MEASURING BIODIVERSITY

A DATA-DRIVEN APPROACH TO GLOBAL NATURE CONSERVATION

Global biodiversity is in crisis. Modern species are going extinct at a rate hundreds of times faster than they have at any other point in human history. The post-2020 biodiversity framework guides global action to preserve and protect nature and its essential services. Producing indicators to track progress on the targets will require monitoring systems to produce primary data and the classification and analysis of that data. Mathematics underpins all of these actions, from the indices used to measure biodiversity to the algorithms speeding up classification. Mathematical and scientific cooperation and technology transfer will help ensure 2030 targets are met en route to the 2050 goal of 'living in harmony with nature'.

Healthy ecosystems are the foundation of human health and well-being. Extraordinarily high extinction rates have degraded ecosystem structure and functionality, lending urgency to global commitments to mitigate biodiversity loss. Numerous efforts have been made to objectively measure biodiversity. Typically this is done using biodiversity indices.

KEY MESSAGES

- ☑ Biodiversity is critical to maintaining healthy ecosystems. Biodiversity indices allow scientists to quantitatively estimate biodiversity from field observations.
- ☑ Biodiversity indices allow ecologists to estimate biological variability in space and time, set biodiversity goals and measure progress toward them, and design interventions to enhance biodiversity and ecosystem sustainability.
- ☑ Non-biased and accurate data is required to compute biodiversity indices. Traditionally, data are collected through ecological field sampling techniques. In recent years, crowdsourcing, citizens science, and artificial intelligence are increasingly used to support both sampling and data analysis.
- ☑ The mathematical underpinnings of biodiversity indices vary widely. Mathematical axioms can be used to choose the best index given the context of a particular application or ecological study.

DOES MORE MEAN BETTER?

The most iconic and simplest measure of biodiversity is species richness — the absolute number of species in an ecosystem. Although it's a key metric widely used by many conservation planners, species richness as a quantitative estimate of biodiversity has shortcomings. Most notably, measurements of species richness tell very little about how common or widespread the individual species are. All species are treated as equal, from the extremely rare to the incredibly abundant. Invasive species, for example, might add to the immediate richness, but their continued presence might ultimately decrease richness as endemic species are squeezed out. Richness is also particularly sensitive to sampling effort, such that the number of species rises with the number and size of sampling units. Measures must be taken to standardize samples and limit sampling errors. Mathematical tools have been developed to optimize sampling design to maximize information and minimize effort.

EVEN OR UNEVEN?

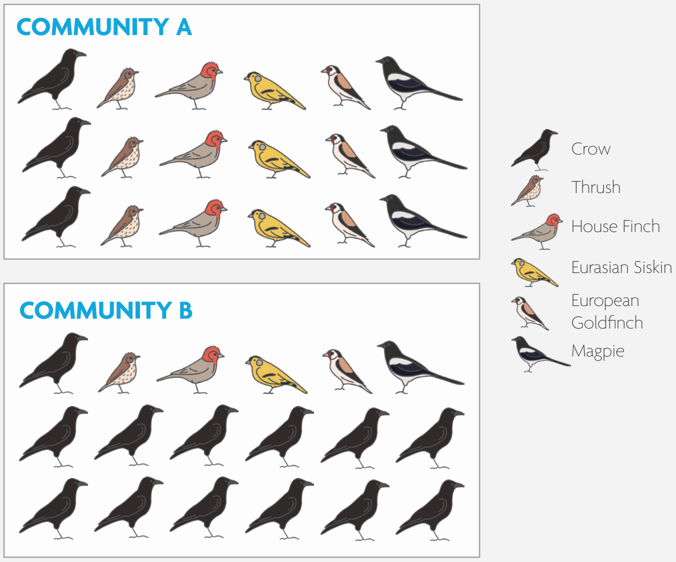
Another important component of ecological diversity is how evenly the individuals are distributed among different species in the community, referred to as evenness. Studies suggest that uneven communities are less resilient to shocks and stresses and more susceptible to invasions.

The most widely used evenness index in ecological literature is based on information theory, namely Claude Shannon's early work on entropy. The Shannon-Wiener Diversity Index quantifies the uncertainty in predicting the species of an individual taken at random from a sample. This uncertainty is largest when the number of individuals in each species is the same. Shannon's Index is generally more influenced by the number of rare species in a community.

One of the best known and earliest evenness measures is the Simpson's Index, used for large sampled communities. This index measures both the number of species present and the proportion of each species. It expresses the probability that two individuals drawn at random belong to the same species. A large value implies a clumping of individuals in a few species, and a small value suggests a more uniform distribution of individuals among the species. Simpson's Index is particularly sensitive to changes in the relative abundances of the most important species.

One problem with traditional diversity measures, in particular evenness indices, is that not all species are equal

VISUALIZING ECOLOGICAL DIVERSITY



In this example, ecologists are comparing passerine birds in two European temperate broadleaf communities. Both Community A and Community B have 18 individuals of different species. In both communities, richness is equal to six. Evenness is how evenly the species are distributed. In Community A, all species are present in equal abundances. Community B is very uneven as it's dominated by crows.

— functionally, evolutionarily, or ecologically. As species' functional and ecological traits result from evolution, some ecologists have suggested incorporating measures of phylogenetic or taxonomic diversity. Evolutionary diversity metrics can help decision-makers assess conservation values of different areas and prioritize conservation of regions that are more functionally and genetically diverse and thus will have the most options to respond to future change.

CHOOSING THE BEST INDEX

A vast number and variety of indices are actively used to measure ecological diversity. The mathematical underpinnings of each of these indices vary widely, making it difficult to choose the best one given the context of a particular application or ecological study. Some researchers have turned to mathematical axioms — unprovable principles accepted as true — to serve as a premise or starting point. Axioms are used to identify the most important properties of diversity indices and select them based on which axioms they satisfy or fail to satisfy. Axiomatic approaches have been widely used in other areas. The famous Arrow Axioms, for example, illustrate the challenges of creating a fair voting structure.

AI MEETS CITIZEN SCIENCE

All biodiversity measurements require data, but acquiring it through conventional field sampling or even remote sensing can be time-consuming and costly. Crowdsourcing and citizen science are proving to be increasingly useful approaches for collecting and classifying biometric data. The Snapshot Serengeti project enlisted volunteers to help classify images collected from hundreds of motion-activated camera traps in Tanzania's Serengeti National Park. More than 30,000 volunteers have helped make over half a million image classifications to date.

Introducing artificial intelligence can address many risks associated with citizen science data collection, from observational biases to classification errors. Artificial intelligence and machine learning techniques are now being used to identify and validate classified images. Deep learning saved an estimated 17,000 hours of human effort in the Snapshot Serengeti project.

When animal images are collected using camera traps, individuals of the same species are most commonly captured in the same habitat. This can lead to computer vision systems classifying the background instead of the animal, resulting in bias. Approaches like co-segmentation get around this by automatically isolating the object of interest without any manual input. State-of-the-art object identification systems use bounding boxes, then resample features for the boxes, and finally use machine learning to classify the objects. Mathematical tools are being developed to train neural networks to identify individuals based on biometric data, such as feather, coat, or skin patterns; facial features such as whisker patterns; footprints; and vocalizations.

CONCLUSIONS

Measurements of biodiversity are essential for monitoring the health of ecosystems. New tools are needed to guide, monitor, and measure progress to halt the loss of biodiversity by 2030 and achieve recovery and restoration by 2050. Mathematical approaches can help strengthen the development and selection of indices and indicators, data collection and validation techniques, and the associated methodologies.

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