Biosphere functional integrity for people and Planet

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Abstract

An Earth System approach to defining the safe and just space for biosphere requires synthetic measures of functional integrity in relation to Nature's local and global scale Contributions to People (NCP). We estimate the minimum level of functional integrity needed to secure multiple critical ecosystem functions and services, including pollination, pest and disease control, water quality regulation, soil protection and recreation in human-modified landscapes. We find that at least 20-25% of relatively diverse semi-natural habitat with native species in each km^2 of land area is needed to maintain a minimum level of multiple NCP. Exact area, quality and configuration required is dependent on local context, and may differ based on landscape types and for individual NCP. More than 60% of human-modified lands have less than 20% semi-natural habitat per km^2, and thus require immediate attention to regenerate functional integrity. Regenerating ecosystem functions in areas with low functional integrity by including at least 20-25% semi-natural habitat of sufficient quality per km^2 will secure ecological functioning in those landscapes consistent with a safe and just space for people and planet.

Key words: Nature's Contributions to People, integrity, biodiversity, ecosystem services, agricultural landscapes

Recent global assessments demonstrate a clear decline in nature with cascading effects on human well-being mediated by both local and global contributions of nature. At a global scale, land use conversion and degradation affect Earth system functions and reduce biosphere capacity to mitigate climate change, weather and hydrological flows. At more local scales, many other benefits are directly or indirectly provided by biodiversity and ecosystem services. The extent of the benefits of ecosystem services, also called “nature’s contributions to people” (NCP) can be differentiated by the scale at which they are provided and the proximity of the beneficiaries[1]. Local scale NCP are particularly important in human-dominated landscapes, yet conservation more often than not focuses on global conservation objectives provided by intact nature[2].

Most attention in biodiversity conservation is given to halting the conversion of remaining natural ecosystems and the unique species they hold[3,4] (CBD Targets 1 and 3). This is a critically important conservation objective which contributes both to halting species loss, and the ecosystem functions and services of intact nature, notably climate mitigation. However, the small areas of habitat in human-dominated and managed lands and waters are often overlooked in conservation policies and global target setting despite the critically important roles they can play in maintaining and supporting human well being, notably food production[5,6]. Human-dominated and managed lands cover about half of the global Earth surface and include a wide range of ecosystems ranging from urban to agricultural in mixed mosaic landscapes[7]. The extinction of ecological function in such a large area is incompatible with numerous sustainable development goals[8]. Conservation efforts should better balance the diversity of important conservation objectives requiring discrete, if not often context specific, interventions[9,10].

While halting rampant loss of intact natural ecosystems and unique species is important for specific Earth system functions such as climate regulation and also has an important ethical imperative, maintaining ecosystem function in landscapes heavily modified by human activity is of high importance from the perspective of a safe and just biosphere for humanity. Therefore, a safe level for the biosphere not only requires intact ecosystems to be conserved and restored, but also restoring functional integrity in human-modified ecosystems to secure and regenerate NCP critical for human well-being. A major challenge in defining safe and just biosphere targets lies in the numerous, and often highly context specific conditions under which biodiversity supports critical Earth systems, and ecosystem processes that contribute to human well-being evading synthetic measures to align and guide policy measures. In the process towards defining targets and actions for the post-2020 Global Biodiversity Framework (GBF) under the Convention on Biological Diversity (CBD) many proposals for such synthetic policy objectives have been made, either expressed as single targets, or as consistent sets of complementary targets[11,12]. Few of these suggestions for biodiversity targets address human-dominated and managed areas explicitly. In this context, particularly under-valued and under-estimated is the functional role biodiversity plays in maintaining or enhancing a good quality of life for all people. Functional integrity has been proposed as such a measure (DeClerck et al. 2022, in review), but clear evidence of the minimum amount of functional integrity needed to stay within a safe and just space for all remains missing[13].

Functional integrity is conceptually defined as an ecosystem's capacity to contribute to biosphere processes and to produce NCP (DeClerck et al. 2022, in review). These include both Earth system-scale processes regulated by the biosphere as well as finer scale NCP provided at the basin, landscape, farm, field, or even neighbourhood scale in urban settings. Large undisturbed natural areas, by definition, have functional integrity because they maintain dominant ecological characteristics of composition, structure, and function as defined by the Global Biodiversity Framework. Functional Integrity is an important complement to biodiversity measures used in conservation biology as it recognizes that nature-based solutions to climate, water, food, and other grand challenges can be provided by highly altered (non-native, or non-intact) ecological communities in agricultural, urban, or other human-dominated areas. The concept of functional integrity is especially useful in describing whether sufficient habitat is retained to support ecological functions and services[14].

Habitats are conditions and resources that when present in an area enable occupancy, including reproduction and survival, by a given organism[15]. Habitat quantity refers to the degree of landscape complexity based on the amount or the proportion of natural and semi-natural elements remaining. Habitat quality is the ability of an ecosystem to provide conditions appropriate for species and populations persistence based on its structural and functional composition. Landscape configuration, in particular fragmentation, modifies the linear distance from habitat, thus reducing services provision such as pollination or pest and disease regulation by mobile insects. Shorter distances and higher connectivity have a positive influence on (mobile) pollinators and natural enemies. However, these effects are very local, context dependent and can vary across taxa[16–18] or the function in question. For the services that are provided by non-mobile functional biological groups (e.g. soil protection, non-point source pollutants capture from surface and subsurface water, natural hazards mitigation), the position or the emplacement of the habitat that provides the services is important and complements linear spatial distance when it reduced slope length (e.g. regularly spaced plantings perpendicular to slopes). Sediment and nutrients capture can be significantly improved from terrestrial run-off through vegetation buffers placed on both sides of streams head water[19]. Habitat can significantly reduce the frequency, and risk of natural hazards such as shallow landslides, floods, soil erosion if the vegetation cover is evenly and carefully distributed in the landscape. Habitat in urban ecosystems, in the form of greenspaces and parks can provide recreational value and follow many patterns of other NCP, whereas the minimum amount, quality, and distance to green space for recreation can be described. Nature for recreation has been demonstrated to contribute significantly to human mental and physical health and well-being. These aforementioned services are particularly important in human-modified lands.

Previous ecological studies have attempted to describe and quantify the relationship between biodiversity and NCP provision. The results of these studies are highly varied, driven in large part by context specific species interactions. More often than not, the relationship between biodiversity and ecosystem function delivery is positive, though the variance in responses is quite high making synthesis difficult. All of these studies, however, demonstrate that below thresholds of quality, quantity, and distance from habitat, ecosystem services are no longer provided. Previous studies have suggested that 10% per km^{-2} may serve as a critical threshold below which nature's contributions to people can no longer reliably be provided[20]; or proposals that >20% might serve as a suitable target[14]. However, these apply to single functions or are based on expert opinions. Synthetic reviews to empirically identify minimum threshold values for functional integrity, have not been conducted to date.

The three variables we consider are quantity, quality, and distance from or distribution of habitat needed to provide a minimum amount of ecosystem service provision. Here, we use a systematic review of 153 published studies (including 72 reviews and meta-analyses) to assess the minimum levels of functional integrity needed to maintain six critical NCP. We mainly synthesize existing reviews and meta-analytical studies that comprise a total of 4463 original studies on the relationship between quality, quantity and distribution of habitat in human-modified landscapes and its impact on NCP provisioning. Through this study, we define how much nature, of what quality, and in what locations is needed to ensure the provisioning of six critical NCP including (1) pollination, (2) pest and disease control, (3) water quality regulation, (4) soil protection, natural hazards mitigation and (5) recreational benefits.

Results

We identified the threshold characteristics in terms of quantity, quality and spatial configuration of semi-natural or natural habitat (hereafter “habitat”) needed to ensure a minimum supply of six NCP. Habitat positively supports maintaining local NCP provided by the biodiversity it harbours. While local context will always be critical, the consistent pattern of all ecological studies is that species, and the services they provide are lost below a certain threshold of habitat needed, and by the maximum distance that service providing organisms can move. The number and abundance of species able to provide pollination or pest control services rapidly declines with the decrease in the area of habitat available and with increasing distance from source habitat. In human-dominated land, fine scale natural features are needed to safeguard functional integrity and secure ecosystem services such as nutrient delivery (e.g. nitrogen fixation: 0.1-1 m, reduction of soil and sediment loss: 0-10 m, pollination and pest control: 0-1000 m).

Habitat quantity

We find that at least 20% semi-natural habitat per km^2 is needed to support pollination and pest control. For specific contexts this minimum area may range from 10 to 50% for pollination while it ranges from 10 to 37.5% for pest and disease regulation. The required proportion of habitat in the landscape needed for protecting soil from water-based erosion is 50% (ranging from 30 to 62.5% for specific contexts) vegetation cover at the landscape scale, while for regulating surface and subsurface water quality from non-point pollutants only about 5 to 6% of the landscape (28m buffer width both sides of streams) is needed though this may range between 1.2-15% depending on context (dependent on buffer width and stream density). Identifying the quantity of habitat for reducing landslide risk is more challenging, with environmental variables (geology, slope geometry, soils, precipitation event frequency, intensity and duration) often over-riding biological ones (vegetation quality). We found only two studies proposing a quantitative threshold limit for regulating landslide risk, advising a minimum of 50% and 60% vegetative cover on steeply sloped lands. For recreational services provided by greenspace in and around urban areas at least 25%

(ranging between 19-30% depending on the context) semi-natural habitat per km^2 is recommended in support of physical and psychological well-being (Figure 1, Table 1).

Spatial configuration and habitat quality for each NCP

NCP are provided by communities of species and their traits. Biophysical services such as sediment interception are primarily delivered by vegetation, which also serves as habitat needed for mobile species providing pollination and pest control services amongst others. Vegetation characteristics define habitat quality including for mobile species whose foraging ranges for home habitat determine maximum distance an ecosystem service can be provided. For three of the six NCP we describe maximum distances between habitats directly providing the service in question, the distance that mobile organisms can forage from host habitat, or in the case of recreation values, the distance that humans can move to access recreational habitat. For each service, a distance from habitat can be described as a function of the dispersal distance of pollinating or pest-regulating . We report on these threshold values.

Pollination, and pest and disease control services are provided by mobile species harboured by habitat embedded in human-modified lands. Increasing the floristic complexity and richness of this habitat generally increases the diversity and abundance of service providing organisms. Pollinating and pest regulating organisms, notably insects, disperse within a maximum distance of 500 m and 1000 m (ranging between <0-2000 m for specific taxa) from the habitat to the target crop field. Beyond this distance the services in question decline significantly or are completely lost (Figure 2, Table 1).

In riparian ecosystems, riparian buffers consisting of high diversity plantings can be an important means of intercepting detached soil particles, pesticides and nutrients from adjacent fields. Slowing the excess water flows across the surface of the land as it passes through dense vegetation can allow larger particles to fall out of solution, and be retained in soils. A diversity of root structures, both fibrous from grasses or tap from woody vegetation increase soil porosity, infiltration and capture of excess nutrients. We find that retaining riparian buffers of at least 28 m width on each side of the stream would amount to 5 - 6% of human-dominated landscapes globally (see methods for more details). Buffers of this size on slopes <23° are able to on average capture >73% [while ranging between 50-90% depending on the context] of nonpoint source pollutants (Table 1, Figure S1). This includes sediment, nutrients, pesticides and salts from upstream agricultural lands.

Preventing particle detachment driving water-bourne erosion is an important complement to interception by riparian buffers or other protecting soil from different types of water erosion (rill, gully, splash or stream bank erosion). Preventing such detachment and erosion requires at least 50 % of diverse mixed rich semi-natural vegetation cover. It needs to be distributed evenly across the landscape on agricultural fields, uplands and around the crop fields to reduce soil loss, on average by at least >71% (while ranging between 50 and 93% in specific contexts) (Table 1, Figure S1). The high minimum value for this service is driven by the mechanics of soil particle detachment soil covering vegetation, either living or dead (e.g. mulch). Numerous interventions are possible including vegetated buffers, woody and grassy hedgerows or agroforestry, ground cover or understory vegetation, inter-row cover crop cover such as grasses and legumes, or even no-till farming.

There is no maximum distance measure for reducing landslide occurrence on hilly terrains defined as slopes >35°. Rather, in such conditions, retaining at least 50% deep rooted perennial native plant cover from diversified fast growing plantings and understory vegetation distributed evenly along the slope with trees emplaced mainly on the toe or the bottom of the slope is most effective[21–23].

The recreational benefits obtained from green space in cities arise from semi-natural vegetation cover or green space (including street trees, tree canopy cover, diverse public parks, zoos and rich woody and grassy parks). In this case, access to green space, or maximum distance that an individual can travel to access such space becomes the measure of interest. 44 (weighted number) studies report on this value proposing that 300 m as a maximum distance people can travel to regularly access recreation services (Figure 2, Table 1). The benefits are reported to be conditional to having an experience of at least >120 minutes of nature exposure per week[24,25] (Figure 2, Table 1). For the services of which the provisioning is not mediated by mobile functional biological groups, the location of habitat matters more than the exact spatial configuration.

Functional integrity thresholds
Our review finds two important threshold values for functional integrity. First at least 20% habitat is needed to ensure multiple services are provided. Second, we identify 500 m as the maximum threshold distance between habitat and target crops benefiting from pollination and pest control services; or of humans moving towards green spaces for recreation benefits. The combination of both habitat quality and distance to habitat thresholds suggests that retaining functional integrity requires >20-25% habitat per km^2 considering a 500 m dispersal radius for mobile organisms (Figure 1, Table 1). In landscapes with high erosion or landslide risk, a greater habitat fraction is needed, with rather specific characteristics in case of landslide risk. While some NCP may still be provided with habitat levels ranging between 10-20%, 90% of the studies we reviewed were not able to detect NCP provisioning when <10% habitat was retained.

The 20% per km^2 describes a nearly universal threshold against which local actions can be aligned. Which types of habitats are most appropriate to ensure functional integrity remains a highly local issue with important flexibility and should be driven by local knowledge, notably by the farming community. We identified a diversity of practices listed in our review including but not limited to floral strips within fields, no mow field margins including annual or perennial species; hedgerows, woody corridors including riparian forest, forest patches, agroforests or other forests. Minimally disturbed grasslands, pastures, or shrublands increase functional integrity. Consistent across all studies is the need for habitat to support functional integrity. The exact amount of habitat most appropriate to support functional integrity is best defined by local contexts and capabilities, verified with local ecological studies.

Current state and spatial distribution
Using the ESA Worldcover 10 m resolution land cover map of freely available satellite-based land cover data, we calculated the current state and spatial distribution of the functional integrity boundary by calculating the percent habitat in 1 km^2 neighbourhoods, after

distinguishing pasture land from (semi-)natural grasslands and testing for distinguishing forest plantations[26]. Our results indicate that 50% of human-modified lands, which account for 35% of all lands globally, are below 10% habitat per km^2 and 64% to 69% of human-modified lands are below the 20%-25% habitat per km^2 threshold respectively (Figure 3, Table 2). While the relatively coarse thematic resolution of the land cover data may lead to an underestimation of habitat in the landscape, it is still likely that half of global human modified landscapes have below minimum habitat required to provide essential NCP, and are thus relying on substitutes for those NCP (honey bees, pesticides, technical means of water regulation and purification), or face absolute shortages. This shortage is especially found in some key global agricultural regions, on which many people depend for either local food systems or that are linked into global value chains. Also, many large cities do not fulfil the threshold.

Discussion

Implications for conservation

The need to conserve large natural areas and prevent conversion to other uses is well documented in conservation biology [20,27,28]; and articulated as Target 1 of the Convention on Biological Diversity (CBD). Approximately 50% of global lands today is under natural land cover with relatively limited levels of disturbance[29]. While the other half has become heavily modified by humanity for agriculture, forestry, animal production or infrastructure including cities and roads. Human-dominated lands remain places where biodiversity can, and must continue to contribute to providing ecosystem functions and services. The results of our study suggest that in about half of these human-dominated lands insufficient functional integrity remains compromising the provisioning of critical NCP.

Habitat quantity, quality and configuration

Our results propose that at least 20-25% habitat per km^{-2} is needed to maintain multiple NCP simultaneously covering both the quantity and distribution of habitat needed to minimally secure these services. The functional integrity threshold is an aggregate measure of minimum habitat requirements. It does not purport to indicate the degree of services provided, but rather indicates the minimum threshold below which the majority of the NCP studied are no longer provided. The minimum threshold is applicable to most human-dominated landscapes[14,30,31], though more habitat areas may be needed in specific contexts and conditions, such as erosion sensitive lands as is indicated by our results. Further increasing landscape complexity through embedded habitat can further secure actual and future provision of NCP to humanity[32] .

Functional integrity, while a useful measure which can be captured with remote sensing, remains incomplete and biassed to the role of above ground habitats in securing NCP. Soil biodiversity contributions to soil quality, belowground carbon capture, nutrient cycling or increasing water holding capacity in field through no-till, or reduced tillage practices, cover crops or leguminous rotation are not captured by our measure despite their important contributions to improving soil biodiversity's contributions to soil health and function. Similarly, practices that reduce excess nutrient run-off are equally important and complement, but do not replace the role of habitat in buffering excess loss to freshwater and marine systems. Reducing the pressures from human-dominated lands increases the capacity of habitat to provide functional integrity. Excessive nutrient use can rapidly exceed the absorption and use capacity of riparian and other vegetated buffers.

The per kilometre complement to the functional integrity measure is important in ensuring and even distribution of habitat across human-dominated landscapes and is driven by observations that the majority of species providing NCP have small home ranges, or are non-mobile. Most ecological studies show non-linear decreases in species diversity, and abundance with increasing distance from habitat edges. Pollination dependent crops located >500 m from suitable habitat are unlikely to benefit from pollination services[33]. The second role of embedded habitat when secured on a per kilometre basis is to fragment agricultural lands, while connecting habitat. Fragmenting agricultural lands reduce the dispersal of agricultural pests between fields[34] while connecting habitat[35]. Securing riparian buffers as a first step would secure approximately 6% km^{-2} if minimum buffer width is used, while contributing to connectivity[1].

Functional integrity provides a useful measure for aligning global action. It emphasises contributions of biodiversity in supporting local NCP, notably those that either improve food production, and those that reduce the negative environmental externalities of food production. It does not replace local knowledge, or the need for locally adapted practices. Which practices are most suited to provide the six NCP analysed here are best determined in situ and can span a broad range of practices cited in our systematic review including, but not limited to, hedgerows, field margins, riparian buffers, wood lots and pastures, agroforests, no-mow zone around fields planted with a diversity of locally adapted species. Local studies, co-designed and conducted with local communities remain critically important to validate effectiveness, and utility of such interventions. Most of these studies remain highly biassed towards high income countries. Which practices are most suitable for agricultural systems in the global south remains critically important and is likely to be the source of important innovation.

In this review, we focused on six NCP cases and thus do not fully capture all facets of biodiversity and ecosystem service provisioning that supports the needs of people. However, the selected NCP are of critical importance to the functioning of the human-dominated landscapes and all are primarily local. These are also representative of the fundamental principles by which biodiversity operates and provides functions. While specific examples of how biodiversity works remain highly diverse, and indeed, are part of the beauty offered by the biological world, the importance of habitat in human-dominated landscapes underpins the basis by which all NCP are offered. A recent study indicates that a 10% increase in tree cover in agricultural landscapes makes a very significant contribution to carbon sequestration (and thus, climate change mitigation)[36] and others have indicated the disproportional value of small patches of habitat in preserving species diversity[37]. Therefore, restoring ecosystem functions underlying NCP will help to strengthen the resilience of ecosystems and the wellbeing of people as a whole, to halt the decline of biodiversity and promote sustainable human development.

Current state and spatial distribution

We find that nearly half of the world's human-dominated lands fall below critical thresholds for functional integrity, and that 50% are below minimum values, severely compromising the capacity of human-modified lands to contribute to NCP provision. Restoring habitat in these places will undoubtedly raise concerns regarding whether such lands can be spared from food production. Functional integrity is, however, needed to increase the resilience of food production and will, in the end, avoid reduction in food production from lack of NCP. HOwever, innovation, notably in agroecological practices, can help to best integrate new habitats in these landscapes. In many lands increasing functional integrity will not be able to replace agricultural lands with habitat, but rather will focus on agroecological practices that can be achieved by better management of the field margins or corridors between fields. Second, the opportunity to restore biodiversity into agriculture is not inherently yield reducing with evidence of a diversity of practices that both improve yields and environmental outcomes for one[38,39], and second that focusing on embedded biodiversity around fields leaves scope for sustainable intensification within fields.

Historically, global monitoring of ecological integrity of human-dominated landscapes has been difficult as habitat comes in small patches often of linear format that are not easily detectable in most global land cover maps that traditionally have coarser resolutions. However, increased availability of real time high resolution data make monitoring functional integrity increasingly easy - for example Sentinel-2 provides multi-band images at 10 metre resolution which permit intra-annual assessments (Sentinel website). Nevertheless, some small sized linear habitats remain difficult to detect - such as no mow field margin, which are known to increase functional integrity. This indicates the need for the deployment of some additional fine scale monitoring tools, such as LiDAR equipped drones or satellites. We have used the most high-resolution land cover product available to make a global assessment. The 10 metre resolution is capable of capturing small patches of habitat as well as many treelines and other landscape elements. However, it does not capture hedgerows, field boundaries as well as grass strips that are managed as semi-natural habitat. Partly this is due to the limited spatial resolution, but also a result of the limited thematic resolution of this product. Unmanaged patches of grassland within large pasture areas may not be distinguished by the data we used to distinguish grassland areas into pasture and (semi)natural grasslands. Similar concerns hold for forest land cover: in case these are monocultures of short-rotation species, their value for delivering services are much less than that of unmanaged diverse forests. Nevertheless, the sensitivity to distinguishing forest plantations from other forests was not large for the global results, but provided clear regional deviations (see SI, section 3.2). Given these limitations our assessment of the current state of functional integrity should be dealt with great care. Nevertheless, it helps to identify those regions where functional integrity is likely to be below a safe boundary and where landscape functionality may be threatened, with implications for human well-being.

Methods

NCP selection.

In our approach, first we used an initial list of the NCP selecting those services which are particularly defined by clear ecological processes, notably the regulating, and supporting services. These include (1) pollination, (2) pest and disease control, (3) water quality regulation, (4) soil protection (5) natural hazards regulations, and (6) recreation. Using a systematic approach (see SI 2.1 section for more detail), we seek three key variables for each ecosystem service to describe the minimum level of functional integrity that secures the ecosystem function underlying the services. First, a qualitative measure of the habitat needed to provide the service. Second, quantitative evaluation of the amount of natural or semi-natural habitat needed (%) per unit area (km^2). And third, the maximum distance between service providers and beneficiaries or the distribution of natural elements (m) before the service in question is no longer provided. We found a total of 153 articles including 72 meta-analysis and review papers relevant to our search. We then performed exploratory analyses to identify generalizable patterns in the scientific literature regarding each service in question.

Minimum values range calculation.

The quantification of the boundary condition has been estimated and extracted either directly from papers' text, tables or Supplementary Information or from figures. In the figures' case, we estimated the minimum threshold of pollination and pest and disease control NCP when the abundance and diversity of services providers dropped significantly before crossing the zero or starting point value. For soil protection and water quality regulation services, the vegetation cover's reduction efficiency and/or buffer effectiveness or reduction capacity, respectively, have been taken into account as a baseline to estimate the minimum vegetation cover and buffer width needed to maintain the provisioning of the aforementioned services. However, the reduction efficiency of vegetation buffers or cover is highly variable across studies and is service and landscape type dependent with no suitable reduction efficiency proposed across the studies. However, in the majority of the studies, the reduction efficiency of different amounts of vegetated buffers exceeds >50%. In our analysis we used >50% buffer or cover effectiveness or reduction rate as a baseline to determine the minimum value required. The buffer width is represented in metres; we then transformed the buffer width into an approximate amount of semi-natural vegetation using the average density of streams globally[40]

For landslide mitigation, the minimum value has been determined from several experimental and modelling studies that calculate the factor of safety (FoS) with presence and absence of plant roots in the soil[41–44]. The factor of safety (FoS) is a crucial indicator of slope stability and is defined as the ratio of the resisting force to the driving force along a failure surface[44]. To have a stable slope, the FoS must be 1.3 is often specified for temporary or low risk slopes and 1.5 for permanent slopes[45]. Thus, we use the 1.3 FoS as a baseline and proxy to determine the minimum vegetation cover needed for maintaining slope stability. For physical and mental health benefits from nature in urban ecosystems, the minimum amount of green space under different forms and quality, as well as its spatial configuration or linear distance (see Table 1) from each neighbourhood has been assessed from several studies analysing the relationship between the amount of the green space in each neighbourhood in cities and people mental and physical well-being, psychological distress level, number of natural-cause mortality, cortisol levels, prescriptions for antidepressants, presence of anxiety, COVID-19 incidence rate and heat stress level.

Once the range of values for the boundary condition of each NCP was determined at landscape scale, we were able to produce maps of ecosystem integrity distribution from existing databases and identify hotspots regions where there are deficits of either measure, and impacts on both Earth System processes, and local NCP. Synthesis what aspects or characteristics of integrity (keystone species and keystone habitat elements that are essential for functioning) are important for decision-making and management.

Functional integrity current state and spatial distribution calculation

We calculated the current state of the functional integrity boundary based on the ESA Worldcover 10 m resolution land cover map (https://esa-worldcover.org/en). We reclassified this to create a binary classification of "natural lands" and "human modified lands". We then calculate an integrity value for each pixel using a focal function where we take the mean of the binary for the 500-metre radius around each pixel and calculate the percentage of pixels that meet different 'integrity thresholds' (10%, 20%, 30%, etc.). We performed an additional sensitivity analysis using the Jung et al.[26] classification to refine the ESA Worldcover 'tree cover' category. For full details see the Supplementary Information.

Acknowledgements

This work is part of the Earth Commission which is hosted by Future Earth and is the science component of the Global Commons Alliance. The Global Commons Alliance is a sponsored project of Rockefeller Philanthropy Advisors, with support from Oak Foundation, MAVA, Porticus, Gordon and Betty Moore Foundation, Herlin Foundation and the Global Environment Facility. The Earth Commission is also supported by the Global Challenges Foundation.

Data Availability Statement

All data analysed in this study are available from the corresponding author on request. Data that support the findings of this study are available within the paper and its references and Supplementary Information.

Author contributions

AM developed the concept and methodology for assessing functional integrity, conducted the systematic review, gathered and analysed data, led the write-up of the paper, and served as a research scientist on the Earth Commission's Biosphere working group.

FD, PHV, DO originated the idea, developed the concept and methodology for assessing functional integrity, contributed to the analysis and write-up and co-led the Earth Commissions Biosphere Working Group.

JFA participated in the conceptual design and writing of the paper, performed the spatial integrity analysis, created the spatial maps, and served on the Earth Commissions Biosphere Working Group

NZ-C contributed to the analysis and the writing of recreational ecosystem services and served as a member of the Earth Commission's Biosphere working group.

NE-C, AF and SJ contributed to the original ideation and analysis of functional integrity, contributed data and to reviewing of the final manuscript

JR participated in the conceptual design and writing of the paper and served on the Earth Commissions Biosphere Working Group.

ICM contributed to analysis of the soil ecosystem services, contributed data, and to reviewing the final manuscript.

BSK contributed to the riparian analysis, writing, and reviewing the final manuscript.

Competing Interests Statement

The authors declare no competing interests

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Table 1. Boundary estimates for the major local ecosystem functions. *The most constraining function (greatest dependence on habitat amount, quality and configuration) per km² is used to describe the landscape scale boundary. All the values are weighted by the number of the papers.*

NCP	Scale	Functional group	Maximum median distance (m)/position	Minimum median habitat amount (%/km²)	Habitat quality needed	Just access
Pollination	Landscape	insects	500 m (mean:843) [15-2000m]	20% (mean:20.63 +-0.86 %) [10-50] (total 172 studies)	Rich diverse habitat with range of native and non-native species (floral strips, floral field margins, floral under story cover; field grassy and woody margins, hedgerows, woody or silvo arable corridors between fields; forest edges and patches surrounding, grassland and shrublands patches surrounding)	Food provision
Pest and disease control	Landscape	insects, birds, arachnids	1000 m (mean:760m) [10-2000m]	20% (mean:19.30 +-0.24%) [10-37.5] (total 260 studies)	Complex habitat with diverse range of rich native species (forest edges and patches surrounding; floral strips, floral field margins, floral under story cover; grassland, pasture and shrubland patches surrounding; floral grassy and woody hedgerows and field margins; woody corridor between fields with floral understory)	Food provision
Recreation	Landscape	plants, birds	300 m (mean:311m) [300-500m]	25% (mean:24.94 +-0.30%) [19-30]	Diverse rich SN green spaces (streets trees canopy cover, public parks, zoos, gardens, woody and grassy parks, meadows)	Physical and mental health or well-being

NCP	Scale	Functional group	Maximum median distance (m)/position	Minimum median habitat amount (%/km^2)	Habitat quality needed	Just access
				(total 50 studies)		
Soil protection	Landscape	plants	Evenly distributed at the landscape scale	50% (mean:43.63 +- 0.56%) [30-62.5] (total 251 studies)	Diverse rich semi-natural vegetation cover (zoned grassy and woody buffers; trees canopy cover; ground cover with dense fibrous roots plants and cover crops such as grasses and legumes; agroforestry and woody and grassy hedgerows; mixed forest, shrublands and grasslands cover; extensive vegetation management with inter-row cover or crop cover, no-till farming, organic farms)	Food provision
Water quality regulation	Landscape	plants	both sides stream head water	5% (mean:5.6+-0.09 %) [1.2-15.3] (total 1480 studies)	Native diverse semi-natural vegetative buffers or strips with diverse range of native species (three zoned buffers"native forest, shrubs and grasses"; forested or mixed forested and grassy buffers; grassy buffers or mixed buffers; wetland)	Health well-being
Natural hazards mitigation	Landscape	plants	landslides:toe or the bottom of the slope	50% (mean:50.5 %)	Semi-natural vegetation cover with diverse native species(native strong deep rooted trees and shrubs with more reinforcing effect and low surcharge(low height and low diameter); spaced	just harm (people life and survivorship)

NCP	Scale	Functional group	Maximum median distance (m)/position	Minimum median habitat amount (%/km^2)	Habitat quality needed	Just access
				(total 2 studies)	young exotic species (18-20 m) such as popular and willows; natural young trees; mixed plantation)	

Table 2. Spatial distribution of the integrity boundary condition. *Integrity is calculated as the average value of the binary classified layer (natural / human-modified) within a 1 km^2 radius for (1) human-modified lands and (2) the total global land surface. We performed an additional sensitivity analysis for the human-modified lands calculation in which we use additional data to more explicitly account for plantations as part of the human-modified landscape. For full methodological details see the Supplementary Information.*

Integrity threshold applied (%)	**Percent land above integrity threshold**		
	Functionally intact human-modified lands (%)	**Functionally intact human-modified lands sensitivity analysis (%)**	**Functionally intact global land surface (%)**
10	***49***	***53***	***63***
15	***41***	***45***	***62***
20	***36***	***39***	***62***
25	***31***	***34***	***61***
30	27	29	61
40	20	21	60
50	14	15	58
60	10	10	57
70	6	6	56
80	4	4	55
90	2	2	53
100	0	0	47

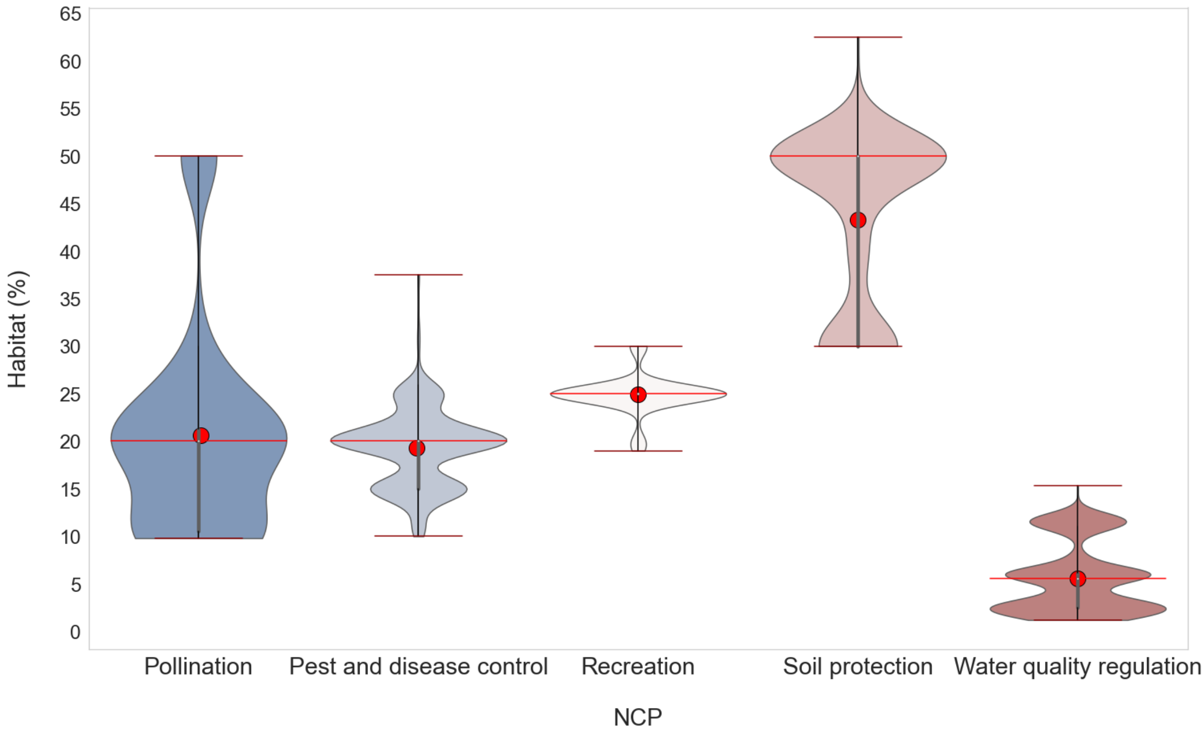

Figure 1. NCP - habitat threshold. *Threshold habitat amount values range (%) for each ecosystem service: pollination (blue violin), pest and disease control (light blue violin), recreation (white violin), soil protection (light red) and water quality regulation (dark red). The lower redline and the top redline correspond to the whiskers (min, max, respectively) that indicate the range of the data, while the redline within the low redline and the top redline represents the median. The violin shape indicates kernel density estimation that shows the distribution of the values. Wider sections of the violin plot represent a higher probability that the number of the papers will take on the given value; the skinnier sections represent a lower probability. The red circles represent NCP's mean habitat amount (%). All the values are weighted by the number of papers.*

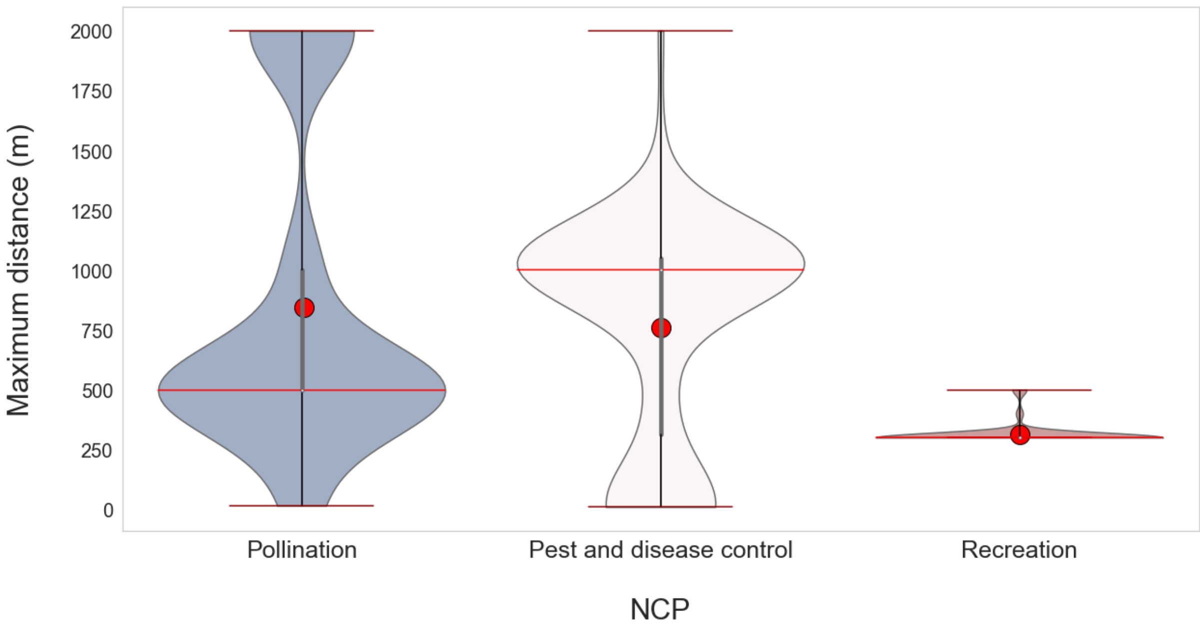

Figure 2. NCP - distance threshold. *Threshold maximum linear distance values range (m) for each ecosystem service: pollination (blue violin), pest and disease control (lwhite violin), recreation (light red violin). The lower redline and the top redline correspond to the whiskers (min, max, respectively) that indicate the range of the data, while the redline within the low redline and the top redline represents the median. The violin shape indicates kernel density estimation that shows the distribution of the values. Wider sections of the violin plot represent a higher probability that the number of the papers will take on the given value; the skinnier sections represent a lower probability. The red circles represent NCP's mean maximum distances (m). All the values are weighted by the number of papers.*

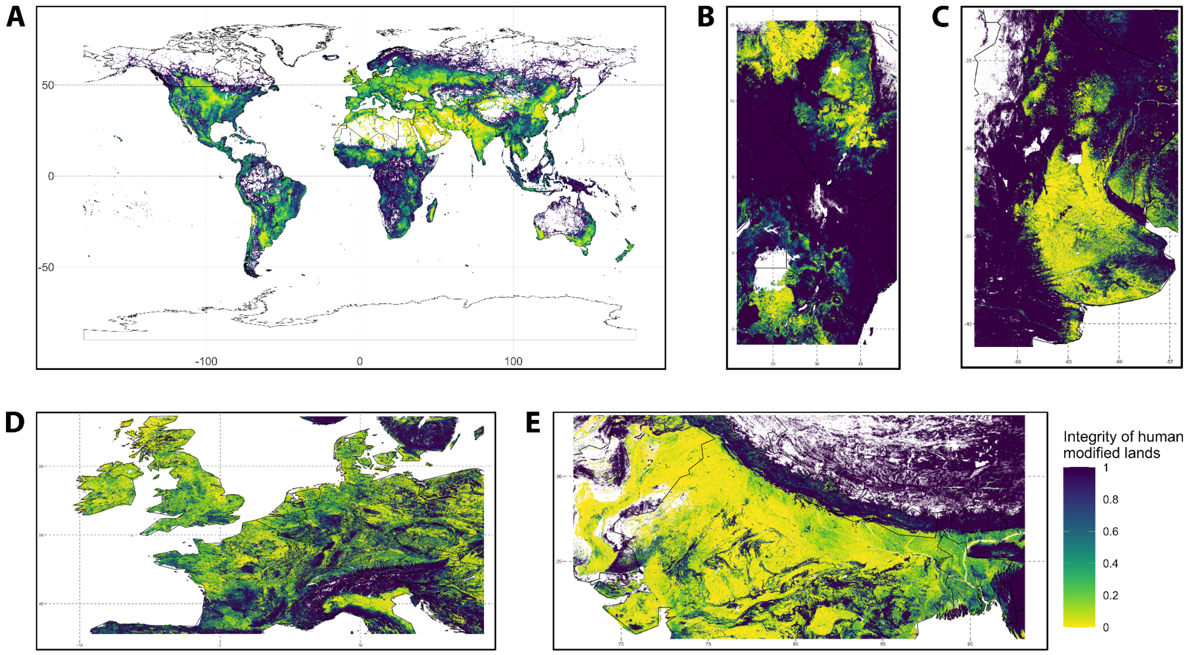

Figure 3. Integrity in human-modified lands. *Per cell habitat integrity in human dominated lands (agricultural and urban landscapes) calculated as the percentage (%) of semi-natural habitat within 1 km*^{2}*. Integrity is calculated at a 10m resolution and then aggregated for display purposes. (A) The global spatial distribution of biosphere functional integrity at a 500 metre scale. More detailed views are shown in the zoom-in panels at a 100 metre resolution for (B) African highlands, (C) Argentinian soybean region, (D) Europe, and (E) Indian ganges plain. Areas colored white indicate regions where there are no human-modified lands.*