KIBALE NATIONAL PARK • Western Uganda • July 23, 2023

ACCELERATING BIODIVERSITY AND ECOSYSTEM REPORTING

FEASIBLE AND COST-EFFECTIVE REPORTING WITH AI, EARTH OBSERVATION, & ECOSYSTEM SCIENCE

planet.   Microsoft   natural capital PROJECT   GUND INSTITUTE FOR ENVIRONMENT

FOREWORD

Ecosystems and biodiversity form the bedrock of human well-being, and are an essential, yet often overlooked, foundation of the global economy. Consider how trees in a forest clean our air, or soil filters our drinking water, how honeybees pollinate our crops, or plants and fungi stimulate the development of medicines.

Despite their vital role, natural systems are being destroyed by the very economic activities that depend on them. According to the Intergovernmental Platform on Biodiversity (IPBES), three-quarters of Earth's landmass and more than half the marine environment have been altered by human actions. Over a quarter of the species that have been assessed are at risk of extinction. The Intergovernmental Panel on Climate Change emphasizes that the loss of ecosystems and biodiversity undermines our ability to tackle the climate crisis, which further threatens the global economy.

The catastrophe of nature loss must be halted and reversed. The first step to address this crisis is measuring the impacts and dependencies of economic activities on ecosystems and biodiversity. These historically have not been measured, and thus effectively were ignored in business accounts and operations. As the saying goes, you can't manage what you don't measure.

Fortunately, international policies and frameworks are emerging that direct companies to assess their impacts and dependencies on nature. Key among these are the European Union's Corporate Sustainability Reporting Directive (CSRD) and the Taskforce on Nature-related Financial Disclosures (TNFD).

Measuring nature may appear to be an overwhelming task. But recent advances in artificial intelligence (AI) and Earth observation (EO) offer companies access to tools that more easily and comprehensively measure and monitor biodiversity and ecosystems. New generations of sensors—on the ground, in the air, and in space—provide an unprecedented level of detail in observational data. Meanwhile, AI is a game-changing tool for making sense of the vast data streams these sensors produce, advancing scientific understanding of our natural world. Cloud computing gives us the ability to systematize these efforts globally and over time. Together, these technologies contribute to a continuous, high-resolution, and science-based system for monitoring the health of Earth's ecosystems.

In short, this technological revolution is making our often-invisible impacts on nature visible, and enabling us to make more informed decisions. New policies and business frameworks are fostering a sea change in the way markets assess nature-based risks and impacts. Nature is moving onto the balance sheet and will need to be a key consideration in how markets evaluate the performance of companies and sectors in the years to come.

As with climate- and carbon-linked disclosure, reporting on nature-related impacts and risks has arrived first in more voluntary schemes, and is now being followed by mandatory, compliance-based forms. Change is coming quickly, so companies around the world need to be prepared.

Microsoft and Planet, along with our academic partners, have developed a detailed overview of science-based tools and data available for ecosystem and biodiversity measurement and reporting. We stand ready to help. Working together, we can weave a more nature-positive future that delivers growth and protects the web of life on which we are all interdependent.

The time to get started is now.

Melanie Nakagawa
Chief Sustainability Officer,
Microsoft

Andrew Zolli
Chief Impact Officer,
Planet

+

TABLE OF CONTENTS

\+

EXECUTIVE SUMMARY

Biodiversity and ecosystem reporting frameworks are emerging in response to extensive nature loss around the world. While companies may be familiar with carbon accounting and reporting, biodiversity and ecosystems reporting involves tracking new metrics and concepts across several scientific disciplines, which may seem daunting. However, recent advances in ecosystem science, Earth observation (EO), and artificial intelligence (AI) make scientifically robust reporting accessible and cost-effective.

In this paper, we provide an overview of available techniques and tools companies can use now to support reporting in line with the voluntary Taskforce on Nature-based Financial Disclosures (TNFD) and the mandatory EU Corporate Sustainability Reporting Directive (CSRD). These frameworks create an obligation for thousands of companies to report how they impact and depend on biodiversity and ecosystems. We also highlight key reporting challenges and provide an overview of some of the emerging tools that may help companies to overcome them.

Three key messages of this paper are:

#1 Mandatory and voluntary reporting on biodiversity and ecosystems have core processes and indicators in common.

We provide a brief overview of the CSRD and TNFD reporting frameworks and demonstrate how they align around the following processes and indicators:

- Material impact, risks and opportunity assessment
- Ecosystem conversion
- Ecosystem management
- Ecosystem extent, condition and connectivity
- State of invasive species
- State of native species

By assessing reporting indicators, companies can better understand their impacts and dependencies on biodiversity and ecosystems and set nature-positive targets and policies.

#2 Companies can start biodiversity and ecosystem reporting today using recent science-based technological advances.

We outline the techniques that make measurement and reporting accessible, with examples of each:

- **Advanced field-based EO** such as bioacoustics and environmental DNA
- **Satellite-based EO** that provides high-frequency, high-resolution global coverage
- **AI** that furnishes insights on ecosystems by integrating and analyzing large amounts of EO and ecosystem science data

#3 Challenges to reporting exist, but can be overcome through collaboration.

We highlight challenges and offer insights on how corporate, regulatory, and scientific actors can collaborate to address them. We also indicate steps companies can take in the meantime to address these challenges:

- **Attributing impacts and informing nature-positive actions.** Address by starting with existing models and measurement approaches, while improving the science and practice of ecosystem change attribution and further developing decision-making tools.

- **Selecting the right metrics.** Address by starting with what is currently operational, while remaining flexible to new metrics and more robust guidelines as reporting evolves.

- **Dealing with data constraints.** Address by using EO and AI to extrapolate to data-poor areas, while working to fill data gaps and increase data accessibility and interoperability.

There is an urgent need to protect and restore nature. Business has an essential role to play in achieving this goal. The first step is for companies to measure their impact and dependencies on nature using the new reporting frameworks. Actors can begin now with available tools while building towards more comprehensive accounting and shaping the trajectory of future biodiversity and ecosystem reporting.

+

INTRODUCTION

Today an estimated one million species are at risk of extinction, and the vast majority of benefits that nature provides to people are in decline.[1,2] Over the past 50 years, wildlife populations have fallen an average of almost 70%.[3] In that same period, the planet lost over 200 million acres of forest.[4] And, since the 1950s, the area covered by coral reefs has dropped by 50%.[5] Human and economic activities have caused this decline, and future human and economic well-being depend on halting and reversing these trends. To bend the curve of biodiversity loss to a nature-positive future, scalable tools and skills are needed to measure ecosystem conditions, assess the contributions of ecosystems to people and the economy, and project and compare alternative futures. To confront this crisis of ecosystem and biodiversity loss and illuminate the materiality of environmental changes to public investors, efforts are accelerating to assess and disclose business impacts and dependencies on nature. These include mandatory reporting regulations such as the EU Corporate Sustainability Reporting Directive (CSRD) and voluntary reporting frameworks like the Taskforce on Nature-Related Financial Disclosures (TNFD) and Science Based Targets for Nature (SBTN). Contrasting with the core metrics for climate reporting, which are already familiar to many companies, the metrics for biodiversity and ecosystems are new to many, and in some cases still emerging. Consequently, to many businesses, reporting biodiversity and ecosystem metrics can appear to be a daunting, potentially unachievable task.

Fortunately, new technologies and science are making biodiversity and ecosystem measurement and reporting more accessible and manageable. In the last decade, rapid advances in ecosystem science, Earth observation (EO), and artificial intelligence (AI) techniques—all enabled by cloud computing and storage—have significantly improved the ability to measure and monitor ecological processes and ecosystem services, their contributions to the economy, and economic activities' impacts on ecosystems and biodiversity.[6] The use of these technologies in environmental measurement rests on a body of scientific literature and industry advances, as we explain below.

This white paper:

- Demonstrates that biodiversity and ecosystem reporting can be streamlined and scientifically robust.

- Highlights examples from both the scientific literature and real-world cases of companies using EO and AI technologies to facilitate scalable and cost-effective reporting.

- Synthesizes opportunities, challenges, and proposed actions for getting started and improving biodiversity and ecosystem measurement and reporting.

In the following sections, we showcase examples of scientifically rigorous, standardized, and scalable tools for the quantification of metrics needed for reporting. Drawing on the EU's Corporate Sustainability Reporting Directive (CSRD) as an example of emerging mandatory environmental reporting frameworks, we provide an overview of the regulation's requirements for biodiversity and ecosystem measurement and reporting, specifically the European Sustainability Reporting Standards (ESRS) E4. We review concrete examples and scientific literature demonstrating how recent advances in EO, AI, and cloud computing technologies can make this reporting accessible, interoperable, and cost-effective. Finally, we outline outstanding challenges and provide a roadmap for companies, researchers, consultants, and regulators to maximize the impact of nature-related reporting.

KEY FRAMEWORKS FOR BIODIVERSITY AND ECOSYSTEM REPORTING

Multiple mandatory and voluntary biodiversity and ecosystem reporting frameworks have recently been introduced. The mandatory EU Corporate Sustainability Reporting Directive (CSRD) compels large companies with business in the EU to disclose their impacts, risks, and opportunities related to biodiversity and ecosystems as part of their broader sustainability reporting obligations. The voluntary Taskforce for Nature-related Financial Disclosures (TNFD) framework guides organizations globally in reporting on nature-related risks and opportunities, with a focus on shifting financial flows towards nature-positive outcomes.[7,8]

Comparison of Biodiversity & Ecosystem Metrics across the CSRD and TNFD

REPORTING UNDER

	CSRD	CSRD & TNFD	TNFD
Ecosystem conversion	—	Conversion over time	Restoration over time
Ecosystem management	—	Changes in management over time Sites in biodiversity-sensitive areas	Area managed Area sustainably managed
Ecosystem extent, condition and connectivity	Change in spatial configuration Change in structural & functional connectivity	Type & extent Condition relative to reference state	Ecosystem pressures
Invasive species	Management of spread Risks posed by invasive species	Management of introduction	—
State of species	Change in habitat	Threatened species Threat status Population size Extinction risk	—

Figure 1: CSRD and TNFD both highlight a number of the same metrics for biodiversity and ecosystem reporting, with a relatively few areas of difference.[7,8]

Fortunately, these two frameworks intentionally seek to align with each other, making it easier for companies within and outside the EU to undertake some of the same biodiversity and ecosystem reporting. Figure 1 demonstrates that the CSRD and TNFD focus on the same core indicators (see Definition: Indicator v. Metric). The CSRD provides more guidance on metrics relevant to the state of ecosystems and species; the TNFD places slightly more emphasis on opportunities, such as restoration, conservation management, and ecosystem services.

For the remainder of this paper, we review the biodiversity and ecosystem indicators in Figure 1 through the lens of CSRD, as it mandates reporting from tens of thousands of companies. Notably, the tools we outline, the examples we review, and the actions we propose are equally applicable to TNFD.

EU Corporate Sustainability Reporting Directive (CSRD)

From 2024, an anticipated 50,000 EU companies and 10,000 non-EU companies are subject to the EU CSRD and its ESRS,[9] which may cover the entirety of companies' value chains from their direct operations to their suppliers. The ESRS address CSRD reporting on climate mitigation and adaptation (E1), pollution (E2), water and marine resources (E3), biodiversity and ecosystems (E4), and resource use and circular economy (E5) (Figure 2). Companies will need to incorporate data on these environmental factors into their workflows for accounting, disclosure, and decision-making.[10,11] In this paper we focus in on ESRS E4.

Companies are subject to the disclosure requirements of ESRS E4 if they have over 750 employees and identify material impacts and dependencies on biodiversity and ecosystems. Although some stipulations are voluntary, including a quantitative description of anticipated financial effects (E4-6), reporting on biodiversity and ecosystem indicators (E4-5) is mandatory for all of the covered companies (Figure 2).

The first step in the process for reporting under CSRD is for a company to evaluate their material impacts and dependencies. CSRD uses "double materiality" wherein companies must consider both how their actions impact biodiversity and ecosystems (that is, impact materiality) and how company finances and business strategies depend on ecosystems and biodiversity, posing risks as they decline and opportunities when risks are mitigated (that is, financial materiality).[12] If a company's double materiality assessment shows that ESRS E4 is material for its business, the company will need to report in accordance with the material ESRS E4 Disclosure Requirements.[13]

Definition: Indicator vs. Metric

The terms "indicator" and "metric" are not used consistently throughout the CSRD. However, CSRD does clearly delineate different high-level categories, and lower-level quantities within those categories. For clarity in this paper, we use the terms as follows:

Indicator: A high-level category, such as "ecosystem condition."

Metric: A lower-level category representing measures of an indicator such as "species richness."

Indicators for Biodiversity and Ecosystem Reporting under CSRD
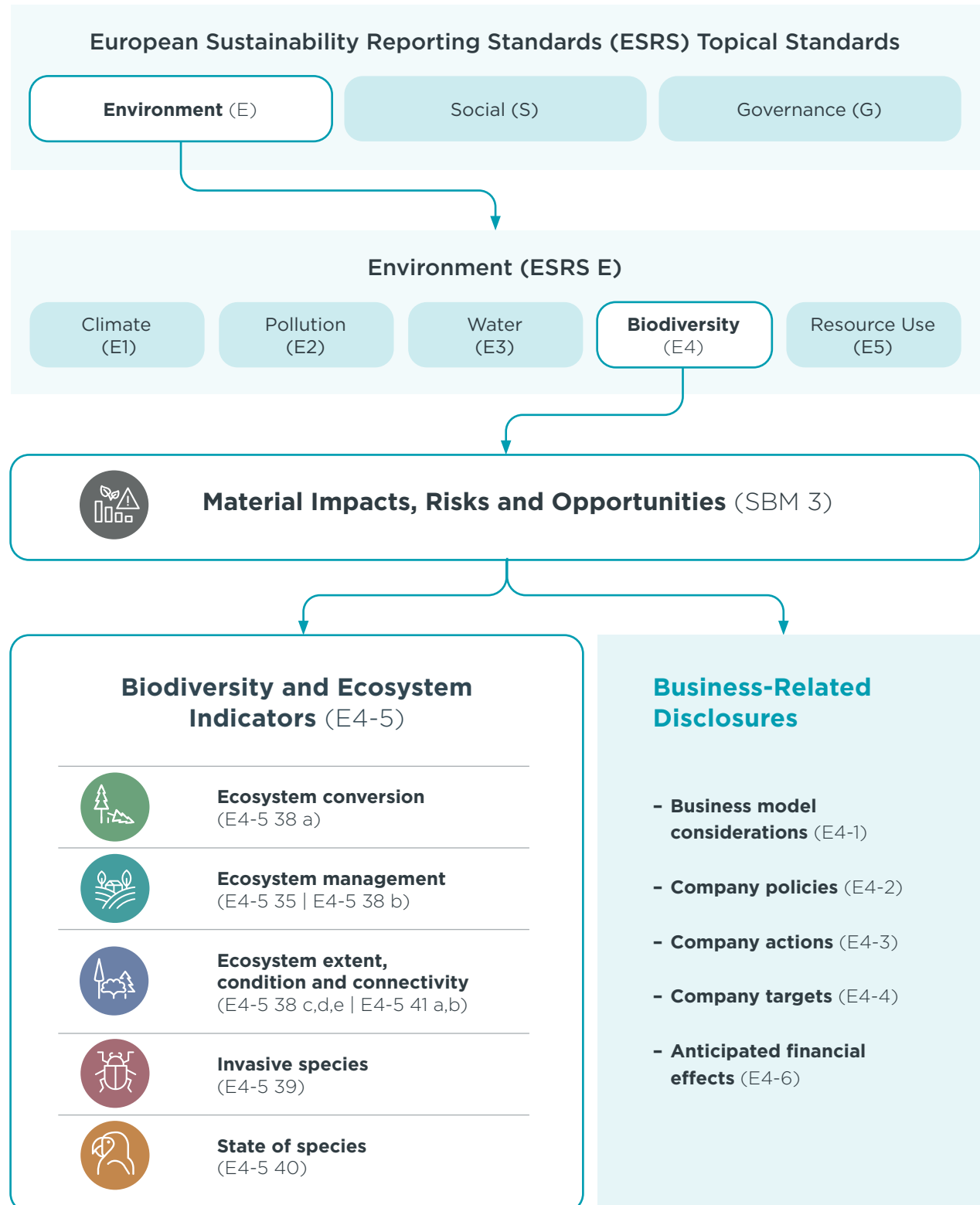

Figure 2: European Sustainability Reporting Standards for the CSRD, including core indicators identified in E4 for biodiversity and ecosystem reporting.

For material impacts, companies are required to (i.e., "shall") assess the following biodiversity and ecosystem indicators (Figure 2):

- Ecosystem conversion from natural spaces to managed systems or built-up areas (E4-5 38a)

- Ecosystem management practices and operations, especially within or near biodiversity-sensitive areas (E4-5 38b)

- Ecosystem extent, condition and connectivity in areas affected by business activities (E4-5 38 c,d,e | E4-5 41 a,b)

- Invasive species introduction, spread, and management (E4-5 39)

- State of species and their risk of extinction related to business operations and supply chains (E4-5 40)

Within these indicators, CSRD provides biodiversity and ecosystem metrics. Some of these lower-level metrics are explicit requirements (i.e., "shall" report), such as proximity of operations to biodiversity-sensitive areas (see Appendix B for definition) (**E4-5 35**), but most are phrased as suggested examples of "relevant" metrics that companies "may" disclose. In other words, companies "shall" report on "relevant" metrics, but in most cases can choose what these metrics will be.

The CSRD explicitly emphasizes change in measured and reported metrics as a means of determining companies' material impacts on biodiversity and ecosystems. Measurement of change requires the establishment of a "reference state" or baseline, marked by the arrival of an operation on-site or change in magnitude of existing operations, for comparison over time (for example, one or five years) (**E4-5 38**).

For companies to assess the required indicators, tools and data are needed that are accessible, interoperable across different sectors and geographies, and ready for integration into operational workflows. This is where EO and AI can make a notable difference. AI techniques have played a growing role in analyzing EO data over time, and the increasing resolution and volume of these data are now driving the development of increasingly sophisticated nature-related AI models that provide more granular insights across a wider range of phenomena. EO and AI can help automate standardized assessments, scale analyses across space and time, and integrate vast and disparate datasets, facilitating meaningful measurements of change and reducing the problems of missing data or mismatches across different measurement techniques. In the following sections, we review how the integration of ecosystem science, EO, and AI can be used to quantify many of the indicators and metrics introduced by the CSRD, as part of its disclosure requirements.

Definition: Different Types of Earth Observations

Earth Observation (EO): Broadly, EO is gathering information about the physical, chemical, and biological systems of the Earth. EO can be categorized into different types based on how information is gathered.

- **Field-based EO:** This EO information is gathered in the field, both using "advanced" techniques like eDNA and bioacoustics, as well as "traditional" techniques like the collection of specimens, point counts, and transects.

- **Satellite EO:** This information is gathered remotely from satellites in orbit and now provides high-resolution, near-daily coverage of the entire Earth.

SCIENCE-BASED, EO- AND AI-ENABLED BIODIVERSITY AND ECOSYSTEM MEASUREMENT AND REPORTING

Effectively measuring changes in biodiversity and ecosystems at scale requires the integration of the ecosystem science, EO, and AI. Ecosystem science provides the foundational understanding of species and ecosystem dynamics necessary to assess the impact of business activities and project how shifting ecological conditions might alter nature's services that businesses depend on. EO is critical for monitoring species and ecosystems over time and tracking change around the world—particularly given the high-frequency, high-resolution global coverage of satellite EO. The analytical power of AI can analyze the vast amounts of data gathered by both advanced field-based EO and satellite EO to detect patterns and anomalies, which traditional analytical techniques cannot. Collectively, ecosystem science, EO, and AI make it possible to assess complex ecosystems through rapid classification, extrapolation, and learning over time, as we describe below.

In the last decade, new sensor data such as eDNA and bioacoustics have produced increasingly advanced field-based EO, which has been consolidated in integrated assessments and platforms. For example, Microsoft Premonition has used AI to compare an eDNA sample with all known organisms, using statistical machine learning to synthesize trillions of DNA comparisons into a probabilistic estimate of the species present in that sample. Importantly, these sensors build on and extend the many standard field work methods, including collection of specimens, point counts, and transects, which will continue to be crucial sources of biodiversity information.

In parallel, EO satellite constellations have produced high-frequency, high-resolution data with comprehensive coverage that captures global changes. Various types of satellite EO can aid in analysis of ecosystems, including multispectral, hyperspectral, synthetic aperture radar, and LiDAR.[14] For example, Planet's PlanetScope provides near-daily global optical imagery at 3-meter resolution and Planet Forest Planetary Variables make use of both optical imagery and space-based and aerial LiDAR to estimate forest height and forest carbon. New AI capabilities can translate EO data streams into tangible insights and enable:

- **Identification:** AI can use field-based EO and satellite EO data to identify and enumerate ecosystems, as well as the flora, fauna, and threats within those ecosystems,[15,16] enhancing wildlife monitoring and ecosystem management efforts.[17]

- **Classification:** AI can classify different types of ecosystems and biodiversity based on field-based EO and/or satellite EO data, and detect and categorize changes and anomalies over time.[15,16,17]

- **Extrapolation:** AI can use field-based EO to train satellite EO-based models, which extrapolate ecosystem insights to larger areas or over time.[14]

- **Forecasting:** Based on time-series trends in both field-based EO and satellite EO data, AI can project alternative future states of ecosystems.[15]

AI provides these capabilities as a repeatable and scalable technique that requires less manual input and promotes time and cost savings. The combination of ecosystem science, satellite and field-based EO, and AI can provide new insights on challenging ecosystem questions (see Example: AI, satellite EO, and field-based EO combined). For example, the Microsoft Planetary Computer includes a managed EO service which uses cloud computing and machine learning to simplify and enhance the analysis of large-scale public and private geospatial datasets for the measuring and monitoring of ecological processes and ecosystem services. In partnership with Chesapeake Conservancy, the **Planetary Computer** is being used to map the land cover and land use of the Chesapeake Bay watershed and identify conservation and restoration opportunities.

The scientific literature and real-world examples from business and civil society illustrate how these technologies can assist in the process of material impact, risk, and opportunities assessment and the measurement of each of the indicators of biodiversity and ecosystems under the CSRD (see overview and example in Figure 3 below).

EXAMPLE: AI, SATELLITE EO, AND FIELD-BASED EO COMBINED

Project Guacamaya and Microsoft AI for Good are using advances in satellite EO, field-based EO data, and AI to gain new insights into the relationship between deforestation and wildlife in critical Amazonian ecosystems.

AI models are being developed to analyze daily high-resolution images from Planet to spotlight areas where illegal deforestation or mining may take place via key indicators like unauthorized roads. Project Guacamaya is also collecting data on native, invasive, and managed species like domesticated cattle from tree-mounted cameras and bioacoustic sensors. Massive amounts of this data can be analyzed via AI with minimal manual validation, reducing time and costs to allow researchers to expand and deepen their research. Analyzing these combined data sources via AI can provide early indication of ecological shifts that need to be addressed.

Top left: Planet imagery of the Colombian Amazon.

Top right: The same imagery with classified agricultural fields.

Bottom: Image of wildlife captured by camera traps in Project Guacamaya. Using AI, a tool has been developed to quickly identify species.

Illustrative Workflow: Biodiversity & Ecosystem Reporting under ESRS E4-5

Scope
Decide what matters

Business activities
What, where,
how much

Double materiality
Business dependence
and impacts on nature

Assess
What's there, how it's changed,
how it might change in the future

Ecosystem Science
+
Satellite EO
+
Field-based EO

AI

Identify
Classify
Extrapolate
Forecast

Report
What you learned and what you're
doing about it

Business-related disclosures

EXAMPLE: AGRIBUSINESS

Agriculture business is *impacting*
a biodiversity-sensitive forest

The business *depends* on the forest for
erosion control and water regulation

Assess CSRD & TNFD Indicators

Ecosystem conversion
Measure how much of the forest has been
converted to agricultural land over time
(area/time)

Ecosystem management
Quantify more efficient agricultural
management to decrease forest
conversion *(yield/area)*

**Ecosystem extent, condition
and connectivity**
Evaluate forest:
- Extent *(area)*
- Condition via species
  richness *(species/area)*
- Connectivity *(size and distance
  between patches)*

Invasive species
Assess:
- Introduced invasive species
  (e.g. emerald ash borer)
- Spread of invasive species
  (area, density)
- Risk posed by invasive species
  (tree deaths/year)

State of species
For threatened species, assess:
- Threat level *(IUCN Red List threat level)*
- Population size *(n)*
- Change in habitat *(area, quality)*

After assessing indicators and metrics for
reporting, companies can build on the
understanding they gain about their
impacts on biodiversity and ecosystems
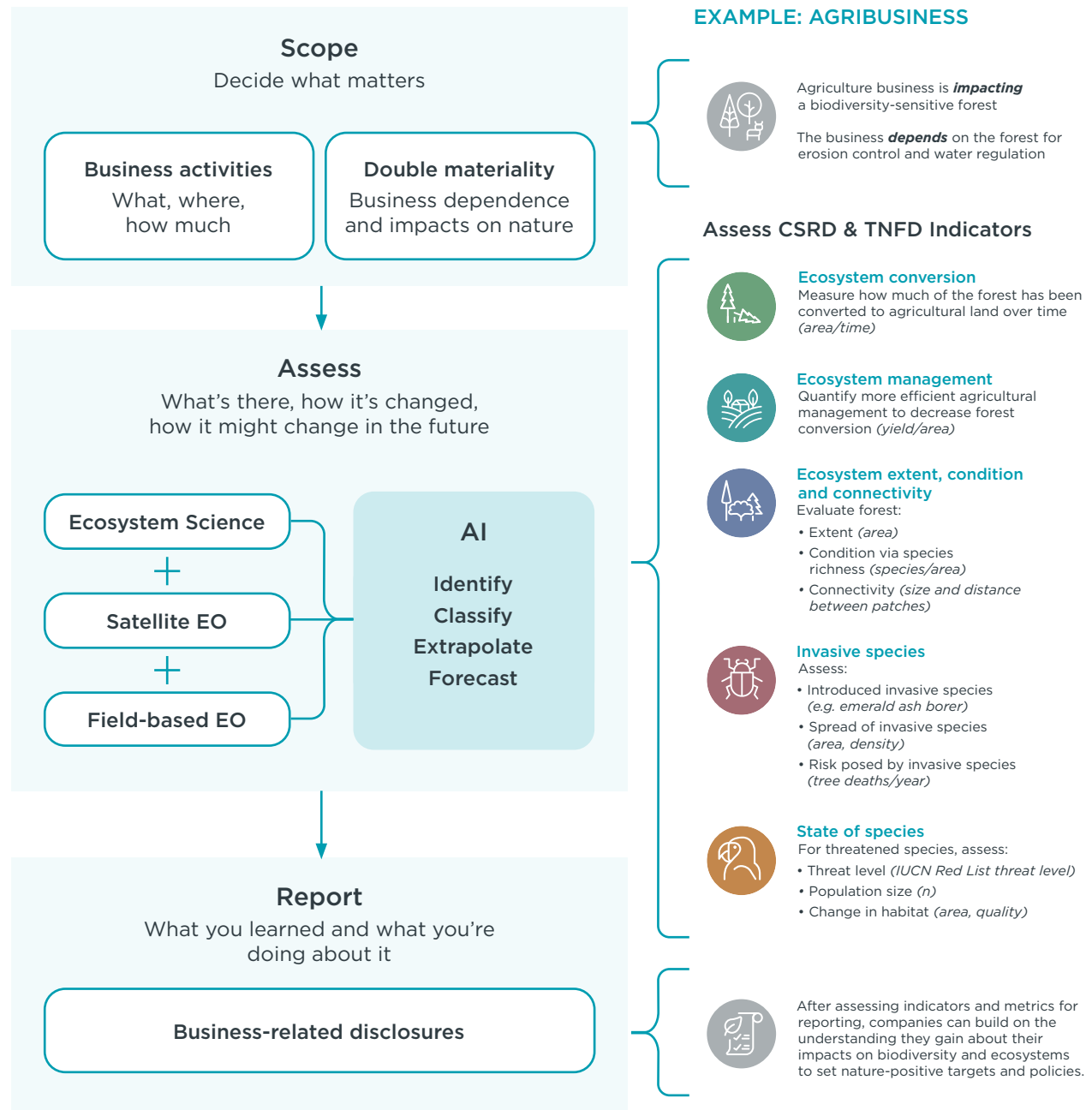to set nature-positive targets and policies.

Figure 3: After scoping business activities and assessing double materiality, the combined techniques and data sources of ecosystem science, field-based EO, and satellite EO can be used with AI to assess each of the indicators under the ESRS E4-5. Examples of metrics and associated measurement units are provided along the right-hand side for an agribusiness. The assessment of these indicators enables understanding of a business's impacts, risks, and opportunities related to biodiversity and ecosystems. Conclusions from this assessment can be synthesized for reporting and used to set business targets and policies for nature-positive actions. A summary of existing metrics, units, and technologies for each indicator can be found in Appendix D.

MATERIAL IMPACTS, RISKS AND OPPORTUNITIES

Under the CSRD, companies shall assess their material impacts, risks, and opportunities with respect to biodiversity and ecosystems (**E4-5 33**) (Figure 2). To do this, companies need to gather information about the type, magnitude, and location of business activities. Satellite EO and AI can be used to automatically geolocate commodity-field boundaries[18] and company assets such as factories, mills, and refineries, which are critical for assessing material impacts and risks (see Ecosystem Reporting in Action Example 1). Once companies locate their interfaces with ecosystems, they must assess both:

• The impacts of business activities on ecosystems and biodiversity.

• The benefits ecosystems and biodiversity provide to business.

An approach to this assessment is measuring the "ecosystem services" for each ecosystem that a business affects or is dependent on. Ecosystem services refers to the flows of benefits from nature that contribute to human well-being , including provision of clean water, flood mitigation, crop pollination, and many others.

Currently available tools, such as the free and open-source InVEST software,[19] enable science-based assessment of many ecosystem services at global to local scales.[20,21,22] Such tools can be of help to businesses in their assessment of material ecosystem and biodiversity impacts and dependencies (see Ecosystem Reporting in Action Example 6).

Satellite EO-based AI models can make it easier and cheaper to trace impacts from company activities to ecosystems and biodiversity, and to quantify ecosystem services for potential inclusion in decision-

ECOSYSTEM REPORTING IN ACTION EXAMPLE 1

PALM OIL MILL • Sumatra, Indonesia • 2020 • SkySat

Global geolocation of supply chains

Ordnance Survey, Esri UK, Deloitte, Planet, and Trase have established the **Supply Chain Data Partnership** (SCDP). SCDP aims to provide a location dataset for global supply chains such as palm oil, soy, and wood-based packaging applications. Pilot efforts by the SCDP are now underway in Brazil and Iowa, US are using high-resolution satellite EO imagery and other geospatial data to automatically identify assets, such as mills, refineries, storage, and transport terminals.

making.[2] For example, satellite imagery has been used to detect land-use change from solar energy development in the US and India[23] and then to evaluate changes in ecosystem services, including the potential gains from integrating native grasslands.[24] EO data has also been used to quantify the relationship between ecosystem fragmentation metrics to ecosystem services (e.g. crop pollination and erosion control).[25] As mentioned above, the CSRD requires examining material impacts, risks, and opportunities. To carry out these analyses, information is needed on company assets (see Ecosystem Reporting in Action Example 1), as well as biodiversity and ecosystem indicators required under ESRS E4-5 (Figure 2). The following subsections describe how these indicators can be feasibly assessed via EO and AI.

INDICATOR: ECOSYSTEM CONVERSION

Under the CSRD, companies that directly contribute to change or alteration of ecosystems must report relevant metrics. One metric suggested by the ESRS E4-5 is "the conversion over time of land cover" (E4-5 38a). Examples of AI techniques using advanced field-based EO and satellite EO to measure land conversion abound throughout the scientific literature for ecosystems ranging from savannas[26,27] to wetlands.[28,29] The CSRD specifically calls out "deforestation or mining"-related conversion as reportable impacts, of which multiple examples can be found in scientific works.[30,31]

Analytics of ecosystem conversion, built on satellite EO and field-based EO using AI techniques, are market-ready. For example, high-resolution, frequent insights on deforestation are accessible to users without the need for custom analysis.[32] Satellite EO and AI techniques are also already used to quantify ecosystem conversion in commodity supply chains (see Ecosystem Reporting in Action Example 2).

ECOSYSTEM REPORTING IN ACTION EXAMPLE 2

DEFORESTATION • North Kalimantan, Indonesia
December 2021 and March 2022

Deforestation in supply chains with satellite EO

The global coverage of high-resolution satellite EO imagery has enabled assessment of ecosystem conversion, such as commodity-driven deforestation, worldwide. Nusantara Atlas has used satellite EO data to quantify the area of primary forest and peatland ecosystems that was converted to plantations in Indonesia and tracked the changes in deforestation rate each year. Relatedly, Palmoil.io has created an integrated "Plot Check" platform where high-resolution satellite EO data can be used to analyze deforestation, overlapping areas, and grievances, providing traceability to private plot boundaries.

INDICATOR: ECOSYSTEM MANAGEMENT

Under the CSRD, companies may report metrics that measure "changes over time in the management of the ecosystem" (**E4-5 38b**). Advanced field-based EO data and high-resolution satellite EO data can be collected and integrated into science-based ecological models using AI. The outputs of these models can be used to quantify impacts and assess ecosystem trends induced by changes in management, such as:

- Effects of aquaculture on mangrove ecosystems[33]

- Effects of dams and urbanization on estuarine ecosystems[34]

- Effects of development on urban forests[35]

- Effects of climate change on food systems[36,37]

Moreover, readily available satellite EO analytics can provide users with accessible insights on ecosystem management impacts and trends (see Ecosystem Reporting in Action Example 3).

Another requirement (that is, "shall") is that companies disclose "the number and area (in hectares) of sites owned, leased or managed in or near protected areas or key biodiversity areas (KBAs)" (**E4-5 35**). The location and boundaries of these KBAs can be found in existing datasets accessible through platforms like IBAT.[38] Satellite EO and AI have been used for monitoring relevant areas and their changes over time.[39,40]

ECOSYSTEM REPORTING IN ACTION EXAMPLE 3
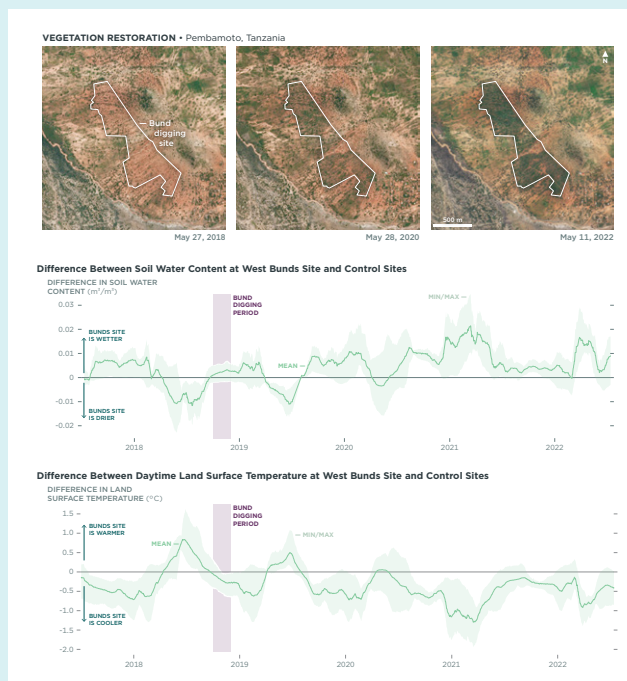
Evaluating the success of regreening drought-laden areas in Tanzania using Planet data.

Ecosystem management outcomes via EO

Fertile areas in East Africa are being degraded into drought-laden deserts due to the loss of native vegetation. **Justdiggit** used satellite EO data to evaluate success of regreening these areas over time from locally dug bunds. Soil moisture and land surface temperature Planetary Variable Analytics, which incorporate satellite EO microwave and infrared data, were used. These analytics quantified the liters of water retained by the soil, degrees of surface temperature change, and vegetation cover, at all project stages—before, during, and after bunds were dug. Satellite EO-derived insights showed that bunds increased soil moisture, lowered temperatures, and increased vegetation. JustDiggit has restored 300,000 hectares and more than 10 million trees in sub-Saharan Africa.

# INDICATOR: ECOSYSTEM EXTENT, CONDITION AND CONNECTIVITY

In addition to ecosystem conversion and management, ESRS E4-5 includes ecosystem extent, condition, and connectivity. Here, we break the indicator into specific metrics and provide examples from scientific literature and industry to demonstrate their use in reporting.

Ecosystem Extent

Companies that identify material impacts related to ecosystems may report on "ecosystem extent" using metrics that measure area coverage of a particular ecosystem (**E4-5 41 a**).

Approaches throughout the scientific literature use robust AI techniques with inputs of advanced field-based EO and satellite EO imagery to produce spatially explicit accounting of extent of ecosystems ranging from African seagrass meadows to Indonesian peatlands.[41,42] These efforts represent a paradigm for ecosystem extent analysis: advanced sensors and field-based EO data can train satellite EO-based AI models to extrapolate ecosystem extent to larger areas and track change over time. The Committee on Earth Observation Satellites (CEOS, an organization of 34 space agencies worldwide) has produced a report elucidating the capacity of satellite EO for measuring the extent of ecosystems.[14] In addition, case studies of satellite EO and AI-derived ecosystem extent measurement in real-world business settings are emerging (see Ecosystem Reporting in Action Example 4).

ECOSYSTEM REPORTING IN ACTION EXAMPLE 4
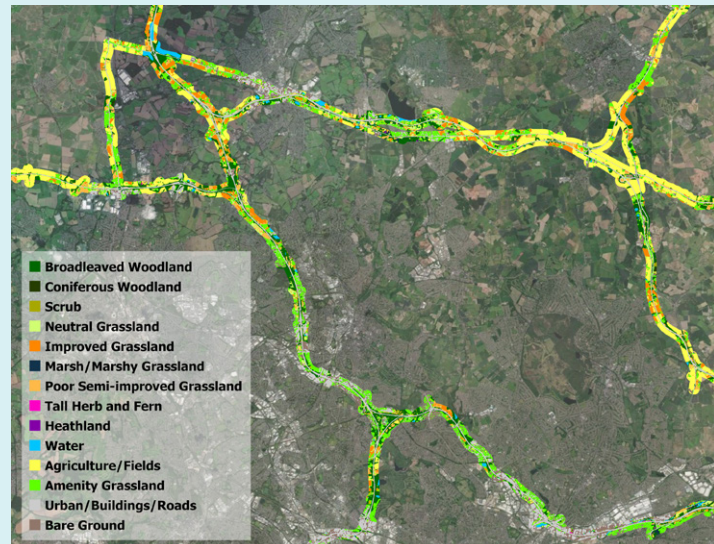
Digital maps of land cover and habitats produced using satellite imagery and machine learning for UK National Highways. Image courtesy of Ramboll.

Mapping ecosystem extent

National Highways UK is required by UK legislation to deliver a 10% net biodiversity gain on infrastructure projects. To help meet these requirements, **Galago by Ramboll** produced network-wide digital maps of land cover and habitats using satellite EO and AI. The success of the project is in its repeatability for annual monitoring purposes. The agency can now understand change over time in land cover across the entire road network, identify locations of biodiversity improvement or decline, and strategically allocate resources to ensure biodiversity net gain in the short, medium, and long term.

A related effort is **Impact Observatory's** new Land Use & Land Cover Maps for Good, derived from satellite EO, that can be used to map ecosystem extent for biodiversity and ecosystem reporting.

Ecosystem Condition

Companies that identify material impacts related to ecosystems must address "ecosystem condition" using metrics that measure (i) "the quality of ecosystems relative to a pre-determined reference state", (ii) "multiple species within an ecosystem," or (iii) "structural components of condition" (**E4-5 41 b**). These metrics fall under three areas: ecosystem composition, function, and structure. Characterizing ecosystem condition is an area of developing scientific understanding for many ecosystem types. One area of scientific advancement is the identification of Essential Biodiversity Variables (EBVs), which can be captured at scale with satellite EO-based tools and can provide inputs to measure this CSRD indicator.[43]
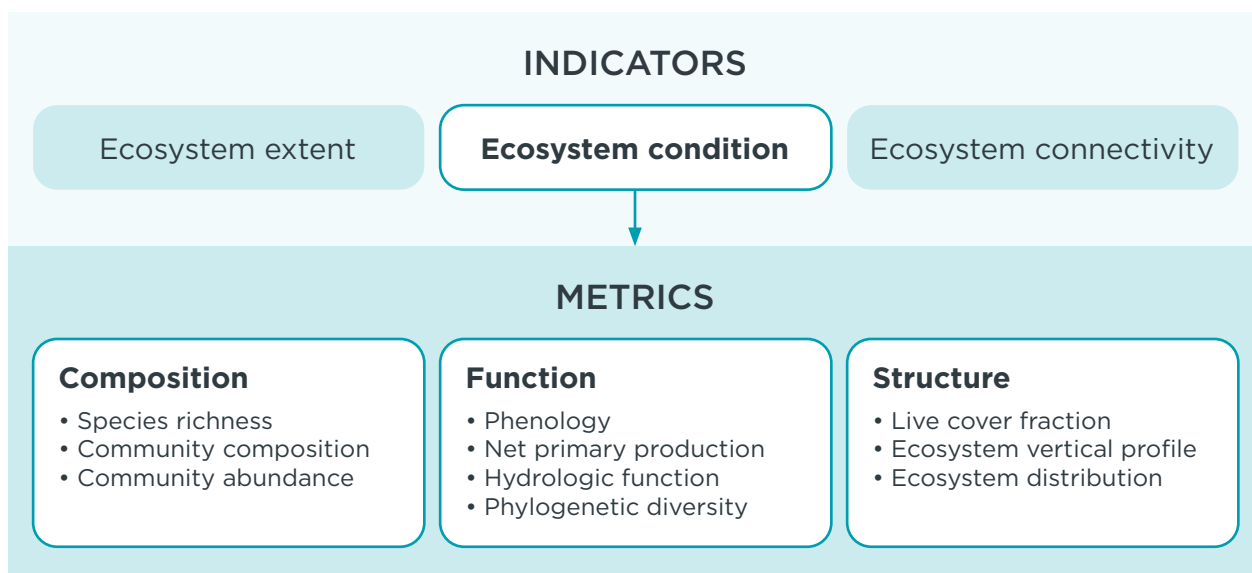

Figure 4: Metrics for the indicator of ecosystem condition (see Appendix B for definitions).

For composition, potential measures include richness, community abundance, and community composition (E4-5 41 b ii). Satellite EO data has been used to assess, for example, bird species richness[44] and plant species diversity in Mediterranean coastal dune ecosystems.[45] It has also been used as an input to analyze ecological community composition, along with Bayesian inference in species distribution models.[46] Large language AI models have the ability to interrogate newly digitized museum collections showing a record of community composition and species richness.[47]

Measures for ecosystem function include phenology, hydrologic function (such as turbidity, discharge), and net primary productivity (NPP, see Appendix B), which can indicate how ecosystem quality is changing relative to a reference state.[48,49] Satellite EO can track plant phenology by measuring, for example, the interannual emergence of green vegetation,[50] as well as assess turbidity in water and water levels, which can be combined with field-based EO to calculate streamflow and water quality in streams and rivers.[51,52] Large language AI models can be used to interrogate newly compiled ecosystem function data in online repositories,[53, 54] and machine learning algorithms can be used to calculate metrics like NPP when combined with satellite and field-based EO data.[48,55]

Ecosystem structure measures, such as ecosystem vertical profile and live cover fraction, have readily available analytics for some ecosystems, such as the Forest Planetary Variables from Planet that quantify forest height and canopy cover.

Ecosystem Connectivity

Companies may also report on the indicator of ecosystem connectivity, which includes changes to "spatial configuration," "structural connectivity," and "functionality connectivity" (**E4-5 38 c-e**) (Figure 5).

INDICATORS

| Ecosystem extent | Ecosystem condition | **Ecosystem connectivity** |

METRICS

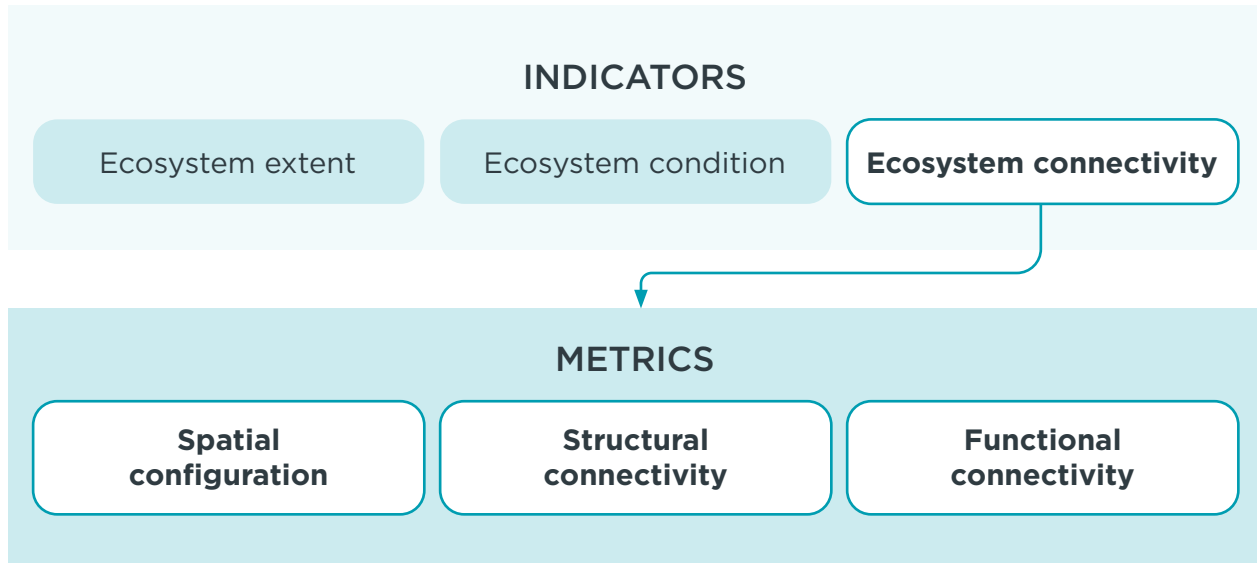| **Spatial configuration** | **Structural connectivity** | **Functional connectivity** |

Figure 5: Metrics for the indicator of ecosystem connectivity (see Appendix B for definitions).

In scientific work on spatial configuration, satellite EO and advanced field-based EO have been used to analyze habitat fragmentation and connectivity. These techniques have been used, for example, to assess habitats of turtles and waterfowl in Canada[56,57] and bears in Spain.[58] Structural connectivity and habitat permeability have been assessed through similar satellite EO techniques analyzing the expansion of ungulate foraging and contraction of grazing vegetation in Africa[59,60] and Northern Europe.[61] Lastly, the movements of fauna—a measure of functional connectivity—have been tracked using a combination of 1) eDNA and cloud computing analyses by Microsoft Premonition[62] and 2) satellite, radio transmitters, camera traps, and community science app-based identification by the platform Movebank.[63]

INDICATOR: INVASIVE SPECIES

Companies that identify material impacts related to invasive alien species will disclose metrics on "the introduction and spread of invasive alien species" and "the risks posed by invasive alien species" (**E4-5 39**). Scalable reporting of introduction, spread, and management of invasive species can draw on rigorous examples of satellite EO and advanced field-based EO utilized by AI. For example, satellite EO data has been used with AI techniques to analyze the spread of invasive vegetation using their unique spectral signatures in the United States[64] and in the Baltics.[65] Satellite EO has been used by companies to assess invasive species of vegetation and establish management regimes (see Ecosystem Reporting in Action Example 5).

ECOSYSTEM REPORTING IN ACTION EXAMPLE 5
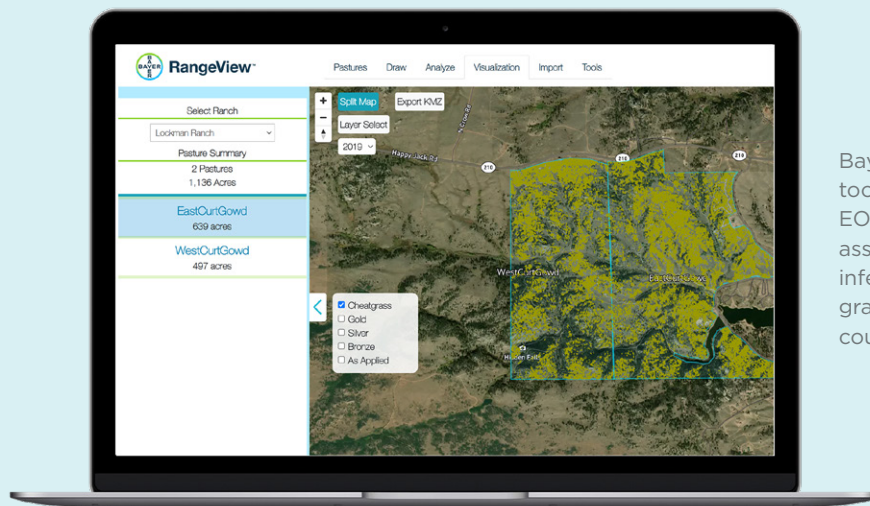
Bayer's RangeView tool uses satellite EO to help ranchers assess pastures with infestation by invasive grasses. Image courtesy of Bayer.

Satellite EO for quantifying and managing invasive species

As invasive plants encroach on pasture and ranch land, land managers need to assess both the available forage and lost capacity owing to annual invasive grasses. Bayer Environmental Science and its partner, LifeScale Analytics, used satellite imagery to help ranchers assess pastures with significant infestation of annual invasive grasses and evaluate the return on investment for treating them. Bayer analysts found that PlanetScope imagery was well-suited to detecting vegetation at the right resolution and frequency to keep pace with the rapid growth rate of invasive vegetation and determine if treatments were effective.

INDICATOR: STATE OF SPECIES

Companies that identify material impacts related to "state of species," including "population size," "extinction risk," or "changes in the number of individuals of a species within a specific area" (E4-E5 40).

Satellite EO can augment recent advances in ecosystem science and field-based EO to improve measures of species. For example, satellite EO data has been used to identify forest areas that could serve as habitat for endangered cotton-top tamarin populations, which facilitated targeted field surveys.[66] It has been used alongside field-camera EO in analysis of logging effects on species occupancy in Belize, including Red-listed endangered species.[67]

Additionally, satellite EO-estimated turbidity has been combined with eDNA to monitor the critically endangered scalloped hammerhead shark in Guam.[68] New constellations of high-resolution satellites offer the opportunity to produce similar turbidity measurements in smaller water bodies.[69]

Anglo American, a mining company collaborating with NatureMetrics,[70] combined species-focused eDNA EO measurements with satellite EO to set baselines and measure biodiversity.[71] Relatedly, Microsoft Premonition cloud-scale metagenomics AI has compared an eDNA sample with all known organisms, using statistical machine learning to synthesize trillions of DNA comparisons into a probabilistic estimate of the species present in a sample. It is being utilized by researchers in the National Science Foundation's Convergence Accelerator program to detect vertebrate, cryptic invertebrate, microbial, and viral species in ecosystems.

Aggregate species indicators, such as Species Threat Abatement and Restoration (STAR), aggregate a variety of species metrics[72] and are available in integrated platforms like IBAT (see Ecosystem Reporting in Action Example 6).

Currently Operational Metrics

The previous sections demonstrate how advances in ecosystem science, EO, and AI can be used to derive a variety of metrics related to biodiversity and ecosystems. Many of the suggested CSRD metrics are currently operational, whether they are available at scale today, can be assessed with new tools that are ready to scale, or are being demonstrated in pilots and prototypes. Table 1 demonstrates the maturity of currently operational metrics for each indicator identified in ESRS E4-5, providing an indication of what companies can incorporate immediately and which methods and metrics may soon be available to be integrated into biodiversity and ecosystem reporting.

ECOSYSTEM REPORTING IN ACTION EXAMPLE 6
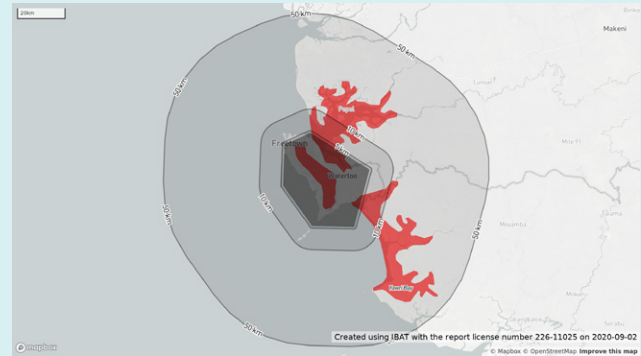
Freetown, Sierra Leone. Displaying project location, Key Biodiversity Areas (red) and buffers of 1 km, 10 km, 50 km. Image courtesy of IBAT.

Species metrics in business-ready platforms

Species metrics are readily operational through platforms such as the Integrated Biodiversity Assessment Tool (IBAT). IBAT includes the IUCN Red List of Threatened Species, which has demonstrated value in business decision-making.[73] The platform houses datasets on protected areas and Key Biodiversity Areas, which are also relevant to ecosystem management (E4-5 35). Integrated Biodiversity Assessment Tool (IBAT) is currently used by over 70 companies and financial institutions including Rio Tinto, Shell, JP Morgan, the World Bank, and General Motors.

Examples of currently operational metrics, delineated by readiness level

	METRICS	AVAILABLE AT SCALE NOW	READY TO SCALE	DEMONSTRATED
INDICATOR: Ecosystem conversion	• Ecosystem conversion over time	**Conversion of forests** Satellite EO-derived forest extent and structure analytics can be used to assess deforestation globally. [1, 2, 3] **Conversion of other terrestrial ecosystems** Satellite EO-derived land use and land cover change are available and frequently updated by geospatial AI at fine spatial scales. [4]	**Conversion due to mining, plantations, and other drivers** Satellite EO imagery has been used to quantify land conversion due to mining, palm oil cultivation, rubber plantations, and other drivers. [5, 6, 7]	**Conversion of coastal ecosystems** Satellite EO-based platforms quantify annual loss in mangrove at coarse spatial scales and emerging analytics track coastal conversion for aquaculture. [8, 9]
INDICATOR: Ecosystem management	• Sites in or near biodiversity-sensitive areas • Change in management over time	**Sites in biodiversity-sensitive areas** Global datasets on high-biodiversity areas are available and incorporated into integrative mapping tools. [10, 11, 12] **Change in restoration management & ecosystem outcomes** Satellite EO-based analytics on forests, land temperature, and soil moisture are globally available to assess improvements from terrestrial vegetation restoration. [1, 13]	**Change in agricultural management** Satellite EO and AI can detect the boundaries of agricultural fields to understand how management practices affect adjacent ecosystems. [14, 15]	**Biodiversity outcomes from change in management** Advanced field-based EO methods like eDNA analyzed by AI have been used to evaluate benefits of reforestation and aquatic restoration to biodiversity. [16, 17, 18]
INDICATOR: Ecosystem extent, condition and connectivity	• Type & extent • Change in condition • Change in spatial configuration • Change in structural and functional connectivity	**Extent of global terrestrial & aquatic ecosystem types** Global datasets on ecoregions are available but are spatially and temporally coarse [19]. There are also coarse EO-derived data on ecosystem extent for forests, freshwater, mangroves, salt marshes, coral reefs, and wetlands. [1, 2, 3, 4, 8, 20, 21, 22] **Change in ecosystem condition for freshwater ecosystems** Satellite EO-based measures of turbidity and surface water can be accessed for freshwater ecosystems at a global scale, but are spatially coarse. [23] **Spatial configuration & structural connectivity for forests globally** Satellite EO-based global datasets of forest landscape integrity are publicly available, but are spatially and temporally coarse. [24]	**Extent at high resolution for focused areas** Satellite EO has been used to provide high-resolution habitat and land cover maps for focused areas. [25] **Change in ecosystem condition using aggregate metrics** Satellite EO-based analytics can quantify "quality hectares" based on a composite index for ecosystem condition. [26].	**Change in functional connectivity** Advanced field-based EO including field cameras [27, 28] and GPS tracking collars [29] have been used to help understand fauna location and movement. [30] **Change in ecosystem condition using community composition** Advanced field-based EO methods like bioacoustics with AI have been used to assess species assemblages in forests. [31, 32]
INDICATOR: Invasive species	• Management of introduction • Management of spread • Risk posed by invasive species	**Introduction & spread of invasive species** Global, national, and subnational datasets track some invasive and nuisance species, though these are often coarse and not frequently updated. [33, 34, 35]	**Management of introduction & spread of invasive species** Advanced field-based EO methods like eDNA sequencing with AI can identify presence of key invasive species. [36]	**Management of spread & risk posed by invasive species** Satellite EO with AI has been used to detect and manage certain invasive plants from space and to minimize risks to agriculture. [37]
INDICATOR: State of species	• Threat status • Population size • Extinction risk • Change in habitat	**Threat status** Global datasets on the distribution of individual threatened species and aggregate species metrics are available and incorporated into integrative mapping tools. [12, 38, 39] **Extinction risk** The STAR metric available in global platforms provides an assessment of risk of species loss or local disappearance using coarse global datasets. [40]	**Population size** The global Biodiversity Intactness Index and integrative mapping tool can quantify change in species presence and abundance in multiple ecosystems. [41, 42, 43, 44]	**Extinction risk using local persistence** Advanced field-based EO methods like eDNA sequencing, camera traps, and bioacoustics with AI have been used to monitor species persistence and occupancy. [28, 45, 46, 47] **Change in habitat** Emerging machine learning tools combining satellite EO and field-based methods can project changes in habitat for individual species and communities. [48, 49, 50]

Table 1: To indicate the array of currently operational inputs for biodiversity and ecosystem reporting, we conducted a time-limited survey of existing tools, platforms, and company experiences for metrics under each indicator. "Available at Scale Now" are plug-and-play platforms and tools for companies, with global scale for reporting today. "Ready to Scale" includes tools, models, and methods that have been used by multiple companies in multiple places, and could soon be established in global, standardized approaches. Those that are "Demonstrated" have been applied in at least one site, demonstrating meaningful and/or cost-effective results. TNFD also provides extensive documentation of datasets and resources available for each of these indicators.[73,74] Note: Use table footnotes to reference specific datasets and tools in Appendix A.

CHALLENGES AND PROPOSED ACTIONS: A ROADMAP FOR IMPROVEMENT

Companies may leverage operational metrics and existing technologies to assist in their ecosystem and biodiversity reporting, even as some challenges remain to be addressed. Companies that begin with these currently operational metrics while remaining cognizant of future developments will likely help shape the trajectory of biodiversity and ecosystem reporting. Following, we highlight three key challenges that remain, and propose actions to overcome them to be able to realize the full potential of nature-related reporting.

CHALLENGE 1
Attributing impacts and informing nature-positive business actions

The goal of biodiversity and ecosystem reporting is to determine how business operations affect ecosystems and catalyze changes that improve social and environmental outcomes.[75] However, the science of detection and attribution of biodiversity and ecosystem change is still in early stages, and rapid understanding of who and what are causing observed ecological changes remains an area of scientific and practical development.[76] Moreover, more advanced tools are needed to project the impacts of alternative actions and support ecosystem management decision-making under uncertainty. Advances in EO and AI are increasingly making detection, attribution, and forecasting more feasible.[77]

To overcome this challenge...

PROPOSED ACTIONS
Regulators, companies, and researchers should improve the science and practice of detecting and attributing biodiversity and ecosystem change, and should continue to develop and apply decision-making tools to inform nature-positive business actions.

Researchers and industry groups can consolidate EO and AI-based asset datasets in public repositories for use in comprehensive detection and attribution across global supply chains. These actors can draw on early reporting to conduct cumulative assessments of ecosystem impacts from business activities to inform future corporate target-setting, as well as regulatory limits on pollution and environmental damage. Likewise, regulators and researchers can measure the nature-positive actions of many companies collectively to produce cumulative results for nature writ large and improve projections of the future state of biodiversity and ecosystems.

To encourage reporting processes that inform business decisions, EU regulators can strengthen the requirements of the CSRD and ESRS E4 by more strongly emphasizing the need for scenario planning, including tools enabled by EO and AI. Researchers can build on existing efforts to incorporate EO and AI into science-based scenario planning and decision support tools that provide rigorous and accessible information to corporate actors.

Meanwhile...

PROPOSED ACTIONS

Companies should rely on existing models and measurement approaches to help detect and attribute changes in biodiversity and ecosystems and forecast the outcomes of alternative business actions.

Starting today, companies can begin to attribute changes to their operations and supply chains by using their own physical asset maps and drawing on EO-informed supply chain mapping efforts (see Ecosystem Reporting in Action Example 1) to assess "where" their operations are, "what" activities are associated with those operations, and "how much" of it is being done (that is, the intensity of a given activity). Where nature-positive actions are underway, companies can use readily available satellite EO analytics to evaluate the results of such activities, understand areas for improvement, and maximize positive impact (see Ecosystem Reporting in Action Example 3).

To inform business decisions, ecosystem service models such as InVEST (see Ecosystem Reporting in Action Example 7) can be used by companies to assess how business activities are affecting ecosystems in the present and explore the possible outcomes of proposed future actions.

ECOSYSTEM REPORTING IN ACTION EXAMPLE 7
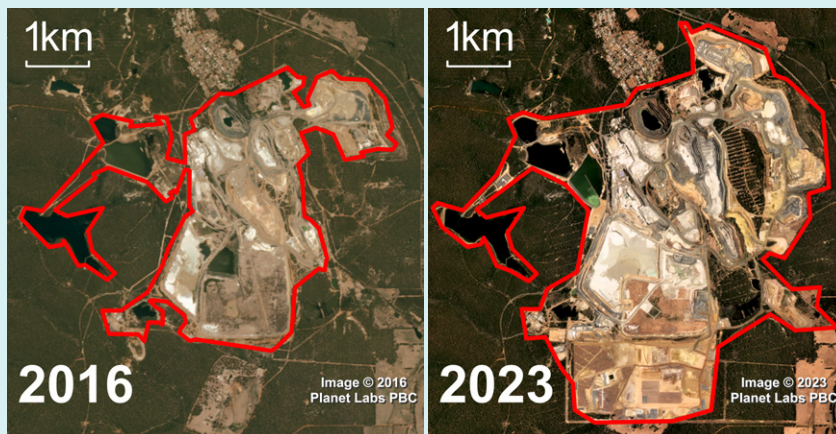
Ecosystem service assessment

Satellite EO and ecosystem services analysis were employed by the Natural Capital Project to assess impacts of lithium mining in the supply chain applicable to TNFD disclosures in collaboration with the Morgan Stanley Institute for Sustainable Investing. Using high-resolution EO, analysts documented how the footprint of mines changed over time. Then, using the global **Ecosystem Services Footprinting Tool,** information on mine extent was translated into tangible impacts on key ecosystem services, such as sediment and nitrogen retention.

Nitrogen retention impact
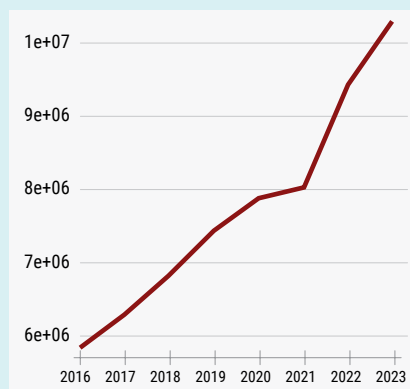
Sediment retention impact
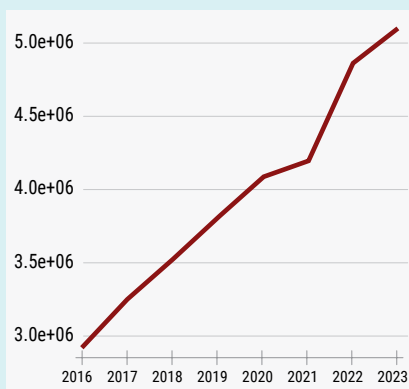
CHALLENGE 2
Selecting the right metrics for each indicator

ESRS E4-5 calls for multiple indicators to be assessed and provides many example metrics under each indicator, but companies are left to select metrics to use. This limited guidance makes it difficult to ensure robust and comparable reporting over time and across companies. To narrow the task for companies and to allow comparability within and across them, a smaller set of standardized required metrics is needed. The challenge remains to reach consensus on more specific guidelines around the selection of such metrics.

While many of the suggested metrics are currently operational, some are still emerging. As biodiversity and ecosystem reporting becomes more widespread, with more data available and with more mature scientific underpinnings and methods, additional metrics will become feasible to report. This will facilitate a fuller picture of biodiversity risks and changes, but could also present challenges in tracking trends over time.

To overcome this challenge…

PROPOSED ACTIONS
Regulators, companies, and researchers must collaborate to establish more robust guidelines for metric selection for each indicator.

Regulators should work with companies to identify standard metrics that are comparable across companies and geographies, while still providing rigorous biodiversity and ecosystem accounting and reporting for each indicator in Figure 2. Researchers can establish robust and standardized methods for agreed-upon metrics.

Meanwhile…

PROPOSED ACTIONS
Companies should start reporting with metrics that are currently operational while remaining flexible to incorporating additional metrics as reporting evolves.

Illustrative examples of currently operational and emerging metrics are provided following:

State of species

Currently operational metric:
The suggested metric of "species range within an ecosystem" (**E4-5 40b**) may be more immediately doable via existing data sources (such as IUCN, PREDICTS, and Map of Life, see Table 1). These metrics may be at a coarser resolution or less up to date than desired, but still provide valuable and actionable insights. They also have the potential to be augmented by EO and AI for improved spatial and temporal resolution.

Emerging metric:
Then, as collection of reporting data expands via advanced field-based EO like eDNA, bioacoustics, and field cameras, the suggested metric of "changes in the number of individuals of a species" (**E4-5 40c**) may become more feasible.

Ecosystem extent, condition and connectivity

Currently operational metric:
The suggested metric of "ecosystem extent" (for example, coral reef or tropical forest cover) (**E4-5 41a**) is readily measurable via EO and AI and provides important insight into ecosystems (see Table 1).

Emerging metric:
As technologies scale for ecosystem reporting, metrics such as "ecosystem functional connectivity" (**E4-5 38e**) may become more feasible.

CHALLENGE 3
Dealing with data constraints

Despite the capabilities of satellite EO and AI described in previous sections, field-based EO data remains an essential component of biodiversity and ecosystem measurement. This applies to both advanced field-based EO, such as eDNA and bioacoustics, as well as standard field work methods, such as collection of specimens, point counts, and transects. As reporting becomes more common, field-based EO data on biodiversity will quickly become a limiting factor both for measurement and for training satellite EO and AI-based model. In addition, some important metrics cannot be assessed via remote sensing.

Currently, scientific understanding and existing field-based datasets are unevenly distributed, with data gaps for key ecosystems (such as grasslands), geographies (such as Africa), and dimensions of biodiversity (such as population genetic diversity). As a result, some geographies and ecosystems have high-resolution data with high confidence, but others will have only coarse or less up-to-date data leading to lower-confidence insights. Initial reporting may have coarser understanding with greater uncertainty for under-represented ecosystems and geographies, leading to potential under- or over-estimation of their value and risks.

To overcome this challenge...

PROPOSED ACTIONS
Regulators, companies, and researchers must collaborate and engage local communities to fill data gaps, establish standards for methods, and increase data accessibility and interoperability.

Ecosystem and biodiversity researchers should strive to gather data on data-poor areas and consolidate these in public databases, in line with the global biodiversity monitoring system (GBiOS) and TNFD's call for a public nature-related data facility. Reporting companies should consider making data that fills the preceding gaps public to avoid duplicating efforts, demonstrate leadership, and contribute to a holistic understanding of dependencies and impacts. This public disclosure of company data has analogues in financial reporting, and regulators should consider incentivizing the consolidation of datasets collected by companies to improve understanding of biodiversity risks and conservation outcomes. This increased collection and consolidation of data is particularly important for field-based EO that trains AI and satellite EO-based models. We recommend that regulators incentivize research institutions to collect and/or consolidate field datasets, which can be supplemented by community science networks. As many of the world's high-biodiversity areas are managed by Indigenous communities, it is important to prioritize collaboration with these communities in data collection and sharing, including the the appropriate incorporation of traditional knowledge.

Regulators, researchers, and science service providers should strive wherever possible to consolidate towards uniform metrics and methods that are comparable across ecosystems, geographies, and time scales. This should be a near-term priority for relevant ecosystem science societies and umbrella organizations for service providers, building on previous efforts and refining existing methods.

Meanwhile...

PROPOSED ACTIONS

Companies and researchers can extrapolate with EO and AI while acknowledging associated uncertainty, and continue to collect additional field data on data-poor areas.

Companies can extrapolate biodiversity and ecosystem metrics to data-poor areas using satellite EO and AI, while being cognizant that there will be higher uncertainty in areas without comprehensive field-based EO data. Individual companies and researchers can continue ongoing efforts to collect field-based EO in data-poor areas and on data-poor species using technology such as Biological Weather Stations (see Ecosystem Reporting in Action Example 8).

ECOSYSTEM REPORTING IN ACTION EXAMPLE 8

Microsoft Premonition biological weather station bio-sensing and bio-sampling solution for monitoring critical and remote environments.

Biological Weather Stations

Most terrestrial animals are invertebrates, integral to ecosystems as predators, prey, pollinators, decomposers, disease vectors, and bioindicators. Microsoft Premonition Biological Weather Stations continuously monitor invertebrate populations using AI on the edge. They intelligently lure, identify species within milliseconds, and collect samples only as needed—providing real-time quantification of key species.

[Microsoft Premonition](#) biological sensing and biological intelligence platforms are being used in Azure infrastructure—providing new tools to help quantify datacenter impacts on surrounding ecosystems.

SUMMARY OF CHALLENGES AND PROPOSED ACTIONS

CHALLENGE	PROPOSED ACTIONS
1 Attributing impacts and informing nature-positive business actions	**To overcome this challenge,** regulators, companies, and researchers must improve the science and practice of detecting and attributing biodiversity and ecosystem change, and should continue to develop and apply decision-making tools to inform nature-positive business actions.
	Meanwhile, companies should rely on existing models and measurement approaches to help detect and attribute changes in biodiversity and ecosystems and forecast the outcomes of alternative business actions.
2 Selecting the right metrics for each indicator	**To overcome this challenge,** regulators, companies, and researchers must collaborate to establish more robust guidelines for metric selection for each indicator.
	Meanwhile, companies should start reporting with metrics that are currently operational while remaining flexible to incorporating additional metrics as reporting evolves.
3 Dealing with data constraints	**To overcome this challenge,** regulators, companies, and researchers must collaborate to fill data gaps, establish standards for methods, and increase data accessibility and interoperability.
	Meanwhile, companies and researchers can extrapolate with EO and AI while acknowledging associated uncertainty, and continue to collect additional field data in data-poor areas.

Table 2: Summary of challenges and proposed actions.

CONCLUSION

In this paper, we illustrate how recent advances in ecosystem science, EO, and AI help companies in making rigorous biodiversity and ecosystem reporting logistically feasible and cost-effective. For each identified indicator under ESRS E4-5 (Figure 2), we review data-gathering and measurement methods and technologies that are well-supported in the scientific literature and have been applied in practice. We conclude that for each identified indicator, metrics and measures are available to assist companies in reporting starting today (Table 1).

We also outline key challenges that corporate, regulatory, and scientific actors need to consider as biodiversity and ecosystem reporting evolves (Table 2). We put forward a proposed roadmap to help address outstanding cross-cutting challenges to realizing the full potential of biodiversity and ecosystem reporting. Companies that begin with the currently operational metrics outlined in Table 1, while remaining cognizant of emerging metrics, are likely to shape the trajectory of biodiversity reporting going forward. The bottom line is that measurements and tools that facilitate biodiversity and ecosystem reporting can be integrated into workflows today with the goal of mitigating impacts and maximizing for better biodiversity outcomes on our shared planet.

+

APPENDIX A: SPECIFIC DATASETS AND DEMONSTRATIONS FROM TABLE 2

1. Planetary Variables, Planet

2. Global Forest Watch, World Resource Institute

3. EU Forest Observatory

4. Land Use and Land Cover Maps for Good, Impact Observatory

5. TNFD case study, Natural Capital Project and Morgan Stanely Institute for Sustainable Investing

6. EUDR Compliance—automated & remote, LiveEO

7. Reduce risks in your palm oil supply chain, Palmoil.io

8. Global mangrove watch

9. Coastal Habitat Mapping: Mangrove and Pond Aquaculture Conversion, Clark Labs

10. World Database on Protected Areas

11. Key Biodiversity Areas

12. Integrated Biodiversity Assessment Tool

13. African restoration from Space Case study, JustDiggit and Planet

14. Planet Data Leveraged To Understand Agricultural Land And Quickly-Changing Environments

15. Automatic field delineation, Sentinel Hub

16. Measuring reforestation success of biodiversity health: Soil fungi as a promising indicator, NatureMetrics

17. Establishing a comprehensive seagrass biodiversity baseline in Falmouth Harbour to support seagrass biodiversity improvement projects across the UK, NatureMetrics

18. A combination of machine learning and eDNA reveals the genetic signature of environmental change at the landscape levels

19. Terrestrial Ecosystems of the World, World Wildlife Fund

20. Global Surface Water Layer, European Commission

21. Allen Coral Atlas

22. Global Wetlands

23. Freshwater Ecosystems Explorer

24. Forest Landscape Integrity Index

25. National Highways—Intelligent Environmental Estate, Galago by Ramboll

26. Quantify nature credits for NbS projects with satellite data, Earth Blox

27. Energy-efficient system for detection of elephants with Machine Learning, Irnas

28. Stories from the Wildlife Insights Community, Wildfire Insights

29. ElephantEdge tracker: breakdown advanced IoT animal tracking solutions, Irnas

30. Elephant Collaring in Kenya, WWF

31. Arbimon

32. Using Tech to Save the Rainforest, Deloitte and Hitachi Vantara, Bioacoustics

33. Current Invasive Plants, US Forest Service

34. Global Invasive Species Database

35. Biodiversity Risk Filter, WWF

36. Microsoft Premonition

37. Detecting And Eradicating Invasive Grass Affecting Pasture and Ranch Land, Bayer and Planet

38. IUCN Red List of threatened species, Integrated Biodiversity Assessment Tool

39. Rarity-weighted species richness, Integrated Biodiversity Assessment Tool

40. Species Threat Abatement and Restoration (STAR), Integrated Biodiversity Assessment Tool

41. Biodiversity Intactness Index, Natural History Museum (London)

42. Biodiversity Intactness Index Available to Financial Markets for the First Time

43. Biodiversity change in the Amazon, NHM Biodiversity Report

44. Evaluating the impact of biodiversity interventions: a pilot study within the Cairngorms National Park, NHM Biodiversity Report

45. Elephant Listening Project, Cornell University

46. How do you measure biodiversity? Take a listen, Zurich Insurance Group

47. eDNA case studies, Nature Metrics

48. A Collaborative Deep Learning Framework for Conservation, Pytorch-Wildlife

49. Perspectives in machine learning for wildlife conservation

50. Reef-Insight: A Framework for Reef Habitat Mapping with Clustering Methods Using Remote Sensing

APPENDIX B: GLOSSARY

Biodiversity-sensitive areas: Biodiversity-sensitive areas are protected areas, UNESCO World Heritage sites, and Key Biodiversity Areas (KBAs), as defined in Appendix D of Annex II to Commission Delegated Regulation (EU) 2021/2139. TNFD additionally includes areas of water risk, rapid decline in ecosystem integrity, and importance for ecosystem service provision in their definition of sensitive areas.

Advanced field-based Earth Observation (EO): New conservation technologies have increased the potential to obtain meaningful, in situ information about ecosystems and species in near-real time, including the following:

- Bioacoustics sensors offer a sense of species richness for birds, insects, and other taxa, as well as detect threats to biodiversity with cloud-based analytics.[81,82,83]

- eDNA and DNA barcoding are beginning to build a reference library of life that can be scanned from local water, soil, and air samples, as well as indicate the presence of invasive species.[84]

- Camera traps combined with AI-enabled species identification are reducing hours needed by experts in the field.[85]

Importantly, these sensors build on and extend the many standard field work methods, including collection of specimens, point counts, and transects, which will continue to be crucial sources of biodiversity information for many places.

Satellite Earth Observation (EO): Satellite EO is the remote detection and monitoring of the Earth's physical characteristics from orbit by measuring traits such as reflected and emitted radiation or gravitational concentrations. These measurements can then be accessed via online databases for analysis and, in conjunction with ground-based data, be used to gain insights on both natural phenomena and human activity.

Artificial intelligence (AI): AI comprises any algorithm or algorithms that use a series of commands, user-defined objectives, or training datasets to classify, predict, optimize, or otherwise detect patterns and anomalies among available data and draw conclusions from them in ways that iteratively approximate neural function.

Species richness: Species richness is the number of unique species in a defined area; it is a count of total species for a site (that is, alpha diversity) or a whole ecosystem or region (that is, gamma diversity), and is considered a key measure of biodiversity.

Phenology: Phenology refers to study of cyclical and seasonal natural phenomena, including the timing of biological events in plants and animals such as germination, migration, and dormancy, and the biotic and abiotic interactions that cause these events to occur.

Phylogenetic diversity: Phylogenetic diversity describes the breadth of evolutionary history represented among the organisms found in a defined area, as defined by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). It is measured using the Tree of Life, and is considered a measure of biodiversity and distinctiveness of species within an ecosystem and between ecosystems.

Hydrologic function: Hydrologic function refers to the ways in which ecosystems facilitate the exchange of water among the ground, surface, and atmospheric reservoirs. The US Bureau of Land Management defines it as the capacity of an area to capture, store, and safely release water collected from precipitation.

Net primary productivity (NPP): NPP is the rate at which energy is stored as biomass by plants or other primary producers and made available for consumers in an ecosystem.

Live cover fraction: Live cover fraction is a given area's presence and horizontal distribution of living organisms, such as vegetation or live hard coral. In terrestrial ecosystems, it is often measured by green vegetation cover, and is considered a measure of ecosystem condition or quality.

Ecosystem vertical profile: Ecosystem vertical profile is the vertical distribution of biomass in ecosystems, both above and below the land surface, as defined by the Group on Earth Observation's Biodiversity Observation Network (GEO BON). It is considered an Essential Biodiversity Variable that can be estimated remotely via satellite EO.

Ecosystem distribution: Ecosystem distribution refers to the pattern or arrangement of ecological types across a given area. This distribution can be mapped and delineated at many different scales, from global to a particular landscape or seascape.

Spatial configuration: Spatial configuration indicates the pattern or arrangement of habitats within a larger area, often measured by size, proximity, number, and connectivity among them. These habitats are referred to as "patches," or are ecologically distinct landscape features, such as a wetland or perennial grassland within a larger region.

Structural connectivity: Structural connectivity describes how the physical arrangement, or spatial configuration, of ecosystems or habitats area are linked or disrupted. It is considered an indicator of ecosystem condition or quality, and it is a predictor of functional connectivity.

Functional connectivity: Functional connectivity is the movement of species, and individuals within a species, across habitats or patches in a larger area, indicating whether these areas tend to house the same individuals or distinct ones because of the degree of exchange and movement possible between them. Areas with low connectivity tend to have patches at a greater distance or with more disturbance, degradation, or loss of habitat between them. Functional connectivity is a measure of ecosystem condition, and it relates to the health of species populations locally.

+ APPENDIX C: ABOUT THE AUTHORS

PLANET

Seamus Lombardo is Impact Metric Associate at Planet, where he supports initiatives to employ satellite data in biodiversity conservation and environmental reporting. He also works to measure and improve the impact of Planet's collaborations with governments, NGOs, and businesses. Seamus's work and publications focus on satellite remote sensing for environmental and humanitarian applications. Previously, he completed his PhD at MIT researching remote sensing and integrated complex systems modeling to support sustainable development.

Tara O'Shea is Senior Global Director of Forests & Land Use at Planet, where she oversees the company's strategy for leverages its Earth observation and analytics technologies to improve global forest monitoring systems today, and account for the value of forests in the global economy tomorrow. Tara has 13 years' experience in sustainability and climate solutions, and holds a Master of Environmental Management and International Development from Duke University and a Bachelor of Science in Environmental Science from Gettysburg College.

Amy Rosenthal is Senior Global Director for Conservation Initiatives at Planet, where she leads the PBC's biodiversity programs. Over the past 20 years, Amy has worked in philanthropy, academia and research, and civil society, focused on the development of science-based, community-centered strategies for nature conservation and sustainability. She has degrees from Stanford University and Amherst College, publishing in the fields of conservation social science, biodiversity & ecosystem services, and decision science.

MICROSOFT

Amy Luers is Global Director for Sustainability Science and Innovation at Microsoft. Previously, she served as executive director of Future Earth, Assistant Director for Climate Resilience and Information at the White House in the Obama Administration, and Senior Environment Manager at Google. She has both a PhD in environmental science and an MA in international policy studies from Stanford University, a BS/MS in environmental systems engineering from Humbold State University, and a BA in philosophy from Middlebury College.

Juan M. Lavista Ferres is Vice President and Chief Data Scientist of the AI for Good Lab at Microsoft. Leading a team of dedicated data scientists and researchers in the domains of AI, machine learning, and statistical modeling, he partners with domain experts, researchers, and organizations worldwide to create a collaborative ecosystem that drives progress toward addressing some of the world's most pressing challenges. Juan dives in to address global challenges armed with a computer science degree from the Catholic University in Uruguay, a graduate degree in Data Mining and Machine Learning from Johns Hopkins University, and a PhD in AI on Healthcare from Vrije Universiteit of Amsterdam.

Benjamin Miller is a postdoctoral scholar at the University of Washington. An ecosystem ecologist by training, Benjamin researches and publishes on the sources and fates of carbon across aquatic and terrestrial ecosystem boundaries, with a special interest in advanced field-based EO techniques. He has degrees from the University of Washington and the University of Michigan.

NATURAL CAPITAL PROJECT, STANFORD UNIVERSITY

Lisa Mandle is Director of Science-Software Integration and a Lead Scientist with the Natural Capital Project. She works to make ecosystem service science accessible and actionable through data and software. Her research sheds light on how land management and infrastructure development affect ecosystem services, social equity, and human health. She is also lead editor of the book *Green Growth That Works,* which provides a practical guide to policy and finance mechanisms from around the world for securing benefits from nature.

NATURAL CAPITAL PROJECT, UNIVERSITY OF MINNESOTA

Stephen Polasky is Regents Professor and Fesler-Lampert Professor of Ecological/Environmental Economics at the University of Minnesota. His research focuses on issues at the intersection of ecology and economics, including work of the value of ecosystem services and natural capital. He is a co-founder of the Natural Capital Project and a member of the U.S. National Academy of Sciences. He received a PhD in economics from the University of Michigan and a BA from Williams College.

UNIVERSITY OF VERMONT'S GUND INSTITUTE

Taylor Ricketts is Gund Professor and Director of the Gund Institute for Environment at the University of Vermont. His recent work has focused on the economic and health benefits provided to people by forests, wetlands, reefs, and other natural areas. He is co-founder of the Natural Capital Project and has also served as an author and editor for two UN-sponsored efforts to assess global ecosystems and their contributions to human well-being . These and other roles are part of a continuing effort to link rigorous research with practical conservation and policy efforts worldwide.

APPENDIX D:

Mapping of metrics, reporting units, and associated technologies for each biodiversity and ecosystem indicator

Indicator	Metric	CSRD	TNFD	Measures	Advanced Field-based EO	Satellite EO	AI
Ecosystem conversion	Conversion over time	✓	✓	Identity & classification of land cover over time		✓	✓
	Restoration overtime		✓	Identity of & classification of land cover & human intervention overtime	✓	✓	✓
Ecosystem management	Sites in or near biodiversity-sensitive areas	✓	✓	Number & area of sites			
	Changes in management over time	✓		Identity of management action & area of application over time	✓	✓	✓
	Area managed		✓	Area	✓	✓	✓
	Area sustainably managed		✓	Area	✓	✓	✓
State of ecosystems	Change in spatial configuration	✓		Physical separation of a habitat over time		✓	✓
	Change in structural connectivity	✓		Distance & physical boundary between separated habitats		✓	✓
	Change in functional connectivity	✓		Presence or absence of indviduals between separated habitats	✓	✓	✓
	Type & extent	✓	✓	Identity & classification of ecosystem type & area		✓	✓
	Condition relative to reference state	✓	✓	A selected measure of habitat quality over time	✓	✓	✓
	Ecosystem pressures		✓	Identity & severity of anthropogenic pressures	✓	✓	✓
Invasive species	Management of introduction	✓	✓	Management action taken against introduction	✓		✓
	Management of spread	✓		Location, rate of spread & action taken to mitigate spread	✓	✓	✓
	Risks posed by invasive species	✓		Identity of social, economic, or ecological harm & severity		✓	✓
State of species	Threat status	✓	✓	Listed status of indicator species	✓		
	Population size	✓	✓	Population size of an indicator or threatened species & change over time	✓	✓	✓
	Change in habitat	✓		Identity of quality habitat occupied & change in area over time	✓	✓	✓
	Extinction risk	✓	✓	Risk of extinction as gauged by change over time in population size & habitat	✓	✓	✓

\+

DISCLOSURES AND COPYRIGHTS

DISCLOSURES

Biodiversity and ecosystem measuring, management, and reporting aided by AI, EO, and ecosystem science may help companies in the future to prepare their voluntary and mandatory disclosures.

The tools described in this white paper do not, on their own, enable companies to comply with the full suite of biodiversity-related disclosures required under the CSRD. The tools may assist companies with metric-related disclosures of ESRS E4, and particularly those of Disclosure Requirement (DR) E4-5 (impact metrics related to biodiversity and ecosystems change). However, subject to the outcome of a company's materiality assessment, CSRD compliance may require disclosures on a range of issues relating to biodiversity, including not only metrics but also transition plans, policies, actions, and targets, among others. Thus, the tools discussed in this white paper are not a complete compliance solution.

Further, this white paper presents emerging technological solutions that remain under development and are not currently available for deployment at scale. Although we expect that these tools will continue to improve, companies may not be able to rely on these or similar tools by the time their mandatory disclosures are due.

To the extent that a company's disclosures (under CSRD or other mandatory or voluntary regimes) rely on AI-generated content, such disclosures will require further review by the company's responsible stakeholders.

Biodiversity and ecosystem measuring, management, and reporting may also be relevant under other legal regimes, such as the UN Conventions on Biological Diversity and Climate Change, as implemented in national frameworks, and/or existing and future mandatory environmental and human rights due diligence rules. This white paper only discusses applications for the AI, EO, and ecosystem science tools related to CSRD/TNFD disclosures, and not application to other legal regimes. Companies must assess their legal obligations, and the extent to which tools exist to assist them, on a case-by-case basis.

COPYRIGHTS

+ REFERENCES

1   Martin. UN Report: Nature's Dangerous Decline 'Unprecedented'; Species Extinction Rates 'Accelerating'. United Nations Sustainable Development https://www.un.org/sustainabledevelopment/blog/2019/05/nature-decline-unprecedented-report/ (2019).

2   Ruckelshaus, M. H. et al. The IPBES Global Assessment: Pathways to Action. *Trends Ecol. Evol.* 35, 407–414 (2020).

3   Almond, R. E. A., Grooten, M., Juffe, B. & Peterson, T. WWF Living Planet Report 2022, Building a Nature-Positive Future. (2022).

4   Estoque, R. C. et al. Spatiotemporal pattern of global forest change over the past 60 years and the forest transition theory. *Environ. Res. Lett.* 17, 084022 (2022).

5   Eddy, T. D. et al. Global decline in capacity of coral reefs to provide ecosystem services. *One Earth* 4, 1278–1285 (2021).

6   Tuia, D. et al. Perspectives in machine learning for wildlife conservation. *Nat. Commun.* 13, 792 (2022).

7   European Comission. Corporate sustainability reporting. https://finance.ec.europa.eu/capital-markets-union-and-financial-markets/ company-reporting-and-auditing/company-reporting/corporate-sustainability-reporting_en (2023).

8   The Taskforce on Nature-related Financial Disclosures. https://tnfd.global/.

9   Holger, D. WSJ News Exclusive | At Least 10,000 Foreign Companies to Be Hit by EU Sustainability Rules. *Wall Street Journal* (2023).

10 Mazar, G. Corporate Sustainability Reporting Directive (CSRD)—KPMG Germany. KPMG https://kpmg.com/de/en/home/insights/ overview/esg/corporate-sustainability-reporting-directive.html (2023).

11 Mary, A. S., Magda Puzniak-Holford, Simon Brennan, Wim Bartels, Laurence Rivat, Julie. European Sustainability Reporting Standards | Unpacking the Commission's first draft Delegated Act. Passle https://emearegulatorystrategy.deloitte.com// post/102iglu/european-sustainability-reporting-standards-unpacking-the-commissions-first-dr (2023).

12 Danes, G., Heintges, S., Mazzeo, P., Villacorta, V. & Trouvain, E. Implementation guidance for the materiality assessment. (2023).

13 Commission Delegated Regulation (EU) 2023/2772 of 31 July 2023 supplementing Directive 2013/34/EU of the European Parliament and of the Council as regards sustainability reporting standards. C(2023) 5303 final. (22.12.2023)

14 Geller, G. N. et al. Space-based Earth Observation and Ecosystem Extent: Exploring Opportunities (2012).

15 Tuia, D. et al., Perspectives in machine learning for wildlife conservation, Nature Communications, 13, 792 (2022).

16 Khan, C. B. et al. A Biologist's Guide to the Galaxy: Leveraging Artificial Intelligence and Very High-Resolution Satellite Imagery to Monitor Marine Mammals from Space. *J. Mar. Sci.* Eng. 11, 595 (2023).

17 Lavista Ferres, J. M. et al. Social connectedness and movements among communities of giraffes vary by sex and age class. *Anim. Behav.* 180, 315–328 (2021).

18 Estes, L. D. et al. High Resolution, Annual Maps of Field Boundaries for Smallholder-Dominated Croplands at National Scales. *Front. Artif. Intell.* 4, (2022).

19 InVEST | The Natural Capital Project. https://naturalcapitalproject.stanford.edu/software/invest (2023).

20 Chaplin-Kramer, R. et al. Global modeling of nature's contributions to people. *Science* 366, 255–258 (2019).

21 Neugarten, R. A. et al. Tools for measuring, modelling, and valuing ecosystem services. (IUCN, 2018). doi:10.2305/IUCN.CH.2018. PAG.28.en.

22 Chaplin-Kramer, R. et al. Mapping the planet's critical natural assets. *Nat. Ecol. Evol.* 7, 51–61 (2023).

23 Ortiz, A. et al. An Artificial Intelligence Dataset for Solar Energy Locations in India. *Sci. Data* 9, 497 (2022).

24   Walston, L. J. et al. Modeling the ecosystem services of native vegetation management practices at solar energy facilities in the
      Midwestern United States. *Ecosyst. Serv.* 47, 101227 (2021).

25   Sitotaw, T. M., Willemen, L., Meshesha, D. & Nelson, A. Empirical Assessments of Local Ecosystem Service Flows in Rural Mosaic
      Landscapes. SSRN Scholarly Paper at https://doi.org/10.2139/ssrn.4536681 (2023).

26   Haddad, I. et al. On the combined use of phenological metrics derived from different PlanetScope vegetation indices for classifying
      savannas in Brazil. *Remote Sens. Appl. Soc. Environ.* 26, 100764 (2022).

27   Taquary, E. C. Deep learning para identificação precisa de desmatamentos através do uso de imagens satelitárias de alta
      resolução. (2019).

28   Nguyen, H.-H. et al. Classification Methods for Mapping Mangrove Extents and Drivers of Change in Thanh Hoa Province, Vietnam
      during 2005-2018. *For. Soc.* 4, 225–242 (2020).

29   Currin, H. Remote Sensing of Georgia Tidal Marsh Habitats Using Aerial Photography and Planetscope Satellite Imagery. Electron.
      Theses Diss. (2023).

30   Francini, S. et al. Near-real time forest change detection using PlanetScope imagery. Eur. J. *Remote Sens.* 53, 233–244 (2020).

31   Zaraza-Aguilera, M. A., Upegui, E. S. & Espejo-Valero, O. J. Change Detection over mining areas using Deep Neural Networks from
      Planetscope image time series. *IEEE Lat. Am. Trans.* 20, 2196–2205 (2022).

32   Forest Carbon: Reliable, Scalable Carbon Estimates. Planet https://www.planet.com/products/forest-carbon/.

33   Nguyen, H.-H., Quang, P., Vu, T. & Tuan, L. MAPPING MANGROVE COVER CHANGE USING PLANETSCOPE DATA (2017-2022) IN
      QUANG YEN TOWN, QUANG NINH PROVINCE TOWARD SUSTAINABLE MANGROVE MANAGEMENT. *J. For. Sci. Technol.* 71–80
      (2022) doi:10.55250/jo.vnuf.2022.13.071-080.

34   Pham, H. N. et al. A new deep learning approach based on bilateral semantic segmentation models for sustainable estuarine
      wetland ecosystem management. *Sci. Total Environ.* 838, 155826 (2022).

35   Twumasi, Y. et al. Fusion of Landsat 8 OLI and PlanetScope Images for Urban Forest Management in Baton Rouge, Louisiana.
      J. Geogr. Inf. Syst. 14, 444–461 (2022).

36   Kazemi Garajeh, M., Salmani, B., Zare Naghadehi, S., Valipoori Goodarzi, H. & Khasraei, A. An integrated approach of remote sensing
      and geospatial analysis for modeling and predicting the impacts of climate change on food security. *Sci. Rep.* 13, 1057 (2023).

37   Seeing African Restoration from Space: Planet and Justdiggit. go.planet.com/justdiggit

38   Integrated Biodiversity Assessment Tool (IBAT). Integrated Biodiversity Assessment Tool (IBAT) https://www.ibat-alliance.org.

39   Beresford, A. E., Donald, P. F. & Buchanan, G. M. Repeatable and standardised monitoring of threats to Key Biodiversity Areas in
      Africa using Google Earth Engine. *Ecol. Indic.* 109, 105763 (2020).

40   Maillard, O., Herzog, S. K., Soria-Auza, R. W. & Vides-Almonacid, R. Impact of Fires on Key Biodiversity Areas (KBAs) and Priority
      Bird Species for Conservation in Bolivia. *Fire* 5, 4 (2022).

41   Traganos, D. et al. Earth observation for ecosystem accounting: spatially explicit national seagrass extent and carbon stock in
      Kenya, Tanzania, Mozambique and Madagascar. *Remote Sens. Ecol. Conserv.* 8, 778–792 (2022).

42   Crowson, M. et al. A comparison of satellite remote sensing data fusion methods to map peat swamp forest loss in Sumatra,
      Indonesia. *Remote Sens. Ecol. Conserv.* 5, 247–258 (2019).

43   Skidmore, A. K. et al. Priority list of biodiversity metrics to observe from space. *Nat. Ecol. Evol.* 5, 896–906 (2021).

44   Silveira, E. M. O. et al. Multi-grain habitat models that combine satellite sensors with different resolutions explain bird species
      richness patterns best. *Remote Sens. Environ.* 295, 113661 (2023).

45   Marzialetti, F. et al. Measuring Alpha and Beta Diversity by Field and Remote-Sensing Data: A Challenge for Coastal Dunes
      Biodiversity Monitoring. *Remote Sens.* 13, 1928 (2021).

46 Pinto-Ledezma, J. N. & Cavender-Bares, J. Predicting species distributions and community composition using satellite remote sensing predictors. *Sci. Rep.* 11, 16448 (2021).

47 Ellwood, E. R. et al. Biodiversity Science and the Twenty-First Century Workforce. *BioScience* 70, 119–121 (2020).

48 Bernhardt, E. S. et al. The metabolic regimes of flowing waters. *Limnol. Oceanogr.* 63, S99–S118 (2018).

49 Zhang, Y. & Ye, A. Improving global gross primary productivity estimation by fusing multi-source data products. *Heliyon* 8, e09153 (2022).

50 Gao, L. et al. Remote sensing algorithms for estimation of fractional vegetation cover using pure vegetation index values: A review. *ISPRS J. Photogramm. Remote Sens.* 159, 364–377 (2020).

51 Hossain, A. K. M. A., Mathias, C. & Blanton, R. Remote Sensing of Turbidity in the Tennessee River Using Landsat 8 Satellite. *Remote Sens.* 13, 3785 (2021).

52 Wang, Z. & Vivoni, E. R. Detecting Streamflow in Dryland Rivers Using CubeSats. *Geophys. Res. Lett.* 49, e2022GL098729 (2022).

53 Ghose, A., Lissandrini, M., Hansen, E. R. & Weidema, B. P. A core ontology for modeling life cycle sustainability assessment on the Semantic Web. *J. Ind. Ecol.* 26, 731–747 (2022).

54 Ung, V. & Buttigieg, P. L. BIOREALM—An ontology of comparative biogeography: New insights into the semantics of biodiversity conservation. *J. Biogeogr.* 50, 1576–1586 (2023).

55 Xu, M. et al. Estimating estuarine primary production using satellite data and machine learning. Int. *J. Appl. Earth Obs. Geoinformation* 110, 102821 (2022).

56 Frost-Wicks, A. Modeling habitat connectivity and movement of Blanding's turtles (Emydoidea blandingii) across a fragmented landscape in Rouge National Urban Park, Ontario, Canada. https://DalSpace.library.dal.ca//handle/10222/76509 (2019).

57 Peters, D. L., Niemann, K. O. & Skelly, R. Remote Sensing of Ecosystem Structure: Fusing Passive and Active Remotely Sensed Data to Characterize a Deltaic Wetland Landscape. *Remote Sens.* 12, 3819 (2020).

58 Cisneros-Araujo, P. et al. The Role of Remote Sensing Data in Habitat Suitability and Connectivity Modeling: Insights from the Cantabrian Brown Bear. *Remote Sens.* 13, 1138 (2021).

59 Rumiano, F. et al. Remote Sensing of Environmental Drivers Influencing the Movement Ecology of Sympatric Wild and Domestic Ungulates in Semi-Arid Savannas, a Review. *Remote Sens.* 12, 3218 (2020).

60 Crego, R. D., Masolele, M. M., Connette, G. & Stabach, J. A. Enhancing Animal Movement Analyses: Spatiotemporal Matching of Animal Positions with Remotely Sensed Data Using Google Earth Engine and R. *Remote Sens.* 13, 4154 (2021).

61 Romtveit, L. et al. Optimal foraging by a large ungulate in an extreme environment: Wild mountain reindeer select snow-free feeding habitats in winter. *Ecol. Evol.* 11, 10409–10420 (2021).

62 Microsoft Premonition. Microsoft Research https://www.microsoft.com/en-us/research/product/microsoft-premonition/.

63 Movebank. https://www.movebank.org/cms/movebank-main.

64 Lake, T. A., Briscoe Runquist, R. D. & Moeller, D. A. Deep learning detects invasive plant species across complex landscapes using Worldview-2 and Planetscope satellite imagery. *Remote Sens. Ecol. Conserv.* 8, 875–889 (2022).

65 Bergamo, T. F. et al. From UAV to PlanetScope: Upscaling fractional cover of an invasive species Rosa rugosa. *J. Environ. Manage.* 336, 117693 (2023).

66 Savage, A. et al. An Assessment of the Population of Cotton-Top Tamarins (Saguinus oedipus) and Their Habitat in Colombia. PLOS ONE 11, e0168324 (2016).

67 Boos, E. & Bruno, K. Caught in the act! Using camera trapping to investigate the link between tropical forest degradation and biodiversity in the Belize Maya Forest. *ISPRS J. Photogramm. Remote Sens.* (2023).

68 Budd, A. et al. Monitoring threatened species with environmental DNA and open ecological data: Local distribution and habitat preferences of scalloped hammerhead sharks (Sphyrna lewini). *Biol. Conserv.* 278, 109881 (2023).

69 Mansaray, A. S. et al. Comparing PlanetScope to Landsat-8 and Sentinel-2 for Sensing Water Quality in Reservoirs in Agricultural Watersheds. *Remote Sens. 13,* 1847 (2021).

70 Anglo American leveraging NatureMetrics 'eDNA' solution to improve biodiversity knowledge at Woodsmith—NatureMetrics. https://www.naturemetrics.com/news/anglo-american-leveraging-naturemetrics-edna-solution-to-improve-biodiversity-knowledge-at-woodsmith.

71 Roston, E. & White, N. Nature's DNA Detectives. Bloomberg.com.

72 Mair, L. et al. A metric for spatially explicit contributions to science-based species targets. *Nat. Ecol. Evol.* 5, 836–844 (2021).

73 Bennun, L. et al. The Value of the IUCN Red List for Business Decision-Making. *Conservation Letters* 11, e12353 (2018)

74 Taskforce on Nature-related Financial Disclosures. Guidance on the identification and assessment of naturerelated issues: The LEAP approach. (2023).

75 Tools Catalogue – TNFD. https://tnfd.global/guidance/tools-catalogue/

76 Scoping report for a methodological assessment of the impact and dependence of business on biodiversity and nature's contributions to people | IPBES secretariat. https://www.ipbes.net/document-library-catalogue/scoping-report-methodological-assessment-impact-and-dependence-business.

77 Gonzalez, A., Chase, J. M. & O'Connor, M. I. A framework for the detection and attribution of biodiversity change. *Philos. Trans. R. Soc. B Biol. Sci.* 378, 20220182 (2023).

78 Chapman, M., Xu, L., Lapeyrolerie, M. & Boettiger, C. Bridging adaptive management and reinforcement learning for more robust decisions. Philos. Trans. *R. Soc. B Biol. Sci.* 378, 20220195 (2023)

79 Christiaen, C. Geolocated asset data: the fundamental building block for geospatial nature risk analysis by financial institutions. in GEO BON Global Conference: Monitoring Biodiversity for Action. Montreal, Canada, October 10-13, 2023 (2023)

80 Jessen, T., Ban, N., Claxton, N. & Darimont, C. Contributions of Indigenous Knowledge to ecological and evolutionary understanding. *Front. Ecol. Environ.* 20, (2021)

81 Aide, T. M. et al. Real-time bioacoustics monitoring and automated species identification. *PeerJ 1,* e103 (2013).

82 Chhaya, V. et al. Community Bioacoustics: Studying Acoustic Community Structure for Ecological and Conservation Insights. *Front. Ecol. Evol.* 9, (2021).

83 Baker, E., Price, B. W., Rycroft, S. D., Hill, J. & Smith, V. S. BioAcoustica: a free and open repository and analysis platform for bioacoustics. *Database* 2015, bav054 (2015).

84 Ruppert, K. M., Kline, R. J. & Rahman, M. S. Past, present, and future perspectives of environmental DNA (eDNA) metabarcoding: A systematic review in methods, monitoring, and applications of global eDNA. *Glob. Ecol. Conserv.* 17, e00547 (2019).

85 Norouzzadeh, M. S. et al. Automatically identifying, counting, and describing wild animals in camera-trap images with deep learning. *Proc. Natl. Acad. Sci.* 115, E5716–E5725 (2018).