The Ecosystem Integrity Index: a novel measure of terrestrial ecosystem integrity with global coverage

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Abstract

We present a novel index that represents, in one combined metric, the integrity of terrestrial ecosystems globally at 1km^2 resolution: the Ecosystem Integrity Index (EII). The index provides a simple, yet scientifically robust, way of measuring, monitoring and reporting on ecosystem integrity at any geographical scale. It is formed of three components, structure, composition, and function, and measured against a natural (current potential) baseline on a scale of 0 to 1. The index has been developed to help national governments measure and report on various of the goals and targets being developed within the draft post-2020 global biodiversity framework being negotiated under the Convention on Biological Diversity, and for non-state actor contributions to also be recognized. In doing so, it will enable these actors to make informed decisions on the conservation, restoration and sustainable use of ecosystems for which they are wholly or partly responsible. We find that ecosystem integrity is rapidly declining in terrestrial areas globally, with countries, on average, retaining less than half of their natural ecosystem integrity with a mean EII across all countries of 0.45 (SD: 0.20). This poses a challenge for nations and businesses seeking to halt and reverse decades of loss of nature around the world, but one that is not insurmountable. With sufficient effort, values of EII can increase at national and other scales, representing progress towards the vision of living in harmony with nature.

Introduction

Ecosystem integrity encompasses the full complexity of an ecosystem, including the physical, biological and functional components, together with their interactions, and measures these against a 'natural' (i.e. current potential) reference level (Carter *et al.,* 2019). Ecosystem integrity is fundamental to the stability of Earth systems on which humanity depends. For instance, natural areas containing ecosystems with higher integrity have greater potential to provide services such as carbon sequestration (Lewis *et al.*, 2009), maintenance of water quality (Mello *et al.*, 2018), climate regulation (Bonan, 2008), pest control (Bianchi *et al.*, 2006), and pollination (Carvalheiro *et al.*, 2010) – as well as supporting higher levels of biodiversity (Gibson, 2011; Barlow *et al.*, 2016).

The importance of healthy ecosystems (ecosystems with high integrity) has been recognised in the context of the three Rio Conventions: the United Nations Convention on Biological Diversity (CBD), the UN Framework Convention on Climate Change (UNFCCC) and the UN Convention to Combat Desertification (UNCCD, 2022).

The current draft of the post-2020 global biodiversity framework includes ambitions for the maintenance, restoration or enhancement of ecosystem integrity within one of its four global goals (CBD, 2022). Alongside the development of the framework itself are the ongoing negotiations around the approach by which Parties to the CBD will monitor and report progress towards its goals and targets. An assessment of ecosystem integrity at national and global scales can support these developments through providing information on relevant baseline states of integrity (for instance, providing a 'natural' or current potential state reference level), as well as supplying a means of monitoring trends in future ecosystem integrity across scales.

Meeting the goals and targets of the draft post-2020 global biodiversity framework will require action not only at the national level (by the 196 parties to the CBD), but also by a range of other actors including businesses. The Ecosystem Integrity Index (EII) has been designed to provide a means of aligning between the goals and targets of the global biodiversity framework and 1) target guidance under development by the Science Based Targets Network (SBTN) and 2) the risk management and disclosure framework under development by the Task Force for Nature-related financial Disclosure (TNFD). Both initiatives have identified the need for a scalable metric of ecosystem integrity, linked to the post-2020 global biodiversity framework, which is readily usable by businesses and financial institutions for evidence-based target setting, monitoring and disclosure (TFND, 2022; SBTN 2020).

Conceptualisation of ecosystem integrity

The concept of ecosystem integrity is not new and first emerged in the work of Leopold (1949). The concept was further developed by Parrish *et al*. (2003), who proposed that 'an ecological system has integrity when its dominant ecological characteristics (e.g., elements of structure, composition, function, and ecological processes) occur within their natural ranges of variation'. Carter *et al.* (2019), simplified this further to define ecosystem integrity as 'the extent to which the composition, structure, and function of an ecosystem fall within their natural range of variation'. Structure comprises the three-dimensional aspect of ecosystems – the biotic and abiotic elements that form the heterogeneous matrix supporting the composition and functioning. Composition refers to the biotic constitution of ecosystems – the pattern of the makeup of species communities and the interactions between them. Function describes the ecological processes and ecosystem services provided by the ecosystem. It follows that any measurement of ecosystem integrity should encompass all three components; however, it should be noted that the components are interdependent and are likely to covary with varying pressures on the system.

Ecosystem integrity has generated considerable interest in recent years with the development of several indices designed to assess changes in ecological factors relating to integrity at a global level or within specific habitat types. Recent work has focussed on measuring ecosystem extent, although there is little scientific consensus on the best way to do this (Sayre *et al.*, 2020; IUCN-CEM, 2022), and on aspects of ecosystem integrity (Beyer *et al.*, 2019; Blumetto *et al.*, 2019; Grantham *et al.,* 2020; Hansen *et al.*, 2021; Mora, 2017; Perkl, 2017), but no previous study provided a combined metric that takes into account all components of integrity within all terrestrial systems. For instance, Grantham et al. (2020) created the Forest Landscape Integrity Index (FLII) integrating data on forest extent, observed and inferred human pressures, and changes in forest connectivity, and an index of ecosystem integrity for agricultural systems was developed by Blumetto *et al.* (2019) to monitor integrity at the farm level.

Despite these various efforts there is currently no index that attempts to bring together structure, composition and functioning into an aggregated measure that can be applied at any scale to all ecosystem types.

Introducing the Ecosystem Integrity Index

Our Ecosystem Integrity Index (EII) quantifies degradation to ecosystem integrity based on an aggregation of all three components: ecosystem structure, composition, and function. This framing is consistent with the definitions provided by Carter *et al.* (2019) and Parrish *et al.* (2003).

The first component of EII, structure, is dependent on habitat area, intactness, and fragmentation. The metric is derived from a total of 12 spatial layers of features associated with anthropogenic pressure on biodiversity, including population density, built-up areas, agriculture, roads, railroads, mining, oil wells, wind turbines and electrical infrastructure. These pressure layers are then aggregated using the methodology described in the Human Modification Index to produce a single pressure layer (Kennedy *et al.,* 2019). We then inputted our new pressure layer to the algorithm described in Beyer *et al.* (2019) that takes into account habitat intactness within a grid cell as well as the influence of habitat quality within neighboring cells, to result in our final structure layer that encompasses impacts of landscape fragmentation as well as local intactness.

The second component captures ecosystem composition, which refers to the identity and variety of life. The metric chosen for this layer is the Biodiversity Intactness Index (BII), which summarizes change in the make-up of ecological communities in response to human pressures (Newbold *et al.,* 2016, Hill *et al.,* 2019). The BII is calculated using two models estimated using data taken from the PREDICTS database (Hudson *et al*., 2017). The first assesses the impact of human pressures on the total abundance of species within a community and the second analyses the similarity between the relative abundance of each of the species in a community in a non-natural landscape with those in a natural landscape. The product of the two models, projected onto maps of human pressures, results in the BII.

The third component captures ecosystem function. The functioning component is estimated using the difference between potential natural and current net primary productivity (NPP) within each 1km grid cell. Current NPP values are taken from remote sensed geospatial layers (Running and Zhao, 2019). Potential natural NPP values are modelled using environmental input data from BIOCLIM (for model details see Methods).

The three component layers are combined into the EII. We used the minimum value approach, in which we take the lowest score of the structure, composition and function layers as the EII value for a grid cell. This method was chosen with the reasoning that the integrity of an ecosystem cannot be higher than the minimum score from any of the three contributing layers. The derived EII, as well as the three components, ranges between 0 and 1, with the most degraded areas having a score approaching zero. To guide management actions, such as identification of areas in which degradation should be avoided, it is useful to distinguish high integrity or 'natural' areas from lower integrity or 'non-natural' areas. The EII provides a continuous scale of naturalness but for simplicity we can adopt a threshold value that distinguishes high integrity areas. Here we use a threshold value of >0.7 to identify areas which retain higher levels of integrity and therefore should be managed to avoid degradation.

Results

Ecosystem integrity is degraded across much of the world with only remote areas in higher latitudes (note that Antarctica was excluded from the analysis), remote areas of rainforest across the tropics, and extremely arid areas across the planet estimated to have extensive areas where ecosystem integrity has been retained (Figure 1).

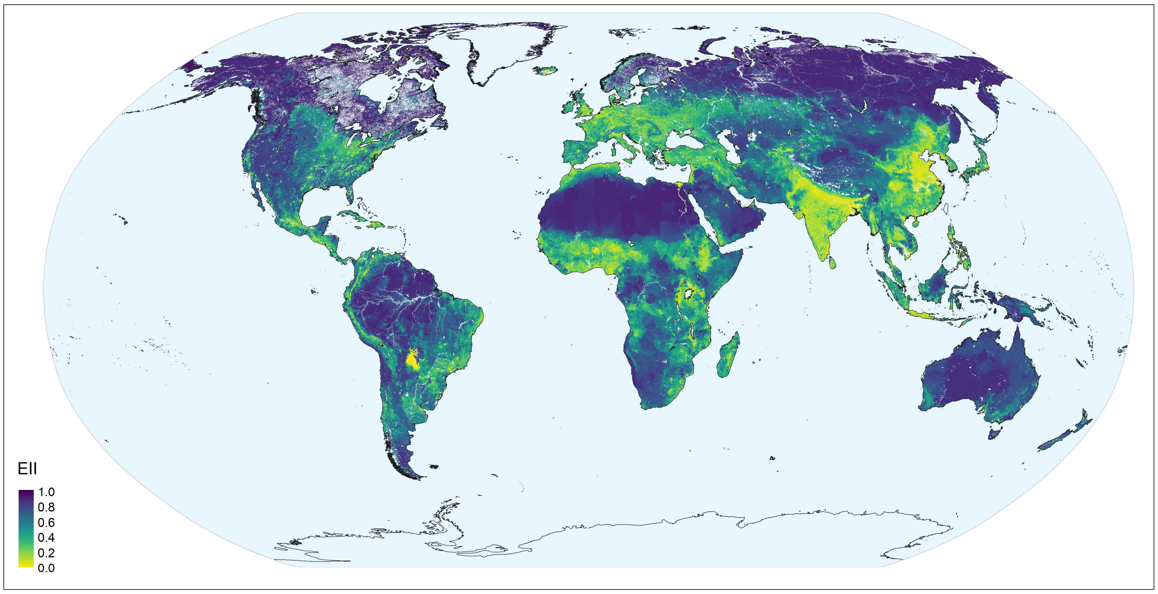

Figure 1. A map of the Ecosystem Integrity Index for all terrestrial areas. Areas with high levels of ecosystem integrity are shown in dark blue, whereas those with highly degraded ecosystem integrity are shown in yellow. Note: the boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations.

When examining the results at an ecoregion level, it is useful to think in terms of the proportion of the ecoregion that has high integrity as well as the mean EII as both measures are likely to be important when considering the health of the ecoregion. Many ecoregions have widespread loss of high integrity (natural) areas and relatively low mean EII including those within the highly biodiverse tropical and subtropical moist broadleaf forests, tropical and subtropical dry broadleaf forests, tropical and subtropical coniferous forests and mangroves (Figure 2). Other ecoregions, such as many within temperate grasslands, savannahs and shrubs, temperate conifer forests, and Mediterranean forests, woodlands and scrub, tend to be characterised by widespread semi-natural areas resulting in a higher mean EII value. Biomes that show relatively consistent levels of degradation across ecoregions include, tropical and subtropical coniferous forests, tropical and subtropical dry broadleaf forests, and boreal forests/taiga, whereas biomes that encompass ecoregions with varied levels of degradation include deserts and xeric shrublands, and tropical and subtropical moist broadleaf forests. These differences are likely to be caused by the utility of the ecoregion for intensive human use based on its environmental features and its accessibility, the size of the ecoregion, and the sensitivity of the ecoregion.

Ecosystem degradation is also widespread at the country scale (Figure 3). Across all 188 countries assessed, the mean EII value was 0.45 (SD:0.20). When comparing between continents, European countries were found to have, on average, the lowest EII scores with a mean value of 0.40 (SD:0.17),

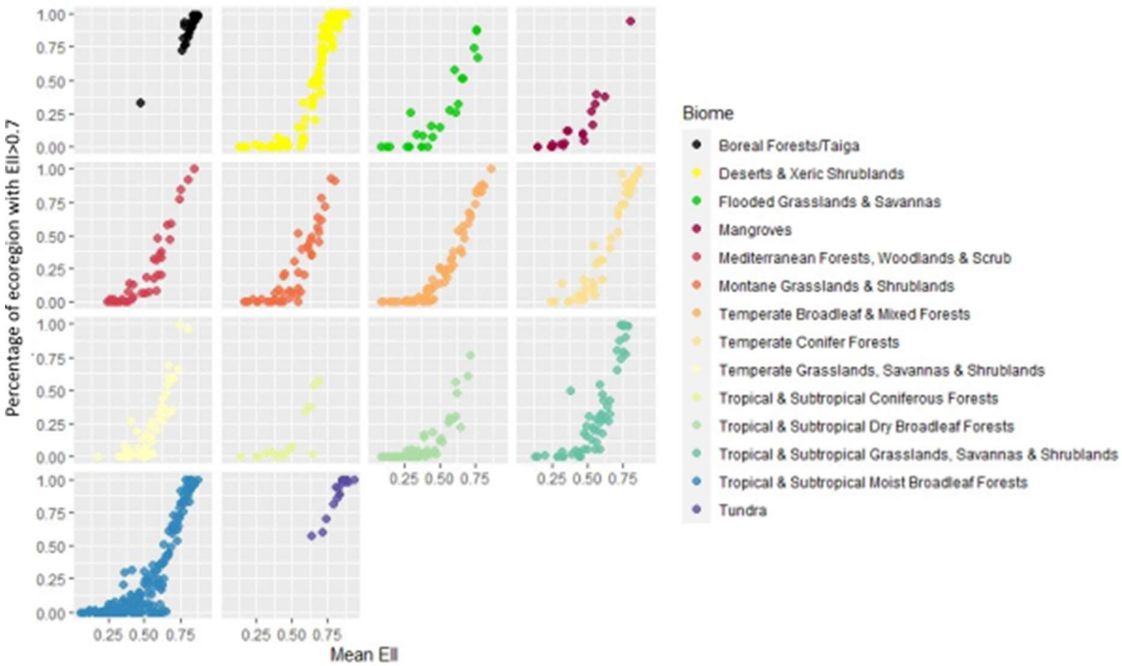

Figure 2. Ecosystem integrity within ecoregions. Each dot represents the values for a single ecoregion as defined by Dinerstein *et al*. (2017). Values for mean EII are compared against values for the percentage of natural or high integrity area (here taken as a threshold of >0.7) within each ecoregion.

and countries in Oceania had the highest EII scores with a mean value of 0.56 (SD:0.17). European countries had the highest proportions of highly degraded land with 40% of land, on average, estimated to have very low EII (<0.3 EII) and only 14% of land, on average, considered to be natural (>0.7 EII).

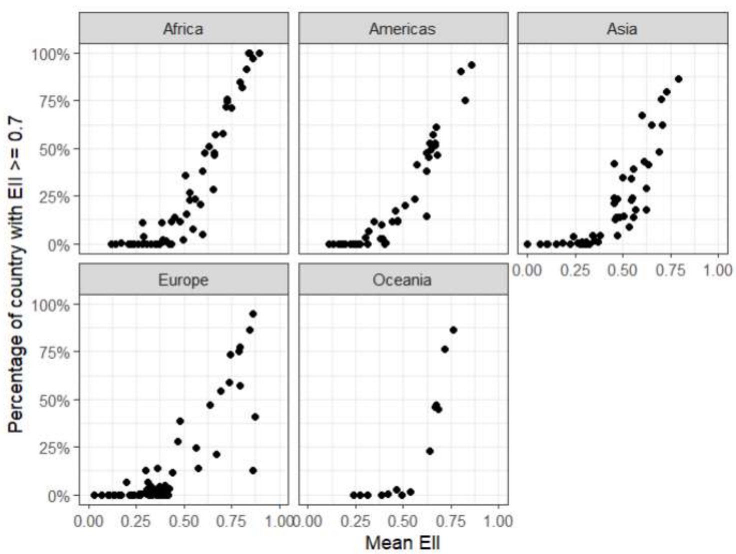

Figure 3. Ecosystem integrity within countries. Each dot represents the values for a single country. Values for mean EII are compared against values for the percentage of natural or high integrity areas.

Discussion

The EII provides a unique insight into how terrestrial ecosystems have been degraded across the world. We have used ecological theory and best available data to create an index at operational scales (1km^2) globally. The index also has the potential to be updated both in terms of temporal change at the 1km^2 scale, and in terms of inclusion of on the ground knowledge of biodiversity responses to ecosystem degradation and land management practices.

We developed this index for two main use cases. The first is for at the national and sub-national scales by countries seeking ways to monitor progress against goals and targets within the post-2020 global biodiversity framework, in particular its proposed Goal A and draft targets 1–3 covering spatial planning, restoration and strengthening networks of protected and conserved areas managed by state and non-state actors including indigenous peoples and local communities. We will include the global EII layer in tools such as the UN Biodiversity Lab (https://unbiodiversitylab.org/) that are being developed to help countries plan for the delivery of these targets and to monitor progress in terms of ecological outcomes.

Our second use case is aimed at the businesses and financial institutions who are starting to include biodiversity measurement in their performance reporting. There is an urgent need for trackable targets using an appropriate set of metrics to enable the private sector to move towards 'nature-positive' outcomes (Locke *et al.,* 2022; Milner-Gulland, 2022). Such outcomes are reliant upon the ability of a business to measure their biodiversity baseline, assess their exposure to biodiversity risk within operations, and to drive innovation towards nature-positive outcomes on the ground through a quantified understanding of the pressure-response relationship. Initiatives such as the Science-based Targets Network and the Taskforce on Nature-related Financial Disclosures are working with businesses and financial institutions, helping them contribute to nature-positive outcomes. They are doing this by developing guidance for businesses to set science-based targets, and by designing robust disclosure frameworks for reporting on impacts and dependencies on nature. In both these initiatives, participating businesses and financial institutions will need to understand where they interact with ecosystems, for example in the "Locate" step in the TNFD LEAP Locate, Evaluate, Assess, Prepare approach (TFND, 2022) and within the "Assess" and "Interpret and Prioritize" steps of the SBTN's 5-step approach) (SBTN, 2020). They will also need to understand how they are impacting and depending on ecosystems before going on to monitor and disclose how the integrity of these ecosystems is increasing or decreasing over time. The EII can help in all these cases.

Linkages of the models used here to emerging temporal 10m land cover products (for instance, the Sentinel-2 10m Land Use/Land Cover Time Series; Karra *et al.,* 2021 or the Dynamic World layer; Brown *et al*., 2022) could provide higher resolution information on biodiversity change at the local scale, enabling more regular updates of the EII.

In the case of both state and non-state actor users, we see the EII being useful alongside other measures of biodiversity. The EII should be seen as complementary to, and ideally used in conjunction with other measures of biodiversity particularly those aimed at a species level, for example measures of species importance and threat across the world, such as the STAR metric based on the IUCN Red List (Mair *et al*., 2021), or range rarity metrics such as those presented in Hill *et al.*, (2019).

Our approach to developing an EII has limitations in that it does not yet directly quantify degradation to ecosystem integrity caused by climate change (although recent climate change impacts may contribute to lower scores). We note that many of the high latitude areas that appear unimpacted in our analysis may be at particular risk from climate change (Beaumont *et al.*, 2011; Asamoah *et al.,* 2021).

It is expected that a loss of EII will lead to a loss of the potential of ecosystems to deliver services, but this relationship is likely to be complex. Ecosystem services may require specific spatial patterns of EII, for instance, some may require high levels of EII but only in discrete areas, whereas others may require a widespread area contributing to the service but less sensitive to the absolute values of EII. Understanding where functioning is at risk, where it may have already crossed tipping points, and how these add up to planetary boundaries, is important when targeting restoration actions.

Further work currently in progress aims to 1) link EII with risk to business operations through loss of ecosystem services, 2) assess business counterfactuals for EII (what would the EII be if a company was not in operation at that site?), and 3) assess production models for EII to guide management actions at the site level. This last step could be aided by a comparison of results with the 'conservation evidence' database and evidence syntheses (https://www.conservationevidence.com/) to assess on the ground sensitivity.

However, despite the caveats, we are confident that EII as developed here is sufficiently robust to demonstrate dramatic degradation to ecosystem integrity over much of the terrestrial area globally. We have designed the EII to be flexible, responsive and updateable, and useful at multiple scales. We believe that this metric therefore provides a viable means for countries and businesses to take action and measure the impacts of their actions at scale in all parts of the world.

Methods

Structure

An ideal measurement of structure should capture both complexity and multi-dimensionality of an ecosystem. This should include a measure of how intact the vertical or internal structure of a given location is, as well as the intactness of such features in the surrounding landscape (Carter *et al*., 2019; Grantham *et al*., 2020; Ehbrecht *et al.*, 2021).

A single range of measurable characteristics is unsuitable for measuring ecosystem structure at the global scale because the 'natural' state of ecosystem structure varies greatly by realm, ecoregion, and habitat type (e.g., Tierney *et al*., 2009). We therefore suggest a system whereby ecosystem structure is not measured directly, with a unique suite of indicators for every habitat in the world, but by proxy, where human pressures are assumed to cumulatively degrade ecosystem structure (e.g., Venter *et al*., 2016; Kennedy *et al*., 2019).

However, connectivity of ecosystems remains an important feature impacting structure across all contexts (Rayfield *et al.*, 2011). For this reason, we adapt methods established by Beyer *et al*. (2019) to produce a layer that is sensitive to habitat patch size, fragmentation, and connectivity. This is achieved by comparing each location on a map not just to a natural reference for that point, but the whole neighbourhood around that point to a counterfactual landscape in which no pressures occur, computed at a scale in agreement with other connectivity metrics (e.g., Saura *et al.*, 2018).

To measure structure, we first built a Human Modification Index (HMI) layer following methods described in Kennedy *et al.* (2019), based on the following pressure layers: croplands, pasturelands, rangelands, plantations, built-up areas, human population density, roads, rails, quarries and mining, wind turbines, electrical infrastructure and powerlines. We used the same pressure intensities described in Kennedy *et al.* (2019). Second, we inverted the human modification layer to transform it in an equivalent of the habitat quality and extent layer in Beyer *et al.* (2019). Finally, we applied their method to introduce the landscape pressure and fragmentation influence to output the final structure layer. These methods include using a moving window that compares the quality of a grid cell with that of cells in their neighbourhood, which we defined as cells within a 27 km distance (i.e., grid cells in a 55km x 55km box were used to estimate the structure of the target cell at the centre of the box). All spatial processing was done in Google Earth Engine with a resolution of 30 arcsec.

Our layer differs from the one produced in the Beyer *et al.* (2019) paper due to the source 'habitat quality' layer. Where the original authors use the Human Footprint Index (HFI) (Venter *et al*., 2016), rescaled with an exponential function, as their layer, we opt for a recreation of the HMI as described by Kennedy *et al.* (2019). This approach has the benefit of meaningful interpretation: an area with a value of 0.5 has twice the 'intactness' of an area with a value of 0.25. It also avoids the double use of neighbourhood functions. For example, the HFI takes roads and applies a buffer to estimate the area of their impact; when the landscape-level effects are calculated this area is then further expanded, which may overestimate the spatial extent of these threats to ecosystem structure. In contrast, the HMI uses the physical footprint of these threats, preventing this issue when comparing at the landscape scale.

Composition

A measure of ecosystem composition should incorporate elements of both species' abundance and community composition (Haase *et al.*, 2018; Carter *et al*., 2019). The Biodiversity Intactness Index (BII) has been suggested as a suitable metric to track global planetary boundaries due to its relevance to ecosystem health and functioning (Steffen *et al*., 2015; Mace *et al*., 2018). The BII estimates the change in the makeup of species communities relative to an 'unimpacted' baseline (Newbold *et al*., 2016). The BII tracks changes in the relative abundance of species within a community (excluding novel species) due to land use changes as well as other human pressures. The BII is based upon modelled relationships estimated using a large taxonomically and geographically representative database (the PREDICTS database) (Hudson *et al.* 2017). Data representing the communities of sites from many land-uses and many taxonomic groups are used to construct hierarchical models for the two elements of the BII, abundance and compositional similarity. These modelled relationships are then projected onto global pressure maps to form the BII layer. The layer included in the EII was published by Hill *et al.* (2018); an updated global layer building on the original 2016 layer (Newbold et al. 2016).

Function

Attempts at mapping ecosystem function have focused on different aspects of the integrity of functioning. Some of these approaches have explored changes in the amounts of specific ecosystem function variables. One example comes from the framework assessing human appropriation of Net Primary Productivity (HANPP), which explores departures from potential NPP values to investigate where human production systems have modified ecosystem functioning and the extent of this change (Mayer *et al.* 2021). Other authors have taken a very different approach to quantifying function, for instance, Faurby and Svenning (2015) estimated changes to the richness of mammalian functional traits. However, no single metric has yet been developed that is considered to represent all aspects of ecosystem function. In the absence of alternative more comprehensive methods, we opted for adapting the approach to focus on one key ecosystem function, NPP, because of its well-documented association with ecosystem functioning (Malhi et al., 2011; Mayer et al., 2021), its advantages in terms of spatial resolution (layers are available in raster format at 1km^2 resolution or higher) and update frequency (e.g., MODIS releases a global new NPP layer annually).

We developed a global layer of potential NPP used as a 'natural' reference and compared it with a current-day NPP layer derived from remote sensing to map proportional losses in NPP. Natural levels of NPP were modelled per grid cell using environmental variables trained on mean NPP levels (Running and Zhao, 2015) measured within strictly managed protected areas (IUCN categories I and II) between 2015 and 2020 (UNEP-WCMC and IUCN, 2017). We used a generalised linear model framework, with a Gamma distribution for the response variable and a log-link. Model selection was undertaken using backwards stepwise selection based on AIC values (Zuur, 2009). Variables were selected for testing based on a literature review of likely predictors of NPP and included: latitude, bioclimatic variables (Fick and Hijmans, 2017) , mean, min and max solar radiation (Fick and Hijmans, 2017); aridity (Global Aridity Index, Zomer and Trabucco, 2022); total nitrogen, cation exchange capacity, predicted sand concentration, pH of water in soil (Poggio *et al.,* 2021); continuous heat-insolation load index (CHILI, Theobald *et al*., 2015); roughness of terrain, slope, topographic position index, terrain ruggedness index (Amatulli *et al.,* 2018); landforms (Sayre *et al.,* 2020). The final model structure included latitude as an interaction with total annual precipitation, mean annual temperature, and the mean temperature of the coldest quarter.

For each grid cell, we calculated the proportion of retained functioning by dividing the current-day NPP value by our natural (model estimated) NPP value. As our focus is on human mediated removal of NPP we rescaled all values >1 to 1.

Aggregation to derive the global Ecosystem Integrity Index

The Ecosystem Integrity Index (EII) value per grid cell is taken from the lowest scoring of the three ecosystem components within that grid cell. This calculation follows the logic that all components of integrity are integral and therefore the overall condition of the ecosystem is determined and limited by the lowest component. This emphasizes the interconnected nature of ecosystem integrity and avoids issues that may have been caused by an averaging/additive approach. For example, phenomena such as extinction debt (Kuussaari *et al.,* 2009) suggest it would be prudent to refrain from allowing moderate values where any one component has been significantly weakened. However, this method cannot distinguish between an area where all three components are degraded versus an area where only a single component is degraded; such comparisons may prove to be important for conservation planning, for instance to predict impacts of restoration.

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