Biosphere functional integrity for people and Planet

Awaz Mohamed[1*], Fabrice DeClerck[2,3], Peter H. Verburg[4,5], David Obura[6], Jesse F. Abrams[7], Noelia Zafra-Calvo[8], Juan Rocha[9,10], Natalia Estrada-Carmona[2], Alexander Fremier[11], Sarah Jones[2], Ina C. Meier[1], Ben Stewart-Koster[12]

[1] Functional Forest Ecology, Universität Hamburg, 22885 Barsbüttel, Germany
[2] Alliance of Bioversity International and CIAT, Montpellier, France
[3] EAT, Oslo, Norway
[4] Institute for Environmental Studies, Vrije Universiteit Amsterdam, Amsterdam, the Netherlands
[5] Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), Birmensdorf, Switzerland
[6] CORDIO East Africa, Mombasa, Kenya
[7] Global Systems Institute, University of Exeter, Exeter EX4 4QE, UK
[8] Basque Centre for Climate Change bc3, Scientific Campus of the University of the Basque Country, Biscay, Spain
[9] Future Earth Secretariat, Stockholm, Sweden.
[10] Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden.
[11] School of Environment, Washington State University, Pullman, WA 99164
[12] Australian Rivers Institute, Griffith University, Brisbane, Australia.

* Corresponding author: Awaz Mohamed, awaz.mohamed2@gmail.com

Abstract
Defining a safe and just space for the biosphere requires global-scale synthetic measures of functional integrity in relation to Nature's Contributions to People (NCP). We estimated, based on a systematic review of the literature, the minimum level of functional integrity needed to secure multiple critical ecosystem services, including pollination, pest and disease control, water quality regulation, soil protection and recreation, in human-modified landscapes. We found that at least 20-25% of relatively diverse semi-natural habitat 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. Today, 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.

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 these benefits, referred to as ecosystem services or 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, but often ignored in global scale studies informing conservation priorities[2].

Most attention in biodiversity conservation is given to halting the conversion of remaining natural ecosystems, the unique species they hold[3,4] and the important contributions they make to Earth System functioning (CBD Targets 1 and 3). 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 areas to agriculture in mixed mosaic landscapes[7]. The loss of ecological function in such areas is incompatible with numerous sustainable development goals[8]. Conservation efforts should better balance the efforts between natural ecosystems and functioning of human-dominated ecosystems to achieve the overall objectives[9,10].

Maintaining ecosystem function in landscapes modified by human activity is of high importance for the viability of humanity. A major challenge in defining global-scale safe and just biosphere targets lies in the numerous, and often highly context specific conditions under which biodiversity supports ecosystem processes that contribute to human well-being. Functional integrity has been proposed as a way to capture these diverse processes in a synthetic measure[49] but clear evidence of the minimum amount of functional integrity needed to stay within a safe and just space for all remains missing[13]. We define functional integrity is as an ecosystem's capacity to contribute to biosphere processes and to produce NCP. 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. Functional integrity is an important complement to biodiversity measures used in conservation biology as it recognizes that 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.

Functional integrity can be used as a proxy for describing whether sufficient semi-natural or natural habitat (hereafter "habitat") is retained to support ecological functions and services[14]. Habitats are conditions and resources that enable occupancy, including reproduction and survival, by a given organism[15]. Habitat quantity is an indicator of landscape complexity based on 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 a specific habitat, thus reducing service provisioning such as pollination or pest regulation by mobile functional species. 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 of the habitat that provides the service 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 through vegetation buffers placed on both sides of stream

headwaters[19]. Well configured habitat can significantly reduce the frequency and risk of natural hazards such as shallow landslides, floods, and soil erosion. Habitat in urban ecosystems, in the form of greenspaces and parks can provide important NCP such as physically and psychologically beneficial experiences that contribute significantly to wellbeing. The minimum amount, quality, and distance for green space to provide this contribution can be described. All aforementioned services are particularly important in human-modified lands.

Previous ecological studies have attempted to describe and quantify the relationship between biodiversity and NCP provisioning. The results of these studies are highly variable, driven in large part by the diversity of context-specific species interactions the exist in Nature[20–24]. The relationship between how much nature is needed, and how much NCP is provided is thus highly variable and not possible to describe. However these same studies consistently demonstrate that below thresholds of quality, quantity, and distance from habitat, ecosystem services are no longer provided. Minimum thresholds of the amount of Nature needed before NCP's are lost, or a boundary condition for functional integrity, can by quantified and synthesized. Previous studies have suggested thresholds in the range of 10-20% of habitat per km^2 for single functions such as pollination, often based on expert judgement[14,25]. However, reviews to identify minimum threshold values for functional integrity for several NCP have not been conducted.

Here, we conduct a systematic review of 153 published studies (including 72 reviews and meta-analyses) on the relationship between habitat and NCP provisioning to assess the minimum levels of functional integrity needed to maintain six critical NCP. The studies that are synthesised comprise a total of 4463 original studies (see Supplemental Information). We identify how much nature is needed, of what quality, and in what locations, to provide the minimum level of integrity that ensures the provisioning of six critical NCP including (1) pollination, (2) pest and disease control, (3) water quality regulation, (4) soil protection, (5) natural hazards mitigation, and (6) physically and psychologically beneficial experiences.

Results

We identified the threshold characteristics in terms of quantity, quality and spatial configuration of habitat needed to ensure a minimum supply of six NCP. While local context is critical, the consistent pattern of all reviewed studies is that species, and the services they provide, are lost below a certain threshold of habitat quantity, and by the maximum linear distance that providing organisms can move.

Habitat quantity

We find that at least 20% of semi-natural habitat is needed to support pollination and pest and disease control. For specific contexts this minimum area may range from 10 to 50% for pollination, while it ranges from 10 to 38% 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 63% for specific contexts) vegetation cover at the landscape scale, while for regulating surface and subsurface water quality from non-point pollutants only requires about 5 to 6% of the landscape (being a buffer of approximately 28 m width on both sides of streams) though this may range between 1.2-15% depending on context (buffer width, slope 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 (>35°). For physically and psychologically beneficial experiences provided by greenspace in and around urban areas at least 25% (ranging between 19-30% depending on the context) semi-natural habitat is recommended (Figure 1, Table 1).

Spatial configuration and habitat quality for each NCP

NCP are provided by communities of species and their traits. Biophysical contributions such as sediment interception are primarily delivered by vegetation, which also serves as habitat needed for mobile species providing pollination and pest control amongst others. Vegetation characteristics define habitat quality with the inclusion of mobile species whose foraging ranges from their home habitat determine the maximum distance at which an NCP can still be provided. For three of the six NCP we describe maximum distances between habitats by the distance that mobile organisms can forage from host habitat, or in the case of physically and psychologically beneficial experiences, the distance that humans can move to access the provider habitat.

Pollination and pest and disease control 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 to 1000 m (ranging between <0-2000 m for specific taxa) from the habitat to the target crop field. Beyond this distance the contributions 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 through dense vegetation allows larger particles to fall out of solution and retained in soils. A diversity of root structures, both fibrous from grasses or tap roots from woody vegetation increase soil porosity, infiltration and capture of excess nutrients. Buffers on slopes <23° on average are able to capture >73% (ranging between 50-90% depending on the context) of non-point source pollutants (Table 1, Figure SI1). This includes sediment, nutrients, pesticides, and salts from upstream agricultural lands.

Preventing particle detachment driving waterborne erosion is an important complement to interception, protecting soil from different types of water erosion (rill, gully, splash, or stream bank erosion). Preventing such detachment and erosion requires at least 50% diverse, 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 SI1). The high minimum value for this contribution is driven by the mechanics of soil particle detachment, soil covering vegetation either living or dead. 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[26–28].

The physical and psychologically beneficial experiences obtained 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. Studies propose 300 m as a maximum distance people should travel to access green spaces (Figure 2, Table six). The benefits are conditional to having an experience of at least >120 minutes of nature exposure per week[29,30] (Figure 2, Table 1).

Functional integrity thresholds

Our review finds two important threshold values for functional integrity. First, at least 20% habitat is needed within the landscape to ensure that multiple NCP are provided. Second, we identify 300 to 500 m as the maximum threshold distance between habitat and target beneficiaries (crops, citizens) for five of the six NCP's evaluated: pollination, pest and disease control, water quality regulation, soil protection, and recreation. Combining habitat quality and distance to habitat thresholds suggests that retaining functional integrity requires >20-25% habitat per km^2 (Figure 1, Table 1). In landscapes with high erosion or landslide risk and cropping systems that involve leaving ground bare for periods of the year, 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 20-25% per km^2 describes a threshold against which local actions can be aligned. Which types of habitats are most appropriate to ensure functional integrity remains a highly local issue and should be driven by local knowledge. 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 also can increase functional integrity.

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 functional integrity by calculating the percent habitat in 1 km^2 neighbourhoods, after distinguishing pasture land from (semi-)natural grasslands and testing for distinguishing forest plantations[31]. 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, SI Table 2). This is significantly higher than previous estimates using lower resolution imagery[49]. While the relatively coarse thematic

resolution of the land cover data may lead to an underestimation of habitat in the landscape, it is, nevertheless, 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 in NCP. 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.

Discussion

Implications for conservation

The need to conserve large natural areas and prevent conversion to other uses is well documented in conservation biology[25,32,33]. About half of the global lands have 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. The results of our study suggests that in at least 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 in each km^2 of land is needed to maintain multiple NCP simultaneously covering both the quantity and distribution of habitat needed to minimally secure these NCP. The functional integrity threshold does not indicate the amount of NCP provided, but rather indicates the minimum threshold below which the majority of the studied NCP are no longer provided. Below 10% all six NCP's are no longer provided. The minimum threshold is applicable to most human-dominated landscapes[14,20,34], though more habitat areas may be needed in specific contexts, 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[35] .

Functional integrity as operationalized in this study is a useful measure as it can be captured with remote sensing, but, it remains incomplete and biased to the role of above-ground habitats in securing NCP. Soil biodiversity contributions to soil quality, belowground carbon capture, nutrient cycling and increasing water holding capacity in fields through no-till, or reduced tillage practices, cover crops or leguminous rotation are not captured by our measure despite their important role in improving 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 capacity of riparian and other vegetated buffers.

The per kilometre functional integrity measure is important in ensuring an 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. The second role of embedding habitat inside the landscape is to fragment agricultural lands, while connecting habitat. Fragmenting agricultural lands reduces

the dispersal of agricultural pests between fields[37] while connecting habitat[38]. Securing riparian buffers is a good first step that would secure at least 6% of habitat per km^2 on average globally while contributing to connectivity[1].

The thresholds of functional integrity identified from empirical data provide 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 (see Supplemental Information). Local studies, co-designed and conducted with local communities remain critically important to validate effectiveness, and utility of such interventions.

In this review, we focused on six NCP and thus do not fully capture all facets of biodiversity and NCP 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. Habitat in human-modified landscapes has, however, wider benefits for achieving global sustainability targets: recent study indicates that a 10% increase in tree cover in agricultural landscapes makes a very significant contribution to global carbon sequestration[39] and others have indicated the disproportional value of small patches of habitat in preserving species diversity[40]. Restoring habitat and the ecosystem functions in human-dominated lands can strengthen the resilience of ecosystems and the wellbeing of people and at the same time contribute to halting the decline of biodiversity.

Current state and spatial distribution

We find that at least half of the world's human-dominated lands fall below critical thresholds for functional integrity, severely compromising the capacity of human-modified lands to contribute to NCP provision. Restoring habitat in these places might compete with or complement increasing food production depending on the location and practices with good evidence the diversification and increase yields. However, human dominated spaces remain biological in nature with strong dependencies on functional integrity to provide multiple NCP's while ensuring the resilience of food production. Maintaining functional integrity in human dominated lands in needed to avoid uncertainty and failures of food production. Therefore, such a trade-off between the area of (semi-) natural habitat and food production is a false one. Innovation, notably in agroecological practices, can help to best integrate new habitats in these landscapes. The opportunity to restore habitat is not inherently yield reducing with evidence of a diversity of practices that both improve yields and environmental outcomes for one[41,42], and second that focusing on embedded biodiversity on field perimeters and riparian edges leaves scope for sustainable intensification within fields.

Historically, global monitoring of ecological integrity of human-dominated landscapes has been difficult as habitat mostly comes in small patches often of linear format that are not easily detectable in most global land cover maps that traditionally have coarser resolutions. Nevertheless, the recent high-resolution land cover product used in the global assessment is capable of capturing small patches of habitat as well as treelines and other landscape

elements. It does not capture hedgerows, field margins and 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 data-product. Unmanaged patches of grassland 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 through remaining challenges of distinguishing natural forests from monocultures of short-rotation species. 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 interpreted with caution. Nevertheless, they are useful to identify those regions where functional integrity is likely to be below a safe boundary, with implications for human well-being. We anticipate that the continued rapid evolution of remote sensing products and artificial intelligence that these detention challenges are likely to be resolved in the near future.

Methods

NCP selection.

We selected NCP which are particularly defined by clear ecological processes across different categories. These include (1) pollination, (2) pest and disease control, (3) water quality regulation, (4) soil protection (5) natural hazards regulations, and (6) physically and psychologically beneficial experiences Using a systematic approach (see Supplemental Information for additional detail and references included), we searched for literature that addressed three key variables for each NCP to describe the minimum level of functional integrity that secures the ecosystem function underlying the provision. First, a quantitative measure of the minimal area of habitat needed to provide the NCP. Second, a qualitative evaluation of the type and quality of the habitat required, and third, the maximum distance between providers and beneficiaries or the distribution of natural elements (m) required for the NCP to be provided. We found a total of 153 articles including 72 meta-analysis and review papers relevant to our search. We performed exploratory analyses to identify generalizable patterns in the scientific literature regarding each NCP in question.

Minimum values range calculation.

The minimum threshold under which NCP are no longer delivered has been estimated and extracted either directly from papers' text, tables or Supplementary Information or from the figures. In the figures' case, we estimated the minimum threshold of pollination and pest and disease control NCP when the abundance and diversity of providers dropped significantly before crossing the zero or starting point value. For soil protection and water quality, the reduction efficiency of vegetative and/or buffer effectiveness or reduction capacity, respectively, have been considered as a baseline to estimate the minimum vegetation cover and buffer width needed to maintain the provisioning of the aforementioned NCP. However, the reduction efficiency of vegetation buffers or cover is highly variable across studies and dependent on the NCP and landscape type, with no suitable reduction efficiency proposed across the studies. In most 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[43]

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[44–47]. 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[47]. 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[48]. Thus, we use the 1.3 FoS as a baseline and proxy to determine the minimum vegetation cover needed for maintaining slope stability. For physically and psychologically beneficial experiences 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, such as 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 analyzed 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 meter resolution land cover map (https://esa-worldcover.org/en), refining the grassland category by distinguishing pasture lands and semi-natural grasslands using based on the habitat map of Jung et al.[31]. 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 calculate the mean of the binary for the 500-metre radius around each pixel and calculate the percentage of pixels that meet different thresholds (10%, 20%, 30%, etc.). We performed an additional sensitivity analysis using the Jung et al.[31] classification to refine the ESA Worldcover 'tree cover' category by distinguishing forest (seen as natural) from plantations (seen as human modified lands). For full details see the Supplementary Information.

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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 methodology for assessing and analysing 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

NZC contributed to the analysis and the writing of physically and psychologically beneficial experiences in nature and served as a member of the Earth Commission's Biosphere working group.

NE-C, AF and SJ contributed to the conceptualisation and methodology for assessing 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 the analysis of the soil ecosystem services and to reviewing the final manuscript.

BSK contributed to the riparian analysis 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 km^2 is used to describe the landscape scale threshold. All the values are weighted by the number of studies included. The total number of studies refers to the total number of studies considered in articles, reviews and meta-analysis.*

NCP	Scale	Taxonomic groups	Maximum median distance (m)/or position	Minimum median habitat amount (%/km^2)	Habitat quality needed
Pollination	Landscape	insects	<500 m (mean:843±32.3 m) [15-2000m] (total 279 studies)	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).
Pest and disease control	Landscape	insects, birds, arachnids	<1000 m (mean:760m±51.12m) [10-2000m] (total 207 studies)	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 corridors between fields with floral understory)
Physically and psychologically beneficial experiences in nature	Landscape	plants, birds	<300 m (mean:311m±6.7m) [300-500m] (total 44 studies)	25% (mean:24.94±0.30%) [19-30] (total 50 studies)	Diverse rich semi-natural green spaces (streets trees canopy cover, public parks, zoos, gardens, woody and grassy parks, meadows)
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)

NCP	Scale	Taxonomic groups	Maximum median distance (m)/or position	Minimum median habitat amount (%/km^2)	Habitat quality needed
Water quality regulation	Landscape	plants	both sides of streams	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)
Natural hazards mitigation	Landscape	plants	landslides: toe slope or slope bottoms	50% (mean:50.5%) (total 2 studies)	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 young exotic species (18-20 m) such as popular and willows; natural young trees; mixed plantation)

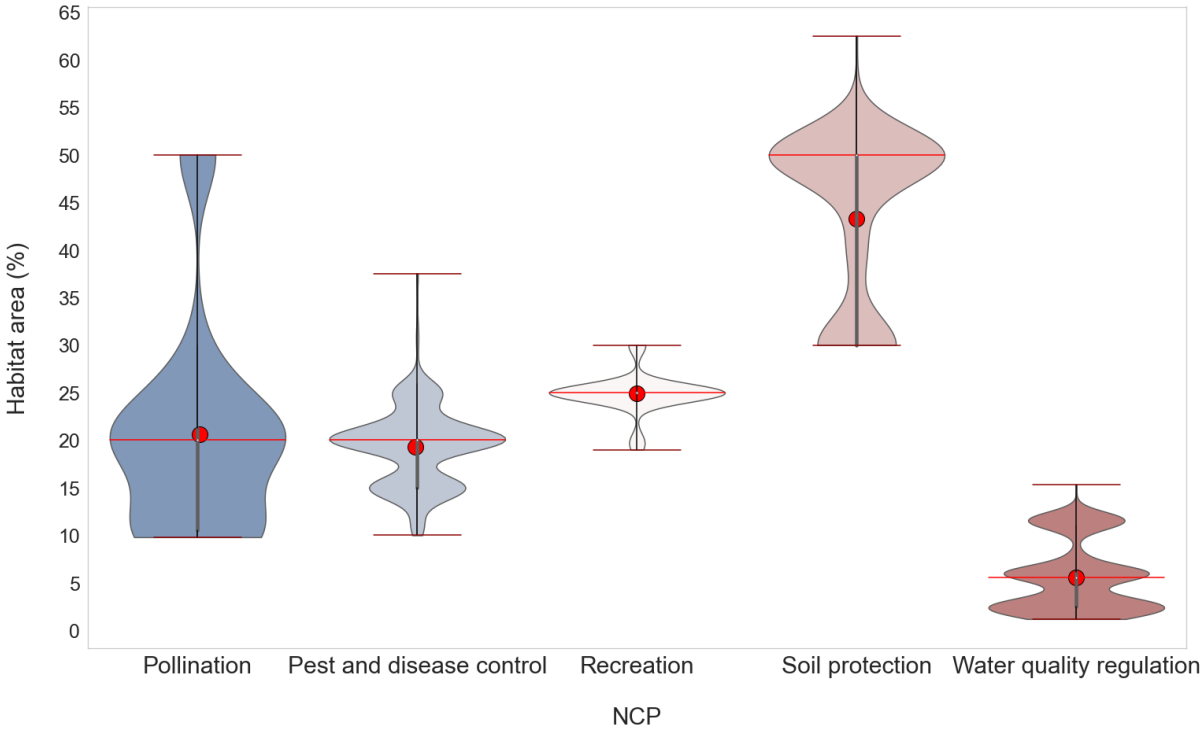

Figure 1. NCP - habitat area threshold. *Threshold habitat amount values range (%) for each ecosystem service: pollination (blue violin), pest and disease control (light blue violin), recreation (white violin), soil protection (light red) and water quality regulation (dark red). The lower redline and 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.*

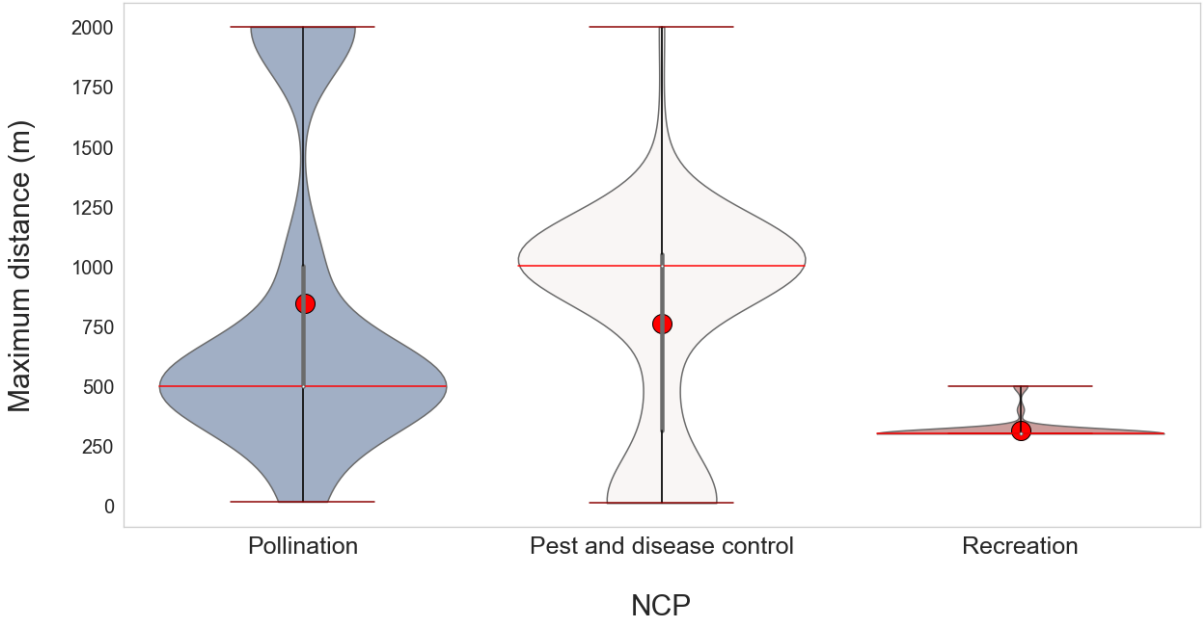

Figure 2. NCP - distance threshold. *Threshold maximum linear distance values range (m) for each ecosystem service: pollination (blue violin), pest and disease control (lwhite violin), recreation (light red violin). The lower redline and the top redline correspond to the whiskers (min, max, respectively) 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.*

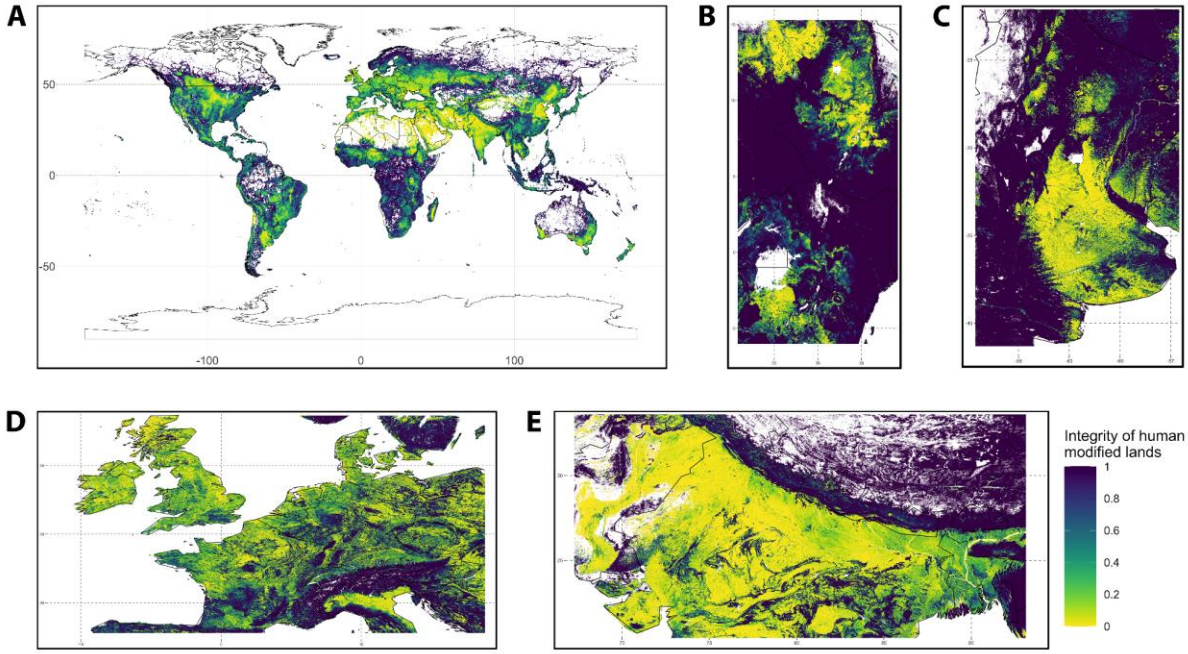

Figure 3. Integrity in human-modified lands. *Per cell habitat integrity in human dominated lands (agricultural and urban landscapes) calculated as the percentage (%) of semi-natural habitat within 1 km^2. Integrity is calculated at a 10m resolution and then aggregated for display purposes. (A) The global 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 Gangetic plain. Areas coloured white indicate regions where there are no human-modified lands.*