Spare half, share the rest: A revised planetary boundary for biodiversity intactness and integrity

Fabrice DeClerck (✉ f.declerck@cgiar.org)

Bioversity International

Sarah Jones

Alliance of Bioversity and CIAT, One CGIAR

Natalia Estrada-Carmona

Bioversity International

Alexander Fremier

Washington State University

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1 Title

2 Spare half, share the rest: A revised planetary boundary for biodiversity intactness and integrity

3 Summary paragraph

4 Setting clear biodiversity targets is a pervasive challenge¹ due to the context-dependent nature
5 of biodiversity that has evaded concise science-based objectives akin to the climate change
6 target of limiting global warming to 1.5°C². Considering the major risk to biodiversity and
7 human wellbeing of continued inaction, it is imperative to identify similarly operational and
8 science-based boundaries supporting the development of targets to safeguard biodiversity and
9 its contributions to human well-being. Confounding goal setting are the two distinct but not
10 mutually exclusive conservation objectives: (1) halting the rampant loss of intact ecosystems,
11 species extinction and population declines, and (2) maintaining biosphere integrity and
12 ecosystem function. We propose a revised planetary boundary for biodiversity: retaining *at*
13 *least* half of the area of each terrestrial ecoregion *biologically intact* to halt the extinction crisis
14 and maintaining *ecosystem integrity* across all lands to preserve and regenerate biosphere,
15 ecosystem functions and their contributions to human well-being. We combine four proxy
16 datasets for biologically intact habitat to identify areas consistently identified as intact and find
17 that 49.6% of the Earth's ice-free land remains *intact*. While this is promising globally, 69% of
18 798 unique ecoregions are less than half intact. For *ecosystem integrity*, we find 18.1% of
19 working lands have severe *ecosystem integrity* deficits precluding the provisioning of biosphere
20 and ecosystem functions. Ninety percent of unique ecoregions have an *ecosystem integrity*
21 deficit. Globally, *intactness* and *integrity* are at or have surpassed boundary limits with
22 degradation of nature critically jeopardizing biosphere capacity to support a safe and just space

23 for humanity. Combined efforts are needed to avoid further loss of and restore *intactness*,
24 while regenerating *integrity* in working lands.

Main text

Introduction

Biodiversity is in crisis facing catastrophic conversion and losses of ecosystems and the unique species and genetic diversity they harbour³⁻⁶. This loss increasingly has regional and global scale impacts on earth systems processes spanning from carbon and water cycles, to pollination and pest and disease regulation⁷. The absence of meaningful system-wide indicators hinders global policy by failing to provide politically relevant status measures and targets to align and galvanize conservation action¹. Without clear, science-based but politically actionable guardrails, we risk losing a pivotal decade of progress in bending the curve on biodiversity loss⁸.

The biodiversity research community has thus far largely resisted setting concise scientific targets due to well-founded concerns that species, and associated ecosystem services, are inherently local and that ecology is more complex and more localized than climate, and thus not amenable to system-wide targets⁹. However, considering the acute nature of the on-going biodiversity crisis⁶, setting evidence-based science targets can be an effective means to foster alignment, identify effective actions, and set up processes to track progress across stakeholder groups¹⁰. As demonstrated by the Paris Climate Convention, and by the EAT-*Lancet* Commission¹¹, global targets can be set that are compatible with local conservation priority setting and that recognize the diversity of context specific conservation actions. More critically, agreed upon targets and system-wide boundary metrics can provide standardized scientific assessments of biodiversity and ecosystem function status and trends that align local action against global goals.

We propose *biodiversity intactness* and *ecosystem integrity* as two complementary planetary boundary measures of biodiversity (Box 1). *Biodiversity intactness* and *ecosystem integrity* are analogous to the first two goals (Goal A and Goal B) proposed by the Convention on Biological Diversity (CBD)¹². Both biodiversity intactness and ecosystem integrity are evaluated here from spatially gridded datasets. These data can be aggregated over any larger region, such as regions defined by administrative (e.g., country, continent) or ecological (e.g., ecosystem, ecoregion, biome, global) boundaries, or a combination of these (e.g., ecoregions within countries) to facilitate setting ecologically meaningful and politically actionable targets. We provide a global assessment of intactness and integrity to facilitate countries setting ambitious goals for protection, restoration, and regeneration.

Biodiversity Intactness

The conceptual definition of biodiversity intactness describes the state of an ecosystem being unimpaired from post-industrial human alteration (Box 1)¹³. Biodiversity intactness is a measure of biodiversity status measured as the relative abundance of originally present species or level of human pressures^{13,14}. Intact areas, by definition have integrity and maintain ecological functions, for example climate mitigation and regulation¹⁴. Retaining intact nature globally is required to halt the loss of wild biodiversity, and both the earth system, and ecosystem services it provides. While nuances of conservation efforts are important, including fragmentation, habitat size and extent, maintaining *at least half* of the global land mass as intact has been proposed as required to avert massive species loss¹⁵⁻¹⁸. Half intact improves on previous articulations of the Biosphere Integrity planetary boundary by adding an area-based

complement to intactness, making it easily operational. Half intact is synonymous with the “no net loss or net gain” targets proposed by the CBD under Goal A. We apply the concept of half intact at the ecoregion level to assess the conservation of the unique local biological composition across the globe that require protection. Intactness levels below this boundary increase irreversible extinction risks, a threshold which has been passed in 69% of ecoregions^{1,15,18}. Remaining above the intactness boundary requires important sparing of terrestrial and aquatic ecosystems from conversion^{19,20}.

Ecosystem Integrity

Integrity is conceptually defined as an ecosystem’s functional capacity to contribute to biosphere processes and to produce ecosystem services (Box 1)²¹. These include both Earth system-scale processes regulated by the biosphere as well as finer scale ecosystem services provided at the basin, landscape, farm, field, or even neighbourhood scale in urban settings^{7,22-25}. Non-intact area can have integrity if they retain sufficient functional biodiversity to support ecosystem service provision²⁶⁻²⁹ irrespective of whether the species or communities they contain are native or not³⁰.

The spatial extent of the services provided by species often operates at the sub-kilometer scale^{25,31-40}. While there is significant context specificity in how biodiversity provides ecosystem services^{41,42}, the decay of ecosystem services with increasing distance from provisioning habitat is consistently demonstrated in agroecological and ecosystem service studies. For example, the number and abundance of species able to provide pollination or pest control services, rapidly decreases with the decrease in the area of habitat available^{33,43-49} and with increasing distance from source habitat^{32-34,37-39,47-57}. Particularly in agricultural landscapes,

ecosystem service provisioning is related to the farm or field scale such as nutrient delivery (e.g. nitrogen fixation (0.1-1 m), reduction of soil and sediment loss (1-10 m), pollination (10-1000 m), pest control (10-1000m))²⁵. Thus, while specific services provided by distinct ecological communities will remain deeply contextual^{41,42}, and the subject of both interesting and important research, evidence suggests that natural habitat extent and proximity is a coarse indicator of potential ecosystem service provisioning. More specifically, the absence of semi-natural or natural habitat within a few hundred meters of any given area indicates insufficient associated biodiversity to provide ecosystem services to that area, particularly services that support food production⁵⁸.

We use the proportion of natural or semi-natural habitat within a landscape as our operational definition of ecosystem integrity (Box 1; see methods for definitions of natural and semi-natural) and propose an integrity boundary of at least 10% natural or semi-natural habitat per square kilometre. This integrity boundary represents the *minimum* surrounding natural or semi-natural habitat needed to maintain the functional biodiversity providing ecosystem services (see methods). Others have proposed a more conservative 20% boundary for maintaining integrity⁴⁴. We compute integrity levels using 10%, 20% and 30% to estimate sensitivity of threshold selection.

Intactness and integrity capture two distinct but complementary conservation priorities: halting extinction loss and maintaining ecosystem and biosphere function. Achieving intactness targets and halting the loss of biodiversity requires reducing and eliminating pressures such as habitat loss and conversion. Restoring intactness is difficult and in the case of species extinction, nearly impossible to fully recover⁵⁹. Integrity, in contrast, is more readily repairable

and can be provided by biodiverse ecosystems with low intactness scores but functional composition approaching that of intact ecosystems (e.g., non-native species or novel ecosystems)²⁶⁻²⁸. This is the premise of nature-based solutions offered by agroecology, regenerative agriculture, or integrated landscape management initiatives^{45,46,60-62}. Integrity targets are achieved by combined actions sparing currently intact ecosystems from conversion, but also requires sharing space for biodiversity in working lands^{20,45,46}.

Box 1: Defining biodiversity intactness and ecosystem integrity and related thresholds

	Biodiversity Intactness	Ecosystem Integrity
Conceptual Definition	The state of an ecosystem's species composition and abundance being unimpaired from post-industrial human alteration	The state of an ecosystem's capacity to provide contributions to Earth system and ecosystem processes
Operational Definitions	Agreement across globally consistent layers of intactness as measured using degree of human modification and/or species composition (see Methods)	Percent of proximate natural or semi-natural habitat (see Methods)
Boundary (evidence-based)	All ecoregions having >50% lands designated intact	An area has >10% proximate natural or semi-natural habitat (see Methods)
Target	Same as Boundary	100% of lands within an ecoregion have >10% surrounding semi-natural or natural lands (see Methods)

Global Status of Biodiversity Intactness

We applied an ensemble approach to map intactness by selecting four available datasets of human influence on the global land surface. We applied a threshold to each of the

datasets to identify areas with the lowest human impact and highest portion of biologically intact land remaining (Supplemental Fig. 1; Supplemental data table 1). We combined the four datasets

Figure 1: (a) Cell-by-cell measures of intactness (ensemble model Et3) and integrity (10% embedded natural lands; (b) Percent intact land by ecoregion; (c) Percent land above the 10% integrity target by ecoregion.

into one ensemble dataset of intactness, by classifying a pixel as intact only when three of the four input datasets agreed (Fig. 1a). The ensemble approach provides a robust description of the extent of biological intactness globally. We found 49.6% of the global ice-free land is intact. However, these intact lands are inequitably distributed across ecoregions. For example, 552 of 798 ecoregions (69%) have less than 50% intact land; and 206 ecoregions have less than 10% intact (Fig 1b Supplemental table 4; 36% of ecoregions or 27% of land surface). Non-arable lands make up 38% of the terrestrial land surface and are dominant areas of intactness: Tundra (100% intact), Boreal Forests/Taiga (99% intact) and Deserts and Xeric Shrublands (77% intact) (Supplemental table 3; data at https://rpubs.com/afremier/SuppTable_Biomes_data_2021). Ensuring that all ecoregions are above the biodiversity intactness boundary level would entail restoring 23.9 million km², or 18.1% of the global land surface, notably in the Tropical and Subtropical Dry Broadleaf Forests and Mangroves biomes (Supplemental Table 3). While restoration can increase intactness in these locations, recovery to preindustrial levels is unlikely (data at https://rpubs.com/afremier/SuppTable_ER_data_2021).

Global Status of Ecosystem Integrity

While important global analysis of ecosystem services have been conducted⁶³, global analyses of ecosystem integrity remain in their infancy and have not been conducted at the ecoregion scale^{64,65}. We used globally available, temporally repeated, and stable land cover mapping dataset created by the European Space Agency Climate Change Initiative (ESACCI-LC) to assess ecosystem integrity. We define lands as having integrity if they have at least 10%

natural or semi-natural habitat within 1 square km. We propose that the boundary condition needs to be met in all lands because retaining ecosystem integrity underpins the provision and resilience of ecosystem services required for human well-being including for example, food, nutrition⁶⁶, climate⁶², and water security^{1,67} (see methods: *Establishing Ecosystem Integrity*).

Globally, 18.2% of all lands, and 23% of the human-dominated lands are below the integrity boundary, an equivalent of 120.0 M km² (Supplemental Table 5). In these areas insufficient ecosystem integrity exists to maintain ecosystem service provision such as pollination of crops, or regulation of agricultural pests and diseases^{43,68}. Increasing the integrity boundary to 20-30% per km² in human dominated lands has been proposed to the CBD¹⁰. We estimate that 32.8% and 40.3% of human dominated lands fail to meet the 20% and 30% integrity boundary respectively (Supplemental Table 5). We find that 741 of 821 ecoregions (90.3%) have integrity deficits on at least some lands (with a 10% boundary). Ecoregions with the largest integrity deficits are concentrated in some of the world's most populous and agriculturally productive regions, namely India's Punjab, the Midwestern states of the United States, north-eastern China, eastern Europe, west Africa, and California's central valley (Fig. 1c, https://rpubs.com/afremier/SuppTable_ER_data_2021). Ecosystem integrity as defined and measured here provides a scalable and repeatable approach for monitoring the nature contributions to people.

Global patterns of ecoregion intactness and integrity

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Combining intactness and integrity as distinct, though interacting biodiversity

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conservation measures reconciles the land-sharing versus land sparing debate^{19,20,45}; which

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while ecologically interesting, has become a dangerous distraction interpreted as an either/or

Figure 2: Intactness and Integrity values for each ecoregion plotted by biome; point size is relative to the size of the ecoregion in question. Colored bins show ecoregions with show intersection of regions with low (<40%), medium (40-60%), medium-high (60-80%), and high (>80%) intactness; and low (<50%), medium (50-80%), and high (>80%) integrity.

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scenario²⁸. In order to secure intactness and integrity, sparing currently intact lands from conversion, restoring ecoregion area to at least half intact, and sharing the rest by embedding natural habitat into human dominated lands to maintain integrity becomes a concise

Figure 3: Mapped Intactness and Integrity values for each ecoregion; Colored bins are taken from figure 2.

conservation objective compatible with the post-2020 Aichi Goals A and B and a quantifiable application of no net loss targets. Plotting the intactness and integrity of ecoregions around the world creates an integrated characterization of biodiversity and ecosystem status (Figs. 2-3) serving as a baseline for the 2020 condition for CBD Goals (i.e., A and B)¹². The joining of national boundaries and ecoregion boundaries created 1745 unique country-ecoregions for which we can provide intactness and integrity status measures (Fig. 3) against which nationally determined contributions towards evidence-based targets for nature can be assessed and set, e.g., to align with the recent proposal emerging from the broad multi-actor dialogues defining a

global goal for nature as "no net-loss of nature from 2020, net-positive by 2030 and full recovery by 2050".

Our analysis identifies three generalized categories of country-ecoregion status of combined intactness and integrity measures: (1) high integrity, high intactness (Fig. 3 dark green regions (29% surface land)), (2) high integrity, low intactness (Fig. 2 & Fig. 3 blue regions (54%)) and (3) low integrity and intactness (Fig. 2 & Fig. 3 pink and red regions (17%)). Regions of high integrity, but low intactness (blue) encompass 54% of the land surface or 71.3 M km². In these country ecoregions intactness has been lost, with high extinction risk or major extinctions having already occurred; yet, they have retained minimum required biodiversity to secure ecosystem services. At the other extreme are country ecoregions which have both low intactness and low integrity. These are regions of significant conservation concern where species conservation objectives are imperilled, quite possibly beyond the point of no return, and where insufficient ecosystem integrity remains to ensure the provisioning of ecosystem services (Fig. 3; pink and red regions). One hundred and thirty-six country ecoregions (17%) covering 21.05 M km² are in this category and at risk of functional collapse.

Avoid loss, Restore Intactness, Regenerate Integrity

The functional role that biodiversity plays in a safe, just, and stable earth system requires a whole Earth approach that maintains integrity across the entire terrestrial landmass. For biosphere level processes, large tracks of intact ecosystems are best suited to stabilize climate, regulate hydrological cycles, and avert mass extinction of biodiversity. Climate regulation is particularly sensitive to the quality and extent of intact tropical and boreal forest

ecosystems^{62,69-71}. Halting the loss of biodiversity, however, requires setting multi-level targets including at ecoregion level in light of the unique combinations and composition of species they represent^{15,17}. Focusing efforts to retain intactness on any single biome or ecoregion is an ecological non-sequitur; the absolute loss of 371 ecoregions with less than 10% intactness, of which have less than 1% intactness, is one of the most sobering results of our analysis. Safeguarding intactness in the remaining 49.6 % of the global land surface is a necessary precondition to maintain ecosystem functions, nature's contribution to people and earth system resilience. Setting more ambitious targets beyond boundary conditions is critical both to further reduce extinction risk and to ensure more resilient biosphere.

Globally there are 65.5 M km² of intact lands, or 49.6% of the land surface (Supp Table 4). Intact areas in ecoregions require continued conservation commitments to achieve no net loss⁷². Returning to intactness levels above boundary conditions (i.e. >50%) for all ecoregions would require restoring 24 M km² of land and, with no additional loss of existing intact land, result in intact land covering 69% of the Earth's terrestrial land. We find that 314 of 1745 (18%) country ecoregions have <10% intact lands which we consider post or near-extinction and possibly non-restorable (Supplemental Table 4, <https://rpubs.com/afremier/CER>). Retaining and restoring the intact areas in these endangered eco-regions needs urgent and critical attention (Figs 2-3).

In light of the critical contributions of biodiversity to human well-being through their role in providing ecosystem services, or nature's contributions to people, the non-intact half of our planet cannot become an ecological sacrifice zone. This half must retain sufficient ecological integrity, through retention of sufficient natural and semi-natural habitat at small and large

scales, to produce food, regulate pests and diseases, provide safe passage to biodiversity, and contribute to gene flow, regulating water cycles, offer spiritual and recreational spaces and mitigating climate change amongst others⁷³. We find that 18.6% of the earth's surface has a critical deficit in ecological integrity where ecosystem services are likely to be at severe risk or are no longer being provided. Regenerating integrity would require efforts on between 12.1-17.5 M km² of land, largely consisting of the diversification of agricultural lands. Countless context specific options for maintaining or regenerating ecological integrity exist and are compatible with food, nutrition, and livelihood security objectives⁷⁴.

Global conservation objectives serve to align national and local conservation actions, and human well-being needs while retaining local decision-making authority. Conservation and restoration actions should match local abilities and priorities starting by targeting key biodiversity areas (KBA's), unique ecological communities, conservation hotspots, and locally intact areas, while recognizing and respecting local and indigenous stewardship. Intactness, as defined here, does not preclude human activities compatible with retaining intactness as found in some forms of rangeland or forest management. Actions for regenerating integrity are similarly diverse and well-documented. The choice whether to set bold targets for intactness and integrity is a socio-political one. Nonetheless, clear, spatially explicit, and biologically meaningful targets of intactness and integrity demonstrate what and where biodiversity has already been lost and serve to help prioritise future policy actions to reduce the risk and consequences of further loss. Our assessment, as that of numerous complementary studies, is that in too many places, the loss of intactness and integrity is too high severely compromising biosphere capacity to provide a safe and just space for humanity⁷⁵.

250 Our intactness and integrity boundaries provide a globally applicable, science based,
251 foundation for target setting that can be operationalized at multiple actionable levels for
252 prioritizing conservation, restoration, and regeneration efforts. Besides, it facilitates traceability
253 and accountability of global trade driving biodiversity loss. Our assessment provides a spatially
254 explicit baseline and targets of both intactness and integrity against which country
255 commitments and efforts can be assessed while leaving ample opportunity for countries and
256 private sector, and their citizenry to identify and implement effective context specific, locally
257 adapted restoration and regeneration actions. It is our hope that such assessments can be used
258 to guide decisive actions in this UN decade of restoration to begin bending the biodiversity
259 curve for no net loss, or net positive by 2030.

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 429

Figures

Figure 1

(a) Cell-by-cell measures of intactness (ensemble model Et3) and integrity (10% embedded natural lands; (b) Percent intact land by ecoregion; (c) Percent land above the 10% integrity target by ecoregion. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

Intactness and Integrity values for each ecoregion plotted by biome; point size is relative to the size of the ecoregion in question. Colored bins show ecoregions with show intersection of regions with low (<40%), medium (40-60%), medium-high (60-80%), and high (>80%) intactness; and low (<50%), medium (50-80%), and high (>80%) integrity.

Figure 3

Mapped Intactness and Integrity values for each ecoregion; Colored bins are taken from figure 2. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

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