudby et al. 2014). Such variables also have the longest historical archive of observations and are fairly robust, and thus enable study of variability and resilience on multi-decadal scales.

There are also several remote sensing products that provide perspective on human activity and change. The most common of these is land use and land cover, which have been mapped using optical data from Landsat and AVHRR since the late 1970s. However, consistency throughout a time series poses a challenge, especially when switching between products, as distinguishing true change from classification variability and error are critical for analysis of resilience within a system, and land cover classifications are notoriously inconsistent even for the same year (Fritz et al. 2011; Congalton et al. 2014). Long time series are critical to studying the response of ecosystems to multi-year drought, gradual changes in community composition, recovery following wildfire, and other relatively slow processes.

Several new sensors are able to capture a set of observations about Earth's socio-ecological systems and provide a different perspective from the legacy optical observations described above. These include observations directly related to vegetation composition (species or plant functional type), structure (e.g., tree canopy height and vertical plankton distribution in aquatic environments), and function (e.g., solar induced fluorescence, stress response). For example, GEDI and ICESat-2 measure 3D canopy structure and complexity, ocean Lidar measures vertical structure in ocean biota and habitat characteristics, and ECOSTRESS captures high-resolution thermal data useful for understanding plant stress. These data provide insights into how the land surface changes in response to environmental change and human activity, as detailed in previous chapters.

Beyond simply mapping the land or the ocean surface, time series data can be used in conjunction with other social or environmental data to infer not only "what" has changed but "why." Other types of existing Earth observation data are useful for resilience studies of SES. For example, Earth observation of nighttime lights offers a unique perspective of human activity that can be used to study how poverty, human infrastructure, and fishing vessel location changes in response to various kinds of disturbance. Li et al. (2017) used nighttime lights data from VIIRS and DMSP to estimate the loss of electric lighting during the recent civil war in Syria. Such information could be used in resilience research as an "of what" (e.g., what is the resilience of Syria's electric infrastructure to social conflict?) or a "to what" (e.g., what is the resilience of some ecological process to the expansion of electric infrastructure and related human development?). These data can also be used to map social processes; Elvidge et al. (2009) and Jean et al. (2016) used nighttime lights with ancillary data to map poverty globally. The growing availability of Volunteered Geographic Information, including geocoded photographs and social media, is making it possible to incorporate human behavior in ways never before possible (Elwood, Goodchild, and Sui 2012).

## Tomorrow (5–10 years) and Beyond

New technology and data products will capture more dimensions of biodiversity and ecosystem function to enable a richer analysis of how ecosystems respond to environmental change. As time series of these data are archived, it will be possible to use them in combination to explore temporal variability in various biodiversity elements and the response to various kinds of perturbations. As introduced in previous chapters of this report, NASA has several important sensors in development that will be useful for resilience studies over time. These include the Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) satellite mission, which will make observations of global ocean color, biogeochemistry, and ecology. The NASA-ISRO Synthetic Aperture Radar (NISAR) satellite mission will record structural information about ecosystem disturbance, as well as other physical processes, such as ice-sheet collapse and other natural hazards. Finally, the Surface Biology and Geology (SBG) mission, currently in development, will provide high resolution hyperspectral data that can reveal much finer ecological variability than currently possible with existing satellite data products.

However, monitoring and modeling resilience always includes a temporal dimension, so new sensors are often not immediately useful for studying long-term change. In some cases, through space-for-time substitution (Damgaard 2019), it may be possible to study resilience with a single snapshot (or short time series) of observations. However, in most cases, a time series longer than the temporal scale of the underlying process is necessary for inference about ecological resilience. Thus, it is critical that, as new sensors are developed, the legacy observations are maintained and intercalibrated. Otherwise, we will have more detailed observations but not the ability to place those observations in the context of prior dynamics.

## Analysis

### Today (0–5 years)

Empirical approaches provide insight into how ecosystems respond to various environmental perturbations. At the global scale, the macroecological literature contains many studies relating attributes of the biosphere and environmental variability to infer relationships where the underlying mechanisms may not be known or well understood. In this way, empirical approaches (including artificial intelligence) are a powerful tool for exploring observed relationships and developing hypotheses that can be further tested and evaluated. Ongoing collection and storage of remote sensing observations is building a very rich archive that can be analyzed to study ecosystem response to various perturbations. An example of this is the pixel/ecosystem level resilience metrics (including time to recovery and rate of recovery) estimated using the LandTrendr/CCDC-type analysis (Kennedy et al. 2018). This is possible for regional to global domains in a cloud-based environment, such as Google Earth Engine or Amazon Cloud.

We also need continued development of ecosystem process models to study feedback between biodiversity and various environmental perturbations across scales from the individual to ecosystem (Fisher et al. 2018; Longo et al. 2018). Process models are incredibly useful tools for simulating how a system could respond to particular perturbations and comparing those predictions with observations. These range from physical models, such as general circulation models, to the more recent general ecosystem models, such as the Madingley model (Purves et al. 2013), that represent processes related to ecology and biodiversity. This general approach is an extremely powerful tool for producing and comparing hind- and forecasts under a range of potential scenarios (Chapter 7). In addition, process-based models offer the possibility of estimating and monitoring parameters that are not directly observable, such as soil organic matter or soil water retention capacity. There is significant room for improvement in our ability to model how ecosystems respond to perturbations. In particular, models that do not accurately quantify uncertainty can offer a false sense of confidence that all the relevant mechanisms have been adequately characterized when they predict current or past conditions. As described above, models parameterized using empirical relationships may not hold under novel environmental conditions or under changing biological composition. Also, many modeling frameworks do not explicitly estimate or propagate uncertainty to the final outputs, which limits our ability to use them for decision-making. However, there has been impressive progress over the past decade to better account for and propagate uncertainties through to the final inference and decision-relevant information (e.g., Gardella et al. 2018).

Our understanding of the connection between indicators of resilience and resilience itself will be improved by measuring both. Ideally, the indicator variables can be used to provide an early warning system of when the resilience of the system is eroding, so it can be corrected and better managed before the next perturbation. In addition to detecting evidence of resilience in process (in response to a perturbation), attributes of a system that build resilience could also be tracked. Slowly changing variables that buffer against regime change (e.g., phosphorus retention capacity near or in a lake or soil carbon in a rangeland or farmland), self-organization of system components (e.g., mosaics of ecosystems in different states of succession), and functional, phylogenetic, and taxonomic biodiversity are all thought to be important indicators of resilience. In many cases, even these indicators, especially of slow variables and self-organization, may need to be represented through ecosystem modeling (e.g., nutrient cycling, long-term dynamic vegetation responses), but remote-sensing has an important role to play in parameterizing, calibrating, and validating such models.

## Tomorrow (5–10 years) and Beyond

Measuring resilience should answer the question of how much perturbation an ecosystem can experience without a systematic change or collapse. The ecological forecasting approach (described in more detail in Chapter 7) describes a holistic framework to build, test, and rapidly improve our ability to model and forecast ecological systems. The ecological forecasting framework is extremely useful for estimating system vulnerability to a particular kind of perturbation and to predict when and how it may respond. This ability to predict also makes it a powerful tool for decision-making. A key objective of the Ecological Forecasting program is to apply scientific results to management efforts that include the detection and prediction of changes in ecosystem resilience and applying solutions to mitigate change. There is growing development of data products based on observations combined with models to estimate important ecological characteristics. In particular, the community effort to establish Essential Biodiversity Variables (EBVs) will lead to indicators of important ecological states (Pereira et al. 2013). EBVs would then be extremely useful for studying the dynamics of and resilience to various environmental perturbations. The growing availability of massive citizen science data is enabling detailed exploration of spatial variability in species distributions and movement (Movebank, eBird, etc.) and phenology (National Phenology Network). Growing digital connectivity allows for semi-automated data collection (such as the time and location of an observation) that can minimize errors associated with citizen science data.

Linking social and environmental processes is a data/observation and conceptual/modeling challenge. Most remote sensing sensors observe discrete locations (pixels), but people are connected by networks not easily seen from space. Of course, all organisms are connected in complex trophic webs, but humans are interconnected to a much larger, deeper degree. In other words, other animals may move, but we can still use Landsat to understand where they are. While higher resolution imagery could help quantify human activity (delineating infrastructure like roads, dams, and buildings), it is exceedingly difficult to capture complex global flows of goods, services, and other systems. However, social data streams are becoming ubiquitous as transactions of all kinds are digitized. Incorporating the human dimension more explicitly as a part of the system may also help improve our ability to understand how humans respond to various kinds of environmental change. Thus, there is an opportunity to link these different perspectives to understand how various types of perturbations (physical or social) affect socioecological systems.

There is also rapid development of machine-learning/artificial intelligence (AI) approaches to explore RS time series that will become more important over the coming decades. One notable challenge will be to “ground” these models with ecological and biological theory to build confidence that they can be used for accurate forecasting under novel conditions (Read et al. 2019). Minimally, AI-based approaches may be a powerful tool for developing hypotheses about the associations between various aspects of the biosphere. AI is good at identifying latent relationships between variables even when no known mechanism connects them, so one must be careful with interpretation. However, this may make them especially useful for monitoring RS-derived ecosystem dynamics and identifying when something unusual is happening (e.g., variables are dissociating). This also represents an opportunity to build relationships with companies in the private sector that are investing heavily in AI technology.

## Field Studies and Experiments

It is important to combine observational studies, like those mentioned above, with planned community-level manipulations to study the impact of perturbation on composition, structure, and function. For example, following the discovery that acid rain was leaching calcium from deciduous forests in the northeastern U.S., it was hypothesized that calcium was leaching from the system and harming trees (Likens 2004). In 1999, a helicopter was used to apply calcium silicate to watershed-scale plots to replenish what was lost and study the effect of that addition over the next few decades. Similar experiments into eutrophication, lake acidification, environmental mercury, and hydro-electric reservoir impacts have been developed in the IISD Experimental Lakes Area in Ontario, Canada (Emmerton 2015). Likewise, long-running grassland experiments investigating the relationship between biodiversity and ecological function have resulted in key findings that biodiversity supports ecosystem resilience to environmental change (Tilman, Reich, and Knops 2006). These manipulative experiments, combined with long-term planning, are expensive and time-consuming, but likely the best way to test theories about how particular ecosystems respond to perturbations. Combined with the ecological forecasting framework, manipulative experiments can even be used to develop rapid experiments to better quantify unknown model parameters (Redmond et al. 2019). However, even these ecosystem-level experiments do not always scale up to explain patterns seen at landscape-to-global scales, and so remote sensing is critically important. Other events that result in (or reduce) perturbations can also be used in combination with remote sensing to enable landscape-scale analysis and monitoring. These include installation of wastewater treatment systems that reduce phosphorus in a wetland, establishment of a protected area that reduce harvesting, or similar unplanned/natural "experiments."

In particular, field studies are most needed in the least understood ecosystems. For example, feedbacks between biodiversity and ecosystem carbon flux in the tropics and arctic/boreal zone have large uncertainties (Schimel et al. 2015). One framework to facilitate regional investigation of biodiversity-ecosystem resilience research is the use of focused field campaigns to collect synchronous observations of related phenomena ranging from atmospheric processes to ecosystem variability (Behrenfeld et al. 2019; Miller et al. 2019). Implementation of biodiversity-oriented field campaigns could help overcome the classic limitation of biodiversity studies by facilitating the synchronous collection of field and RS datasets, with a focus on characterizing and explaining the spatial variability of biodiversity and related ecosystem-level functions and services, as well as their temporal dynamics, in relation to environmental variability.

## 4. CONSIDERATIONS FOR NASA

Understanding ecological resilience and its impact on society requires the landscape- to global-scale observations NASA provides. Therefore, NASA plays a key role in resilience research and its applications. Temporally, it is a bit more complicated, because a time series longer than the temporal scale of the underlying process is usually needed to make inferences about ecological resilience. While the observational record goes back more than 40 years, ongoing collection and access to past data is critical. NASA, along with USGS, has done an admirable job at archiving these historical data, making them accessible, and harmonizing them across different sensors so they are available to the research and applied communities NASA supports.

These facts, combined with NASA's emphasis on technology and end-to-end systems, puts it in a unique position to innovate and provide support and leadership for the study of ecological resilience and its implications for society. With this in mind, this final section provides a range of suggestions for NASA to consider that would enhance utilization of NASA's observations and models, as well as advance understanding of ecological resilience and its societal relevance.

- **Continue collection, archival, calibration, and processing of NASA's multi-decadal satellite record.** Given the importance of time-series to study disturbance and resilience, NASA should continue to develop and maintain seamless analysis-ready datasets (ARDs), such as those applied retrospectively to data from Landsat 4–8 for CONUS (Dwyer et al. 2018). Like the sophisticated MODIS data processing workflows (Justice et al. 2002), the Landsat archive could be reprocessed as sensors change and algorithms improve. This would enable more reliable inter-sensor calibration and time series analysis that would reduce the burden of quality control, atmospheric correction, and calibration on individual researchers (Dwyer et al. 2018).
- **Develop cross-platform "harmonized" Earth observation products to further enhance the quality of long-term records of change.** A good example is the Harmonized Landsat and Sentinel-2 (HLS) surface reflectance data product, which includes atmospheric correction, cloud and cloud-shadow masking, spatial co-registration, bidirectional reflectance distribution function normalization, and spectral bandpass adjustment (Claverie et al. 2018). Ideally,

cross-sensor calibration would include estimates of uncertainty to quantify the errors introduced by combining data from different sensors. As new sensors are developed, they should be calibrated with existing sensors. In some cases, this could include production of legacy products from next generation sensors. For example, "Landsat-like" observations could be generated from the SBG sensor to maintain calibrated legacy observations if the Landsat program ends. Development of standardized, analysis-ready datasets would enable quantification of past disturbance and recovery trajectories to improve our understanding of when and how ecosystems can continue particular functions following perturbation and when they collapse.

- **Support, possibly through collaboration, of long-term *in situ* monitoring of indicators representing the health and/or structure of the ecosystem designed for integration with EO.** As described in this chapter and Chapter 3, this would enable detection of homeostasis or rebounding in response to disturbance and stress, which is necessary to understanding the resistance and resilience of ecosystems. An important question is which traits and functions—at several biological scales, from the individual through populations, communities, and ecosystems—provide resilience. Combining remotely sensed observations with field-measured trait data will profoundly enhance our understanding of these processes. Likewise, ongoing restoration projects could be monitored as "experiments" in ecological resilience.
- **Increase support for research into socio-ecological systems, especially in the context of monitoring and managing ecological resilience to environmental variability.** Humans have become an important environmental force and NASA has the opportunity to better understand this ecological impact. Improving our ability to monitor social, political, and economic perturbations and tying them to NASA's Earth observations and models will enable a deeper understanding of the factors affecting socio-ecological resilience. We also encourage the NASA Biological Diversity and Ecological Forecasting program elements to seek out opportunities to network with other funding agencies within and outside of NASA to support transdisciplinary and synergistic research. Joint funding partners may include the Department of Energy or National Science Foundation, including its "Biodiversity on a Changing Planet" and "Resilient and Sustainable Infrastructures" programs.
- **Facilitate research to improve our ability to forecast responses to events and validate those predictions with new observations.** This approach is

explained in more detail in Chapter 7. The ecological forecasting framework is well suited to investigations of ecological resilience because short-term predictions following a perturbation can be compared to incoming observations and used to refine the underlying models. There are also opportunities for "ecological hindcasting" using the existing archive of RS products, together with modern observations and models, to develop and test our understanding of system dynamics through past environmental variability. In particular, seasonal climate forecasts could be used to predict future disturbance (e.g., wildfire, hurricanes, heatwaves) and how ecosystems will respond.

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# 7

# PREDICTING AND PROJECTING CHANGES IN BIODIVERSITY AND ECOSYSTEM SERVICES

## *What is needed to predict changes in biodiversity and ecosystem services, and to provide managers, stakeholders, and the public with the best possible information and tools with which to make environmental decisions?*

## Key Points

- Because the natural systems upon which humans depend are undergoing unprecedented change, the ability to forecast change over multiple time-scales and provide decision-makers and other stakeholders with relevant information and tools is more important than ever.
- Remote sensing plays a key role in forecasting the dynamics of many terrestrial and marine systems; however, the discipline of ecological forecasting is still young and further development is needed to fully extract the value in NASA's data for the benefit of society.
- Forecasts need to be produced in coordination with stakeholders and with consideration for how forecasts are used and interpreted; to date, incorporation of stakeholder needs into forecasting tools has lagged behind basic science advances.
- Iterative forecasts, which are updated as new observations become available, provide a powerful opportunity to improve environmental decision making, accelerate basic research, and adaptively refine management and monitoring efforts.
- Forecasting models have not yet taken full advantage of multisensor data (e.g., Lidar, thermal, microwave, hyperspectral) or of fusing remote sensing with *in situ* observations.

- NASA should facilitate advancement toward the next generation of forecast models, especially models with more explicit mechanistic bases.
- NASA should support development of shared, sustainable, community cyberinfrastructure to facilitate ecological forecasting research and operations.
- NASA should facilitate broader collaboration on research teams by including social scientists and fostering development of a forecasting Community of Practice.

## 1. IMPORTANCE

As established in the preceding chapters, humankind relies on the function and diversity of natural systems to flourish. At the same time, we are in an era of unprecedented environmental change. It is therefore critical to go beyond just understanding how and why natural systems are changing. We need to provide managers, stakeholders, and the public the best possible information with which to make decisions about anticipated changes before they occur. In other words, we need the capacity to forecast change. Development of ecological forecasts leverages existing scientific knowledge, but also requires continued question-based or hypothesis-driven science to fill gaps in our forecasting capacities. By continually confronting forecasts with new observations, we can iteratively refine our understanding, test hypotheses, and improve forecasts while simultaneously meeting the needs of society.

Clarity requires consistent terminology. This chapter adopts the definitions used by Clark et al. (2001) and Dietze (2017a), who define **predictions** as quantitative estimates of a future state based on current understanding, data, and conditions (e.g., a weather forecast). **Projections** include scenarios and/or decision alternatives for at least a subset of inputs (e.g., climate projections under different emissions scenarios). **Forecasting** is used as an umbrella term encompassing probabilistic predictions and projections. **Forecasting** time scales include near-term forecasts, which are daily to decadal and can include either predictions or projections, and long-term forecasts, which are multi-decadal to centennial and always projections.

This section focuses on cross-cutting challenges surrounding the provision of decision-relevant information and explicit ecological forecasts. Specifically, we provide the conceptual framework and vocabulary necessary for cross-cutting activities that will enable society to take appropriate actions to address the current unprecedented scale of environmental change. Every day, individuals, companies, and governments make countless decisions related to managing and conserving biological diversity. Major policy and regulatory decisions also require information on biodiversity and foresight into future environmental change (e.g., water quality, nutrition, pollination, land- and seascape design, etc.). Ecological forecasts will allow us to answer decision-relevant questions, such as: Will a distinct and beneficial ecosystem service, such as pollination or water quality, change if a specific action is taken by a particular industry or government sector? Will possible changes in biodiversity due to a natural process affect ecosystem function and services or lead to the loss of an important ecological or commercial species? How are ecosystems likely to change on a sub-seasonal, inter-annual, and long-term basis and how does this affect when and where specific conservation and management options (e.g., restoration, invasive species management, bycatch avoidance) will be most effective?

Examples of ecological forecasts exist in virtually every part of ecology and for every kingdom of life, spanning terrestrial, freshwater, and marine systems and covering ecosystem processes (e.g., productivity, carbon pools, water quality, biogeochemical rates) and population/community dynamics (e.g., threatened and endangered species, harvesting and bycatch, invasive species, restoration, zoonotic disease, plant pests and pathogens, microbiomes, etc.). Given this, and the extensive discussions of biodiversity research needs in previous chapters, this chapter does not focus on prioritizing specific forecasting topics, but rather on development of the forecasting community as a whole.

Forecasts embody our best quantitative estimates of possible futures, under the *status quo* or different decision scenarios. They are based on mathematical representations or models that synthesize our understanding of past patterns, experiments, and theory. Most are not simple, linear functions of easily observable variables. Furthermore, the predictive skill and accuracy of models typically is highest when the observations being incorporated are quality-assessed and fit for use.

To be useful in guiding decisions, forecasts also need to be communicated clearly. Some forecasts may need to incorporate decision scenarios to provide actionable alternatives to the *status quo*. This means the science underlying forecasts also needs to be clear and understandable to be considered credible by (often) non-scientist policymakers, managers, and the general public.

Ecological forecasts have frequently focused on longer time scales, which often differ from the time scales of actionable policy (e.g., a term of office). While global policies respond (somewhat) to long-term, large-scale projections, and the long-term is important for strategic planning in conservation and management, most decision-making focuses on near-term issues and can occur at scales from global all the way down to individuals. Because of this, iterative ecological forecasts, which provide continually updated actionable predictions about changes in ecosystems and their services, are an emerging area of research and development. These near-term predictions, alone or combined with projections under alternative management scenarios, allow society to anticipate challenges on decision-relevant timescales, adapt to change (including changing conditions, as well as improvements to information used in forecasting), and improve decisions at all scales (from individual citizens to nations). One of the appealing features of iterative methods is they have a continual feedback loop of testing and learning built into the forecasting process (e.g., assimilating real-time NASA data to validate the most recent forecast and refine the parameters and initial conditions for the next forecast). Regardless of timescale, forecasts are most useful when they can directly inform specific decisions and are easily falsifiable. Finally, forecasts are generally more impactful when they also connect to policy priorities. For example, the White House's Fiscal Year 2021 Administration Research and Development Budget Priorities identified Earth system predictability as a high-level national priority that "will enhance the nation's economic vitality, national security, and environmental quality." Forecasts are also needed to help address the UN Sustainable Development Goals and Convention on Biological Diversity.

Below, we discuss the current state of knowledge related to ecological forecasting, focusing on linking data to models and how these models support stakeholders, before turning to key future needs. Key needs include new observational capacities, as well as more theory and analytical frameworks and experimental approaches. Also critical is the need for capacity building and establishing partnerships across a broad societal spectrum. The section closes with a list of important considerations for NASA.

## 2. CURRENT STATE OF KNOWLEDGE

Most ecological models in wide use have been developed over the course of decades, and almost all models that have the capability to predict biodiversity (Chapter 3), or address questions of biodiversity and ecosystem function (Chapters 2 and 5), are based on a long history of ecological research going back decades. However, reliable and useful forecasting depends on several key factors beyond just good models and data, as enumerated below. First, forecasts are sensitive to the latency of data used by models (i.e., the lag between data collection and availability), with the impact of latency dependent on the relative rate of the phenomena being studied. Forecasts may also be sensitive to periodic gaps in data (e.g., from cloud cover). Second, quick and efficient communication of forecasts (especially for short-term predictions or projections) strongly affects the likelihood that forecasts will be actionable. Third, forecasts also need to be open and trustworthy. Openness and rapid publication of data, methods, documentation, code, and results facilitate the vetting of models and data products, enhance collaboration, and enable better iterative refinement. Open science also enables greater input from stakeholders to ensure the right information becomes available at appropriate time intervals. Finally, many forecasts need to assimilate data from across many sources, ranging from community science and crowd-sourced observations to satellite imagery. This requires robust data ingest pipelines whose characteristics include: reliable access to interoperable observations with quantified uncertainties, interchangeable data formats, detailed metadata, well-documented provenance and traceability (including versioning options to enable reproducibility of earlier versions), and the ability to incorporate new data streams with low latency.

While current models have proven to be informative, our capacity to forecast needs to evolve in response to: 1) our changing understanding of drivers of biodiversity (Chapter 3) and advances in understanding functional, genetic, and phylogenetic diversity, in addition to species diversity, 2) new data streams able to better characterize ecosystems, and 3) the changing needs of stakeholders to manage Earth's ecosystems and adapt to changing threats.

## Drivers of Biodiversity

As detailed in previous chapters (e.g., Chapter 3), the drivers of all forms of diversity are complex and not fully understood. Readily available and widely used climatic, topo-edaphic, land use/land cover, and aquatic (freshwater, coastal, and ocean) habitat drivers have proved important for describing biodiversity patterns, but to forecast biodiversity change we need to better understand the mechanisms underlying these patterns. As new data emerge and models are improved, it is highly likely the patterns in our forecast errors will identify flaws in current theories, raise new questions, and drive innovation in basic science.

## Bringing Data to Models

An important bottleneck to improved forecasting is that current models have not leveraged the full range of data available to characterize biodiversity. Since the Landsat era began in the 1970s, characterization of biodiversity (and Earth system processes in general) has mostly been based on indices (such as NDVI and ocean chlorophyll), variability in those indices, or image classifications, all derived from multispectral imagery such as Landsat or MODIS. However, historical bottlenecks in data processing infrastructure have limited the ability to integrate these data into forecasts, and while this has improved considerably in recent years, data integration will take time and infrastructure access and training is still not universal. Furthermore, a range of exciting new technologies currently in space or soon to be deployed already offer and will continue to expand ways to characterize life and its functioning. Although some of these are covered in other chapters, there may be emerging approaches that can bring other biodiversity characteristics into view or may be useful as inputs to models.

A key reason efforts to incorporate remote sensing measurements into models have been uneven is because of the challenge of translating raw physical quantities from multiple remote sensing instruments into harmonized quantities useful to biodiversity/ecosystem models. Specifically, there is the need to translate data from new measurements, including SAR, TIR, imaging spectroscopy, Lidar, and SIF, into biodiversity-specific information usable in forecasting models, whether for estimating input parameters/drivers or evaluating model outcomes. There is a pressing need for basic research to understand what elements of biodiversity are captured through the incorporation of these new measurements. Likewise, basic research is still required to make use of additional data sources that might also serve to parameterize next-generation models. In addition, these efforts rely on the accumulation of field data for model calibration and ground-truthing. Moving forward, it is worth acknowledging that integrating remotely sensed data streams into models follows two general approaches: (A) translation of raw observations (e.g., radiance) into biologically meaningful quantities (Leaf-area index (LAI), canopy, or phytoplankton functional traits) that can be used as inputs into models or compared with model output; or (B) translation of a modeled quantity into the domain of remote sensing observations (e.g., translate modeled LAI into predicted spectral reflectances through radiative transfer models; Shiklomanov et al. 2021). While the former approach is currently much more common, the latter is often more internally consistent, allows data to constrain models more directly, and frequently provides greater transferability to new sensors.

Finally, we also need suitable forecasting models that utilize biodiversity data, as well as our knowledge of how biodiversity affects ecosystem processes. For example, Earth system models simplify the biological functional diversity of all trophic levels (e.g., representing vegetation in terms of plant functional types (PFTs)). This approach is insufficient to properly represent ecosystem behavior with respect to climate dynamics (Fisher et al. 2018; Fisher and Koven 2020; IOCCG 2020). If remote sensing data were to better characterize within-site, within-landscape, and/or within-region heterogeneity (e.g., functional diversity, edaphic variability), we may be able to better capture temporal, as well as spatial, dynamics in forecasting models and generate less-uncertain estimates of ecosystem function and services to decision-makers, as well as to the general public.

## Needs of Stakeholders

Core constituencies consuming ecological forecasts and/or using decision support tools include government agencies at local to national scales, and nonprofits and industries with an interest in natural resources, public health, security, sustainability, and/or regulatory compliance. In addition to these core constituencies, some forecasts engage a larger but more diffuse group of end users, such as individual fishers responding to daily fish bycatch maps or community members responding to warnings about harmful algal blooms. Forecasting aimed at informing decision-making raises a number of important questions that go beyond basic science: Are our models forecasting the response variables most critical to a range of stakeholders? Do the spatial and temporal scales and resolutions at which we can make skillful predictions match the scales stakeholders need? Is this information being presented in ways that are accessible to end users? Are the time lags in our ability to produce forecasts (in terms of data lags in operational forecasts and in the time needed to develop new forecasts) too slow to respond to stakeholder needs? Forecasts generated by current models (either raw output or high-level derived products) do not always provide managers with the measures or metrics they need. Efforts are needed to translate forecasts into value-added information that stakeholders can use directly without further processing, or alternatively, to reformulate forecasting models to produce information usable by managers.

Tools currently used by stakeholders include heuristic models, mechanistic models, and purely data-driven models. However, most forecasts are not yet fully utilizing NASA data across the forecasting process (e.g., model development and calibration; forecast validation and verification; model initial conditions, drivers, and covariates; constraints within iterative data assimilation) and many forecasts make no use of any NASA data. There are many reasons for this, including: a desire to maintain continuity with existing tools; unfamiliar formats; limited funding for translating research into operations; real and perceived barriers to entry for using newer NASA data; new approaches not having reached sufficient maturity (e.g., NASA Application Readiness Levels); or gaps in the basic research connecting new data to forecasts. Overall, an important process where NASA can focus efforts (on its own or in coordination with other agencies) is in providing mechanisms for research to be guided by stakeholder needs and for collaborations to foster feedback between applications and research. This will promote the iterative development of ecological forecasts. We need to better identify the range of forecasts and decision support tools needed by stakeholders (e.g., through boundary organizations, listening sessions, surveys/market research) and to better engage them in the coproduction of forecasts from an earlier stage in the development cycle. Adopting a new model toward meaningful stakeholder engagement that focuses on stakeholder priorities, objectives, and capacity at every stage of a

**Box 7-1:** Forecasting Essential Biodiversity Variables.

Although papers and reports have broadly laid out the numerous opportunities for ecological forecasting to promote ecological research and environmental management (Dietze et al. 2018; Groom et al. 2019; Muelbert et al. 2019; Bradford et al. 2020), an important opportunity at the intersection of the NASA Biodiversity and Ecological Forecasting programs is to specifically target development of forecasts for the Essential Biodiversity Variables (EBVs). As noted in previous chapters, the GEO BON EBVs represent an emerging international consensus about monitoring priorities. Effective biodiversity management in the twenty-first century will require moving beyond just monitoring the EBVs to making iterative predictions about how they will change under the status quo and projections about how they might respond to different management and policy interventions.

forecasting project, from inception to product delivery, is needed to ensure forecasting products directly meet stakeholder needs.

## 3. WHAT IS NEEDED

Building on the Current State of Knowledge discussed in the previous section, this section discusses the observations, capacity building (human and technological), analytical tools, theory, experiments, social science, and partner engagement needed to improve ecological forecasting and decision making around biodiversity. Within these areas, long-term projections and iterative near-term predictions, projections, and decision-making are addressed.

### Observations

Remote sensing observations play an essential role in forecasting many terrestrial and marine systems. One reason why is that forecasts and decisions frequently consider larger areas or extrapolations to areas beyond intensive field monitoring locations. By contrast, due to issues of scale, freshwater forecasts (e.g., rivers, small reservoirs) currently tend to rely less on remote sensing and more on *in situ* sensors than their terrestrial and marine counterparts.

Another key reason remote sensing is essential is that near-term forecasting places a high premium on low data latency (i.e., rapid data availability). The shorter the time scale of near-term predictions or projections, the more this is exacerbated (e.g., a forecast for tomorrow requires a lower latency than a forecast for next year). This focus on latency means there is a tendency to rely on sensor-based data over field- and lab-data, and a tendency to rely on agency and citizen science data over academic data, where there is a greater tendency to withhold data until publication (though open science efforts are improving this, for example, NASA's Transition to Open Science (TOPS) initiative).

Most ecological forecasts are also driven by meteorological data, but currently this is predominantly limited to near-term weather predictions (<16 days) and long-term climate projections (multi-decadal to centennial). There are important scientific and decision problems at subseasonal-to-seasonal (S2S) and interannual-to-decadal (I2D) timescales where ecological forecasts are not being produced because of limited availability of meteorological forecasts as drivers. At longer time scales, improvements in S2S and I2D meteorological forecasts (e.g., ENSO) would immediately benefit ecological forecasting. Although this is a national priority, and large investments are being made, we are still years away from the next generation of these forecasts becoming operational.

Beyond meteorological drivers, forecasting any ecological process requires an ability to forecast the covariates used to predict that process. NASA's Ecological Forecasting program might benefit from considering what covariate forecasts are most commonly needed by other downstream forecasts (e.g., an ecological forecast of biodiversity may depend on another ecological forecast of habitat change as an input). Supporting the development of such covariate forecasts may thus amplify the impact of the program.

The use of remote sensing in current ecological forecasting efforts is predominantly focused on multispectral inputs. However, looking forward there is a huge, underdeveloped opportunity for the assimilation of multisensor data (Lidar, thermal, microwave, hyperspectral, etc.) and multi-sensor fusion between remote sensing and *in situ* sensors and observations, particularly when it comes to biodiversity conservation (Myers et al. 2021). The barriers to implementing this immediately have more to do with awareness, training, data delivery infrastructure, and funding/incentives than methodological constraints, although there are still statistical data fusion challenges that need to be better addressed (Dietze 2017a; Fer et al. 2018; Zipkin et al. 2021). There is also an underexploited opportunity to leverage high temporal resolution data within forecasts, such as geostationary satellites (e.g., NOAA GOES 5-min temporal resolution), the fusion across multiple lower-frequency satellites (MODIS, VIIRS, Landsat, Sentinel), and commercial smallsats (e.g., Planet), drones, and airborne platforms. High temporal resolution data are particularly valuable for iterative forecasting and for detecting natural and anthropogenic disturbance events. While the importance of fusing data across scales has been noted (Chapter 5), the iterative model-based assimilation methods highlighted in this chapter provide an important opportunity to improve how model-data fusion is done.

As noted in Chapters 2 and 3, data on species distribution, abundance, diversity, and ecosystem services cannot be remotely observed for many taxa, particularly microbes, most animals, and higher trophic levels. To develop a large-scale understanding of the consequences of drivers, such as climate, weather, and land use, which in many cases are detectable by remote sensing, we must improve the availability of ground-truth field data at large extents (spatial, temporal, genetic, taxonomic, phylogenetic). At longer time scales, there is an underdeveloped opportunity to leverage forecasts to guide *in situ* data collection; in particular, to improve our capacity for adaptive monitoring based on the predictions made by forecasts. Such systems could alter where, when, and what we measure in response to either forecast uncertainty (i.e., needs for additional constraint) or a divergence in predictions across models (which represent opportunities to test/refute hypotheses). From a remote sensing perspective, adaptive monitoring should include the ability to target specific locations and times using "taskable" satellites, as well as the ability to deploy crewed or uncrewed airborne sensors on demand. Similarly, forecast technologies can play a more active role in the deployment of new sensors or platforms, for example through Observing System Simulation Experiments (Zeng et al. 2020). Such simulations are used in other disciplines to deploy sensors but have not yet played a large role in improving the use of Earth observation data in ecological forecasts.

## Capacity Building

For many reasons, the status quo in ecological forecasting has resulted in construction of many "one-off," ad hoc forecasts when instead socio-technical coordination is needed (Dietze et al. 2018). A lack of coordination across forecast teams limits our collective ability to build broader technical capabilities (Fer et al. 2021) or a more general understanding of predictability. The lack of past technical coordination is understandable given the then nascent state of the field; when the NASA Ecological Forecasting program was launched in 2003, there was not yet a community to coordinate, tools to generalize, or forecasts to standardize. Continuing to develop and operate forecasts independently results in a considerable amount of redundant work because many forecasts share the same structures, data sources, and assimilation algorithms and have the same need for automation. Automation and system reliability also demand a level of expertise beyond the capabilities of most ecologists, representing a barrier-to-entry, and thus a barrier to growth, with a steep learning curve. Moving toward community cyberinfrastructure that supports reliable, fully operational systems (e.g., reusable, modular pipelines) would provide an important economy of scale and facilitate further theory development and technical innovation.

Looking forward to the near future, there are immediate steps NASA and others could take to begin acting in a more coordinated manner. First, efforts are emerging across the ecological forecasting community to come together, including: launch of the Ecological Forecasting Initiative (EFI, https://ecoforecast.org), a grass-roots consortium working to build and support a forecasting community of practice; recent and upcoming forecasting workshops by EFI, USGS, NEON, NCAR, GEO, and the Gordon Conferences; a growing number of organized sessions at major conferences (ESA, AGU, ASLO, AMS, etc.); and rapid growth in the number of ecological forecasting courses (academic year graduate courses and short courses). NASA representatives have participated in a number of these efforts but could play a more active role in supporting their growth and coordination.

Second, emerging from these efforts have been calls to establish community standards for the open archiving of new and existing ecological forecasts and associated metadata. Standards for model inputs and forecast outputs (and their associated metadata) would immediately facilitate the capability to do cross-forecast syntheses and make it easier for end users and third parties to use the forecasts generated by the community, as all forecasts would be available in a predictable format. Adherence to standards is also a prerequisite to developing reusable or interoperable tools or workflows. Standards would facilitate creation of community interfaces, visualization and decision support tools, APIs, and other tools for dissemination. It would also be easier to develop community archives for forecast products. As part of EFI's Research Coordination Network, a set of proposed conventions have been developed across multiple working groups (Dietze et al. 2021). We encourage NASA to participate in the development of community standards around ecological forecasting and adopt such standards moving forward in the forecasts it develops or supports.

Over the longer term, an open, robust, community-scale cyberinfrastructure is needed to support the accessibility and scalability of ecological forecasting approaches (Fer et al. 2021). Because the financial and technical cost of building and maintaining forecasting workflows are nontrivial, development of community tools would reduce barriers to entry, resulting in more forecasts being able to make the leap from prototype model to automated forecast to operational tool, in less time and at lower cost. Building and maintaining community tools will require community structures for providing coordination and direction to the development process (e.g., how will contributed code be evaluated and adopted) and employment of individuals dedicated to software maintenance.

Whether NASA takes a leadership role in these efforts or is part of a broader coalition supporting these tools (e.g., an interagency working group), the NASA community has a lot to contribute. First, NASA has already supported development of a large number of ecological forecast workflows that should be analyzed as part of the design process of any community tool (e.g., What worked? What didn't? What can be repurposed/generalized). Second, NASA's existing operational weather and atmospheric chemistry forecasting system (the GEOS model) and land data assimilation system (LIS) provide direct experience with the operational, iterative assimilation of NASA data products into complex modeling pipelines. Finally, NASA has considerable experience with cyberinfrastructure development at this scale (e.g., the DAACs, NASA Managed Cloud computing Environments (MCE), and High-End Computing (HEC) Program supercomputers) and more broadly, with the management of large projects at the interface between science and engineering.

One challenging problem in community forecasting cyberinfrastructure is that many ecological forecasts are of "medium" size. Small forecasts are ones that are low frequency and deal with low data volumes, and thus can persist without specialized workflows (e.g., they can be run manually). Large forecasts (e.g., numerical weather prediction) are supported by highly specialized, system-specific workflows that have dedicated staff and resources. The medium-sized problems that dominate ecological forecasting, by contrast, require nontrivial automation but rarely have dedicated staff and resources, and thus require sharable, reusable tools to spread across a community. Fortunately, examples of such tools, such as the PEcAn model-data informatics toolset (https://pecanproject.github.io/; Fer et al. 2021), are already developed and we encourage further such developments.

To work toward this goal of community cyberinfrastructure (CI), we encourage NASA to: (A) help build and support the community coalition required for the development and maintenance of shared tools (e.g., via workshops, working groups or other coordination mechanisms); (B) incentivize NASA ecological forecasting projects to use community tools; (C) consider setting aside a portion of its Ecological Forecasting portfolio to directly support community cyberinfrastructure development (e.g., through RFPs); and (D) include forecast CI costs as part of its ongoing budget, rather than just as a short-term proposal-driven investment, much like how the DAACs receive long-term support for data archiving and dissemination. Finally, forecast archiving is a critical part of any forecasting cyberinfrastructure, and it is important that forecasts adhere to Findable, Accessible, Interoperable, Reusable (FAIR) principles. Forecast archiving arguably falls within the scope of the existing DAACs or via partnerships. If nothing else, NASA should extend its current archiving approaches and capabilities to provide a persistent, automated archive for the ecological forecasts it supports.

Over the longer term, it is also important that community building efforts move toward the professionalization of ecological forecasting. This will need to include not only technical training, but also training in forecast ethics and social science (e.g., economics, decision science, sociology) and ultimately should lead to professional certification of individuals, as in weather forecasting. Professional certification will be a matter of liability and trust. Unlike in weather forecasting, currently anyone can produce and disseminate an "ecological forecast," regardless of qualifications or forecast quality. There is a need to clarify who/what entity has the legal authority (and responsibility) to produce various ecological forecasts (e.g., NOAA's fishery stock projections and harmful algal bloom forecasts). As ecological forecasting matures, broader societal discussions are needed about which forecasts should be public goods that are free to all (analogous to NOAA weather alerts) and which should be market-driven.

## Analysis

Analytical tools play a critical role spanning across the models used to make forecasts, statistical tools used to assimilate data into models, cyberinfrastructure that allows forecasts to be automated, and decision support tools that provide this information to decision-makers. Key areas where rapid progress is most needed include dynamical modeling, training, data assimilation, and uncertainty propagation.

**Dynamic Modeling:** Current ecological forecasts predominantly rely on static models that do not assimilate new observations—each new forecast is run with an updated set of drivers (e.g., new weather forecasts) but does not leverage observations about the state of the ecological system to improve forecasts of that system. For example, most current phenological forecasts do not adjust their predictions if observations suggest a transition (e.g., leaf fall) is running ahead or behind what the model forecasts. For some forecasts, the lack of data assimilation is due to data latency—currently, new observations do not become available fast enough to be useful to forecasts. In other cases, it can reflect a research tradition that has not yet embraced dynamic models (e.g., phenology threshold models, species distribution models) or a lack of familiarity or training in these methods.

**Training:** Few graduate programs in ecology offer courses in ecological forecasting and iterative data assimilation approaches. Methodologically, basic approaches to data assimilation have been in use in the physical environmental sciences for decades (e.g., weather forecasts) and have become increasingly accessible to ecologists (Dietze 2017a). NASA could work with organizations developing forecasting training materials, send researchers to existing workshops, support new training workshops, or help in the dissemination of online and blended course material. NASA could also support student exchanges so individuals on new forecasting projects can apprentice with experienced forecasters.

**Data Assimilation:** Most existing data assimilation (DA) algorithms are optimized to constrain initial conditions—not coincidentally, the exact forecasting problem faced in numerical weather prediction. But many ecological problems violate the assumptions of these algorithms, either because they are dominated by different uncertainties or the data or models are structured differently (e.g., a great deal of population data is discrete [counts], zero-bound, and zero-inflated, and often conflicts with the standard Gaussian assumption in DA approaches). Therefore, there is a need to develop new iterative DA approaches for ecological forecasts. Many DA approaches are inherently Bayesian (forecast prior is updated to an analysis posterior) and while general, flexible tools for Bayesian statistical inference exist (e.g., BUGS, JAGS, STAN, NIMBLE) that should facilitate algorithm development, in practice most do not yet support the iterative approaches to inference that, conceptually, is one of the key strengths of Bayes.

**Uncertainty Propagation:** Another near-term effort the community needs to undertake is more robust uncertainty reporting, accounting, and partitioning in data products and forecasts. Fundamentally, all approaches to combining models and data explicitly or implicitly weights each in proportion to its uncertainties. Therefore, for NASA data products to be incorporated into forecasts, not only do they need to include uncertainty estimates, but those estimates need to be robust. Currently, too few NASA data products used by the community include uncertainty estimates and many products with uncertainty estimates have systematic underestimates in uncertainty reporting (e.g., due to propagating only a subset of uncertainties or dropping covariances), leading to the data receiving too much weight and the overall forecast being overconfident. A common challenge of using geospatial data of all kinds (including remote sensing) is partitioning uncertainties into components (e.g., systematic bias, random error, spatially autocorrelated error) that allow them to be correctly aggregated in space and time. For example, if the error estimates in individual pixels are treated as random and independent, then reported uncertainties will quickly become negligible if one aggregates over larger areas. By contrast, autocorrelated errors average out much slower than random errors, and systematic errors do not average out at all at scale. There are multiple ways NASA could address these issues, but the simplest for most end users would be to increase production of ensemble data products. Ensemble error propagation methods are robust, and the training required to correctly propagate uncertainties with ensemble-based data products is accessible at the undergraduate level (i.e., apply any operation to each ensemble member individually, average across ensemble members as the last step). That said, ensemble approaches could further exacerbate the challenge of NASA's massive data volumes, which are on pace to increase rapidly.

On the forecast side, uncertainty quantification and propagation play a key role in ecological forecasting (and science more broadly), as uncertainties are central to how we interpret our analyses and predictions scientifically (e.g., hypothesis testing) and in decision-making (e.g., risk). Models that underestimate uncertainties will be given too much weight during data assimilation, which in the extreme case can lead to filter divergence—a forecast that becomes so confident in itself that it ignores (diverges from] any new observations. Scientifically, uncertainty partitioning involves breaking up the overall predictive uncertainty into the contributions from different components: initial conditions, drivers/covariates, parameters, random effects, and process error (Dietze 2017b). Within an individual forecast, this can then identify which uncertainties most limit predictability, and thus which uncertainties to focus further effort on reducing. To make an analogy, the discovery by Lorenz (1963) that the atmosphere is chaotic led to the conclusion that the dominant uncertainty in numerical weather prediction is initial condition error. This theoretical finding translates into billions of dollars of investment each year in monitoring and data assimilation technology that is fundamentally designed to minimize initial condition error. To date, ecological forecasting has progressed without even asking, let alone answering, which uncertainties dominate which forecasts. These analyses can help make monitoring and forecasting more cost effective and help better align forecast horizons with the temporal and spatial scales relevant to decision-making. Without this understanding, we are at high risk of poorly prioritizing efforts. Beyond practical monitoring needs, uncertainty partitioning also raises fundamental theoretical questions about our understanding of the predictability of ecological systems.

## Theory

While NASA's past Ecological Forecasting efforts have focused primarily on applications, there is a strong argument that ecological forecasting represents a key win-win for simultaneously responding to urgent societal needs for better environmental decision-making while fundamentally accelerating and improving basic science. If we adopt an iterative approach, where previous forecasts are confronted with new data and used to update our future forecasts (e.g., constrain parameters and states, refine model structures), then the process of making forecasts will accelerate the pace of science, helping us learn faster and reject hypotheses more quickly. Rather than fixating on rejecting null hypotheses, forecasts force us to make predictions that genuinely represent our current understanding of how systems work, while at the same time are specific, quantitative, and thus falsifiable. In addition, forecasting improves the quality of our science by making it more robust. Forecasting is essentially a form of preregistration—hypotheses about a system are locked in and recorded (preferably publicly) before new data are collected. At the same time, forecasting provides a degree of natural protection against overfitting. Unlike when all data are in hand and can fit any number of candidate models, it is much harder to overfit when being validated against something that has not happened yet. Those future data also provide out-of-sample validation, requiring us to test models against data different from those used to build the model. In many ways, forecasting thus forces us to confront the crisis of reproducibility head-on.

At a larger scale, predictability itself is emerging as a research interest in ecology (e.g., Petchey et al. 2015; Dietze 2017b). In this broader scope, overarching questions are being asked about why some ecological processes are more predictable than others and what are the characteristics of systems that help explain the patterns of predictability (e.g., biological traits, phylogenetic constraints, system interactions, abiotic environment). Key to answering many of these questions is development of sufficiently large sets of forecasts to allow researchers to perform comparative analyses that look at overarching patterns and test theories about overarching mechanisms. Key questions include: what are the relative contributions of different uncertainties to system predictability? how does predictability change across scales? and, how transferable are different forecasts across space, time, and system? Overall, comparative analyses of predictability will help us answer deep questions about the drivers of ecological dynamics and help us develop and refine theories that link different parts of ecology. When encountering new problems, these overarching theories and patterns also help us anticipate how to approach the forecasting problem and how to prioritize monitoring and modeling efforts.

NASA can play a key role in these within-system and across-system advances in ecological theory as it has funded, and continues to fund, a large number of ecological forecasts, and its data products serve as inputs to an even larger number of ecological forecasts. At a minimum, NASA's participation (if not leadership) in such syntheses is critical to its success. Beyond this, NASA has the authority to encourage (and possibly enforce) the open, FAIR archiving of forecast outputs and models/workflows as part of future RFPs, as well as to directly support proposals that engage in this type of cross-forecast synthesis. As noted previously, NASA also has considerable prior experience and infrastructure it could leverage in support of the standards, archiving, management, and cyberinfrastructure requirements that enable such theoretical advances.

## Experiment

While most ecological forecasts occur in observational systems, experiments still play an important role in forecast development, improvement, and use. First, there are a number of automated forecasts that have been run within experimental systems, such as the Portal long-term rodent exclosure experiment (White et al. 2018), DOE's SPRUCE experiment

(Huang et al. 2019), and drought experiments in the southwest (Redmond et al. 2019). These applications synergistically leverage the previously discussed theoretical strengths of forecasts (e.g., forcing specific, quantitative predictions about how the experiment will turn out) and the causal strength of experiments. Second, in an applied setting there is a deep, but currently underexploited, connection between forecasting and adaptive management and monitoring approaches (Dietze et al. 2018). In adaptive management, the experimenter takes an iterative 'learn as we go' approach that is deeply rooted in the idea of treating management and policy as experiments that help humanity understand how to manage systems sustainably. Adaptive management is highly synergistic with iterative forecasts—forecasts provide explicit predictions and projections of the likely outcomes under different decision alternatives, which are then validated by continued monitoring. Similarly, adaptive monitoring approaches use forecasts as a natural experiment, concentrating measurements at the times and places where either forecast uncertainty is high or where alternative forecast models diverge (allowing observations to refute at least one of the alternative hypotheses). Overall, NASA could more actively encourage incorporation of experimental manipulations, adaptive management, and adaptive monitoring into its forecasting portfolio.

## Social Science and Partner Engagement

A final set of challenges is related to the social and organizational components of research in this area. Previous sections showed ecological forecasting requires expertise in not only ecology, but also the physical and computational environmental sciences (e.g., informatics, statistics, data assimilation, cyberinfrastructure). In addition, most forecasts also require a collaboration with social and decision scientists, as well as partners, stakeholders, and end users. Forecasts that operate under the "if you build it, they will come" mindset, without active engagement with partners/users, are liable to fail due to lack of uptake and engagement. Best practices argue for a team science-oriented co-production approach to forecast development, with partners involved from day one in the specification of objectives, development of metrics, and generation of decision alternatives. Involving partners from the beginning is also critical to transitioning forecasts from an initial research phase into sustained operations. Many promising forecasting studies die in the gulf between research to operations (R2O), as this generally requires a hand-off in funding and support from one agency/organization to another.

The approach NASA has taken to funding Ecological Forecasting projects has greatly facilitated the R2O transition, as the partner organization must be specified as part of the proposal submission process. Despite the success of the *a priori* requirement for an organizational partner, it may also have unintended consequences, such as discouraging submissions from early career scientists, who rarely have an established network of relationships with non-academic partners as more senior scientists. Yet, early career scientists often possess the most cutting-edge technical training and greater capacity to dive into new topics/partnerships. NASA could promote mechanisms for pairing stakeholder forecasting needs with forecast researchers who have relevant skill sets, either on its own or in partnership with boundary organizations.

Beyond partners, forecast projects can also benefit from active engagement with social and decision scientists. Few ecologists are trained to know the ins-and-outs of how environmental decisions are made in practice, the theoretical basis for how to analyze decisions under uncertainty, or the cognitive biases and heuristics that may lead to their forecasts being misinterpreted and misapplied. Social scientists help us better understand who is using a given forecast, how their actions may change based on that forecast, and how these actions affect individuals. We cannot build "better" forecasts without a better understanding of the ways stakeholders engage with forecasts. Furthermore, some forecasts may require not just models and predictions about the natural system itself, but also forecasts about the coupled human-natural system. Other agencies, such as NOAA and USGS, have benefited from including social scientists on their forecast research teams. NASA could similarly work to ensure its Biodiversity and Ecological Forecasting RFPs recognize the value of interdisciplinary research teams and to build a portfolio that includes social and decision scientists on more research teams. For NASA's Ecological Forecasting RFP in particular, which already heavily emphasizes construction of decision support tools, we encourage clarifying that proposals should demonstrate familiarity, if not expertise, with the research and best practices in this area and that project management should include a plan for how user input will be solicited and how forecast usability will be assessed. Individuals with relevant expertise may include people trained in social sciences, such as economics, sociology, psychology, and decision-making, but also urban planners and engineers who focus on human-computer interfaces.

Finally, similar to earlier suggestions for community forecasting tools and cyberinfrastructure, NASA would also benefit from working with the community to build open, shared tools and best practices for decision support, forecast dissemination, and interactive visualization. Particularly valuable would be efforts to harmonize scenario tools with forecasting tools, so decision-support considering different management options (e.g., assisted revegetation, restrictions on use) can represent realistic ecosystem responses to those interventions. This would also enable a new generation of biodiversity and ecosystem service models that respond in more nuanced ways to changes in ecosystem condition (e.g., primary productivity, structural complexity), not just the areal extent of land use and land use change (Chapter 4).

# 4. CONSIDERATIONS FOR NASA

NASA already plays a major role in advancing ecological forecasting and is in a unique position to further guide and lead cross-cutting capacity building efforts for this still-young community. NASA generates science-quality data that are critical components of many models, either as direct inputs and drivers or indirect data constraints on model state variables or parameters. NASA data provide the basis for scenario-building at regional to global scales and the space-for-time data necessary to test scenario outcomes. NASA also has experience developing operational, reliable systems and has a mission-oriented focus that aligns with the goals of ecological forecasting and decision support.

NASA can support, via multiple mechanisms, the fundamental coordination needed between modelers, informaticians, and engineers, along with broader stakeholders that other agencies, such as NSF, are less likely to support. Still, many key drivers (e.g., species interactions), ecosystems (e.g., below ground and deep ocean ecosystems), and clades (e.g., animals) do not lend themselves well to direct measurement by remote sensing, although some may soon evolve (e.g., ICARUS, ocean Lidar missions). This implies that improving ecological forecasting requires more fundamental investigation (how biodiversity is related to things NASA can measure) as well as new, integrated data collection methods, both remote and *in situ*, tuned to drivers or measurements of biodiversity and ecosystem services.

The following recommendations, many of which are closely related, suggest key ways NASA can enhance the advancement and impact of ecological forecasting.

- **Lead development of the community tools, models, and cyberinfrastructure needed for the next generation of forecasts.** NASA can play a key role in facilitating the transition from "boutique" forecasting applications to an open set of interoperable community tools and applications. This would reduce redundant efforts across groups, lower the barrier to entry for forecasting teams (in terms of costs, technical expertise, and time to deployment), increase reliability, reduce maintenance costs, and facilitate transitions from research to operations. Specifically, this next generation should feature:
  - Automated repeatable forecast workflows
  - Data products with well quantified uncertainties
  - Data assimilation

- Iterative model refinement
- Explicit uncertainty accounting
- A shared clearinghouse for modeling, dissemination, and visualization tools
- Standards (e.g., NASA should require its funded projects to meet FAIR principles)
- Archiving of and shared access to forecast outputs and models/workflows
- Coordination between NASA's Research, Applied Sciences, and ESTO programs for synergistic calls for proposals to facilitate these enhancements

- **Train the next generation of ecological forecasters.** As a developing discipline, training in ecological forecasting approaches is critical. This includes the more tangible aspects of scientific and technical training in, for example, ecology, system modeling, and data science. However, the next generation of forecasters will also need to adopt more of a team science approach to support true system development, so there is a social as well as technical component to developing the needed capacity (Farrell et al. 2021). NASA should actively support both types of training (e.g., through FINESST and other solicitations).
- **Strengthen and broaden connection to end users, particularly decision-makers.** Connectors to organizations with mandates to report at the national and international level can ensure forecasts are broadly disseminated, related to societal targets and goals, and well-utilized. Building on a record of successful stakeholder engagement in the Applied Sciences program, NASA should support and promote the use of forecasts in adaptive management and monitoring, ensure early user engagement to enhance translation to stakeholders, and promote mechanisms for pairing stakeholder needs with researchers. Product formats and tools must be appropriate for use by decision-makers. To achieve all of this, NASA needs to support the inclusion of social and decision scientists on research teams.
- **Support activities that focus on forecasts that are explicitly process- and mechanism-based.** NASA should support: 1) the study of biodiversity-ecosystem relationships at broad scales using remotely sensed data with a focus on incorporation of key facets of biodiversity that can be described mechanistically, and then, 2) incorporating those findings into models, in particular toward the goal of better mechanism-based ecological forecasting. This should include

developing quantitative forecasts for experimental manipulations before and during their operation, rather than *post hoc*.

- **Support efforts to build a community of practice around ecological forecasting.** This involves all of the above-mentioned elements where NASA can play a convening role and help develop core community needs and approaches.

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# 8

# DISCUSSION OF CONSIDERATIONS FOR NASA

The preceding six chapters explore various aspects of biodiversity, the role of remote sensing, and its application to decision-making. They explain the various ways in which biodiversity is important (Chapter 2), discuss its origins in the context of environmental, evolutionary, and human societal drivers (Chapter 3), and explore the interaction between humans, biodiversity, and the benefits humans derive from biodiversity and the ecosystems it supports (Chapter 4). The multiscale nature of biodiversity and its implications in understanding and monitoring it were examined (Chapter 5), and the importance of ecosystem resilience and the challenges associated with understanding how ecosystem functions and services respond to and recover from disturbance were described (Chapter 6). Finally, drawing from these earlier chapters, the role and importance of ecological forecasting, modeling, and the challenges and areas needing enhancement to better support forecasting and decision-making was outlined (Chapter 7).

Each chapter's Considerations for NASA outlines a range of ideas with the potential to enhance the impact of the Biological Diversity and Ecological Forecasting program elements over the coming decade. Taken together, these sections provide context and a body of insight into the role NASA can play in understanding, informing responsible management, and protecting life on Earth.

This chapter distills the 45 Considerations for NASA into six overarching themes:

- **Partnership and collaboration on biodiversity activities**
- **Biodiversity observations from space**
- **Biodiversity observations *in situ***
- **Biodiversity data products**
- **Biodiversity and ecological modeling and forecasting**
- **Capacity for biodiversity research, applications, and monitoring**

These themes provide a top-level perspective on the Considerations for NASA, thus highlighting and helping to communicate the most common ideas from the report. This will aid in understanding, exploring, and incorporating the Considerations as the program elements, and NASA as a whole, plan for the next decade. Six overarching themes cannot cleanly capture all the ideas from the chapters, so a complete list of the individual Considerations is included in Appendix C.

## Partnership and Collaboration on Biodiversity Activities

> *Seek out and support complementary partnerships and collaborative activities to advance utilization of remote sensing for biodiversity research and its application for societal benefit*

Every organization, including NASA's Biological Diversity and Ecological Forecasting program elements, focuses on its areas of expertise. Understanding and protecting Earth's complex web of biodiversity and how humans interact with it requires expertise and activities in a wide range of areas, including those that lie outside the boundaries of these programs or NASA as a whole. This has become increasingly true as science knowledge, as well as the threats to biodiversity, have increased. Complementary partnerships and collaborations—including those with the social sciences—can expand program reach and increase impact. NASA should consider ideas such as the following, many of which are related:

- **Collaborative problem solving.** Enhance collaboration with organizations outside NASA or among programs within NASA by actively funding projects of mutual interest. For example, NASA could create collaborative teams to ensure a holistic, multidisciplinary approach to solving carefully selected problems, many of which are discussed in this report. These could be addressed via coordinated solicitations that involve other NASA entities, other agencies (e.g., NOAA), or other organizations. This would enhance partnerships and lead to future collaborations and, ultimately, increased impact. Multi-disciplinary teams could include social scientists, ecologists, evolutionary biologists, natural resource managers, and other non-remote sensing scientists—groups typically outside of NASA's "traditional" users—yet whose participation is now essential to understanding, managing, and protecting life on Earth.
- **International collaboration.** International collaboration can increase impact by broadening the pool of scientists, users, and challenges that remote sensing can address. Working more closely with other space agencies or programs, perhaps through the Committee on Earth Observation Satellites (CEOS), could help fill gaps in space-based observations and data products. Currently, biodiversity has a very minor role in CEOS.

- **Integration.** Maximizing the impact of remote sensing for biodiversity science and conservation requires working with a range of ecological realms, data sources, and users. However, bringing these often disparate pieces together is challenging. For example, terrestrial, marine, and freshwater ecosystems interact and should be studied together and, similarly, natural ecosystems are profoundly affected by humans and should be studied along with socioeconomics. NASA Interdisciplinary Research in Earth Science solicitations, and joint solicitations with other organizations, may be useful vehicles for addressing these areas.
- **Ties to end-using organizations.** More ties with, for example, U.S. land management agencies, would help prioritize development of appropriate products and tools, as well as increase user awareness of current capabilities and help ensure transfer of value (particularly, useful and usable products) to these stakeholders.

## Biodiversity Observations from Space

*Ensure the continued availability of biodiversity-relevant observations from space.*

The use and importance of observations from space to understand biodiversity, how it is changing, and how society should respond is rapidly expanding. It is essential that these observations not only continue to be available but also that new technology expands their quality and scope. As threats to biodiversity and the services it provides to humans increase, this availability becomes even more important.

- **Long-term continuity.** NASA, along with NOAA and USGS, must ensure long-term observational records. A consistent observational time series is essential to monitor change over time and the variables being monitored must be consistently calibrated and processed so actual change can be discriminated from artifacts due to differences in observational source or data processing.
- **New technology.** Continue to explore new remote sensing technologies to expand the range of information available; this should be done in coordination with other space agencies (e.g., via CEOS). As new technology becomes available, it should be put into space. Currently, global repeat Lidar data are not available or firmly planned.
- **International coordination.** Many countries collect satellite data; coordinating with them can enhance and further harmonize the long-term observational record and the development of integrated data products. CEOS has an important role to play in that coordination.

- **Open access.** NASA must continue to demonstrate and promote the benefits of free and open access to observations and data products. Not only did opening up the Landsat archive in 2012 enable game-changing time series analyses but it was a model for other agencies and programs. CEOS has an important role to play in open access.
- **Value of remote sensing to society.** The value to society and its dependence on space-based observations must be continuously demonstrated. This requires active public outreach beyond scientific publications and meetings. NASA Public Affairs and Media Offices need to be aware of successes, and solicitations could require some type of outreach activity.

## Biodiversity Observations *in situ*

> *Improve* in situ *observations so they can better support understanding biodiversity from space.*

In general, biodiversity cannot be observed directly from space; instead, observations are correlated with *in situ* data to infer what is happening on Earth. Thus, it is hard to overstate the importance of *in situ* observations to NASA's Biological Diversity and Ecological Forecasting program elements and there are significant benefits to enhancing their variety, resolution, scope, quantity, and quality. The focus should be on species diversity, abundance, and distribution, and on ecosystem physical structure and function, but related environmental and socioeconomic drivers are also important. Pathways for NASA to consider include:

- **Partnerships.** NASA is already partnering with Conservation International and has supported the Marine Biodiversity Observation Network (MBON). Such partnerships should be expanded to include a broader range of organizations so as to increase the amount, value, and impact of the *in situ* data available. A coordinated, multi-organizational approach would be ideal, potentially facilitated by GEO BON.
- **Guidance from models.** Models can be used to develop *in situ* data collection strategies and guide decisions about where to invest the most time and effort. For example, models can help identify which variables are most important and which most need improvement.
- **New observational technology.** NASA is a world leader in technology and system development. This expertise should be used to enhance *in situ* data collection systems and networks, for example by collaborating with the NASA Earth Science

Technology Office, organizations that collect *in situ* data, and perhaps the private tech sector. Increased automation of *in situ* monitoring systems is a top priority.

- **Standardized protocols and formats.** Data providers often use different collection protocols and provide data in a variety of formats, making data from different sources difficult to combine. Standards enhance usability, accessibility, and scalability. NASA, in collaboration with other organizations, could encourage wider use of standards or enforce such standards for NASA-funded projects.

## Biodiversity Data Products

*Provide more higher-level data products, increase their breadth, and enhance their discoverability and usability.*

Many of the higher-level data products biodiversity users need are not available because missions often stop processing at Level 2 (MODIS is an exception). Landsat, for example—perhaps the most widely used remotely sensed collection in the world—currently supports only four Level 3 products. More broadly, although tools used to find and access data products have improved, their ease of use often remains limited, thus preventing extraction of the full value inherent in NASA's observations. Steps to consider include:

- **Landsat products.** Generate a suite of Landsat products similar to those provided by MODIS. Researchers need 30 m resolution data to understand finer-grained patterns and processes than those accessible from the much coarser MODIS data.
- **Research-to-operations.** Move more products from the research realm to operational standard product status; to feed that process, support development of more higher-level product algorithms.
- **Formats.** Data formats are often a barrier to utilization, particularly for some stakeholders, such as environmental decision-makers, so data formats should include those that allow broadest use. Additionally, the concept of Analysis Ready Data (ARD) should be broadly applied—ARD simplifies data utilization by, for example, providing radiometrically normalized and co-registered data that can directly support time series and change analysis.
- **Standards.** Data and data products come from many sources and often differ in ways that complicate utilization, particularly for time series, change studies, and generation of multi-source data products. Standards help address this problem and also facilitate multi-source data harmonization. NASA should promote, and perhaps enforce, product standards; for example, solicitations could include standards requirements on output products.

- **Multi-source integration.** By incorporating complementary information, multi-source products can provide insights that are otherwise not available. For example, optical and radar data characterize different aspects of forests and together provide a more complete picture of forest status. NASA should facilitate development of more products that integrate data from multiple sources, including space-based sensors as well as *in situ*, socio-economic, and model data.

## Biodiversity and Ecological Modeling and Forecasting

> *Enhance and utilize models to forecast biodiversity change and its impacts, guide decisions and policies, and facilitate research.*

Models and forecasts are essential to decisions and policy-making. For example, forecasts can paint a picture of the future trajectory of climate and land use change and their impacts, and thus guide adaptation planning and policy. Forecasts can improve decision-making by helping users assess the potential outcomes of alternative decision or policy options, and models also have a key role in research, such as in understanding ecosystem assembly or function. NASA can help enhance modeling and forecasting capabilities in a variety of ways, including:

- **Community-scale cyberinfrastructure.** The forecasting community lacks an appropriate cyberinfrastructure within which to develop and share its work, limiting operationalization and use of forecasts for decision-making. Examples of steps NASA could take include encouraging development of community tools through solicitations and providing post-project support for forecasting capabilities to ensure their use and maturation beyond the typical lifetime of a project.
- **Forecast output standards.** Output standards are essential for cross-forecast syntheses, reusable workflows, easy access by third party users or tool developers, and useful archives that support forecast reuse in a manner analogous to image archives. Development of these standards would increase the value of NASA's data and the forecasts that use it.
- **Uncertainty quantification of outputs.** Because their reputation depends on making good decisions, decision-makers need to know how "good" a forecast is for it to be useful in the decision-making process. NASA should support efforts to improve quantification of uncertainty associated with observational and forecasted data products; this will build end user confidence and increase use of forecasts for decision-making.

- **Uncertainty quantification of inputs.** The uncertainties of the observational products used as inputs by forecasting models is of inconsistent quality. NASA should improve the uncertainty quantification of these observational products so as to improve the uncertainty associated with the resulting forecasts.
- **Role in integration.** Integration across scales, ecological realms, sensors, and datasets is important for understanding biodiversity and providing impactful information for managers. For example, creating maps of species distribution utilizes models to combine remote sensing and *in situ* data. While such models for species distribution are now commonplace, new models are needed to integrate information in other areas.

## Capacity for Biodiversity Research, Applications, and Monitoring

> *Support capacity development to increase utilization of NASA observations and biodiversity-relevant products.*

Remote sensing largely remains an area of specialization that is outside the repertoire of many potential users, limiting its impact, and thus the value extracted from NASA's data. NASA can address this challenge in a variety of ways, including:

- **Training.** Continue to increase the skills of users who lack a background in remote sensing, such as through the excellent training offered by the NASA ARSET program.
- **Intuitive tools that facilitate application.** In addition to user training, an organization's capacity and impact can be increased if they have access to tools that enhance the ability to find and apply data. Examples include visualization tools, as well as software tools that can generate derived products.
- **Early career scientists.** Continue supporting the development and engagement of early career scientists and scientists from under-represented groups to ensure continuity and expansion of expertise into the future. The NASA FINESST, NASA Post-doctoral Program, and NASA New Investigator Program are all excellent current examples of this type of support.
- **Undergraduate and graduate.** Continue to support undergraduate and graduate student research, such as through the DEVELOP program.
- **Early start.** Inspire students in the classroom and elsewhere, at all levels, as is done for the planetary realm; inspire students to ask for more. For example, convey the message that every pixel is actually a biological observation that can

be used to understand how life on Earth is changing—this will help mainstream the use of satellite images to solve scientific and societal problems.

These six overarching themes consolidate the Considerations developed by the expert working group. The complete list of Considerations from all chapters is provided in Appendix C.

## Conclusion

Chapters 2 through 6 explore six key areas of direct relevance to NASA's Biological Diversity and Ecological Forecasting program elements. Each explains why that area is important and how it is relevant to NASA and to human society. The discussions on the current state of knowledge—what we know and what we don't know but need to know—puts each area into a more comprehensive context and provides the basis for the Considerations for NASA summarized here. These considerations provide important inputs to the Biological Diversity and Ecological Forecasting program elements as they, and NASA as a whole, plan for the next decade.

The timing of this report is particularly relevant as it coincides with decadal planning for NASA Earth Science and the UN Convention on Biological Diversity—as well as a decade that will offer continuing threats to biodiversity and ecosystem services. NASA's Biological Diversity and Ecological Forecasting program elements, along with other programs at NASA and elsewhere, have a critical role to play in monitoring biodiversity and facilitating the use of remote sensing for understanding, managing, and protecting life on Earth in this period of change.

# Appendix A

## WHITE PAPER SOLICITATION

# NASA Biological Diversity and Ecological Forecasting Programs: White Papers on Important Questions

The NASA Biological Diversity and Ecological Forecasting programs have established a Working Group to support development of a report exploring the questions, challenges and opportunities for these programs over the next decade. The purpose of this report is to:

- Collect community input
- Identify the key scientific and applications questions relevant to the programs
- Suggest programmatic approaches to achieving these questions
- Convey (to all stakeholders) what these programs do

The report will be developed by a small and diverse group of experts based on input from the broad community. A key component of that input will take the form of brief "White Papers." Although each of these is limited to a single page they are intended to reflect deeper thinking; the single page format will facilitate focused responses and will enable the group to assimilate the many submissions expected.

*The core of the report will consist of a small number of key, overarching questions that the two programs could address to advance the understanding and conservation of life on this planet.* Each question will be annotated with supporting information such as why addressing it is important, what observations and data products are needed, and the likely challenges.

*We are soliciting your ideas for these key questions.* Please use the attached template. You are welcome to submit more than one White Paper but **please limit each paper to only one question**.

Note also the following guidelines that define the "Parameter Space" within which your submissions should stay. This is important because the questions and how they are addressed need to be something NASA to which can respond.

### White Paper Parameter Space

This parameter space provides the context within which the programs operate.

- NASA data: Because these are NASA programs their work must utilize NASA observations and model outputs
- Ecosystems covered: terrestrial, freshwater, and marine
- Biodiversity levels: ecosystems, species, and genes
- Impact: Each question should be central to our understanding of the natural world; for more applied questions, addressing them should lead to better decision making, management, and policy
- Risk: Thinking Big is good and thoughtful risks are fine and encouraged; high-risk activities may not make good candidates unless the potential value is also high
- Program relevance: ideally, questions should be relevant to both the Biological Diversity and Ecological Forecasting programs

### Background information:
### The NASA Biological Diversity and Ecological Forecasting Programs

These programs are focused on understanding and saving life on Earth. In case you are not familiar with them this summary will provide some context for the White Paper submissions.

*Biological Diversity Program.* The Biological Diversity research program uses NASA observations and models to improve our understanding of biological diversity, how and why it is changing, and its effects on and interactions with the Earth system. NASA explores patterns of biological diversity on land and in water using observations from satellites, airborne and seaborne platforms, and *in situ* surveys. These observations are well-suited for detecting such patterns, especially at the ecosystem level, but also at finer community and species levels. Through a combination of observations and models, NASA further seeks to identify the geophysical and ecological processes that result in the patterns of biological diversity our observations detect. This process-oriented research aligns the Biological Diversity research program with activities of other NASA Earth Science programs, such as efforts to track the biogeochemical cycling of elements like carbon and studies of the water cycle.

*Ecological Forecasting Program.* The Ecological Forecasting applications program promotes the use of Earth observations and models to analyze and forecast, with uncertainties captured, the impact of natural and human-caused changes affecting ecosystems, species, and genes. Primary users of program outputs are natural resource managers (freshwater, marine, and terrestrial) and people and organizations involved in conservation and ecosystem management. The program utilizes information from the physical, biological, and social sciences to develop products and tools that support effective resource management and improved resource policies. A key aspect of these products and tools is that they are specifically designed to be consistent with the target user's needs and level of expertise, leading to an understanding of the root cause of change and facilitating an appropriate response.

**Instructions:**

- The template is mostly self-explanatory (questions? Please send to gary.n.geller@jpl.nasa.gov). But a key aspect of every submission is to be both brief and focused.
- One question per submission, but you are welcome to make multiple submissions.
- If you prefer to remain anonymous, leave your name off the submission form. Although your name may be visible in your email response, the Working Group that assimilates the responses will only have access to the submitted form.
- If there are multiple authors and you cannot fit them in the space provided, include the author list in the cover email.
- Keep the "parameter space" in mind so that your thoughts and suggestions are something NASA can respond to.
- **Please respond by 14 December 2018** by forwarding your submission to nasawhitepaper@jpl.nasa.gov

# NASA Biological Diversity and Ecological Forecasting Programs: White Papers on Important Questions

Send submissions to nasawhitepaper@jpl.nasa.gov by 14 December 2018

*One question per submission; overall limit of one page, 10 pt font or larger. Multiple submissions okay.*

| |
|---|
| **Descriptive Title** *(100 characters max)***:** |
| **Author(s) and Affiliations:** |
| **Keywords to categorize the question:** |
| **The question** (*succinctly and carefully stated):* |
| **Objectives** *(what does the answer tell us that we need to know?):* |
| **Justification** *(why is answering this question important? What is its relevance to society and the program?):* |
| **Users and beneficiaries** *(who would use the answer and benefit from it?):* |
| **What is needed to answer the question** *(measurements, derived products, activities, outside dependencies…Be sure to keep within the "Parameter Space" described earlier. Please use bulleted list.):* |
| **Challenges** *(what could make it hard to do, e.g., algorithm maturity, accuracy, quantifying uncertainty, obtaining sufficient field data, sustainability, etc. Why has it not been done before? Please use bulleted list.):* |
| **Anything else** *(include any other thoughts or comments here):* |

# Appendix B

## KEY VARIABLES FOR HUMAN IMPACTS AND BENEFITS

This table summarizes 1) key variables describing human impacts on and benefits from nature and 2) currently available observations and upcoming prospects for satellite missions and algorithms for monitoring these variables with remote sensing. These observations have broad applications beyond human impacts and benefits.

**Table B-1.** Summary of Key Variables and Observations

| Key Variables | Human Impacts on and Benefits from Nature | Current Observations | Prospects |
|---|---|---|---|
| **Habitat Extent** | • Current terrestrial, coastal, and marine ecosystems → input to Ecosystem Service models<br>• Habitat change (urbanization, agricultural expansion/contraction, deforestation/afforestation, conversion of mangroves and wetlands to aquaculture ponds, etc.)<br>• Invasive species spread | Land Cover classifications (Global: MODIS/VIIRS; Regional/Continental: Landsat/Sentinel-1, 2, 3)<br>Time series analyses (Landsat CCDC)<br>Global forest dynamics (Landsat) | Global 10–30 m LC classification (e.g., Boston University GLanCE MeaSUREs project)<br>Global Surface Reflectance Landsat ARD<br>Global Harmonized Landsat Sentinel-2 data<br>Global phenometrics, coastal and ocean high temporal and spatial variability<br>*Upcoming satellite missions:* SBG, PACE, GLIMR |
| **Primary Productivity/ Phenology** | • Crop yields<br>• Forest and rangeland degradation<br>• Shrub encroachment due to climate change<br>• Change to evapotranspiration<br>• Abundance, biomass, and phenology of phytoplankton responses to watershed and coastal disturbance (nutrient pollution)<br>• Ocean productivity loss as stratification occurs | Vegetation continuous fields (MODIS-VIIRS)<br>Impervious surface (Landsat)<br>Vegetation indices seasonal/annual trends (AVHRR/MODIS, Landsat, BFAST, LandTrendr etc.) | SMA (Landsat, Sentinel-2), ocean (biomass, fluorescence, functional groups, water quality, benthos, productivity)<br><br>SBG<br>*Upcoming satellite missions:* Sentinel-2c, PACE, GLIMR |

| Key Variables | Human Impacts on and Benefits from Nature | Current Observations | Prospects |
|---|---|---|---|
| **Plant Species Composition** | • Forestry affecting tree species composition<br>• Invasive species spread<br>• Provision of edible and medicinal plants<br>• Resources for animal ES providers (e.g., pollinators, birds)<br>• Crop types (affecting pollination dependency and evaporative water demand)<br>• Phytoplankton functional types and species shifts (harmful algal blooms) in response to watershed and coastal disturbance and pollution | No standard products, largely ad-hoc classifications of optical satellite data (Landsat, Sentinel-2) | USFS Northern Research Station tree species mapping for US<br>Coastal and ocean phytoplankton functional groups, phenology, and trends of change |
| **Ecosystem Structure** | • Natural forests vs. plantations<br>• Thinning, selective logging, timber poaching<br>• Changing habitat niches<br>• Biomass and carbon storage<br>• Vertical migration of phytoplankton in the oceans in response to chemistry, temperature changes and harmful algal blooms | Lidar (Local: airborne; Global: ICESat, GEDI)<br>Radar (Regional Sentinel-1)<br>Image fusion (GEDI-Landsat interpolations) | Radar (Global Sentinel-1)<br>Structure From Motion Pointclouds (high-res imagery)<br>Large-area crown delineation (high-res segmentation) |
| **Animal Movement** | • Human impacts on wildlife populations and movement<br>• Provisioning of bush meat<br>• Predators of livestock<br>• Grazing intensity/demand for rangeland ES<br>• Fisheries stocks | ICARUS | No prospects |
| **Freshwater** | • Organic matter from headwaters to coast<br>• Riparian shading<br>• Aquatic pollution: turbidity in streams, algal blooms<br>• Location of streams (and access to surface water)<br>• River flow<br>• Flooded area extent<br>• Groundwater dependent ecosystems and their Ecosystem Services<br>• Groundwater quality<br>• Groundwater depletion<br>• Loss of aquifers | No current observations | GRACE<br>GRACE-FO |

| Key Variables | Human Impacts on and Benefits from Nature | Current Observations | Prospects |
|---|---|---|---|
| **Fires** | • Human ignitions changing fire patterns<br>• Climate change leading to longer fire seasons and increasing fire intensity<br>• Fuel buildup due to fire suppression and invasive species spread<br>• Consequences for air quality, impacts on human health | Active fire detection (MODIS/VIIRS, ASTER, coarse-resolution from GOES)<br>Burned area mapping (MODIS/VIIRS, Landsat, US: Landsat burned area ARD) | 30 m burned area maps (for USA) |
| **Human Activity** | • Settlements<br>• Road networks for nature accessibility/threats<br>• Other infrastructure (e.g., dams, water transfers, coastal/flood protection, types of buildings/ structures) dependent on ES<br>• Best management practices<br>• Agriculture/aquaculture intensity (irrigation, fertilizer/pollution)<br>• Light and noise pollution<br>• Tracking (illegal) fishing vessels<br>• Socio-economic/ demographic mapping for ES beneficiaries | Night-time lights (DMSP, VIIRS)<br>Optical imagery (urban LC, and imperviousness; high-res segmentation (Microsoft building footprints)<br>Radar (TanDEM-X Global Urban Footprint map) | Radar (Sentinel-1 Urban footprint map), VIIRS day/night band |
| **Topography** | • Ancillary variable in SDMs and hydrological ES models<br>• Important for climate change resilience and evolutionary potential<br>• Used in combination with roads and waterways for nature access | Radar (SRTM; TanDEM-X Global 90, and 30 m) | SFM point-clouds (high-res imagery)<br>*Upcoming:* Free 12.5 m TanDEM-X |
| **Land Surface Temperature** | • Fragmentation affecting microclimates<br>• Loss of thermal refugia<br>• Land use affecting frozen ground | MODIS/VIIRS LST<br>Landsat TIRS data<br>U.S. Landsat LST ARD<br>MeaSUREs freeze/thaw data | Global Landsat LST Temperature ARD<br>Split-window algorithm for Landsat TIRS |
| **Snow and Ice** | • Land use affecting snow accumulation, melt, and ablation<br>• Seasonal water availability (via hydrologic models) | AVHRR/MODIS snow cover | No prospects |
| **Precipitation** | • Ancillary variable in SDMs and hydrological ES models<br>• Input to forage/vegetation models for ES | TRMM<br>GPM | No prospects |

| Key Variables | Human Impacts on and Benefits from Nature | Current Observations | Prospects |
|---|---|---|---|
| **Soils** | • Soil moisture<br>• Land degradation:<br>• Soil erosion (from wind and water)<br>• Salinization (due to irrigation) | SMAP | No prospects |

# Appendix C

## COMPLETE LIST OF CONSIDERATIONS FOR NASA

| Chapter | Considerations for NASA |
|---|---|
| **2: Biodiversity: What is Biodiversity and Why is it important?** | • Identify science and technological means needed to better quantify biodiversity, phenology, energy, and materials flow related to ecosystem function and services<br>• Stimulate the convergence of observing frameworks (ECV, EBV, EOV, EESV, etc.)<br>• Integrate observing systems<br>• Define joint theoretical and practical research opportunities that foster collaboration between terrestrial, aquatic, and atmospheric research communities<br>• Link the socio-economic needs of the general public and specific stakeholder requirements with biodiversity research and ecological forecasting<br>• Focus on Grand Science Questions and the needs of society<br>• Foster collaborations across NASA science programs<br>• Ensure access to space to deploy the necessary sensors and data communications infrastructure for biodiversity and ecological forecasting research and applications<br>• Expand capacity development opportunities<br>• Implement strategies to foster the success of multidisciplinary teams<br>• Require combined remote sensing observations to follow standard protocols<br>• Continue to engage in and grow partnerships, including with the private sector<br>• Play a leading role nationally and internationally in promoting research, partnerships, and new technology development to enhance regional and global biodiversity observations |
| **3: Drivers of Biodiversity: What determines the world's biodiversity and How are these drivers changing?** | • Continue and enhance long-term time series of biodiversity change and biotic and abiotic drivers from space<br>• Enhance collection of biotic and abiotic *in situ* information by investing in process and field campaigns and deploying autonomous *in situ* or animal tracking measurement systems<br>• Enhance and establish partnerships with other U.S. federal and state agencies, philanthropic organizations, and biodiversity observation networks<br>• Enhance modeling capabilities that link biodiversity change to biotic and abiotic driver variability and generate forecasts |

| Chapter | Considerations for NASA |
|---|---|
| | • Produce high to medium resolution (1 to 100 m) analysis-ready data of biodiversity drivers from existing Earth observation data<br>• Encourage research with an evolutionary perspective that incorporates the tree of life, genetic, genomic, and metabolomic data (*omics, etc.), traits, and communities<br>• Promote new concepts and approaches to estimate biodiversity and its drivers that are not currently observable from space<br>• Improve *in situ* capabilities with multidimensional assessment of data gaps, new approaches, and a prioritization of measurements that maximize the biodiversity relevance of remote sensing data<br>• Explore radically different remote sensing approaches to observe biodiversity change in relation to driver variability |
| **4: People, Biodiversity, and Ecosystem Services: How do humans, biodiversity, and the environment affect each other?** | • Expand capabilities for integrating ecological and social variables<br>• Provide new datasets to facilitate modeling human–environment interactions<br>• Form inter-agency partnerships to enable creation of new, or integration with existing, spatially explicit social datasets<br>• Foster the formation of diverse and interdisciplinary teams to tackle research problems on human-environment interactions<br>• Create a new thematic area in "Human Benefits and Effects" within the Biological Diversity and Ecological Forecasting program elements and explore partnerships with other funding agencies to achieve joint objectives |
| **5: Scales of Biodiversity: How do processes occurring at different scales of space, time, and biological organization interact?** | • Continue critical investments in Earth-orbiting satellite platforms<br>• Advance existing and develop new remote sensing techniques<br>• Prioritize coordinated design of multi-sensor-platform systems<br>• Strengthen inter-agency (national, local) and international partnerships<br>• Advance and employ methods that combine remote sensing and *in situ* observations<br>• Invest in research that leverages data systems and new knowledge into decision making tools<br>• Participate in and contribute observations, models, and knowledge in support of a "biodiversity reanalysis"<br>• Play a critical role in meeting the myriad challenges of society |

| Chapter | Considerations for NASA |
| --- | --- |
| **6: Biodiversity and Ecosystem Resilience: Does biodiversity increase ecosystem resilience to environmental change?** | • Continue collection, archival, calibration, and processing of NASA's multi-decadal satellite record<br>• Develop cross-platform 'harmonized' Earth observation products to further enhance the quality of long-term records of change<br>• Support, possibly through collaboration, of long-term *in situ* monitoring of indicators representing the health and/or structure of the ecosystem designed for integration with EO<br>• Increase support for research into socio-ecological systems, especially in the context of monitoring and managing ecological resilience to environmental variability<br>• Facilitate research to improve our ability to forecast responses to events and validate those predictions with new observations |
| **7: Predicting and Projecting Changes in Biodiversity and Ecosystem Services: What is needed to predict changes in biodiversity and ecosystem services and to provide managers, stakeholders, and the public with the best possible information and tools with which to make environmental decisions?** | • Lead development of the community tools, models, and cyberinfrastructure needed for the next generation of forecasts<br>• Train the next generation of ecological forecasters<br>• Strengthen and broaden connection to end users, particularly decision-makers<br>• Support activities that focus on forecasts that are explicitly process- and mechanism-based<br>• Support efforts to build a community of practice around ecological forecasting |