CODEX PLANETARIUS ▪ RESEARCH ▪ DECEMBER 2024

CODEX PLANETARIUS

Biodiversity as a Key Variable in *Codex Planetarius*

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About *Codex Planetarius*

Codex Planetarius is a proposed system of minimum environmental performance standards for producing globally traded food. It is modeled on the *Codex Alimentarius*, a set of minimum mandatory health and safety standards for globally traded food. The goal of Codex Planetarius is to measure and manage the key environmental impacts of food production, acknowledging that while some resources may be renewable, they may be consumed at a faster rate than the planet can renew them.

The global production of food has had the largest impact of any human activity on the planet. Continuing increases in population and per capita income, accompanied by dietary shifts, are putting even more pressure on the planet and its ability to regenerate renewable resources. We need to reduce food production's key impacts.

The impacts of food production are not spread evenly among producers. Data across commodities suggest that the bottom 10-20% of producers account for 60-80% of the impacts associated globally with producing any commodity, even though they produce only 5-10% of the product. We need to focus on the bottom.

Once approved, *Codex Planetarius* will provide governments and trade authorities with a baseline for environmental performance in the global trade of food and soft commodities. It won't replace what governments already do. Rather, it will help build consensus about key impacts, how to measure them, and what minimum acceptable performance should be for global trade. We need a common escalator of continuous improvement.

These papers are part of a multiyear proof of concept to answer questions and explore issues, launch an informed discussion, and help create a pathway to assess the overall viability of *Codex Planetarius*. We believe *Codex Planetarius* would improve food production and reduce its environmental impact on the planet.

This proof-of-concept research and analysis is funded by the Gordon and Betty Moore Foundation and led by World Wildlife Fund in collaboration with a number of global organizations and experts. For more information, visit www.codexplanetarius.org

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Introduction

There is no agriculture without biodiversity. All food comes from plants and animals and their genetic variations have enabled improved varieties, dramatically increasing production. All food relies directly or indirectly on the fertility of soils made possible by more animals and plants. Ecosystems make agriculture possible through provisioning services such as production of biomass and genetic materials and regulating services including climate regulation, evapotranspiration, soil quality, sediment retention, nutrient cycling water regulation and pollination (IUCN 2024).

And yet, food production is one of the major drivers in the loss of biodiversity. The Living Planet Report (2024) details such impacts: for example agriculture results in: 27% of greenhouse gas emissions; 70% of freshwater withdrawals, a main threat to 86% of species at risk of extinction and 90% of tropical extinction.

IUCN (2024) calculates that about 37% of the world's land area is devoted to agriculture, making it the world's largest terrestrial ecosystem (DeClerck et al. 2023). Agricultural land consists of 11% croplands, 25% pasturelands and 1% plantations. Many of the threats posed by agriculture are direct, through conversion of natural habitats to agricultural uses and through water use. Threats are also indirect through introduction of invasive alien species, nutrient loading, soil erosion, agrochemicals and climate change.

However, the distinction between agricultural lands and non-agricultural lands is not binary. Biodiversity is abundant in agricultural lands whether in unplowed field margins, wood lots, irrigation ditches, soils and the very genetic material of the domesticated animals and plants. Natural ecosystems are converted to agriculture, abandoned and then return to some manner of semi-natural system. Agricultural systems such as agroforestry are designed to include native biodiversity and crops on the same land and mariculture of seaweed can increase habitat for native marine life.

Agricultural lands have increased five-fold over the last 300 years, first in Europe and Asia and more recently in Africa, the Americas, and Oceania (IUCN 2024). As witnessed by the push to establish *Codex Planetarius*, there is broad recognition that agricultural practices must change to save the climate, the planet, and humankind. In its 2024 Living Planet Report, WWF proposes that "nature-positive" production be scaled to provide enough food for everyone while also allowing biodiversity to flourish. But what does this mean? And how would you measure it? In this paper we review the history, definitions and uses of the term biodiversity and use that as a background for proposing three related metrics to assess the biodiversity impacts of food production.

Biodiversity: How it has been Defined and Used

Biodiversity is both simple and difficult to define. It is often glossed as "the variety and variability of life" or "all life on earth" or "the heartbeat of our living planet." Such general definitions make the term relevant to a very wide range of stakeholders. Agricultural scientists and others concerned about the loss of crop and livestock breeds become advocates for biodiversity as well as the importance of agrobiodiversity. Ethnobiologists working with agriculturalists growing traditional landraces join the biodiversity bandwagon, as do pharmaceutical companies prospecting for new drugs in wild species. Zoos and botanical gardens, seeking new support for their traditional breeding of endangered species, join indigenous and traditional peoples who positioned themselves as keepers of biodiversity. The biodiversity conservation advocates are a diverse lot.

The roots of the term biodiversity are located in the late 1950s in the work of Hutchinson and MacArthur (discussion drawn from Redford and Mace 2018; Sanderson and Redford 1997 and Takacs 1996; see these references for a full list of citations). In the 1970s, the richness of species was called "natural diversity" by The Nature Conservancy while others described "genetic diversity." In 1980, Thomas Lovejoy used the term "biological diversity" without defining it, and the 1980 Annual Report of the U.S. Council on Environmental Quality also used a definition of biological diversity that included the concepts of genetic diversity and species richness.

Early support for the newly emerging term of biodiversity came from a wide range of stakeholders, but most influential were a handful of U.S. and British academics and conservationists, in particular E. O. Wilson, Peter Raven, Norman Myers, and Thomas Lovejoy. What these people had in common was a deep affinity for species. Led by Wilson and Raven, taxonomists themselves, and united by a common love of tropical forests and deep concern about their destruction, biodiversity rapidly became cast as the number of species in an area—for which tropical forests were particularly notable. Tropical forests and biodiversity continue to be inextricably connected in the minds of many publics and policy professionals. However, this single focus was never meant to be the case.

Despite the lack of a specific definition, the term was picked up by the U.S. Government, which convened a "Strategy Conference on Biological Diversity," and in 1983 it became the goal of legislation passed by the U.S. Congress. By the mid-1980s, the first full definitions of the term were published by Burley (1984) and Norse et al. (1986). In 1988, E. O. Wilson edited the book Biodiversity based on a U.S. National Academy of Sciences meeting entitled "The National Forum on BioDiversity." This meeting focused on the value of biodiversity with talks from development experts, economists, and ethicists joining natural scientists in outlining what became known as the biodiversity crisis (Wilson 1988).

The term came into common use but it was not until the Convention on Biological Diversity signed by 150 government leaders at the 1990 Rio Earth Summit that a widely accepted formal definition was provided: "Biological diversity means the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems."

Biodiversity in this definition is most commonly interpreted as occurring at three major levels: genes, species, and ecosystems though some also include populations, communities, biomes and in WWF's Living Planet Report (2024) population diversity and ecosystem functional diversity as well. The specific ways of measuring biodiversity vary by different practitioners (see Mace 2014) but often include the following:

- Diversity of the genetic component refers to the variability within a species, as measured by the variation in genes within a particular species, subspecies, or population.
- Diversity of the species component refers to the variety of living species and their component populations at the local, regional, or global scale.
- Diversity of the ecosystem component refers to a group of diverse organisms, guilds, and patch types occurring in the same environment or area, and strongly interacting through trophic, spatial biotic, and abiotic relationships.

In a seminal, though often ignored, paper Reed Noss (1990) created a monitoring framework for biodiversity that expanded each of these three components such that each one also had three attributes: structure, function and composition. Redford and Richter (1999) used this system of three components – genes, species and ecosystems, each with three attributes – structure, function, and composition to assess the impacts of different human uses on biodiversity **(Table 1, page 8)**.

Biodiversity, glossed as all life on earth, is found everywhere. Initially the discussion was centered on terrestrial systems though active work and lobbying from marine scientists extended the world's concern to the oceans as well. Life in freshwater is incredibly important yet remains the least considered of the earth's major biomes.

In a similar fashion, species of mammals and birds were initially the major focus, joined by amphibians and later by plants and fishes. A major recent effort by scientists has pushed fungi into the limelight. Left little considered are forms of life that are too small to be observed by the human eye. These microbes include bacteria, viruses, fungi, archaea, and protists and represent over half the species in the world (Anthony et al. 2023). Soil is a place where many microbes are found yet both soil and its fauna have received little consideration by the biodiversity conservation community.

Two terms that are often used in discussions of biodiversity and whose use produces confusion are "habitat" and "ecosystem services." Habitat is used colloquially to represent ecosystems in general, yet in its proper usage the term refers only to the ecosystems in which a given species lives. So, for example, the habitat of most species of reef-building corals is shallow warm-water oceans while the habitat of North American moose is temperate forests and semi-forested areas. Habitat is not the same as ecosystem.

Ecosystem services is a term developed to increase public support for nature by documenting human dependence on ecological life support systems (Gómez-Baggethun et al. 2010). The concept became mainstreamed in the 1990s with the 2003 Millennium Ecosystem Assessment putting ecosystem services firmly on the policy agenda. The concept has more recently been taken up in the tools of nature-based solutions and other policy instruments. As discussed above, ecosystem services are only a subset of the ecosystem component of biodiversity – the "function" attribute. And it is only part of the functions of ecosystem as, though little discussed, the attention is almost exclusively on those ecosystem functions that are of benefit to humans (e.g. nutrient cycling). Left out of most discussions are what have come to be called "ecosystem disservices" (only disservices to humans) such as disease and flooding (see Truchy et al. 2015). Ecosystem services are not equivalent to biodiversity – making up only a small part of the whole.

Biodiversity, as a term, has had limited uptake by the publics of the world and one survey of consumers revealed that many thought it was a form of washing powder. It was developed as a technocratic response to the even vaguer term "nature." The policy community adopted "biodiversity" as a term of art and it underpins the creation of the Convention on Biological Diversity, the most significant global treaty in nature conservation. The term "nature" remains more common in European languages and, after being supplanted by "biodiversity" has seen its use rebounding in popularity through recent terms such as "nature-based solutions" and "natural capital." If people think that biodiversity is a difficult-to-define term they should heed the literary scholar Raymond Williams who wrote that "nature" is the most complicated word in the English language. This paper will use biodiversity as a term as there is a solid literature of decades that allow the term to be parsed – a quality that "nature" does not have. The term itself remains important in policy and implementation circles through instruments such as the Kunming-Montreal Global Biodiversity Framework, the Taskforce on Nature-related Financial Disclosures and the International Advisory Panel on Biodiversity Credits (both of which uses the CBD definition).

Biodiversity is often thought of as a single thing when in fact it has multiple meanings and interpretations that differ in technical and value-based ways (this discussion drawn from Redford and Mace 2018; see Pascual et al. 2023 and Diaz and Malhi 2022). The inclusiveness and broad set of constituencies that promulgated the term in the 1990s has resulted in the plethora of values represented by all those declaring their interest in biodiversity (Pascual et al. 2017). Unlike other international environment issues such as climate change or desertification, the precise objects of interest and targets for action in biodiversity conservation are broad and vague. No one seems to be “against” biodiversity. Different values are embraced, often implicitly, and increasingly explicitly. As such, the global conservation community does not necessarily have the same values as local conservation groups, indigenous people, national development officials, international aid donors, or multinational businesses.

Given the vague ways in which biodiversity is used, these different groups can often seem to be in harmony with one another’s values with no apparent trade-offs. This is well illustrated by the recent discussion about the role of indigenous and traditional peoples as stewards of biodiversity (Fernández-Llamazares et al. 2024). It is only when specific actions are proposed that the veneer of biodiversity as all things to all people is scraped away, reflecting the need to have stakeholder values laid out early in all negotiating arenas and to consider the existence of trade-offs and the need to negotiate them explicitly.

Conservation biology is “inescapably normative” (Barry and Oelschlaeger 1996), and values are an important part of its study. There are other types of values that underpin work on biodiversity including social, economic, relational, and cultural values. Decisions and positions that are argued on the basis of evidence may often be in disagreement due to lack of acknowledgment of divergent values. Biodiversity is not a term with a universally agreed-upon definition. Rather it is a value proposition: diversity is good and should be maintained. As such, the definition shifts like a skin over the underlying social values, and those stakeholders whose values are taken into consideration. As politics is the public contestation of values so biodiversity conservation is politics (Sanderson and Redford 1997).

How Biodiversity is Measured

Defining an entity should be tightly linked to measuring that entity. However, this is often not the case with simpler proxies standing in for the more complicated whole. This is nowhere more true than with biodiversity. As a multi-faceted, multi-scaled, value-laden, widely adopted but poorly defined term it is understandable that measuring biodiversity per se is not straightforward. Different disciplines favor different measures of biodiversity (from Redford and Mace 2018). Ecologists tend to think about biodiversity in terms of the forms and functions of organisms in a place, especially in a community or an ecosystem, because it is the structuring of varieties in space and time that leads to functions and dynamics that they seek to understand. Similarly, evolutionary biologists think about the dynamics, but with an increasing focus on the historical or inherited variation, and therefore the genetic and phylogenetic attributes. Conservation biologists are sometimes concerned with function and process, but often also with preservation of species or genetic diversity, seeking efficient and achievable solutions to the allocation of limited resources. For nature conservationists and wildlife managers, biodiversity often simply means the maintenance of wild habitats and species.

In other disciplines, the concept of biodiversity often lacks the notion of diversity; for example, in economics, biodiversity is generally understood simply to mean species, natural resources, or forests. To the business community the term biodiversity is currently largely replaced by “nature” which makes measurement even more difficult.

To many people outside the conservation science community and to a vocal and powerful part of this same community, the species component is used as a surrogate for overall biodiversity. This has been propelled by the depth and extent of species assessments throughout the world as carried out through IUCN’s Species Survival Commission. For example, WWF’s “Living Planet Index” is based almost entirely on vertebrate species abundances and the new IUCN paper on agriculture and biodiversity has a similar species focus. The focus on species led to the creation of the concept of “hotspots” as priority areas for global conservation – a priority based on the abundance and threat to species. The ecosystem component of biodiversity has received significantly less attention and the genetic component hardly any at all, although this is beginning to change (see Heuertz et al. 2023).

In practice, metrics used for biodiversity assessment in conservation do include other attributes of species. Especially important here is the state of the species assemblage in an area relative to some reference state, often pre-disturbance by industrialized humans. Measures of intactness (lack of disturbance), native-ness (species native to the area), and endemism (species that are only found in the local area) are thus all commonly prioritized in conservation planning. Levels of extinction risk are often important modifiers, especially in plans for protection and restoration with priority given to species closer to a risk of extinction.

The measurement of diversity in ecological communities has a long and rich history in ecological and evolutionary science that is rather weakly linked to the conservation and policy activities. The ecological science metrics focus strongly on species richness as well as abundance. Abundance is important because many ecological processes are more affected by biomass than by diversity alone (Diaz et al. 2007). These measures vary over time and space. These studies show how local (or small-scale) biodiversity change may be very different in both extent and nature from global (or large-scale) biodiversity change. Local diversity loss is variable but often smaller than global diversity loss, because local losses may be at least partially compensated for by non-native species migrating in, and generalist, wide-ranging species replacing local specialists. Compositional changes driven by land-use change and intensification may be very profound (Newbold et al. 2015) and may have important consequences locally as well as globally, especially considering the potential consequences for ecological functions.

The number of proposed metrics for measuring biodiversity is overwhelming. A recent review (Burgess et al. 2024) reviewed 573 biodiversity-related metrics, indicators, indices and layers. Of these 227 are spatial data layers and 272 are temporal indicators. In another review Strange et al. (2024) categorized biodiversity metrics (not exhaustive) as: abundance, area, connectivity, density, distinctiveness, diversity (functional, genetic, phylogenetic), habitat, richness, abundance and richness, complementarity, disturbance, rarity, and uncertainty. And as applications become more powerful so too do definitions with new models and methods creating even more complex approaches (Pollock et al. 2020). Despite the wealth of biodiversity metrics there are calls for new ones (Hawkins 2024), particularly those that are "bottom-up" with a focus on their use by companies assessing and managing their impacts on biodiversity (c.f. Hawkins et al. 2024).

In **Table 2 (Page 9)**, I list a few of the currently discussed biodiversity metrics, their biodiversity focus and a source. As is clear from the Burgess review this is only a small portion of those currently being proposed and/or implemented.

Recognizing the difficulty that this lack of standardization poses for policy making, there has been a recent effort to identify a set of "essential biodiversity variables" (EBVs) intended to constitute a more manageable set of metrics for policy makers, yet representing the most important patterns in a range of policy-relevant contexts. Originally proposed by Pereira et al. **(2013 – see Table 3, page 10)** these EBVs have spawned an ever-growing set of modifications and additional candidate variables (e.g. Schmeller et al. 2017, 2018 – see **Table 4, page 11**).

EBVs are being promulgated and curated by the Group on Earth Observations Biodiversity Observation Network (GEO BON) (https://geobon.org/ebvs/what-are-ebvs/) which has maintained adherence to the original set of variables promulgated by Pereira et al in 2013. They are committed to carrying forward this approach (c.f. GEO BON Strategic Plan 2023-2036). However, discussion continues with some (e.g. Brummitt et al. 2016) proposing a redefinition: an EBV is a critical biological variable that characterizes an aspect of biodiversity, functioning as the interface between raw data and indicators. Discussion, disagreement and modifications will undoubtedly continue.

EBVs belong to a family of global variables that include Global Climate Variables and Global Ocean Variables. The family is growing with proposed EBVs for genetic composition and the proposed Essential Ecosystem Service Variables (Schwantes et al. 2024) grouped into six classes: ecological supply, use, demand, anthropogenic contribution, instrumental value, and relational value.

Even the "essential" set of EBVs contains six classes of metrics and over 25 categories of measurement. Without doubt, this complexity is an obstacle to the establishment of goals and targets, but it is also important to recognize that there is no single simple measure of biodiversity, especially given the very wide range of values, purposes, and contexts to which science and policy may be applied. In recent years, there have been dramatic improvements in the availability of both species and landscape occurrence data as well as remote-sensed tools and analytical models (including emerging artificial intelligence applications). These will help in measuring biodiversity but do not help in simplifying the tangle of metrics on offer.

The existence of a small number of variables developed by the climate change community and laid out in the Paris Agreement has caused users to demand a similar set of globally applicable biodiversity metrics. But biodiversity is even more complicated than the global climate system and such a demand will remain forever unmet.

There will never be a single metric for biodiversity, or even a small number of metrics that will be fit for purpose for all users. As discussed above there are different levels, components and scales for biodiversity and different uses and values that underlie users desire to measure it. Different user communities require biodiversity metrics (drawn from Burgess et al. 2024). The main user groups are governments (including policymakers and public bodies/authorities at national, subnational, and even city levels), business- and trade-related bodies (corporations with supply chains, financial institutions, credit ratings agencies, trade organizations, intergovernmental trade agreements), technical agencies [international organizations, nongovernmental organizations (NGOs), universities], and civil society encompassing local communities and citizens (Indigenous peoples, general public, resource users).

Biodiversity and Food Production

There is no agriculture without biodiversity. Hunting, fishing, and gathering are based on wild biodiversity, as is extensive grazing in many parts of the world. Crops are biodiversity, as are domesticated animals and the wild relatives of both. Fisheries rely on marine biodiversity. Improved yields are possible through the genetic component of biodiversity. Soils are productive because of biodiversity and in many places biodiversity is involved in production of rain.

Yet agriculture is not kind to biodiversity. It is responsible for about 90% of global deforestation and the concomitant loss and degradation of ecosystems and species populations (https://www.fao.org/forest-resources-assessment/remote-sensing/fra-2020-remote-sensing-survey/en/). Fertilizers and pesticides are major sources of pollution both on land as well as in freshwater and marine systems. And soil degradation affects one-third of the world's soils (Elouafia 2024).

Global recognition of these negative impacts led to the adoption of Target 10 in the Global Biodiversity Framework. This Target commits signatories to "Ensure that areas under agriculture, aquaculture, fisheries and forestry are managed sustainably, in particular through the sustainable use of biodiversity, including through a substantial increase of the application of biodiversity friendly practices, such as sustainable intensification, agroecological and other innovative approaches contributing to the resilience and long-term efficiency and productivity of these production systems and to food security, conserving and restoring biodiversity and maintaining nature's contributions to people, including ecosystem functions and services" (https://www.cbd.int/gbf/targets/10). **Table 5 (page 12)** displays the 10 indicators linked to Target 10. They are varied and extensive, and many are not clearly linked to biodiversity.

Yet clearly addressing agriculture's direct impacts on biodiversity is not, in and of itself, enough. As the 2018 report by TEEB, " The Economics of Ecosystems and Biodiversity" states, biodiversity is a part of what they term "eco-agri-food systems, a collective term for "the vast and interacting complex of ecosystems, agricultural lands, pastures, inland fisheries, labour, infrastructure, technology, policies, culture, traditions, and institutions (including markets) that are variously involved in growing, processing, distributing and consuming food." And this multi-faceted system is changing constantly in response to climate change (Yang et al. 2024).

Agriculture and food production have much wider negative impacts on biodiversity than those at the immediate place of production. Transportation, packaging, run-off impacts of fertilizers and food waste are just a few. Agricultural production systems also play a part in zoonotic and other diseases (Sheopon et al. 2023). Aquaculture has its own set of overlapping impacts on biodiversity (Jiang et al. 2022) as do capture fisheries and other forms of ocean resource exploitation (Sala et al. 2021). Yet agricultural lands can also produce ecosystem services such as erosion and flood control, pollinator habitat, carbon sequestration, viewscapes and recreation opportunities (Bennett et al. 2021).

Agricultural production for both national consumption and international trade affect biodiversity. A robust literature examines the "embodied" biodiversity impacts of trade (e.g. Irwin et al. 2022, Boakes et al. 2024, Marquardt et al. 2021). This literature can inform the general background of *Codex Planetarius* and be important in its justification but it is of less utility in developing biodiversity measures because it is mostly based on aggregate statistics, whether these be regional, ecoregional or national. For data availability reasons, these analyses mostly focus on the species component of biodiversity developing indices such as the Species Habitat Index (Schwarzmueller and Kastner 20210), local species richness and rarity-weighted species richness (Boakes et al. 2024), the Biodiversity Intactness Index, which measures the average abundance of originally present species relative to abundance in undisturbed habitat (Newbold et al. 2016), or the increasingly used IUCN STAR index, derived from the IUCN Red List of Threatened Species that measures the potential contributions available towards the global goal of reducing extinction risk, through specific threat abatement or restoration actions (IUCN. 2024).

The question of scale, with its two parts extent and grain, is vital when thinking about food production and biodiversity impact as mentioned above. Extent is the defined spatial area and grain (or resolution) is the smallest area being measured. In this paper we take the position that the focus will be on the region within a given country in which a given crop is grown – the extent. The grain is the individual field in which that crop is grown. It is unknown to what extent data are available to meet this structure and this may need to be modified as the *Codex* is developed.

Proposed Variables

The impact of food production on biodiversity is a key part of the *Codex*. But it is one of the most difficult to implement. As discussed above, the concept of biodiversity is multifaceted, multi-dimensional, cross-scale and value laden. It occurs across the full range of food production land and seascapes, from backyard gardens to largescale ocean capture fisheries. Biodiversity is also linked to all of the other metrics under consideration, influencing them while in turn being influenced by them. Just think about freshwater and its relation to biodiversity and the recent understanding of groundwater as part of hidden global keystone ecosystems (Sacco et al. 2023).

No single metric captures all relevant aspects of biodiversity and none of them taken individually can provide a full picture of the patterns of change (Santini et al. 2016). The choice of and management response to any selected metric will affect our interpretation of biodiversity change more generally. With this substantial caveat we propose three biodiversity metrics to consider for inclusion into the *Codex*. First is one that starts at the farm boundary and looks inward, at soil and soil biodiversity, using as a proxy the percent of fields left under vegetative cover, itself a proxy for soil carbon. Second is one that starts at the farm boundary and looks outward, at the natural ecosystem that was converted to create the field with particular attention to high priority ecosystems. Third is a metric that is probably most relevant to fisheries – the direct exploitation of threatened, endangered or protected species.

As mentioned throughout this account there is a bias towards focusing on terrestrial food production, almost exclusively agriculture. Marine and freshwater food production systems are addressed at the end, and without an equivalent attention to detail, and may need further development directed specifically and their impacts on biodiversity.

a. Soil and biodiversity

The vast majority of the attention of the conservation community has focused on larger animals – particularly birds, mammals and amphibians and charismatic plants like trees and cacti. And on ecosystems like tropical forests and coral reefs. Biodiversity at the microscopic scale has been largely ignored, although there are indications that that is starting to change. Soil, the basis for all terrestrial agriculture, and one of the world's largest ecosystems, is home for a remarkable amount of biodiversity and provides vital ecosystem services to humans and other species. Yet it has suffered with virtually no attention from the global conservation community.

Soil is a complex system at the intersection of the atmosphere, lithosphere, hydrosphere and biosphere and there are numerous types of soils throughout the world that serve as habitat to high biodiversity. Soil living organisms from microbes to moles are estimated to comprise approximately 59% of all biodiversity (Anthony et al.2023). The FAO et al (2020) define soil biodiversity as "the variety of life belowground, from genes and species to the communities they form, as well as the ecological complexes to which they contribute and to which they belong, from soil micro-habitats to landscapes".

Soil biodiversity and ecosystem functions are very complicated and poorly understood. Until recently research has focused on understanding the role of above-ground biodiversity in ecosystem functions and services with much less attention to the ecology of below-ground systems.

Soils provide provisioning ecosystem services such as nutrient cycling and food production; regulating ecosystem services such as climate regulation, regulation of waterflow, soil carbon cycles, and biodiversity conservation; and cultural services.

Yet all is not well with the world's soil ecosystem. Threats to soil biodiversity include deforestation, urbanization, agricultural intensification, loss of soil organic matter and soil organic carbon, soil compaction and scaling, soil acidification and nutrient imbalances, pollution, salinization and sodification, fire, erosion, climate change and invasive species (FAO et al. 2020). The world's cultivated soils have lost between 25 to 75% of their original carbon stocks, which is released into the atmosphere in the form of carbon dioxide (CO2) (Global Soil Partnership; Eisenhauer et al. 2024)

Ninety-five percent of humanity's food is directly or indirectly produced on soils. (Global Soil Partnership). The drive to increase food production has caused a focus on only one of soil's many functions and concomitant degradation of its other functions which in extreme cases has led to complete loss or extensive degradation (Evangelista et al. 2023). Concern for this trend has led to development of several overlapping concepts: soil fertility, soil quality, and soil security. Soil fertility refers to soil's role in crop production, soil quality describes a soil's ability to function for agriculture and its immediate environmental context, such as water quality and plant and animal health, and soil security relates to the need for access to soil ecosystem services to be on the same level as other human rights, and is therefore often used in a policy context (Lehmann et al. 2020).

The challenge for *Codex Planetarius* is to find a metric that is scientifically justifiable, broadly applicable, and fairly easy to measure. Recent studies suggest that microbial diversity could be used as a proxy to predict functioning in natural biomes (Delgado-Baquerizo et al., 2016, 2020) and Banerjee and van der Heijden (2023) list over 40 soil microbiome functions that directly or indirectly contribute to soil, plant, animal, and human health. Romero et al. (2023) suggest that preserving the diversity of soil bacterial and eukaryotic communities is crucial to ensure the provisioning of multiple ecosystem functions, particularly those directly related to food provision (Gao et al. 2024). However, the technologies for measuring soil microbial diversity are neither standardized nor broadly available and therefore this promising avenue for developing a metric for *Codex* is not currently worth pursuing at this point.

The EU's passing of its Soil Health Law means that there has been a focus on how to measure soil health. A recent article (van der Putten et al. 2023) concludes however that "finding effective, easy-to-measure indicators for soil health is challenging, because there is no one-size-fits-all indicator for all circumstances ..." In a similar vein, a review of country approaches to soil biodiversity by the CBD (2020) concludes that: "While some countries have established indicators and monitoring tools for soil biodiversity, for the majority of countries there is a lack of knowledge, capacity and resources to implement soil health principles …"

The challenge therefore is to propose a metric that can be used immediately by all countries. Soil organic carbon, per se might be a measure to consider as FAO et al. (2020) argue that soil organic carbon is a main resource for soil organisms and that soils with higher levels contain larger microbial biomass. However, the effects of soil organic carbon loss on soil biodiversity are globally poorly understood due to lack of data, poor understanding of mechanisms and the linked nature of threats (DeClerck et al. 2023).

Jason Clay (pers. comm.) has suggested that the percent of agricultural land under vegetative cover such as a cover crop or agricultural waste left in the field could be such a measure. Such vegetative cover is part of what DeClerck et al. (2023) refer to as "conservation agriculture" that aims to support a soil biodiversity capable of regenerating soil carbon pools.

Recent reviews of the impact of cover crops on soils support this as a possible metric but warn that there is a great deal of variability across soil texture, regional climate, rainfall and cover crop practices (Scavo et al. 2022, Fohrafellner et al. 2024). Hao et al. (2023) warn that "the long-term regional systematic research of soil physics, chemistry and biology makes it difficult to forecast future implications of cover crops on soil health indicators.

Development of a new metric/indicator for the *Codex* would greatly benefit from consultation with some of the soil biodiversity groups such as the International Network on Soil Biodiversity, FAO's Global Soil Partnership, the Global Soil Biodiversity Initiative, the International Initiative for the Conservation and Sustainable Use of Soil Biodiversity, and the Soil Biodiversity Observation Network (SoilBON)

b. Biodiversity and landscapes

A metric directed at the soil underlying all terrestrial food production is necessary but not sufficient for the purposes of *Codex Planetarius.* Agriculture is the largest contributor to biodiversity loss (Dudley and Alexander 2017) with 83% of total species loss due to agriculture for domestic consumption and 17% due to the production for export (IPBES 2019). Over half of the surface of the Earth is under cover of anthropic origin, including agricultural lands, pasture and range lands and cities. Agricultural expansion is by far the most widespread of land cover changes (IPBES 2019).

Therefore, *Codex Planetarius* must include an index that addresses loss in area of terrestrial ecosystems due to agricultural expansion. In particular, a metric that tells the buyer if any relatively intact natural ecosystems have been lost to production of the agricultural product of interest. The metric should specify the duration that the product has been produced on an already-converted field, perhaps in increments of: less than one year, one to three years; three to 10; and greater than 10 years.

Not all ecosystems are equal so the focus should be on agriculture's impact on largely intact ecosystems with an original set of native species interacting in ways largely independent of direct human influence. Further attention should be paid to avoiding impact to ecosystems included on the IUCN Red List of ecosystems (https://iucnrle.org/global-eco-typo; Keith et al. 2013, 2022 and Nicholson et al. 2024). It is important to note that this Red List of Ecosystems includes not only terrestrial ecosystems but freshwater and marine ones as well.

In addition, there should be an emphasis on agricultural production not impacting Key Biodiversity Areas (https://www.keybiodiversityareas.org). KBAs are sites contributing significantly to the global persistence of biodiversity. Criteria for a KBA include the presence of: threatened species, geographically restricted biodiversity, high ecological integrity, significant biological processes, and high irreplaceability (IUCN 2016).

An ecosystem metric such as proposed here is concordant with one of the Science Based Targets Networks (https://sciencebasedtargetsnetwork.org/about/hubs/biodiversity/) which includes a call for no conversion of natural ecosystems. Mazur et al. (2024) have developed a "SBTN Natural Lands Map" which would be useful in applying the ecosystem metric to terrestrial ecosystems.

c. Biodiversity and landscapes

The third part of the biodiversity metric is directed at direct use of endangered, threatened and protected species in food production and is mostly applicable in fisheries. This is consistent with Target 3 of the proposed Ocean Science-based Targets of the Science Based Targets Network (https://sciencebasedtargetsnetwork.org/companies/take-action/set-targets/ocean-targets/ocean-hub-public-consultation/).

d. Biodiversity in other biomes

The three components of a biodiversity metric discussed above are largely, though not exclusively, relevant to terrestrially-based food production. However, food production in freshwater, mangrove and marine systems also impacts biodiversity. Both the IUCN Red List of Ecosystems and KBAs extend to these other ecosystems. However, it might be necessary to incorporate other components that are directed specifically at freshwater and marine systems. It could be that metrics developed for other aspects of the *Codex* could serve as biodiversity proxies – for example the metric proposed by Richter (in draft) for freshwater states that "All blue water used in food production will be extracted from sources that are not being depleted from over-extraction." This might serve as a useful proxy for freshwater as well. Certainly the species component discussed above is of direct relevance to fisheries in both freshwater and marine systems.

e. Caveats and complications

As discussed above, land devoted to food production interdigitates with lands and waters directly or indirectly delivering biodiversity conservation. The pattern of this interdigitation varies over time and space. Land is put into agriculture and taken out of agriculture following policy and economic changes such as the U.S. Conservation Reserve Program. Throughout the world extensive areas formerly farmed are now abandoned and are actively or passively "rewilding" (Araújo and Alagador 2024, Zheng et al. 2023).

There is a long and active debate about "land sparing" vs. "land sharing", two ends of a continuum of options to balance agricultural production and biodiversity conservation. Agricultural intensification increases food production per area – at least over the short term whereas adding more diverse vegetation back into the landscape conserves biodiversity and, in some cases, increases agricultural yields (Kremen 2020). This continuum is part of the challenge in determining what metrics to choose for the *Codex* and the scale at which to apply measurement.

These three metrics we are proposing will not measure everything that needs to change to make agriculture more compatible with biodiversity. Much has been written about other types of interventions and modifications that are critically important. These include (drawn from DeClerck et al 2023):

- Ensuring that at least 10–20% o semi-natural habitat per km^2 is protected to ensure ecosystem functions, notably, pollination, biological pest control and climate regulation, and to prevent soil erosion, nutrient loss and water contamination
- Reduce impacts of nutrient losses, biocides and other pollutants to air, soil and water
- Regenerate ecosystem services provided by biodiversity in all agricultural lands
- Diversify strategies within fields, between fields and across landscapes to bolster ecosystem services
- Reduce water use through changes in technologies and practices

Movement on these fronts, while critical, will not be tracked with the proposed metrics.

An additional concern is that the *Codex* is retroactive – after an area is already under agriculture. To conserve biodiversity it is also vital to limit the spread of agriculture into biodiversity critical areas such as KBAs or Red List Ecosystems. Hoang et al. (2023) provide one of many analyses to inform how to map out potential conflicts between global agriculture and terrestrial conservation.

Changing climate is already affecting food production throughout the globe. Metrics such as proposed here may need to be changed or modified as the impacts of such changes are determined. Climate change will also affect all the other *Codex* variables with as of yet undetermined impacts of these biodiversity metrics. A process of monitoring and adaptation will be key to producing a useful and robust system.

f. New approaches/technologies

The development of new approaches and technologies means that the suggested metrics need to be continuously evaluated both for their relevance and their measurement. Several emerging trends are worth keeping an eye on:

- Incorporation of traditional and indigenous knowledge (c.f. Ogar et al. 2020)
- Digital twinning as a way of remotely evaluating effectiveness of metrics and measurements (Afsar et al. 2024)
- New approaches to satellite remote sensing (Timmermans and Kissling 2023) including monitoring genetic diversity (ISSI International Team et al. preprint)
- Creation of the technologies to "listen" to biodiversity in the soil (Metcalf et al. 2024)
- New DNA technologies to measure soil biodiversity (Anthony et al. 2023)
- Creation of the "Omic BON" – a thematic Biodiversity Observation Network to observe biomolecules in organisms and the environment (DNA and RNA sequences, proteins, metabolites and other biomolecules) (Meyer et al. 2023)
- Automation and artificial intelligence (Garcia et al. 2023)
- Modifying the proposed Food Sustainability Index which would include artificial intelligence, remote sensing and empirical observations with system dynamics modeling (Biswas et al. 2024)

Tables

Table 1. Attributes of each biodiversity component emphasizing those measures useful in determining potential effects of human use.*

Biodiversity Components	Attributes		
	Composition	Structure	Function
Community/ ecosystem	Presence, richness, frequency, and relative abundance of patch types, guilds, and species; proportions of endemic, exotic, threatened, and endangered species; proportions of generalists and specialists; life form proportions (e.g., C4:C3 plants)	Patch size-frequency distributions; patch spatial configuration and connectivity; trophic structure; vegetation physiognomy; seral stage diversity and areal extent; stream channel form; abundance and distribution of structural elements (e.g., poolriffle-run ratios, abundance of large woody debris and snags)	Extent/spread, frequency/return interval, predictability, timing, intensity, and duration of disturbance processes; patch turnover rates, energy flow rates and patterns; nutrient delivery and cycling rates; biomass productivity; herbivory; parasitism and predation rates; pollination success; geomorphic process rates; flux rates in water budget components; water chemistry and temperature variation
Population/ species	Abundance, biomass, or density; frequency, importance, or cover value	Dispersion (i.e.,microdistribution); range (i.e., macrodistribution); metapopulation spatial configuration; population structure	Demographic processes (e.g., fertility, recruitment rate, survivorship, dispersal, mortality); metapopulation exchange rates; individual growth rates
Genetic	Allelic diversity; presence of particular rare alleles, deleterious recessives, or karyotypic variants	Effective population size; heterozygosity; chromosomal or phenotypic polymorphism; generation overlap; heritability	Inbreeding depression; outbreeding rate; rate of genetic drift; gene flow, mutation rate; selection intensity

** Modified from Noss 1990.*

Table 2. Select indication of recent biodiversity metrics

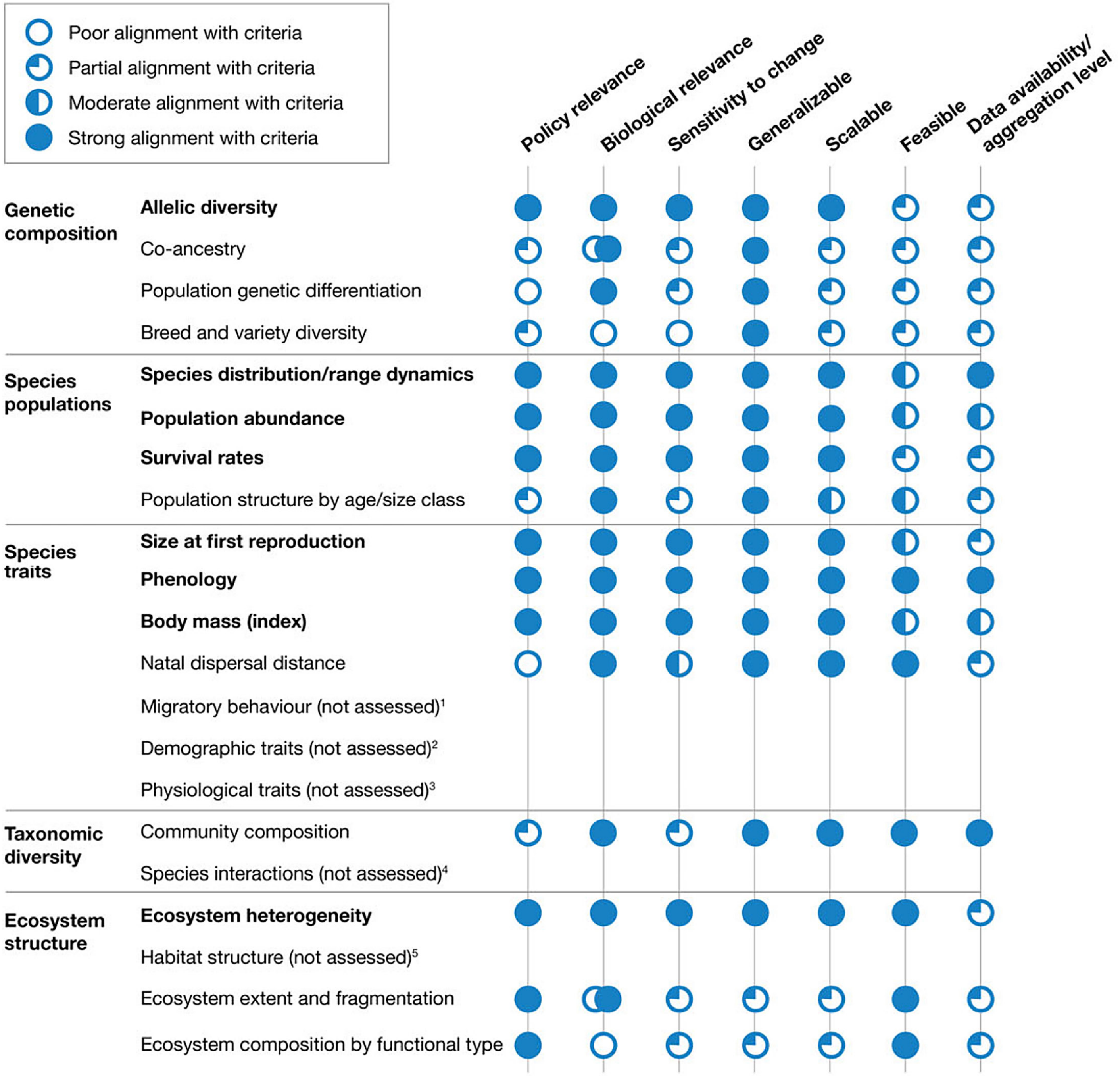
Name/Application	Biodiversity Focus	Reference
Forest integrity	Integrity of ecosystems	Hansen et al. 2021
UN System of Environmental-Economic Accounting Ecosystem Accounting		https://seea.un.org/ecosystem-accounting
Offset exchanges	Various biodiversity	Marshall et al. 2019
Aichi Targets	Various biodiversity	Xu et al. 2021
Essential Ocean Variables	Marine	Rolle et al. 2023
Ocean Health Index	Marine	Halpern 2020
Essential Biodiversity Variables	Various	Pereira et al. 2013
Essential Ecosystem Service Variables	Ecosystem function	Schwantes et al. 2024
Essential environmental impact variables	Operational issues	Wassenius et al. 2024
Living Planet Index	Species populations mostly	https://www.livingplanetindex.org
Species Threat Abatement and Restoration	Species extinction risk	https://iucn.org/resources/conservation-tool/species-threat-abatement-and-restoration-star-metric
Science-based targets for nature	Ecosystems	Mazur et al. 2024
Land Degradation	Functions	Orr et al. 2017
Convention on Biological Diversity	All	https://www.cbd.int/gbf/related/monitoring
Global Biodiversity Framework monitoring	All	https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-05-en.pdf
Global Biodiversity Observing System	National BON variables	Gonzalez et al. 2023
Nature's Metric	Ecosystem condition	https://www.naturemetrics.com/news/ecosystem-condition-the-key-to-achieving-cop16-biodiversity-goals

Table 3. Attributes of each biodiversity component emphasizing those measures useful in determining potential effects of human use.*

Examples of Candidate Essential Biodiversity Variables					
EBV Class	**EBV Examples**	**Measurement and Scalability**	**Temporal Sensitivity**	**Feasibility**	**Relevance for CBD targets and indicators (1,9)**
Genetic composition	Allelic diversity	Genotypes of selected species (e.g., endangered, domesticated) at representative locations	Generation time	Data available for many species and for several locations, but little global systematic sampling.	**Targets:** 12, 13. Indicators: Trends in genetic diversity of selected species and of domesticated animals and cultivated plants; RLI.
Species populations	Abundances and distributions	Counts or presence surveys for groups of species easy to monitor or important for ES, over an extensive network of sites, complemented with incidental data.	1 to >10 years	Standardized counts under way for some taxa but geographically restricted. Presence data collected for more taxa. Ongoing data integration efforts (Global Biodiversity Information Facility, Map of Life).	**Targets:** 4, 5, 6, 7, 8, 9, 10, 11, 12, 14, 15. **Indicators:** LPI; WBI; RLI; population and extinction risk trends of target species, forest specialists in forests under restoration, and species that provide ES; trends in invasive alien species; trends in climatic impacts on populations.
Species traits	Phenology	Timing of leaf coloration by RS, with in situ validation.	1 year	Several ongoing initiatives (Phenological Eyes Network, PhenoCam, etc.)	**Targets:** 10, 15. **Indicators:** Trends in extent and rate of shifts of boundaries of vulnerable ecosystems.
Community composition	Taxonomic diversity	Consistent multitaxa surveys and metagenomics at select locations.	5 to >10 years	Ongoing at intensive monitoring sites (opportunities for expansion). Metagenomics and hyperspectral RS emerging.	**Targets:** 18, 10, 14. **Indicators:** Trends in condition and vulnerability of ecosystems; trends in climatic impacts on community composition.
Ecosystem structure	Habitat structure	RS of cover (or biomass) by height (or depth) globally or regionally.	1 to 5 years	Global terrestrial maps available with RS (e.g., Light Detection and Ranging). Marine and freshwater habitats mapped by combining RS and in situ data.	**Targets**: 5, 11, 14, 15. **Indicators:** Extent of forest and forest types; mangrove extent; seagrass extent; extent of habitats that provide carbon storage.
Ecosystem function	Nutrient retention	Nutrient output/input ratios measured at select locations. Combine with RS to model regionally.	1 year	Intensive monitoring sites exist for N saturation in acid-deposition areas and P retention in affected rivers.	**Targets:** 5, 8, 14. **Indicators:** Trends in delivery of multiple ES; trends in condition and vulnerability of ecosystems.

From Pereira et al. 2013

Table 4. Summary of assessment of candidate essential biodiversity variables (EBVs), with the EBVs prioritized here shown in bold (From Schmeller et al. 2018)



○ Poor alignment with criteria
◔ Partial alignment with criteria
◑ Moderate alignment with criteria
● Strong alignment with criteria

		Policy relevance	Biological relevance	Sensitivity to change	Generalizable	Scalable	Feasible	Data availability/ aggregation level
Genetic composition	**Allelic diversity**	●	●	●	●	●	◔	◔
	Co-ancestry	◔	○●	◔	●	◔	◔	◔
	Population genetic differentiation	○	●	◔	●	◔	◔	◔
	Breed and variety diversity	◔	○	○	●	◔	◔	◔
Species populations	**Species distribution/range dynamics**	●	●	●	●	●	◑	●
	Population abundance	●	●	●	●	●	◑	◑
	Survival rates	●	●	●	●	●	◔	◔
	Population structure by age/size class	◔	●	◔	●	◑	◑	◔
Species traits	**Size at first reproduction**	●	●	●	●	●	◑	◔
	Phenology	●	●	●	●	●	●	●
	Body mass (index)	●	●	●	●	●	◑	◑
	Natal dispersal distance	○	●	◑	●	●	●	◔
	Migratory behaviour (not assessed)[1]							
	Demographic traits (not assessed)[2]							
	Physiological traits (not assessed)[3]							
Taxonomic diversity	Community composition	◔	●	◔	●	●	●	●
	Species interactions (not assessed)[4]							
Ecosystem structure	**Ecosystem heterogeneity**	●	●	●	●	●	●	◔
	Habitat structure (not assessed)[5]							
	Ecosystem extent and fragmentation	●	○●	◔	◔	◔	●	◔
	Ecosystem composition by functional type	●	○	◔	◔	◔	●	◔

Table 5. Target 10 of GBF Indicators

Headline indicators:
10.1 Proportion of agricultural area under productive and sustainable agriculture
10.2 Progress towards sustainable forest management
Component indicators:
Area of forest under sustainable management: total forest management certification by Forest Stewardship Council and Programme for the Endorsement of Forest Certification
Average income of small-scale food producers by sex and indigenous status
Complementary indicators:
Agrobiodiversity Index
Changes in soil organic carbon stocks
Red List Index (wild relatives of domesticated animals)
Red List Index (pollinating species)
Proportion of local breeds classified as being at risk of extinction
Proportion of land that is degraded over total land area

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