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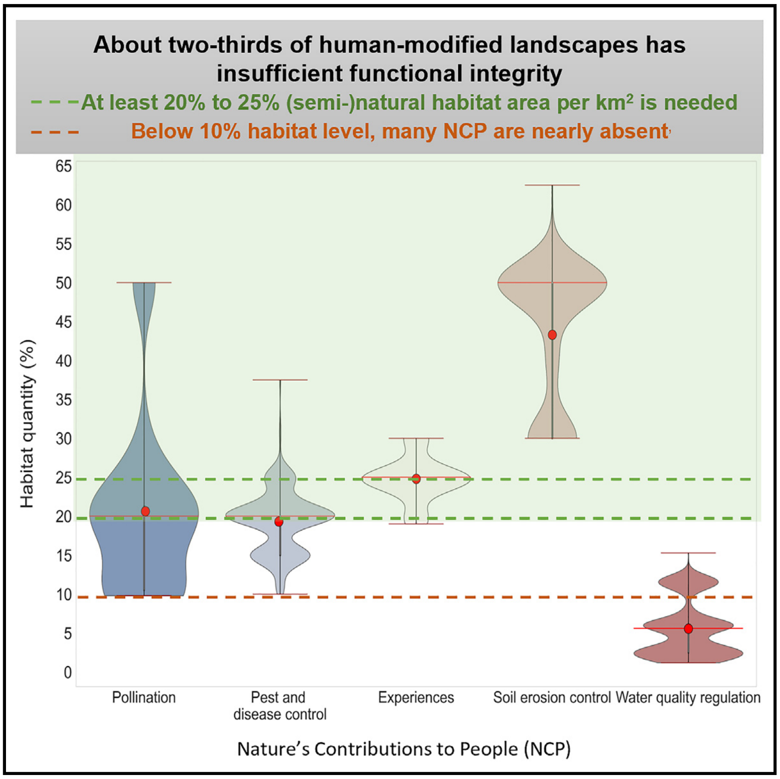
Securing Nature's Contributions to People requires at least 20%–25% (semi-)natural habitat in human-modified landscapes

Graphical abstract



Highlights

- We assess habitat quantity, quality, and spatial configuration in human-modified landscapes
- At least 20%–25% habitat per km^2 is needed to sustain nature's contributions to people
- Only one-third of global human-modified lands meet this minimum level
- Local actions should be adopted based on community needs, knowledge, and capacities

Authors

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In brief

Biodiversity loss threatens crucial human well-being aspects, including food production, water quality, climate regulation, and recreation. We assess the minimum level of (semi-)natural habitat in agricultural and urban areas to sustain these benefits. We find that below 20%–25% (semi-)natural habitat per km^2, the supply of these benefits significantly declines. Alarmingly, two-thirds of global urban and agricultural lands fall below this level. Our study offers a broad target for conservation efforts beyond natural areas to enhance human well-being.

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Securing Nature's Contributions to People requires at least 20%–25% (semi-)natural habitat in human-modified landscapes

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SCIENCE FOR SOCIETY Biodiversity is rapidly declining, affecting benefits critical to human well-being, including food production, water quality, climate regulation, and recreation spaces. This decline is particularly challenging in urban and agricultural areas significantly modified by humans but where reliance on biodiversity's benefits is nevertheless high. We assess the minimum level of (semi-)natural habitat needed in human-modified landscapes to support the supply of these benefits. We find that biodiversity's capacity to pollinate crops, regulate pests and diseases, maintain clear water, and limit soil erosion significantly declines when habitat area falls below 20%–25% per km^2. This same limit applies in urban areas to maintain recreation spaces for people. We find that approximately two-thirds of agricultural and urban areas globally fall below this level. This broad target can be used in urban and agricultural areas to manage and regenerate ecosystem functions to enhance human well-being.

SUMMARY

The cascading effects of biodiversity decline on human well-being present a pressing challenge for sustainable development. Conservation efforts often prioritize safeguarding specific species, habitats, or intact ecosystems but overlook biodiversity's fundamental role in providing Nature's Contributions to People (NCP) in human-modified landscapes. Here, we systematically review 154 peer-reviewed studies to estimate the minimum levels of (semi-)natural habitat quantity, quality, and spatial configuration needed in human-modified landscapes to secure functional integrity essential for sustaining NCP provision. We find that the provision of multiple NCP is threatened when (semi-)natural habitat in the landscape falls below an area of 20%–25% for each km^2. Five NCP almost completely disappear below a level of 10% habitat. The exact quantity, quality, and spatial configuration of habitat required depends on local context and specific NCP. Today, about two-thirds of human-modified lands have insufficient (semi-)natural habitat, requiring action for NCP regeneration. Our findings serve as a generic guideline to target conservation actions outside natural areas.

INTRODUCTION

Recent global assessments demonstrate a clear decline in living nature and its contributions to people with cascading effects on human well-being.[1] Such contributions range from climate, water, and nutrient cycle regulation at global and regional scales to pollination, pest control, and physical and psychological experiences at local scales. These benefits are generally referred to as ecosystem services or Nature's Contributions to People (NCP) and comprise the ecosystem functions that directly or indirectly contribute to human well-being and quality of life.[2] Local-scale NCP are particularly important in human-modified landscapes due to the intensive interaction between human populations and natural ecosystems, often having a high number of beneficiaries and a greater potential for the use of NCP. These areas, however, are often ignored in global-scale studies informing conservation priorities that tend to focus on intact natural lands and wilderness areas.[3]

Biodiversity has multiple facets, including genes, species, populations, evolutionary history, ecosystem functions, and contributions to people, as well as a variety of social and cultural dimensions. Most attention in biodiversity conservation is given to halting the conversion of remaining intact natural ecosystems, protecting the unique species they hold,[4,5] and the important contributions they make to Earth system functioning (goal A of the Kunming-Montreal Global Biodiversity Framework). These are critically important conservation objectives; however, (semi-)natural habitats in human-modified lands and waters are often overlooked in conservation policies and global target setting, despite the critical roles they play in supporting human well-being[6] as well as in conserving biodiversity.[7] Human-modified lands cover approximately 50% of the ice-free terrestrial land area and range from urban to agricultural areas.[8] The significant decline of ecosystem functions and contributions to people in such areas is incompatible with several of the Sustainable Development Goals and the agreed targets of the Kunming-Montreal Global Biodiversity Framework, notably Target 10 on sustainable production.[9] However, we currently lack generalizable and operational metrics describing the functions of biodiversity embedded within human-modified lands and the minimum level of biodiversity in these landscapes needed to support human well-being.[10,11] Identifying such metrics is challenged by the highly context-specific conditions under which biodiversity supports multiple ecosystem processes in human-modified landscapes, making it also challenging to define synthetic policy objectives.[10]

A functional integrity metric has been proposed to capture the multiple dimensions and interactions between species and the environment in a synthetic measure,[12,13] but clear evidence of the minimum level of functional integrity required remains missing.[14] In this study, we refer to functional integrity as the capacity of the ecosystem to contribute to biosphere processes and to sustain multiple NCP provision through the presence of ecologically functional communities of species. It addresses both Earth-system-scale biosphere regulation processes and landscape-scale provisioning of local NCP. Functional integrity complements biodiversity metrics used in conservation biology by recognizing the important NCP that can be provided by natural vegetation but also by altered (non-native or non-intact) vegetation in agricultural, urban, and other human-modified areas. Our reference to a minimum level of functional integrity refers to a level of ecosystem function below which there is a substantial risk of experiencing a strong decline in NCP provision, jeopardizing the well-being of those dependent on these NCP. This minimum level should not be interpreted as the amount required for sufficient NCP provision, nor as an estimate of NCP supply, as both can strongly vary depending on the local context.

NCP provision is dependent on the quantity, quality, and spatial configuration of available (semi-)natural habitat (hereafter "habitat") within the landscape, which can be used as a proxy measure of functional integrity.[15] Habitat quantity refers to the proportion of (semi-)natural elements present in a landscape. Habitat quality is a measure of the ability of a habitat to host and maintain species required for specific ecological functions and services. The structure and composition of a habitat are strong determinants of its quality.[16] The spatial configuration of habitat in the landscape influences landscape connectivity and the distribution of NCP-providing organisms. This includes both the proximity to habitat and the location of habitat that supports NCP provision. Adjacency is an important element of NCP provisioning, notably in managed lands where distances between habitat (NCP source) and crops or people (NCP beneficiary) can vary. Habitat location within a landscape is also important for regulating water quality, particularly in riparian zones, whereas the distance to source habitat determines access by mobile NCP-providing organisms. These include pollinators and pest and disease-controlling organisms where the foraging range from the home habitat determines the maximum linear distance for NCP provision. Adjacency also applies to experiences, where physical access or a reasonable distance from human residence determines its potential use. The combination of quantity, quality, and spatial configuration of habitat collectively underpins functional integrity.

The required habitat quantity, quality, and spatial configuration for NCP provision are strongly context dependent and differ depending on the NCP, landscape type, and the taxa involved.[17–19] Shorter linear distances from source habitat (a few hundred meters) and higher connectivity have an important positive impact on mobile pollinators and pest regulator diversity.[18] For NCP provided by sessile or low-mobility functional groups (e.g., soil erosion control, capture of non-point-source pollutants from surface and subsurface water, or natural hazards mitigation), habitat location is extremely important. For example, sediment and nutrient capture are significantly improved through vegetation buffers along both sides of waterways, in particular on stream headwaters.[20] Likewise, habitat strategically located in targeted landscape positions can significantly reduce the frequency, risk, and impact 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 well-being.[21]

Numerous ecological studies have studied aspects of the relationship between habitat quantity, quality, and spatial configuration and the provisioning of NCP. Although these studies confirm the high context specificity and variability of such relationships, they consistently indicate that, below certain levels of habitat quantity, quality, and spatial configuration, NCP provisioning strongly declines or is even no longer provided.[22–26] Studies on pollination and pest control suggest required levels of 10%–20% habitat per km^2, often based on expert judgment, valid in a specific land-use or landscape types.[15,27,28] To our knowledge, a synthesis of minimum levels for functional integrity across several NCP and across a wide range of landscapes has not been conducted to date. Such a synthesis would serve as a generally applicable guide and provide an overview of the

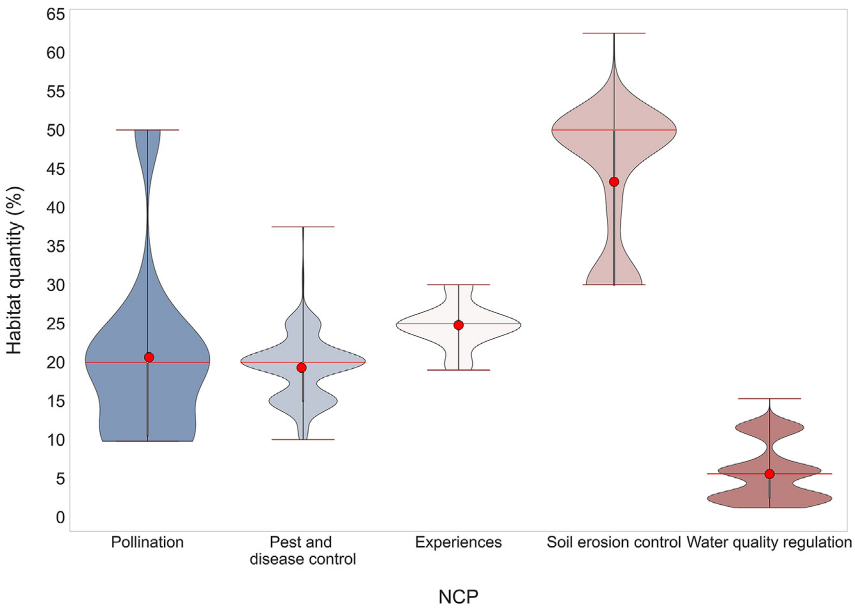

Figure 1. Minimum quantity of habitat required for provisioning of each NCP

The lower and upper red lines correspond to the whiskers (minimum and maximum, respectively), which indicate the range of the data. The middle red line represents the median, while the red dots represent the weighted mean value. The violin shape indicates kernel density estimation based on the number of original papers included in the meta-analyses/reviews reporting the given value. Wider sections of the violin plot represent a larger number of papers underlying the given value; the thinner sections represent a lower body of evidence. All the values are weighted by the number of papers.

order of magnitude of (semi-)natural habitat required in human-modified landscapes. It also contributes to more effective and targeted conservation and restoration strategies, promoting sustainable NCP provisioning and safeguarding the well-being of people reliant on these NCP.

Here, we attempt to determine the minimum quantity, quality, and spatial configuration needs of (semi-)natural habitat in human-modified landscapes. These minimum needs indicate the minimum level of functional integrity essential for maintaining NCP provision. To achieve this, we conducted a systematic review of the literature, analyzing 74 quantitative peer-reviewed reviews and 80 narrative studies, comprising in total 4,277 original studies. We identify the level below which six critical NCP significantly decline. Our key findings, therefore, delineate the critical habitat levels necessary for maintaining the following NCP provision: (1) pollination, (2) pest and disease control, (3) water quality regulation, (4) soil erosion control, (5) natural hazards mitigation, and (6) physical and psychological beneficial experiences for individuals that spend time in natural environments (hereafter "experiences"). Our analysis indicates that the capacity of human-modified landscapes to provide NCP significantly declines below 20%–25% of habitat per km^2, with five NCP provisions almost completely disappearing below the 10% habitat level. Currently, about two-thirds of global human-modified landscapes lack sufficient area of (semi-)natural habitat within the landscape to secure this minimum level of NCP provision. Our proposed levels serve as a general guideline for prioritizing conservation initiatives and formulating adaptive, scalable policies beyond natural areas.

RESULTS

Methods summary

We have selected five regulating and one non-material NCP that are related to biodiversity and ecosystem functions in different ways while directly affecting local well-being. These include water quality regulation, soil erosion control, crop pollination, pest control, and benefits for human health. We use a systematic literature review protocol of the peer-reviewed literature to quantitatively synthesize the evidence on the minimal conditions in terms of quantity, quality, and spatial configuration of (semi-)natural habitat necessary for the provision of the six aforementioned NCP in highly transformed human-modified landscapes (see "experimental procedures" section for detailed methods). Minimum values required refer to the level under which the NCP show a sharp decline or reach very low values. The median among these observed minimum values is used to determine the level of (semi-)natural habitat area minimally needed within the landscape. This level is assumed to secure the multiple ecological functions that underlie the selected NCP, irrespective of the existence of demand for those NCP. All values used in establishing the minimum conditions required are weighted by the number of papers included in each analyzed review or meta-analysis and represent the median for each NCP. The values range for individual NCP reflects variations between studies, whereas the values range across all NCP represents the variation in median values from the different NCP.

Habitat quantity

Within the body of literature collected, we coded publications based on their findings concerning the minimum amount of (semi-)natural habitat needed within the landscape to secure six critical local NCP. A total of 94 synthetic and original studies, encompassing 2,125 original studies, reported relevant information. Our review concluded that at least 20% habitat is needed to support pollination and pest and disease control, with a range of 10%–50% for pollination, and 10%–38% for pest and disease control, depending on the context. For experiences provided by green spaces, at least 25% habitat is required, ranging between 19% and 30% depending on the context (Figure 1; Table 1). Given the dominance of urban studies for this NCP, our minimum quantity value might be unrepresentative of non-urban areas due to variations in transportation options and alternatives to urban green spaces such as surrounding croplands.

To protect soil from water-based erosion, at least 50% habitat at the landscape level is required, with a range of 30%–63% for specific contexts, depending on slope angle, rainfall intensity,

Table 1. Estimates of habitat levels for NCP provision

NCP	Taxonomic groups cited	Minimum habitat quantity (% km^{-2}) [range]	Maximum distance (m)/or position [range]	Landscape elements needed
Pollination	insects	20% (mean: 21% ± 1%) [10%–50%] (total: 172 studies)	<500 m (mean: 989 ± 43 m) [15–2,000 m] (total: 288 studies)	rich, diverse habitat with native and non-native species (floral strips, floral field margins, floral understory cover; grassy and woody margins of fields, hedgerows, woody or silvo-arable corridors between fields; forest edges and patches surrounding grassland and shrublands patches)
Pest and disease control	insects, birds, arachnids	20% (mean: 19% ± 0.2%) [10%–38%] (total: 260 studies)	<500 m (mean: 606 ± 23 m) [10–2,000 m] (total: 207 studies)	complex habitat with a diverse range of native species (forest edges and patches; floral strips, floral field margins, floral understory cover; grassland, pasture, and shrubland surrounding patches; grassy and woody hedgerows and field margins; woody corridors between fields with floral understory)
Experiences	plants, birds	25% (mean: 25% ± 0.6%) [19%–30%] (total: 26 studies)	<300 m (mean: 311 ± 7 m) [300–500 m] (total: 45 studies)	diverse, rich (semi-)natural green spaces (streets trees canopy cover, public parks, zoos, gardens, woody and grassy parks, meadows)
Soil erosion control	plants	50% (mean: 44% ± 0.6%) [30%–63%] (total: 251 studies)	evenly distributed at the landscape scale	diverse, rich (semi-)natural vegetation cover (zoned grassy and woody buffers; tree canopy cover; ground cover with dense fibrous roots; 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)
Water quality regulation	plants	6% (mean: 6% ± 0.1%) [1.2%–15%] (total: 1,480 studies)	both sides of streams	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	plants	50% (mean: 50.5%) (total: two studies)	landslides: slope base or slope bottom	(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)

Values constraining the provisioning of the NCP for habitat quantity, quality, and spatial configuration are indicated as levels and represent the median. All the values are weighted by the number of studies included in the review studies analyzed. The total number of studies refers to the total number of primary studies considered in articles, reviews, and meta-analyses.

and landscape type. Regulating stream water quality from non-point-source pollutants requires a buffer of approximately 28 m in width on each side of streams. Considering global stream densities, this minimum buffer width, on average, would correspond to approximately 6% habitat per km^2 (Figure 1; Table 1). The total quantity of habitat needed for specific water quality functions ranges between 1.2% and 15% depending on the function in question (nutrient, sediment or pesticide interception and capture), slope angle, and stream density.

Identifying the quantity of habitat for reducing landslide risk (natural hazards mitigation) is more challenging, with environmental variables (geology, slope geometry, soil type, precipitation event frequency, intensity, and duration) often overriding biological ones (vegetation presence) (Figure 1; Table 1). We found two studies proposing a quantitative estimate for regulating landslide risk, advising a minimum of 50% and 60% permanent vegetative cover on steeply sloped lands (>35°), respectively.[29,30]

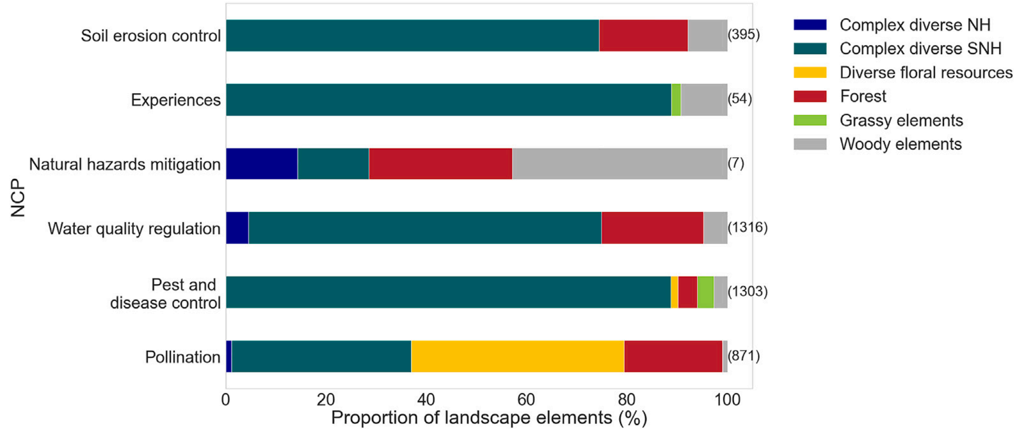

Figure 2. Landscape elements required for provisioning of each NCP

The stacked bar chart showing the proportion of papers recommending specific landscape elements categories that improve habitat quality and support the provisioning of each NCP. Each bar in the chart represents a whole weighted number of papers analyzed for each NCP (in parentheses), and segments in the bar with different colors represent different landscape element categories. Natrual habitat: NH; (semi-)natural habitat: SNH.

Habitat quality

In our survey, we found 136 synthetic and original papers (encompassing 3,755 original studies in total) recommending a measure of habitat quality in their findings, often expressed as the range of landscape elements required to support the underlying ecological function. We identified six categories of landscape elements for enhancing NCP provision: (1) complex diverse (semi)-natural habitat, (2) complex diverse natural habitat, (3) diverse floral resources, (4) forest, (5) grassy elements, and (6) woody elements (Figure 2; Table S1). Natural habitats are areas that have not been significantly modified by human activities and retain a high level of biodiversity and ecological integrity. Semi-natural habitats, on the other hand, are areas that have been modified to some extent by human activities but still have many ecological processes intact.[1] Diverse floral resources encompass habitats rich in flowering plants, while grassy elements are dominated by grasses and herbaceous plants. Forests indicate a minimum land area of 0.05–1.0 ha with tree cover of 10%–30% or more, featuring trees capable of reaching 2–5 m height at maturity, either in closed or open forest formations, whereas woody elements comprise shrubs and trees contributing to landscape diversity and structural complexity (e.g., shelterbelts, hedgerows, and street trees).[31] The range of landscape elements reported in the reviewed literature can take various forms, including strips, patches, hedgerows, field margins, field borders, ground cover, canopy cover, and buffers, and, in urban areas, gardens, zoos, and parks. The quality of habitat required varies depending on the specific NCP (Figure 2). Nevertheless, Figure 2 illustrates that 79% of studies we reviewed indicated heterogeneous landscapes consisting of complex, diverse (semi-)natural habitat as the most suitable for supporting multiple NCP provision. Figure 2 also indicates that pollinators demonstrated a notable inclination toward thriving within rich floristic habitat, particularly those incorporating wild and native species. In contrast, pest and disease control organisms tend to be more abundant in complex, diverse (semi-)natural habitats dominated by diverse woody or grassy elements rather than being determined by floral resource availability (Figure 2). For experiences in urban areas, structurally complex diverse (semi-)natural vegetation including street trees, public parks, and green spaces are most often habitats mentioned in the reviewed studies.

The evidence gathered from our study indicates that, to prevent particle detachment driving soil erosion and to intercept detached soil particles transported by water erosion, a structurally complex, diverse (semi-)natural vegetation cover (encompassing both permanent canopy and ground covers) is required. This encompasses vegetated buffers, woody and grassy hedgerows or agroforests, ground cover or understory vegetation, inter-row vegetated strips, or crop cover with grasses or legumes, with a dominance of forest and woody elements.

Our reviewed papers indicate that structurally complex and highly diverse riparian buffers (e.g., zoned buffers consisting of grassy, shrub, and woody elements), including native species with diverse root structures, especially when combined with high stem density, are an important means of slowing excess water flows and intercepting detached soil particles (sediment), pesticides, and nutrients from adjacent fields (Figure 2). For steep slopes, multiple studies emphasize that deep-rooted perennial cover from diversified fast-growing plantings and understory vegetation are most effective in reducing landslides.[29,32,33]

Spatial configuration

We identified 39 synthetic and original papers (representing 415 studies in total) reporting findings on habitat placement within the landscape and the required maximum linear distance for mobile organisms to access resources from their home habitat. For pollination and pest and disease control, notably by insects, our study indicates for both organisms (based on 288 individual studies for pollination and 207 studies for pest and disease control) a maximum linear foraging distance of 500 m (ranging between <0 and 2,000 m for specific taxa within each NCP, underlying the variations observed in different studies) from their host habitat to the target crop field (Figure 3; Table 1). For experiences obtained in urban ecosystems, most analyzed studies (45 studies in total) indicate 300 m as a maximum reasonable

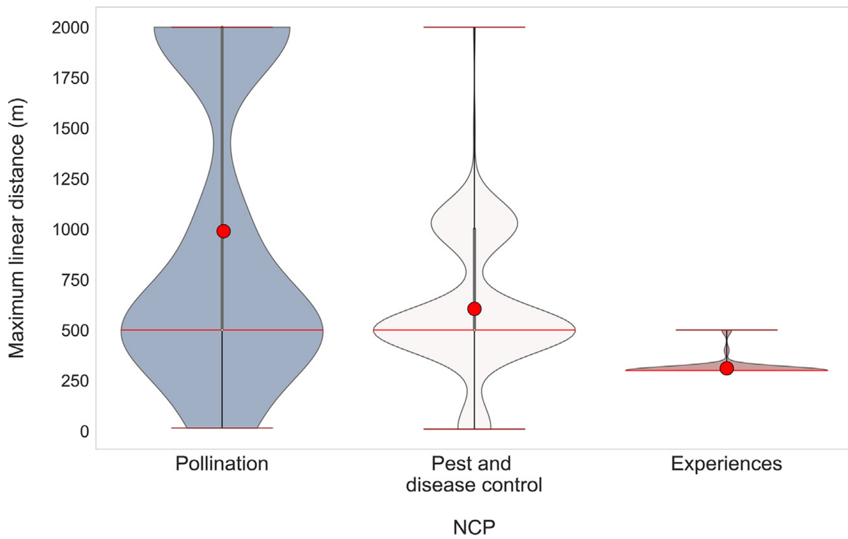

Figure 3. Maximum linear distance values between habitat and beneficiaries (in meters) for each NCP

The lower red line and the top red line correspond to the whiskers (minimum and maximum, respectively), which indicate the range of the data. The middle red line represents the median, while the red dots represent the weighted mean value. The violin shape indicates kernel density estimation based on the number of original papers included in the meta-analyses/reviews reporting the given value. Wider sections of the violin plot represent a larger number of papers underlying the given value; the thinner sections represent a lower body of evidence. All the values are weighted by the number of papers.

distance for people to access green spaces based on the identified positive health impacts of experiencing at least >120 min of nature exposure per week[21,34] (Figure 3). We identified from the collective evidence 300 m (for citizens) to 500 m (for pollination and pest and disease control, representing the most limiting median value among these NCP) as the maximum distance between habitat and target beneficiaries (Figure 3). These distances represent the minimum conditions required in terms of spatial configuration; beyond these levels, the NCP provision declines significantly or becomes almost completely absent.

Our review indicates that a complex and diverse vegetation cover that encompasses at least 50% of the land, with an even distribution across the landscape on and around agricultural fields, results in, on average, more than 71% soil loss reduction (with variations ranging between 50% and 93% in specific contexts) (Table 1; Figure S1). The exact value for this contribution is driven by the mechanics of soil particle detachment, soil covering vegetation, or litter, which, in theory, should include coverage across all surfaces.

For particle or nutrient interception by riparian buffers, the spatial configuration requirements we synthesized are quite specific, concentrating on the margins of rivers and streams. Despite variations depending on the levels of pollutants and sediment, our review indicates that vegetative buffers of at least 28 m, located on both sides of a stream headwater and close to the water body, notably on slopes <23°, on average, are generally able to capture more than 73% of non-point-source pollutants (with variations ranging between 50% and 90% depending on the context) (Table 1; Figure S1). These pollutants include sediment, nutrients, pesticides, and salts from upstream agricultural lands.

We did not identify and review a specific maximum distance from habitat for enhancing slope stability and reducing landslide occurrence on steep terrains (slopes > 35°) due to the lack of a straightforward relationship between slope stability and the distance between habitat and the locations of potential erosion. Nevertheless, the position and distribution of habitat are more crucial factors in these landscapes than merely the distance between the benefiting area and the habitat. Some studies indicate that, on these slopes, retaining at least 50% complex, diverse (semi-)natural vegetation cover, distributed evenly with trees (the heaviest elements) placed mainly on the base or the bottom of the slope, is most effective.[29,30,35]

Functional integrity levels

Based on our review of minimum levels for habitat quantity, quality, and spatial configuration across the six NCP assessed, we propose a general integrative measure of functional integrity that underpins the provisioning of multiple NCP in human-modified landscapes. We emphasize that our methodology focuses on the minimum levels of habitat quantity, quality, and spatial configuration necessary for securing NCP provision across diverse landscapes. This is distinct from attempting to quantify the optimal levels needed to meet demand. When habitat quantity, quality, and spatial configuration are combined, we estimate that at least 20%–25% complex, diverse (semi-)natural habitat is required for each km^2 in human-modified landscapes to secure ecological functions underlying multiple NCP provision (Table 1). This estimate is based on the minimum needs across the six NCP, below which NCP provision experiences a strong decline (Table 1). Requirements for individual NCP were determined by the median of the values reported in individual studies. Using the median implies that, in certain contexts, a higher quantity of (semi-)natural vegetation is needed, while in others a smaller area might be sufficient (see Note S1 for more details). The results further indicate that, for areas with high erosion or landslide risk, a greater habitat fraction is necessary (50% habitat per km^2). Conversely, in specific contexts such as doubling crop diversity, or for some specific NCP such as water quality regulation, NCP provision may still be achieved with habitat areas as low as 10%–20%. This variation in the exact quantity required underlines the critical need to adapt these estimates to align with the specific conditions of each location, accounting for both the local context and the demand for NCP. However, our analysis indicates that, below 10% habitat level, NCP provision becomes practically absent across five NCP, as shown in Figure 1, indicating that ecosystem functions supporting NCP provision become unviable below this level. This finding is revealed in 95% of the studies that we reviewed based on habitat quantity.

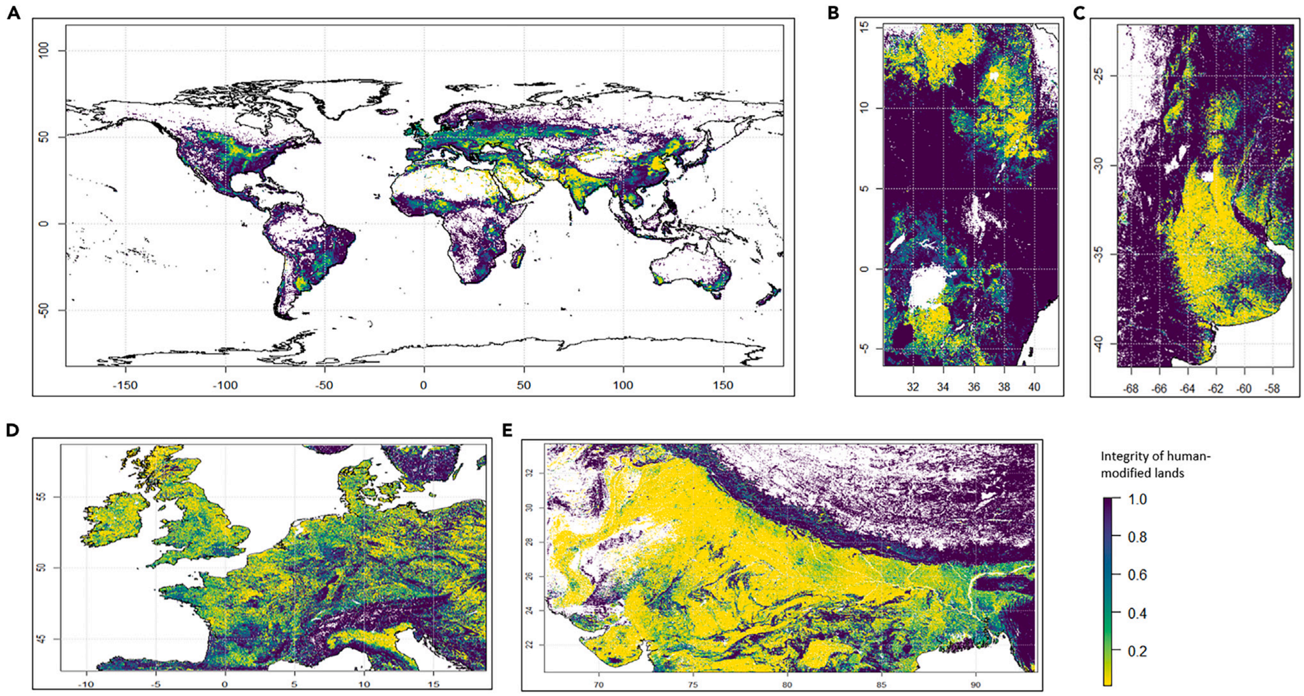

Figure 4. Current state of functional integrity in human-modified lands

Habitat functional integrity in human-modified lands (agricultural and urban landscapes) calculated as the percentage (%) of (semi-)natural habitat within 1 km^2. Functional integrity is calculated at a 10-m resolution and then aggregated for display purposes. (A) The global spatial distribution of biosphere functional integrity at a 500-m scale. More detailed views are shown in the zoom-in panels at a 100-m resolution for (B) East-African highlands and savannah, (C) Argentinian soybean region, (D) west-central Europe, and (E) Indian Gangetic plain. Areas colored white indicate regions where there are no human-modified lands in our analysis.

Current state and spatial distribution

Using the European Space Agency (ESA) 10-m resolution land-cover map of openly available satellite-based land-cover data, we estimated the current state and spatial distribution of functional integrity by calculating the percentage of habitat per 1-km^2 neighborhoods after distinguishing pastureland from (semi-)natural grasslands and testing for distinguishing forest plantations from (semi-)natural forests.[36] Our results indicate that about 50% of human-modified lands are below the level of 10% habitat per km^2, and 64% and 70% of human-modified lands are below 20% and 25% habitat per km^2, respectively (Figure 4; Table S2). This implies that 20% of human-modified lands have a habitat area between 10% and 25% per km^2.These areas are likely to have only a limited provision of NCP, depending on their dependence on external inputs (e.g., pesticides) and their vulnerability to climate change. Hence, only 30% of human-modified lands meet the minimum level for NCP provision with embedded habitat exceeding 25% habitat per km^2. A significantly higher area than previously estimated, using lower-resolution imagery, has insufficient functional integrity.[12] While the limited thematic resolution of the land-cover data and assumptions made in the analysis may lead to an underestimation of habitat in the landscape, particularly in terms of small-scale elements (i.e., floral resources, grassy patches, and hedgerows), it is likely that approximately two-thirds of all global human-modified landscapes fall below the 20% per km^2 minimum required to provide essential NCP and are thus heavily reliant on substitutes for those NCP (domesticated honeybees, pesticides, technical means of water regulation and purification) or face absolute shortages in NCP. This shortage is especially found in the intensively farmed regions important to global food systems, threatening the long-term resilience and adaptive capacity of food production systems.

DISCUSSION

Conservation initiatives have often overlooked the crucial role of biodiversity in delivering and supporting key NCP that underpin human well-being, specifically in human-modified lands. Our study synthesized existing literature to determine the minimum quantity, quality, and spatial configuration of (semi-)natural habitat needed in human-modified landscapes for securing the ecological functions that underlie NCP provision, referred to as functional integrity. Below these minimum levels, there is a high risk that human-modified landscapes experience a severe decline in their capacity to support NCP provision, jeopardizing the well-being of those dependent on these NCP.

Implications of results

Our findings add to a growing body of evidence, suggesting that the decline of biodiversity under certain levels is contributing to a significant decline in NCP provision for the people who rely on them.[15,37] We find that a median of at least 20%–25% (semi-)natural habitat per km^2 (ranging from 6% to 50% for individual NCP depending on the context) is needed in human-modified landscapes to support multiple NCP provision. Below a 10% habitat per km^2 level, almost all studies indicated that five of the studied NCP provisions sharply declined to a very low level or were almost completely absent. For individual NCP, a lower level sometimes is possible. For example, for water quality, 6% might be sufficient, based on the minimum buffer width required for riparian strips, depending on the drainage density of the area and steepness.

NCP are delivered by communities of species across taxa and their traits. Vegetation characteristics define habitat quality and provide biophysical contributions such as sediment interception while providing resources for mobile species that contribute to pollination and pest control. Our analysis aligns and extends the existing knowledge by focusing on the incorporation of complex diverse (semi-)natural elements (Table 1; Table S1). Although many NCP can be procured with non-native species,[38,39] incorporating embedded habitats that promote native species, and improving connectivity within fragmented landscapes can provide additional biodiversity conservation benefits.[40] This also supports the protection of cultural heritage and local knowledge.[41] Complementary to this, increasing intra-field diversity of the agricultural/modified elements[26,42] and field edge density[22] and decreasing field sizes[26] may also increase landscape heterogeneity but does not replace the positive effect of the area of (semi-)natural elements on functional integrity. Which practices, types of habitats, or landscape elements are most appropriate to ensure functional integrity remains a highly local issue and requires input from local knowledge.[43]

Ensuring access to appropriate habitat (or landscape elements) at a sub-kilometer scale is important across all human-modified landscapes. Larger areas in one place cannot substitute for smaller areas in another. This is driven by the fact that the majority of species providing NCP have small home ranges or are non-mobile. Numerous ecological studies also show non-linear decreases in species diversity and abundance with increasing distance from habitat edges.[44,45] An additional benefit of embedding habitats within human-modified landscapes is the fragmentation of large areas of agricultural lands. This strategy reduces the dispersal of agricultural pests between fields[46] while connecting habitat of species that can reduce pest pressure.[47] It also contributes to reducing soil erosion and improving soil biological activity and fertility. Securing riparian buffers is a good first step and would, for example, secure about 6% of habitat per km^2 on average globally, while contributing to connectivity.[48]

The minimum functional integrity level identified here is applicable to most human-modified landscapes that have demand for one or more of the considered NCP.[15,28,37,49] Local demand for specific NCP can vary strongly, depending on factors such as cropping systems' dependence on pollination, topography, population density, and societal needs.[50–52] Rather than identifying the required supply to meet this demand, our study identifies the minimum level of functional integrity necessary to secure ecological functions in human-modified lands, emphasizing biodiversity's functional contributions in supporting both regulating and non-material NCP at local scales. This includes contributions that either improve food production or reduce its negative environmental impacts, as well as those that promote people's mental and physical well-being. Meeting NCP demand, in many conditions and contexts, will require habitat quantity, quality, and spatial distribution levels that are greater than the minimum values identified here. Therefore, local implementation needs to go beyond this analysis and adjust the requirements for diverse socioecological contexts and specific NCP demands and relations between NCP supply and ecological functions. Engaging with local communities and implementing locally adapted practices are fundamental steps in identifying which NCP to prioritize and the critical habitats that provide them to ensure effective conservation strategies and foster equitable and sustainable ecological practices.[43]

Methodological considerations

Although our review approach may have overlooked some important primary research articles, this is unlikely to have influenced our results, as the results indicate a high level of agreement among the current, large, body of evidence. The analyzed studies cover a diverse range of locations across the globe. Nevertheless, these types of studies often reveal strong biases due to the locations where primary research is conducted as is common in ecological research, suggesting that some biomes might be underrepresented.[53] While we did not fully capture all facets of biodiversity and NCP that are essential for supporting human needs, the majority of the NCP we selected represent a core set of regulating ecosystem functions that are important at local scales and essential for human well-being. However, functional integrity as operationalized in this study is unable to capture finer-scale NCP provision, notably those related to soil biodiversity and ecosystems. These include soil quality, belowground carbon sequestration, nutrient cycling, and increased water-holding capacity in fields. This is evident in the higher minimum level identified for soil and canopy cover to prevent soil particle detachment (>50% vegetation cover). Our measure of functional integrity does not also capture complementary practices that can either improve NCP production or reduce pressures on habitat to provide NCP. For example, no-till or reduced-tillage practices, improved nutrient-use efficiency, cover crops, or leguminous rotations reduce erosion and nutrient loss but are not captured by the metric we proposed. Complementary metrics and practices incorporating soil biodiversity and soil-based NCP are equally important and call for greater integration of ecological principles across all land surfaces.[54–56] While field-scale practices that reduce excess nutrient run-off directly from human-modified lands (e.g., field tillage practices) are important, they complement but do not replace the role of habitat in buffering soil, nutrient, and pollutants' loss to aquatic ecosystems.[57] It is also important to note that excessive nutrient application can rapidly exceed the absorption capacity of riparian and other vegetated buffers; therefore, reducing such pressures can increase the capacity of habitat to maintain functional integrity.

Historically, global monitoring of functional integrity of human-modified landscapes has been challenging, as habitat mostly comes in small patches, often of linear format, that are not easily detectable in most coarse-resolution global (and regional) land-cover maps. The recent high-resolution Sentinel images (10-m resolution) used here can capture relatively small patches. However, even these data might still underestimate habitat as they do not capture linear elements such as hedgerows, field margins, floral strips, and grass strips that are managed as (semi-)natural habitat. This is partially due to the limited spatial resolution but also a result of the limited thematic resolution of this data product and the absence of information on vertical or 3D structures (e.g., vegetation height). For example, unmanaged patches of grassland are not sufficiently distinguished from pasture and (semi-)natural grasslands, and low-intensity pastureland may have good ecological condition. Similar concerns hold for forest land cover through remaining challenges of distinguishing between different types of forests. For example, we could not distinguish natural forests from monocultures of short-rotation species in our analysis. We tested the sensitivity of the results to distinguishing forest plantations from other forests. While the impact on the global results was small, it did show clear regional deviations (Table S2). Finally, the results of our analysis are sensitive to the classification of bare lands as either being a natural habitat or a human-modified land cover, which is not distinguished in the data used. Given these limitations, our assessment of the current state of functional integrity should be interpreted with caution. We anticipate that, with continued rapid evolution of remote-sensing products and artificial intelligence, these detection challenges will be reduced in the near future. Early analysis of satellite imagery using deep learning to monitor highly heterogeneous areas have been published[58] but are not yet openly available for inclusion in our assessment.

Current state and habitat restoration pros and cons

Despite the challenges of detecting small-scale landscape elements in highly heterogeneous areas, as highlighted by the aforementioned issues, we estimate that at least two-thirds of the global human-modified lands fall below critical levels for functional integrity, severely compromising the capacity of human-modified lands to contribute to NCP provision. In agricultural and urban landscapes, the natural vegetation has frequently been removed to accommodate the growing demands for housing and agricultural production. Competition for land may limit space for restoring natural elements. Therefore, restoring habitats in these places is often interpreted as conflicting with the provision of material NCP and might compete with ambitions of increasing food production as well as with the needs and priorities of local communities (e.g., housing). In reality, this perceived conflict does not always preclude mutually beneficial outcomes, and the magnitude and direction of the effect can vary largely depending on local context. The literature shows evidence that, in many places, a diversity of practices improve both yields and environmental outcomes and that embedded biodiversity on field perimeters and riparian buffers leaves scope for sustainable intensification within fields.[59–61] Well-functioning ecosystems can support the provisioning of material NCP through contributions such as climate regulation, nutrient cycling, and pest control. These contributions are particularly useful when reducing the environmental impact of pesticides and fertilizers is necessary. Therefore, the generalized trade-off between the area of natural habitat and food production is, in some cases, a misconception. Locally appropriate conservation options can be effective in managing and mitigating potential conflicts between material and non-material NCP. Implementing notably modern agroecological practices and nature-based solutions can help to better integrate new habitats in these landscapes and minimize trade-offs. Adopting diverse crop rotations and mixed cropping systems maintains habitat heterogeneity, supports various species, and promotes ecosystem resilience.[62,63] Other benefits of habitat in human-modified landscapes include the significant contributions of an increase in tree cover in agricultural landscapes (e.g., agroforestry systems) to soil health, water retention, and global carbon sequestration.[64] Strategically placing small patches of habitat in human-modified landscapes, combined with innovative techniques such as precision agriculture practices, may also have disproportionate value in preserving species diversity[65] while also optimizing agricultural productivity.[66]

Conclusions and future directions

Restoring habitats and their ecosystem functions in human-modified landscapes can help strengthen the resilience of these areas toward climate change.[67] Therefore, the benefits of at least meeting the minimum habitat level identified in our study offer broader benefits that extend beyond the analyzed NCP. Notably, our critical finding (supported by 95% of the studies we reviewed) that NCP provision is likely to be largely absent for five NCP when habitat level drops below 10% of the landscape emphasizes the urgent need for policy intervention in areas with habitat below that level. We stress that the minimum level identified here is a minimal requirement to secure ecosystem functions underlying multiple NCP provision, rather than an optimal level required to meet demands for NCP. Contextualized strategies, responding to local demands for NCP, can further optimize the benefits of such habitat within the landscape and contribute to safeguarding biodiversity, promoting ecosystem stability, and contributing to overall human well-being. The shortcomings of (semi-)natural habitat in many landscapes across the globe reconfirm the high importance of not only focusing conservation and restoration efforts on intact natural or wilderness areas. Conservation and restoration efforts, especially in the UN decade of restoration, also have prime importance in strongly modified landscapes.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Awaz Mohamed (awaz.mohamed2@gmail.com)

Materials availability

This study did not generate new unique materials.

Data and code availability

All datasets and codes generated in this study to estimate the current state and to produce the maps, as well as the full list of studies used in NCP analysis, have been deposited at DataversNL under https://doi.org/10.34894/V6WWTS, and are publicly available as of the date of publication. The dataset generated to estimate functional integrity level and to produce the figures will be shared openly by the lead contact upon request after publication.

Methods

NCP selection

We selected NCP for human-modified lands that are underpinned by various specific ecological processes. Notably, we focused on five regulating and one non-material NCP that are related to biodiversity and ecosystem function and directly affect the well-being of local people and their quality of life in different manners, from regulating the quality of water, to pollinating many crops, to underpinning multiple dimensions of human health. These include (1) pollination; (2) pest and disease control; (3) physical and psychological experiences in nature, termed "experiences [2]; (4) soil erosion control; (5) water quality regulation; and (6) natural hazards mitigation. We define human-modified lands as the inhabited, used, and working lands of the world (e.g., heavily modified anthromes) where the ecosystem is dominated by human activities that have largely changed the natural ecosystem functions and composition. In our study, we considered a wide range of human-modified lands, including urban areas, forest plantations, and agricultural lands.

Literature search strategy

We conducted a literature search of peer-reviewed reviews and meta-analyses following the Preferred Reporting Items for Systematic Review and Meta-Analyses guidelines (PRISMA).[68] We employed two to three keywords and terms standardized, combining specific NCP, habitat or vegetation, and landscape scale. We analyzed (1) pollination ("pollinat*" AND "habitat" AND "landscape), (2) pest and disease control ("Biological control*" AND "habitat" AND "landscape"), (3) physical and psychological experiences ("physical AND psychological*" AND "well-being*" AND "nature*"), (4) water quality regulation ("riparian buffer*" AND "width*"), (5) soil erosion control ("soil erosion*" AND "vegetation*" AND "landscape*"), and (6) natural hazards ("landslide*" AND "vegetation cover*"). All searches were conducted on Web of Science (Clarivate Analytics, Philadelphia, PA, USA). Additional reviews and primary papers were identified from other sources, whether suggested by experts (regardless the year of publication) or similar searches on Google Scholar engine using an additional search string for each NCP (e.g., "pollination OR pollinators*"; habitat*; landscape configuration*; landscape complexity*; landscape heterogeneity*). We screened the first two pages of Google search results, selecting relevant articles based on the titles and abstracts (Figure S2). The output of these queries was saved to the Zotero open-source software (Zotero site: www.zotero.org), where all papers and citations were managed.

Eligibility criteria

Before proceeding with the evaluation process, we established predetermined criteria for inclusion. We adhered to the following guidelines to select potentially relevant references for subsequent stages of evaluation: Reviews and meta-analyses needed to be published in peer-reviewed journals between January 2010 and December 2021 and be in English. Each source should focus on which taxonomic groups provide that NCP, the area and the quality of (semi-)natural habitat including relevant landscape elements, the distance, location, or placement of landscape elements, and a description of the spatial relationship between biodiversity and the specific NCP. We assumed that the majority of review papers published between 2010 and 2021 were built on primary research articles, some of these originating from before 2010. There were no restrictions imposed concerning methods used, landscape type, or study location. Any references not fulfilling any of the above criteria or clearly being out of scope (i.e., did not report outcomes on habitat quantity, quality, or spatial configuration) were excluded from the analysis. However, for some NCP where only a limited number of review papers was available ($\leq$5 reviews, covering <50 original papers in total), such as experiences or landslide mitigation, we randomly incorporated a selected number of primary research articles from experts and other sources to ensure a better balance in the number of papers included across different NCP. Our preliminary search yielded 411 papers in total after duplicates were removed.

Study selection

We initially screened all papers (n = 411) based on titles and abstracts to identify potentially eligible and relevant reviews. Abstracts that did not fulfill at least one of our aforementioned inclusion criteria or were deemed irrelevant to the topic upon closer inspection were excluded. We then skimmed through the full-text articles to further assess the quality and relevance. We included papers addressing at least one of three key variables for each NCP to delineate the minimum level of functional integrity that secures the ecosystem functions underlying the NCP. These encompass (1) a quantitative measure of the minimum habitat required for supporting NCP provision, (2) a qualitative evaluation of landscape elements' type and quality required, and (3) the maximum distance between providers and beneficiaries (in meters) or the spatial configuration of landscape elements required for supporting NCP provision. Papers that did not meet the inclusion criteria were excluded (Figure S2). Our search yielded a total of 154 articles (the full list of publications is available in the repository, under the "data and code availability" section), comprising 74 meta-analyses and reviews and 80 primary research articles conducted in different locations around the world (Figure S2). While acknowledging that some primary articles may have been included in multiple reviews and meta-analyses, we could not verify this across all reviews. To further reduce biases due to unequal levels of evidence in review papers, we weighted the calculations by the number of papers included in each review and meta-analysis used.

Data extraction and management

We extracted data from all eligible reviews and original articles and tabulated them using a set of data extraction forms developed for this study. We gathered the following information: name of the first author, publication year, journal name, study's location, nature of the paper, number of papers included, estimated minimum habitat quantity, description of habitat elements, landscape elements recommended, estimated maximum linear distance from source habitat or the location and emplacement of habitat, functional group providing the NCP, slope, buffer or vegetation cover efficiency in reducing soil loss or non-point pollutants, and estimated minimum buffer width.

Minimum level estimation

In the reviewed studies, we determined the minimum habitat value in the landscape below which the function underlying each NCP shows a strong decline or is almost completely absent. This determination was based on the information reported in the text, tables, figures, and supplemental information provided in the individual papers. Below this minimum habitat level, certain ecological functions may lack resilience, with the habitat possibly being insufficient to maintain ecological functions due to the loss of critical species or viable population levels to overcome shocks. For pollination and pest and disease control NCP, when a figure displayed the relationship between the abundance or diversity of NCP-providing organisms and habitat area, we determined the minimum area of habitat quantity by identifying the point where their abundance or diversity strongly declined to zero or a minimal value slightly above zero (Figure S3). This decline in the abundance and diversity of NCP-providing organisms indicates a strong decline to very low level or the complete loss of the ecological functions or associated NCP. For benefits from experiences, we assessed the minimum amount of green spaces of various forms and qualities required in urban ecosystems, considering their spatial configuration or linear distance (see Table 1) from each neighborhood. These values were derived from studies examining the link between the amount of green space in each neighborhood in cities and people's mental and physical well-being. These studies measured variables 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[69–71] as indicators of mental and physical well-being. We determined the minimum area of habitat quantity by pinpointing the point where these aforementioned variables sharply dropped to zero or nearly zero. In general, habitat quantity estimation was made irrespective of variations in contexts, methods, relationship types, or locations between studies.

For soil erosion control and water quality regulation, we examined studies exploring the efficiency (measured as percentage) of vegetation cover and vegetated buffers in reducing soil loss and pollutants. However, efficiency varies highly between studies and depends on the specific NCP and landscape type. Hence, there is no universally agreed-upon minimum efficiency level proposed across these studies. In 90% of the reviewed studies, different amounts of vegetated buffers exhibited efficiency exceeding 50%. Therefore, we adopted >50% efficiency as a baseline in our analysis to determine the minimum required vegetation value. The buffer width was represented in meters. To transform this buffer width into an approximate amount of (semi-)natural vegetation per km^2, comparable with other NCP, we used the global average density of streams.[72]

For natural hazard mitigation, particularly landslide mitigation, the minimum value level of habitat quantity required has been derived from experimental and modeling studies assessing the factor of safety (FoS) in relationship to the presence and absence of plant roots in the soil.[33,73–75] 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.[75] Maintaining a slope stability often requires a FoS value of 1.3 for temporary or low-risk slopes and 1.5 for high-risk slopes.[76] Therefore, we use the 1.3 FoS as a baseline in our analysis to determine the minimum vegetation cover required for maintaining slope stability.

To assess habitat quality, we analyzed the literature collected that recommended various landscape elements essential for the survival of individuals and the persistence of populations that contribute to these NCP. Based on our analysis, we identified common landscape elements across the reviewed studies and classified them into six categories, guided by each paper's recommendation and different contexts. These are complex diverse (semi-)natural habitat, complex diverse natural habitat, diverse floral resources, forest, grassy elements, and woody elements (Table S1 for more details). Some studies broadly described these categories without mentioning any specific landscape elements, while others provided more specific descriptions, mentioning particular landscape elements.

To assess spatial configuration needs for three of the six NCP provided by mobile organisms (pollination, pest and disease control, and experiences), we estimated the maximum linear distance these mobile organisms forage or travel from their home habitat to access resources. For the remaining three NCP provided by non-mobile organisms (water quality regulation, soil erosion control, and natural hazard regulation), we extracted recommended habitat placement and location descriptions that support NCP.

Once minimum habitat quantity, quality, and spatial configuration values were established for each NCP at the landscape scale, we performed exploratory analyses to identify general patterns in the literature regarding the three key variables for each specific NCP. All analyses were conducted using the Python language (Python 3.6) within the Anaconda platform (Seaborn and matplotlib libraries). We then assessed which characteristics of functional integrity (habitat quantity, habitat quality, and spatial configuration essential for functioning) are important for decision makers and management.

Functional integrity: Current state and spatial distribution

We assessed the current state of the functional integrity level using the ESA WorldCover 10-m resolution land-cover map (https://esa-worldcover.org/en). First, we created a binary map of what entails habitat within human-modified landscapes. We refined the grassland category to distinguish pasturelands from (semi-)natural grasslands by overlaying the habitat map from Jung et al.[36] Specifically, areas classified as grassland in the ESA WorldCover 10-m resolution land-cover map, which overlapped with the area classified as "artificial – terrestrial" by Jung et al.,[36] were reclassified as pastureland. All remaining grassland areas were reclassified as "natural grassland." We then reclassified the refined map to create a binary classification of "natural lands" and "human-modified lands" (Table S3). As this is based on land-cover data only, we acknowledge the likely underestimation of human modification of nature in this map. We calculated a functional integrity value for each pixel using a focal function where we calculated the percentage of habitat cover in a 500-m radius around each pixel. We calculated the percentage of pixels that met or exceeded different critical levels of functional integrity (10%, 20%, 25%) on a global scale and on an ecoregion scale. Furthermore, we performed an additional sensitivity analysis using the Jung et al.[36] classification to refine the ESA WorldCover 10-m resolution land-cover map "tree cover" category. We reclassified pixels where the ESA WorldCover 10-m resolution land-cover area classified as tree cover overlapped with areas classified as plantations by Jung et al.[36] All other ESA WorldCover 10-m resolution land-cover tree-cover pixels were reclassified as natural tree cover. Natural tree cover was assigned a 1 and "plantations" was assigned a 0 in the binary classification. We then followed the same procedure as above to calculate functional integrity value (Table S2). All analyses were done using the native Google Earth Engine interface.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2023.12.008.

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AUTHOR CONTRIBUTIONS

A.M. developed the methodology for assessing and analyzing functional integrity, participated in the conceptual design, conducted the systematic review, gathered and analyzed data, led the write-up of the paper, and served as a research scientist on the Earth Commission's Biosphere interactions working group. F.D.C., P.H.V., and D.O. 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. J.F.A. 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. N.Z.C. contributed to the analysis and the writing of physically and psychologically beneficial experiences in nature. N.E.-C., A.F., and S.J. contributed to the conceptualization and methodology for assessing functional integrity and to reviewing of the final manuscript. J.R. participated in the conceptual design and writing of the paper and served on the Earth Commissions Biosphere Working Group. I.C.M. contributed to the analysis of the soil erosion control NCP and to reviewing the final manuscript. B.S.K. contributed to the riparian analysis and reviewing the final manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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REFERENCES

1. Brondizio, E.S., Settele, J., Díaz, S., and Ngo, H.T. (2019). Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.
2. Díaz, S., Pascual, U., Stenseke, M., Martín-López, B., Watson, R.T., Molnár, Z., Hill, R., Chan, K.M.A., Baste, I.A., Brauman, K.A., et al. (2018). Assessing nature's contributions to people. Science *359*, 270–272.
3. Pollock, L.J., O'Connor, L.M.J., Mokany, K., Rosauer, D.F., Talluto, M.V., and Thuiller, W. (2020). Protecting Biodiversity (in All Its Complexity): New Models and Methods. Trends Ecol. Evol. *35*, 1119–1128.
4. Allan, J.R., Possingham, H.P., Atkinson, S.C., Waldron, A., Di Marco, M., Butchart, S.H.M., Adams, V.M., Kissling, W.D., Worsdell, T., Sandbrook, C., et al. (2022). The minimum land area requiring conservation attention to safeguard biodiversity. Science *376*, 1094–1101.
5. Watson, J.E., Venter, O., Lee, J., Jones, K.R., Robinson, J.G., Possingham, H.P., and Allan, J.R. (2018). Protect the Last of the Wild (Nature Publishing Group).
6. Carmenta, R., Steward, A., Albuquerque, A., Carneiro, R., Vira, B., and Estrada Carmona, N. (2022). The comparative performance of land

sharing, land sparing type interventions on place-based human well-being. People Nat. *5*, 1804–1821.

7. Estrada-Carmona, N., Sánchez, A.C., Remans, R., and Jones, S.K. (2022). Complex agricultural landscapes host more biodiversity than simple ones: A global meta-analysis. Proc. Natl. Acad. Sci. USA *119*, e2203385119.
8. Brondízio, E., Settele, J., Diaz, S., Ngo, H.T., Experts, G., and Mohamed, A. (2021). Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (zenodo).
9. Wood, S.L., Jones, S.K., Johnson, J.A., Brauman, K.A., Chaplin-Kramer, R., Fremier, A., Girvetz, E., Gordon, L.J., Kappel, C.V., Mandle, L., et al. (2018). Distilling the role of ecosystem services in the Sustainable Development. Ecosyst. Serv. *29*, 70–82.
10. Díaz, S., Zafra-Calvo, N., Purvis, A., Verburg, P.H., Obura, D., Leadley, P., Chaplin-Kramer, R., De Meester, L., Dulloo, E., Martín-López, B., et al. (2020). Set ambitious goals for biodiversity and sustainability. Science *370*, 411–413.
11. Leadley, P., Gonzalez, A., Obura, D., Krug, C.B., Londoño-Murcia, M.C., Millette, K.L., Radulovici, A., Rankovic, A., Shannon, L.J., Archer, E., et al. (2022). Achieving global biodiversity goals by 2050 requires urgent and integrated actions. One Earth *5*, 597–603.
12. Declerck, F., Jones, S., Estrada-Carmona, N., and Fremier, A. (2021). Spare Half, Share the Rest: A Revised Planetary Boundary for Biodiversity Intactness and Integrity.
13. Rockström, J., Gupta, J., Qin, D., Lade, S., Abrams, J.F., Andersen, L., Armstrong McKay, D.I., Bai, X., Bala, G., Bunn, S., et al. (2023). Safe and just Earth system boundaries. Nature *619*, 102–111.
14. Gupta, J., Liverman, D., Prodani, K., Aldunce, P., Bai, X., Broadgate, W., Ciobanu, D., Gifford, L., Gordon, C., Hurlbert, M., et al. (2023). Earth system justice needed to identify and live within Earth system boundaries. Nat. Sustain. *6*, 630–638.
15. Garibaldi, L.A., Oddi, F.J., Miguez, F.E., Bartomeus, I., Orr, M.C., Jobbágy, E.G., Kremen, C., Schulte, L.A., Hughes, A.C., Bagnato, C., et al. (2021). Working landscapes need at least 20% native habitat. Conserv. Lett. *14*, e12773.
16. Hall, L.S., Krausman, P.R., and Morrison, M.L. (1997). The Habitat Concept and a Plea for Standard Terminology. Wildl. Soc. Bull. *25*, 173–182.
17. Cariveau, D.P., Bruninga-Socolar, B., and Pardee, G.L. (2020). A review of the challenges and opportunities for restoring animal-mediated pollination of native plants. Emerg. Top. LIFE Sci. *4*, 99–109.
18. Garibaldi, L.A., Steffan-Dewenter, I., Kremen, C., Morales, J.M., Bommarco, R., Cunningham, S.A., Carvalheiro, L.G., Chacoff, N.P., Dudenhöffer, J.H., Greenleaf, S.S., et al. (2011). Stability of pollination services decreases with isolation from natural areas despite honey bee visits. Ecol. Lett. *14*, 1062–1072.
19. Albrecht, M., Knecht, A., Riesen, M., Rutz, T., and Ganser, D. (2021). Time since establishment drives bee and hoverfly diversity, abundance of crop-pollinating bees and aphidophagous hoverflies in perennial wildflower strips. Basic Appl. Ecol. *57*, 102–114.
20. Luke, S.H., Slade, E.M., Gray, C.L., Annammala, K.V., Drewer, J., Williamson, J., Agama, A.L., Ationg, M., Mitchell, S.L., Vairappan, C.S., et al. (2019). Riparian buffers in tropical agriculture: Scientific support, effectiveness and directions for policy. J. Appl. Ecol. *56*, 85–92.
21. Olafsdottir, G., Cloke, P., Schulz, A., van Dyck, Z., Eysteinsson, T., Thorleifsdottir, B., and Vögele, C. (2020). Health Benefits of Walking in Nature: A Randomized Controlled Study Under Conditions of Real-Life Stress. Environ. Behav. *52*, 248–274.
22. Martin, E.A., Dainese, M., Clough, Y., Báldi, A., Bommarco, R., Gagic, V., Garratt, M.P.D., Holzschuh, A., Kleijn, D., Kovács-Hostyánszki, A., et al. (2019). The interplay of landscape composition and configuration: new pathways to manage functional biodiversity and agroecosystem services across Europe. Ecol. Lett. *22*, 1083–1094.
23. Staton, T., Walters, R.J., Smith, J., and Girling, R.D. (2019). Evaluating the effects of integrating trees into temperate arable systems on pest control and pollination. Agric. Syst. *176*, 102676.
24. Zamorano, J., Bartomeus, I., Grez, A.A., and Garibaldi, L.A. (2020). Field margin floral enhancements increase pollinator diversity at the field edge but show no consistent spillover into the crop field: a meta-analysis. INSECT Conserv. Divers. *13*, 519–531.
25. Kennedy, C.M., Lonsdorf, E., Neel, M.C., Williams, N.M., Ricketts, T.H., Winfree, R., Bommarco, R., Brittain, C., Burley, A.L., Cariveau, D., et al. (2013). A global quantitative synthesis of local and landscape effects on wild bee pollinators in agroecosystems. Ecol. Lett. *16*, 584–599.
26. Clélia, S., Gross, N., Baillod, A.B., Bertrand, C., Carrié, R., Hass, A., Henckel, L., Miguet, P., Vuillot, C., Alignier, A., et al. (2019). Increasing crop heterogeneity enhances multitrophic diversity across agricultural regions. Proc. Natl. Acad. Sci. USA *116*, 16442–16447.
27. Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., et al. (2019). Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet *393*, 447–492.
28. Eeraerts, M. (2023). A minimum of 15% semi-natural habitat facilitates adequate wild pollinator visitation to a pollinator-dependent crop. Biol. Conserv. *278*, 109887.
29. Tang, Y., Bossard, C., and Reidhead, J. (2015). Effects of percent cover of Japanese cedar in forests on slope slides in Sichuan, China. Ecol. Eng. *74*, 42–47.
30. Spiekermann, R.I., McColl, S., Fuller, I., Dymond, J., Burkitt, L., and Smith, H.G. (2021). Quantifying the influence of individual trees on slope stability at landscape scale. J. Environ. Manag. *286*, 112194.
31. Assessment, F.F.R. (2015). Terms and Definitions (FRA)(2012) Forest Resources Assessment Working Paper 180 (Rome Food Agric. Organ. U. N).
32. Rossi, L.M.W., Rapidel, B., Roupsard, O., Villatoro-sánchez, M., Mao, Z., Nespoulous, J., Perez, J., Prieto, I., Roumet, C., Metselaar, K., et al. (2017). Sensitivity of the landslide model LAPSUS_LS to vegetation and soil parameters. Ecol. Eng. *109*, 249–255.
33. Emadi-Tafti, M., Ataie-Ashtiani, B., and Hosseini, S.M. (2021). Integrated impacts of vegetation and soil type on slope stability: A case study of Kheyrud Forest, Iran. Ecol. Model. *446*, 109498.
34. White, M.P., Alcock, I., Grellier, J., Wheeler, B.W., Hartig, T., Warber, S.L., Bone, A., Depledge, M.H., and Fleming, L.E. (2019). Spending at least 120 minutes a week in nature is associated with good health and well-being. Sci. Rep. *9*, 7730.
35. Spiekermann, R.,I., Smith, H.G., McColl, S., Burkitt, L., and Fuller, I.C. (2022). Quantifying effectiveness of trees for landslide erosion control. Geomorphology *396*, 107993.
36. Jung, M., Dahal, P.R., Butchart, S.H.M., Donald, P.F., De Lamo, X., Lesiv, M., Kapos, V., Rondinini, C., and Visconti, P. (2020). A global map of terrestrial habitat types. Sci. Data *7*, 256.
37. Tscharntke, T., Grass, I., Wanger, T.C., Westphal, C., and Batáry, P. (2021). Beyond organic farming - harnessing biodiversity-friendly landscapes. Trends Ecol. Evol. *36*, 919–930.
38. Dickie, I.A., Bennett, B.M., Burrows, L.E., Nuñez, M.A., Peltzer, D.A., Porté, A., Richardson, D.M., Rejmánek, M., Rundel, P.W., and van Wilgen, B.W. (2014). Conflicting values: ecosystem services and invasive tree management. Biol. Invasions *16*, 705–719.
39. Riley, C.B., Herms, D.A., and Gardiner, M.M. (2018). Exotic trees contribute to urban forest diversity and ecosystem services in inner-city Cleveland, OH. Urban For. Urban Green. *29*, 367–376.
40. M'Gonigle, L.K., Ponisio, L.C., Cutler, K., and Kremen, C. (2015). Habitat restoration promotes pollinator persistence and colonization in intensively managed agriculture. Ecol. Appl. *25*, 1557–1565.
41. Müller, S.M., Peisker, J., Bieling, C., Linnemann, K., Reidl, K., and Schmieder, K. (2019). The Importance of Cultural Ecosystem Services

and Biodiversity for Landscape Visitors in the Biosphere Reserve Swabian Alb (Germany). Sustainability *11*, 2650.

42. Aguilera, G., Roslin, T., Miller, K., Tamburini, G., Birkhofer, K., Caballero-Lopez, B., Lindström, S.A., Öckinger, E., Rundlöf, M., Rusch, A., et al. (2020). Crop diversity benefits carabid and pollinator communities in landscapes with semi-natural habitats. J. Appl. Ecol. *57*, 2170–2179.
43. Obura, D.O., Katerere, Y., Mayet, M., Kaelo, D., Msweli, S., Mather, K., Harris, J., Louis, M., Kramer, R., Teferi, T., et al. (2021). Integrate biodiversity targets from local to global levels. Science *373*, 746–748.
44. Kolb, S., Uzman, D., Leyer, I., Reineke, A., and Entling, M.H. (2020). Differential effects of semi-natural habitats and organic management on spiders in viticultural landscapes. Agric. Ecosyst. Environ. *287*, 106695.
45. Lajos, K., Samu, F., Bihaly, Á.D., Fülöp, D., and Sárospataki, M. (2021). Landscape structure affects the sunflower visiting frequency of insect pollinators. Sci. Rep. *11*, 8147.
46. Avelino, J., Romero-Gurdián, A., Cruz-Cuellar, H.F., and Declerck, F.A.J. (2012). Landscape context and scale differentially impact coffee leaf rust, coffee berry borer, and coffee root-knot nematodes. Ecol. Appl. *22*, 584–596.
47. Estrada-Carmona, N., Martínez-Salinas, A., DeClerck, F.A.J., Vílchez-Mendoza, S., and Garbach, K. (2019). Managing the farmscape for connectivity increases conservation value for tropical bird species with different forest-dependencies. J. Environ. Manag. *250*, 109504.
48. Fremier, A.K., DeClerck, F.A.J., Bosque-Pérez, N.A., Carmona, N.E., Hill, R., Joyal, T., Keesecker, L., Klos, P.Z., Martínez-Salinas, A., Niemeyer, R., et al. (2013). Understanding Spatiotemporal Lags in Ecosystem Services to Improve Incentives. Bioscience *63*, 472–482.
49. Martin, E.A., Seo, B., Park, C.-R., Reineking, B., and Steffan-Dewenter, I. (2016). Scale-dependent effects of landscape composition and configuration on natural enemy diversity, crop herbivory, and yields. Ecol. Appl. *26*, 448–462.
50. Moi, D., Romero, G., Sobral-Souza, T., Cardinale, B., Kratina, P., Perkins, D., de Mello, F.T., Jeppesen, E., Heino, J., and Lansac-Tôha, F. (2021). Human pressure drives biodiversity–multifunctionality relationships in neotropical wetlands. Nature Ecology & Evolution *6*, 1279–1289.
51. Wolff, S., Schulp, C.J.E., and Verburg, P.H. (2015). Mapping ecosystem services demand: A review of current research and future perspectives. Ecol. Indicat. *55*, 159–171.
52. Chaplin-Kramer, R., Sharp, R.P., Weil, C., Bennett, E.M., Pascual, U., Arkema, K.K., Brauman, K.A., Bryant, B.P., Guerry, A.D., Haddad, N.M., et al. (2019). Global modeling of nature's contributions to people. Science *366*, 255–258.
53. Martin, L.J., Blossey, B., and Ellis, E. (2012). Mapping where ecologists work: biases in the global distribution of terrestrial ecological observations. Front. Ecol. Environ. *10*, 195–201.
54. Guerra, C.A., Berdugo, M., Eldridge, D.J., Eisenhauer, N., Singh, B.K., Cui, H., Abades, S., Alfaro, F.D., Bamigboye, A.R., Bastida, F., et al. (2022). Global hotspots for soil nature conservation. Nature *610*, 693–698.
55. Veen, G.F., Wubs, E.R.J., Bardgett, R.D., Barrios, E., Bradford, M.A., Carvalho, S., De Deyn, G.B., de Vries, F.T., Giller, K.E., Kleijn, D., et al. (2019). Applying the Aboveground-Belowground Interaction Concept in Agriculture: Spatio-Temporal Scales Matter. Front. Ecol. Evol. *7*.
56. FAO, I. (2020). State of Knowledge of Soil Biodiversity-status, Challenges and Potentialities, Report 2020 (FAO Rome).
57. Pusey, B.J., and Arthington, A.H. (2003). Importance of the riparian zone to the conservation and management of freshwater fish: a review. Mar. Freshw. Res. *54*, 1–16.
58. Brandt, J., and Stolle, F. (2021). A global method to identify trees outside of closed-canopy forests with medium-resolution satellite imagery. Int. J. Rem. Sens. *42*, 1713–1737.
59. Garbach, K., Milder, J.C., DeClerck, F.A., Montenegro de Wit, M., Driscoll, L., and Gemmill-Herren, B. (2017). Examining multi-functionality for crop yield and ecosystem services in five systems of agroecological intensification. Int. J. Agric. Sustain. *15*, 11–28.
60. Tamburini, G., Santoiemma, G., O'Rourke, M.E., Bommarco, R., Chaplin-Kramer, R., Dainese, M., Karp, D.S., Kim, T.N., Martin, E.A., Petersen, M., and Marini, L. (2020). Species traits elucidate crop pest response to landscape composition: a global analysis. Proc. Biol. Sci. *287*, 20202116.
61. Jones, S.K., Sánchez, A.C., Beillouin, D., Juventia, S.D., Mosnier, A., Remans, R., and Estrada Carmona, N. (2023). Achieving win-win outcomes for biodiversity and yield through diversified farming. Basic Appl. Ecol. *67*, 14–31.
62. Shah, K.K., Modi, B., Pandey, H.P., Subedi, A., Aryal, G., Pandey, M., and Shrestha, J. (2021). Diversified Crop Rotation: An Approach for Sustainable Agriculture Production. Adv. Agric. *2021*, 1–9.
63. Lichtenberg, E.M., Kennedy, C.M., Kremen, C., Batáry, P., Berendse, F., Bommarco, R., Bosque-Pérez, N.A., Carvalheiro, L.G., Snyder, W.E., Williams, N.M., et al. (2017). A global synthesis of the effects of diversified farming systems on arthropod diversity within fields and across agricultural landscapes. Global Change Biol. *23*, 4946–4957.
64. Zomer, R.J., Bossio, D.A., Trabucco, A., Noordwijk, M.v., and Xu, J. (2022). Global carbon sequestration potential of agroforestry and increased tree cover on agricultural land. C. *2*, 1–10.
65. Arroyo-Rodríguez, V., Fahrig, L., Tabarelli, M., Watling, J.I., Tischendorf, L., Benchimol, M., Cazetta, E., Faria, D., Leal, I.R., Melo, F.P.L., et al. (2020). Designing optimal human-modified landscapes for forest biodiversity conservation. Ecol. Lett. *23*, 1404–1420.
66. Balafoutis, A., Beck, B., Fountas, S., Vangeyte, J., Wal, T., Soto, I., Gómez-Barbero, M., Barnes, A., and Eory, V. (2017). Precision agriculture technologies positively contributing to GHG emissions mitigation, farm productivity and economics. Sustainability *9*, 1339.
67. Kremen, C., and Merenlender, A.M. (2018). Landscapes that work for biodiversity and people. Science *362*, eaau6020.
68. Moher, D., Liberati, A., Tetzlaff, J., and Altman, D.G.; PRISMA Group (2009). Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. Ann. Intern. Med. *151*, 264–269.
69. Rahman, M.A., Franceschi, E., Pattnaik, N., Moser-Reischl, A., Hartmann, C., Paeth, H., Pretzsch, H., Rötzer, T., and Pauleit, S. (2022). Spatial and temporal changes of outdoor thermal stress: influence of urban land cover types. Sci. Rep. *12*, 671.
70. Moreira, T.C.L., Polize, J.L., Brito, M., da Silva Filho, D.F., Chiavegato Filho, A.D.P., Viana, M.C., Andrade, L.H., and Mauad, T. (2022). Assessing the impact of urban environment and green infrastructure on mental health: results from the São Paulo Megacity Mental Health Survey. J. Expo. Sci. Environ. Epidemiol. *32*, 205–212.
71. Barboza, E.P., Cirach, M., Khomenko, S., Iungman, T., Mueller, N., Barrera-Gómez, J., Rojas-Rueda, D., Kondo, M., and Nieuwenhuijsen, M. (2021). Green space and mortality in European cities: a health impact assessment study. Lancet Planet. Health *5*, e718–e730.
72. Lin, P., Pan, M., Wood, E.F., Yamazaki, D., and Allen, G.H. (2021). A new vector-based global river network dataset accounting for variable drainage density. Sci. Data *8*, 28.
73. Genet, M., Kokutse, N., Stokes, A., Fourcaud, T., Cai, X., Ji, J., and Mickovski, S. (2008). Root reinforcement in plantations of Cryptomeria japonica D. Don: effect of tree age and stand structure on slope stability. For. Ecol. Manage. *256*, 1517–1526.
74. Gentile, F., Elia, G., and Elia, R. (2010). Analysis of the stability of slopes reinforced by roots. In DESIGN AND NATURE V: COMPARING DESIGN IN NATURE WITH SCIENCE AND ENGINEERING WIT Transactions on Ecology and the Environment, C. Brebbia and A. Carpi, eds. (Int Journal Design & Ecodynam), p. 189+.
75. Beegum, S., P J, J., Emil, D., Sudheer, K., and Das, S. (2021). Integrated Simulation Modeling Approach for Investigating Pore Water Pressure Induced Landslides. Preprint at.
76. Chen, Z., Mi, H., Zhang, F., and Wang, X. (2003). A simplified method for 3D slope stability analysis. Can. Geotech. J. *40*, 675–683.

One Earth, Volume *7*

Supplemental information

Securing Nature's Contributions to People requires at least 20%–25% (semi-)natural habitat in human-modified landscapes

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Supplemental items:

Supplemental Figures

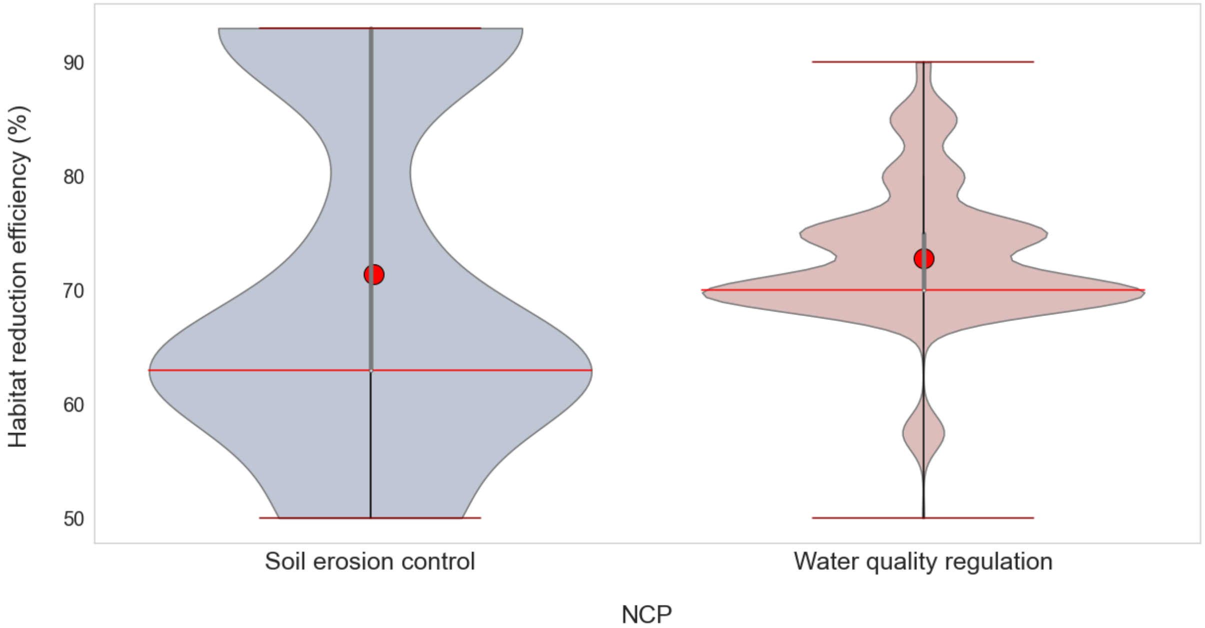

Figure S1. Habitat efficiency level (%) *for soil protection from water erosion control (gray) and water quality regulation from non-point pollutants (light red), related to the Results section. The lower redline and the top redline correspond to the whiskers (min, max, respectively) that indicate the range of the data, while the mid-figure 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 efficiency (%). All the values are weighted by the number of papers.*

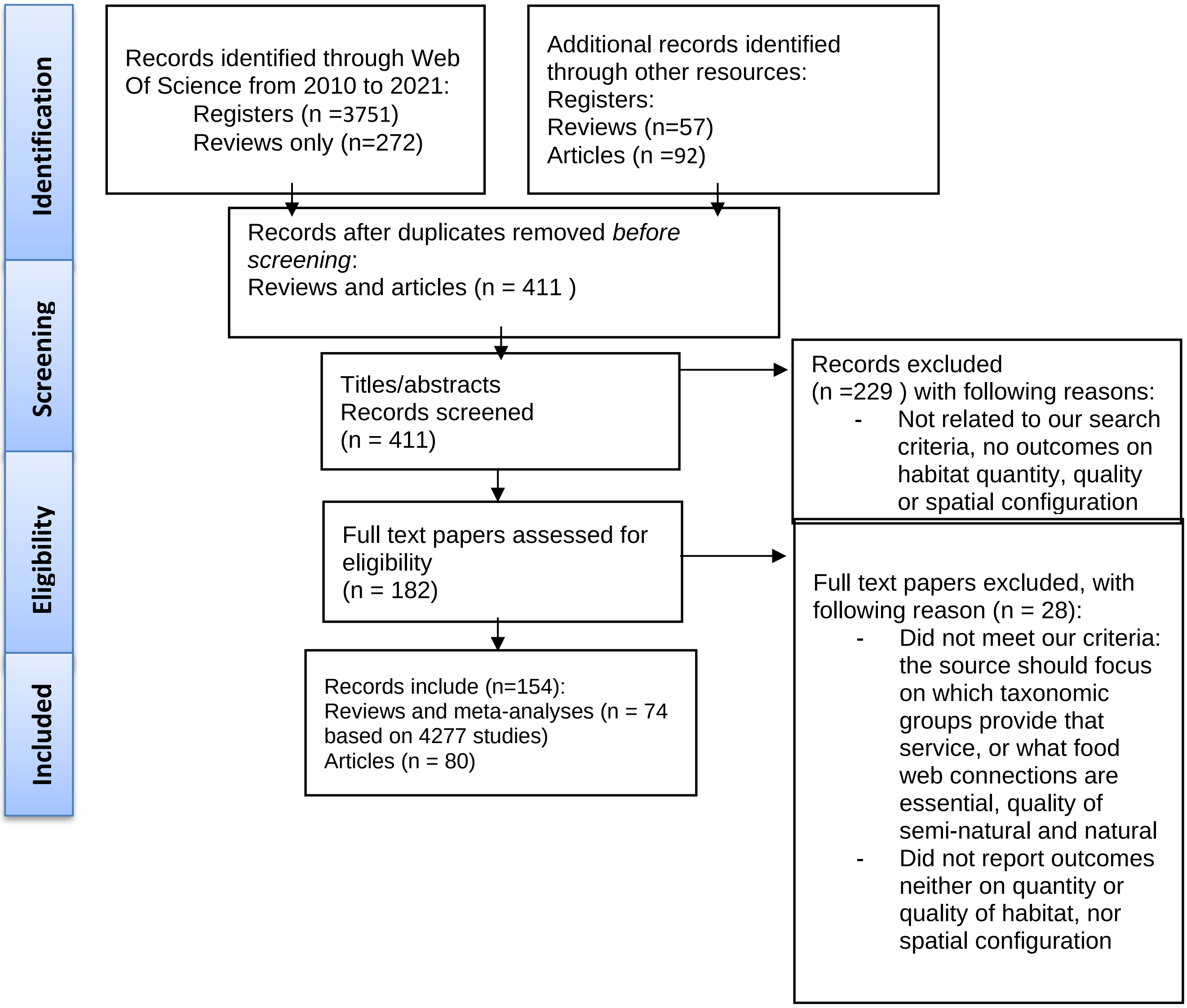

Figure S2. PRISMA flow diagram for systematic reviews, which included searches of databases and registers, related to Methods subsection under Experimental Procedures.

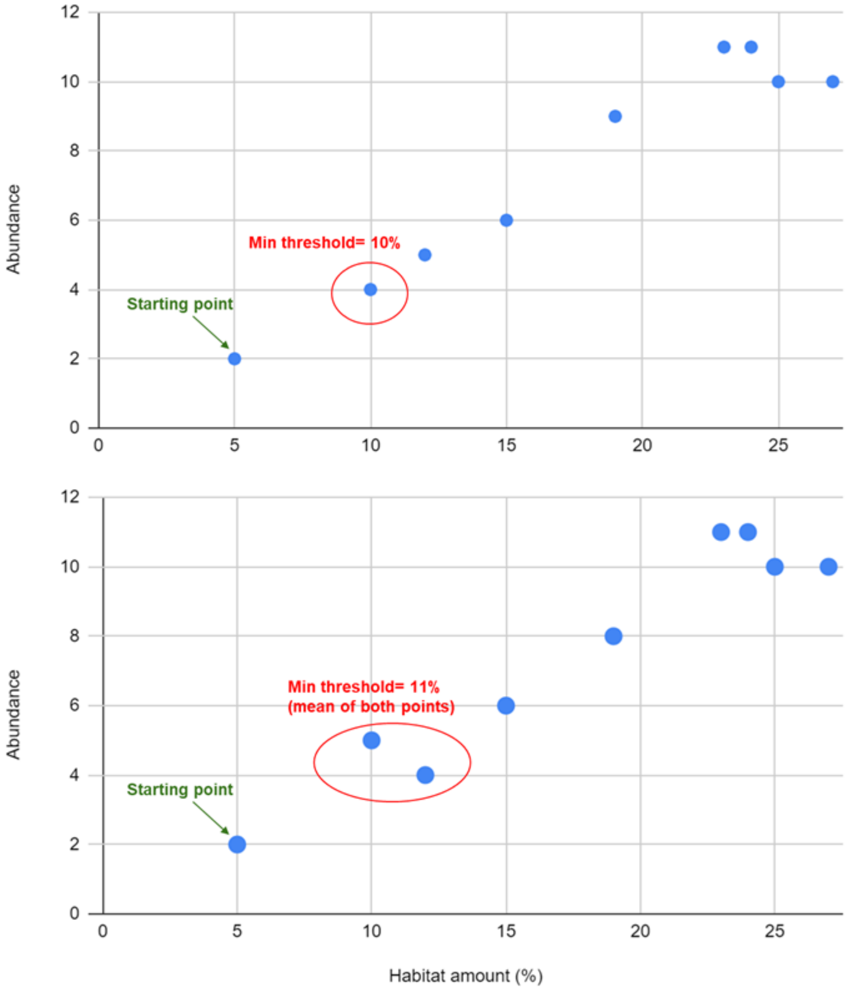

Figure S3. Illustration figure showing two examples of the method of extracting the minimum values from the reviewed studies figures when the starting point is not zero, related to Methods subsection under Experimental Procedures.

Supplemental Tables

Table S1. Landscapes elements categories and included elements underlying habitat quality for each category across 136 studies reviewed including 73 articles and 63 reviews and meta-analyses (based on 3868 papers), related to the Results section.

Landscape elements categories	**Included landscapes elements' description**
Diverse floral resources	Floral stripes and patches within orchards, rich diverse native and wildflower floral strips, flowering ground cover, diverse floral field margins, native and non native flowering herbaceous strips adjacent fields.
Complex diverse SNH	mixed of different elements: small patches of forest , pasture, grassland, shrubland surrounding, complex hedgerows with grassy elements or woody and rich floral understory species, prairie strips, diverse rich field margins with higher native and introduced plants and trees, diverse field border species, agri-environment schemes(e.g., wildflower strips/areas, grassy field margins, organic farming), vegetation cover in inter-row, mixed plantation, heterogeneous diverse SNH, forest edges, green spaces and domestic gardens, zoos, diverse urban parks, public parks, castle parks, disaggregated forested area, small water bodies, open lawns and trees, zoned woody, shrubby and grassy buffers, wetland, diverse ground cover.
Complex diverse NH	Diverse natural species, heterogenous natural buffer, native forested, shrubs, grassy buffer, natural forest, diverse native natural habitat fragments in mosaic landscapes, old natural field margins, natural heterogeneous vegetation cover, vegetation cover with diverse native deep rooted species with more reinforcing effect and low surcharge, natural young trees
Woody elements	Silvoarable alleys, agroforestry, narrow woodland corridors, woody corridors that fragment fields, woody vegetation margins, hedgerows, trees canopy cover, street trees, native shrubland, hardwood buffer, native diverse woody buffer.
Grassy elements	patches of grassland surrounding, diverse SN pasture and field border, diverse rich patches of urban meadow
Forest	forest cover surrounding, forest edges associated with fallow or hedges, forest patches surrounding, forest corridors, diverse forested native and non native buffer, deep rooted natural forest species

Table S2. Spatial distribution of the functional integrity levels. *Functional integrity is calculated as the average value of the binary classified layer (natural/human-modified) within a 1 km² 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, related to the Results section.*

Functional integrity level applied (%)	**Percent land above functional integrity level**		
	Functionally intact human-modified lands (%)	**Functionally intact human-modified lands sensitivity analysis (%)**	**Functionally intact global land surface (%)**
10	***48***	***52***	***62***
15	***41***	***44***	***61***
20	***36***	***39***	***61***
25	***30***	***30***	***60***
30	26	29	60
40	19	21	59
50	13	14	57
60	9	9	56
70	6	6	55
80	3	3	54
90	1	1	52
100	0	0	46

Table S3. Land cover classification, related to Methods subsection under Experimental Procedures.

Land cover classification	Binary classification
tree cover	1
shrubland	1
natural grassland	1
herbaceous wetland	1
moss and lichen	1
mangroves	1
cropland	0
built-up areas	0
pastureland	0
bare/sparse vegetation	NA
snow and ice	NA
permanent water bodies	NA

Note S1:Mechanics of NCP provision and contextualization, related to the Results section.

Substantial local variations are the norm in NCP research, particularly concerning the contribution of a single species to a single NCP. The specific habitat quantity can vary strongly depending on factors such as landscape type[1], management regime intensity, agricultural practices and crop diversity[2–4], crop type[5], field size[3], field edge density and NCP providers or taxa[6]. For example, in intensified landscapes, the required habitat quantity increases with increasing management intensity. However, increasing the habitat quantity (>20%) in these intensified landscapes can be challenging and sometimes might have a negative impact on crop yield. Alternatively, increasing crop diversity (by at least doubling) can positively affect multi-trophic diversity (e.g., resulting in up to four times more pollinators) if the habitat quantity remains above 10%, supporting the "landscape complementation" hypothesis[3,7]. Moreover, decreasing the average field size and the number of crop-crop borders can enhance multi-trophic diversity and landscape connectivity, even in the absence of habitat between fields[2,8–11]. The impact of habitat quantity predominantly affects arthropod diversity[7,12,13] compared to arthropod abundance which shows inconsistent responses, notably across specialist and generalist arthropods[14,15].

Urban well-being is significantly influenced by the presence and amount of green spaces. Many studies emphasize the importance of increasing green spaces in urban areas to reduce psychological stress levels, cortisol levels, and prescriptions for antidepressants, and to decrease anxiety and premature mortality, while contributing to the development of healthy, livable and sustainable cities. For example, increasing the canopy cover from 20 to 30% of the city land surface could prevent 400 deaths annually[16], while increasing the proportion of green spaces from 6.5% to 19.6% in one neighborhood could prevent 60 deaths annually[17].

Vegetation plays a critical role in controlling soil erosion. Maintaining a certain minimum amount of vegetation cover can mitigate soil erosion. In general, countless studies upon which this minimum amount was based were conducted on erosion-sensitive terrains, therefore, it is likely that less sensitive areas might require a lower habitat quantity to prevent soil loss. The impact of vegetation cover on soil loss and runoff includes redistributing rainfall through canopy interception, stemflow and throughfall, which in turn control various mechanisms of soil erosion, including rill and inter-rill, splash and gully erosion. Previous studies suggest that maintaining more than 40-60% vegetation cover is necessary to prevent accelerated erosion, notably on sloped terrains. Below this level, the risk of soil erosion becomes extremely high, with erosion rates increasing by 100-1000%[18–20].

To prevent surface and subsurface pollution from agricultural upland areas from entering streams, lakes or wetland ecosystems a minimum buffer level is required along streams. This buffer width can vary depending on local contextual conditions such as slope, topography and ecoregion climate regime, upland land-use management intensity, rainfall intensity, and the specific pollutant in question (e.g., nutrients, sediments, pesticides). For example, as the slope increases, the necessary buffer width also increase, necessitating, on average, an additional of 0.8-1 m to the baseline buffer width for every 1% increase of slope[21]. A wider buffer may be essential in tropical ecoregions compared to temperate ones [22]. A greater buffer width is also needed when adjacent land-use intensity is high or if the target objective of the management is to maintain biodiversity[23,24]. Vegetation, compared to bare soil, has been extensively used as a natural protection against factors that trigger landslides and debris flow in hilly landscapes (>30°)[25,26].

Although a certain amount of habitat per km^2 in our study secures the provisioning of multiple NCP, the spatial configuration, linear distance or location of the habitat, as well as its quality in landscape management, are crucial to enhance biodiversity, and ensure ecosystem functional integrity that maintain desired levels of functions and services. The exact configuration and quality of habitat needed depends on the local context, including landscape type, management regime, topography, the specific function, and the functional groups that provide the NCP. This provides significant flexibility and options for local communities in identifying and implementing the most suitable practices based on available local ecological evidence and knowledge.

The impact of habitat isolation on mobile functional groups varies significantly across different taxa and depends on the availability of resources for nesting or mating sites, habitat quality, and the foraging ranges of each taxon[27–30]. For example, when habitats are isolated from target crops by more than 1-2km, there is a significant reduction in the visitation rate of bumblebees, hoverflies and solitary bees. In contrast, honey bees or butterflies which have longer distance foraging ranges and thus are less affected by isolation[30–32]. The responses of these organisms to different landscapes elements also vary, with some species favoring specific types of habitats[33–35].

The term ‘experiences’ has been embraced by IPBES and has been used by Diaz et al.[36] (NCP16) to refer to the benefits, both physical and mental health, that result from engaging in activities within nature. These experiences can range from recreation, leisure, aesthetic enjoyment, etc., for physical and psychological well being. Exercising or walking in nature, rather than simply watching nature scenes or exercising in isolation, leads to lower cortisol level, and reduced prevalence of depression, anxiety and stress, even under high periodic life stress[37]. Access to high-quality green spaces, enriched with plant, butterfly, and bird diversity[38] is linked to positive outcomes in human physical and community wellbeing [39,40], although in some studies found the impact neutral. The spatial configuration of these green spaces also has implications for human mental health. Residents within urban landscapes that have a disaggregated distribution of urban green spaces (i.e., numerous small green spaces and small-sized water bodies) report less psychological distress compared to those close to a single large green space.

Soil erosion results in the loss of the most fertile topsoil and is accelerated by human activity such as land use and farming practices, as well as climate change. The efficiency of perennial vegetative cover in reducing soil loss depends on factors such as vegetation type, slope, target erosion type, soil type, and ecoregion[41]. Forests are more efficient in reducing soil loss in sloping farmlands (slope >25°) compared to grasslands or shrublands, which are more effective on gentle slope (>0-25°). Croplands and orchards exhibit the highest soil loss value among land-use types[41]. To reduce splash erosion, establishing shrubs with sufficient canopy cover is required[42,43], while dense and deep plant roots are essential for controlling rill and ephemeral gully erosion[44]. High-density agroforestry systems can reduce soil erosion rates by 50% compared to crop monocultures[45]. Proper vegetation cover selection, based on landscape type, management objective, and slope, can significantly reduce soil erosion rates.

The efficiency of vegetated buffers in pollutants removal or reduction is largely controlled by buffers placement, vegetation type, plant density, and buffer zone width[46,47]. Implementing vegetated buffers on headwater streams is essential for maintaining water quality in those streams. Grassy buffers or mixed grass-woody vegetation are more effective in trapping sediment than they are in removing total nitrogen[47], whereas forested buffers are most effective in removing excess nitrogen[48,49] or phosphorus from the surface runoff[46]. The design and quality of vegetated buffers are tailored to align with the specific management goals and local conditions. Using a variety of species, both native and non-native, distributed in either two or three-tiered structures (e.g., forested, grassed) or mixed buffers (such as woody, herbaceous species or wetlands), is most effective at trapping non-point pollutants and maintaining the integrity of streams, lakes, and wetlands. These vegetated buffers should be established on both sides of the headwater streams where the removal efficiency and processing are mostly achieved. To maximize these benefits, agricultural land-use and urbanization (e.g., roads) practices should be carefully planned across entire catchments[22].

Vegetation contributes to slope stability through two mechanisms: modifying the soil moisture regime and bolstering soil retention through plant roots. The Factor of safety (FoS) has been widely used in modelling studies as a proxy of vegetation cover’s efficiency in landslides reduction and slope stabilization[50,51]. FoS is estimated considering many factors such as vegetation transmissivity, soil physical properties, soil cohesion, additional cohesion from plant roots [52,53], slope geometry, rainfall intensity, vegetation type, plants roots architecture and depth, trees placement on the slope, and their size, age and density[54–56]. For example, slope stability increases in natural hillslopes populated by native mixed forest species (FoS of 1.3) compared to modified hillslopes (e.g., hillslope with road cuts FoS of 0.95), even with increased pore pressure in the natural hillslopes[55]. The FoS decreases as rainfall intensity increases, notably in modified hillslopes[56]. Trees positioned at the base of slopes are more effective (increasing the FoS by 7%) in reducing landslides (by 95%) compared to other forms of vegetation. Conversely, placing trees on the mid-slope or on ridge tops decreases FoS by 43%, especially in hilly terrains (slope >35°)[43,57]. Slopes exceeding 60° have a low probability of sliding if they are covered with over 80% of their total length by perennial vegetation consisting of a mix tree species, primarily native species[58]. To mitigate landslides, adopting suitable vegetation quality composed of a mixed tree species, spaced no more than 18-20 m apart, along the base or the toe of slopes is recommended.

Supplemental References

1. Tscharntke, T., Karp, D.S., Chaplin-Kramer, R., Batary, P., DeClerck, F., Gratton, C., Hunt, L., Ives, A., Jonsson, M., Larsen, A., et al. (2016). When natural habitat fails to enhance biological pest control - Five hypotheses. Biol. Conserv. *204*, 449–458. 10.1016/j.biocon.2016.10.001.

2. Hass, A.L., Kormann, U.G., Tscharntke, T., Clough, Y., Baillod, A.B., Sirami, C., Fahrig, L., Martin, J.-L., Baudry, J., Bertrand, C., et al. (2018). Landscape configurational heterogeneity by small-scale agriculture, not crop diversity, maintains pollinators and plant reproduction in western Europe. Proc. R. Soc. B-Biol. Sci. *285*. 10.1098/rspb.2017.2242.

3. Sirami Clélia, Gross Nicolas, Baillod Aliette Bosem, Bertrand Colette, Carrié Romain, Hass Annika, Henckel Laura, Miguet Paul, Vuillot Carole, Alignier Audrey, et al. (2019). Increasing crop heterogeneity enhances multitrophic diversity across agricultural regions. Proc. Natl. Acad. Sci. *116*, 16442–16447. 10.1073/pnas.1906419116.

4. Letourneau, D.K., Allen, S.G.B., Kula, R.R., Sharkey, M.J., and Stireman, J.O., III (2015). Habitat eradication and cropland intensification may reduce parasitoid diversity and natural pest control services in annual crop fields. Elem.-Sci. Anthr. *3*. 10.12952/journal.elementa.000069.

5. Shackelford, G., Steward, P., Benton, T., Kunin, W., Potts, S., Biesmeijer, J., and Sait, S. (2013). Comparison of pollinators and natural enemies: a meta-analysis of landscape and local effects on abundance and richness in crops. Biol. Rev. *88*, 1002–1021. 10.1111/brv.12040.

6. Wu, P., Dai, P., Wang, M., Feng, S., Olhnuud, A., Xu, H., Li, X., and Liu, Y. (2021). Improving Habitat Quality at the Local and Landscape Scales Increases Wild Bee Assemblages and Associated Pollination Services in Apple Orchards in China. Front. Ecol. Evol. *9*. 10.3389/fevo.2021.621469.

7. Aguilera, G., Roslin, T., Miller, K., Tamburini, G., Birkhofer, K., Caballero-Lopez, B., Lindstrom, S.A.-M., Ockinger, E., Rundlof, M., Rusch, A., et al. (2020). Crop diversity benefits carabid and pollinator communities in landscapes with semi-natural habitats. J. Appl. Ecol. *57*, 2170–2179. 10.1111/1365-2664.13712.

8. Haan, N.L., Zhang, Y., and Landis, D.A. (2020). Predicting Landscape Configuration Effects on Agricultural Pest Suppression. TRENDS Ecol. Evol. *35*, 175–186. 10.1016/j.tree.2019.10.003.

9. Rusch, A., Valantin-Morison, M., Sarthou, J.P., and Roger-Estrade, J. (2013). Effect of crop management and landscape context on insect pest populations and crop damage. Agric. Ecosyst. Environ. *166*, 118–125. 10.1016/j.agee.2011.05.004.

10. Avelino, J., Romero-Gurdián, A., Cruz-Cuellar, H.F., and Declerck, F.A. (2012). Landscape context and scale differentially impact coffee leaf rust, coffee berry borer, and coffee root-knot nematodes. Ecol. Appl. *22*, 584–596.

11. Larsen, A., and Noack, F. (2017). Identifying the landscape drivers of agricultural insecticide use leveraging evidence from 100,000 fields. Proc. Natl. Acad. Sci. U. S. A. *114*, 5473–5478. 10.1073/pnas.1620674114.

12. Aviron, S., Lalechere, E., Duflot, R., Parisey, N., and Poggi, S. (2018). Connectivity of cropped vs. semi-natural habitats mediates biodiversity: A case study of carabid beetles communities. Agric. Ecosyst. Environ. *268*, 34–43. 10.1016/j.agee.2018.08.025.

13. Watson, J., Wolf, A., and Ascher, J. (2011). Forested Landscapes Promote Richness and Abundance of Native Bees (Hymenoptera: Apoidea: Anthophila) in Wisconsin Apple Orchards. Environ. Entomol. *40*, 621–632. 10.1603/EN10231.

14. Dassou, A.G., and Tixier, P. (2016). Response of pest control by generalist predators to local-scale plant diversity: a meta-analysis. Ecol. Evol. *6*, 1143–1153. 10.1002/ece3.1917.

15. Chaplin-Kramer, R., O'Rourke, M.E., Blitzer, E.J., and Kremen, C. (2011). A meta-analysis of crop pest and natural enemy response to landscape complexity. Ecol. Lett. *14*, 922–932. 10.1111/j.1461-0248.2011.01642.x.

16. Kondo, M.C., Mueller, N., Locke, D.H., Roman, L.A., Rojas-Rueda, D., Schinasi, L.H., Gascon, M., and Nieuwenhuijsen, M.J. (2020). Health impact assessment of Philadelphia's 2025 tree canopy cover goals. LANCET Planet. Health *4*, E149–E157.

17. Mueller, N., Rojas-Rueda, D., Khreis, H., Cirach, M., Andrés, D., Ballester, J., Bartoll, X., Daher, C., Deluca, A., Echave, C., et al. (2020). Changing the urban design of cities for health: The superblock model. Environ. Int. *134*, 105132. 10.1016/j.envint.2019.105132.

18. Xu, C., Yang, Z., Qian, W., Chen, S., Xiaofei, L., Weisheng, L., Xiong, D., Jiang, M., Chang, C.-T., Huang, J.-C., et al. (2019). Runoff and soil erosion responses to rainfall and vegetation cover under various afforestation management in subtropical montane forest. Land Degrad. Dev. *30*, 1711–1724. 10.1002/ldr.3377.

19. Vanacker, V., Bellin, N., Molina, A., and Kubik, P.W. (2014). Erosion regulation as a function of human disturbances to vegetation cover: a conceptual model. Landsc. Ecol. *29*, 293–309.

20. Prasetyo, A., Setyawan, C., and Tirtalistyani, R. (2021). Vegetation cover modelling for soil erosion control in agricultural watershed. In (IOP Publishing), p. 012033.

21. Lee, P., Smyth, C., and Boutin, S. (2004). Quantitative review of riparian buffer width guidelines from Canada and the United States. J. Environ. Manage. *70*, 165–180. 10.1016/j.jenvman.2003.11.009.

22. Luke, S.H., Slade, E.M., Gray, C.L., Annammala, K., V., Drewer, J., Williamson, J., Agama, A.L., Ationg, M., Mitchell, S.L., Vairappan, C.S., et al. (2019). Riparian buffers in tropical agriculture: Scientific support, effectiveness and directions for policy. J. Appl. Ecol. *56*, 85–92. 10.1111/1365-2664.13280.

23. Hansen, B., Reich, P., Cavagnaro, T., and Lake, P. (2015). Challenges in applying scientific evidence to width recommendations for riparian management in agricultural Australia. Ecol. Manag. Restor. *16*, 50–57. 10.1111/emr.12149.

24. Hansen, B., Reich, P., and Cavagnaro, T. (2010). Minimum width requirements for riparian zones to protect flowing waters and to conserve biodiversity: a review and recommendations With application to the State of Victoria.

25. Spiekermann, R.I., McColl, S., Fuller, I., Dymond, J., Burkitt, L., and Smith, H.G. (2021). Quantifying the influence of individual trees on slope stability at landscape scale. J. Environ. Manage. *286*. 10.1016/j.jenvman.2021.112194.

26. Klemas, V. (2014). Remote Sensing of Riparian and Wetland Buffers: An Overview. J. Coast. Res. *30*, 869–880. 10.2112/JCOASTRES-D-14-00013.1.

27. Lajos, K., Csaszar, O., Sarospataki, M., Samu, F., and Toth, F. (2020). Linear woody landscape elements may help to mitigate leaf surface loss caused by the cereal leaf beetle. Landsc. Ecol. *35*, 2225–2238. 10.1007/s10980-020-01097-3.

28. Rahimi, E., Barghjelveh, S., and Dong, P. (2021). Using the Lonsdorf model for estimating habitat loss and fragmentation effects on pollination service. Ecol. Process. *10*. 10.1186/s13717-021-00291-8.

29. Bailey, S., Requier, F., Nusillard, B., Roberts, S.P.M., Potts, S.G., and Bouget, C. (2014). Distance from forest edge affects bee pollinators in oilseed rape fields. Ecol. Evol. *4*, 370–380. 10.1002/ece3.924.

30. Woodcock, B., Bullock, J., McCracken, M., Chapman, R., Ball, S., Edwards, M., Nowakowski, M., and Pywell, R. (2016). Spill-over of pest control and pollination services into arable crops. Agric. Ecosyst. Environ. *231*, 15–23. 10.1016/j.agee.2016.06.023.

31. Dainese, M., Luna, D.I., Sitzia, T., and Marini, L. (2015). Testing scale-dependent effects of seminatural habitats on farmland biodiversity. Ecol. Appl. *25*, 1681–1690. 10.1890/14-1321.1.

32. Garibaldi, L., Steffan-Dewenter, I., Kremen, C., Morales, J., Bommarco, R., Cunningham, S., Carvalheiro, L., Chacoff, N., Dudenhoffer, J., Greenleaf, S., et al. (2011). Stability of pollination services decreases with isolation from natural areas despite honey bee visits. Ecol. Lett. *14*, 1062–1072. 10.1111/j.1461-0248.2011.01669.x.

33. Albrecht, M., Kleijn, D., Williams, N.M., Tschumi, M., Blaauw, B.R., Bommarco, R., Campbell, A.J., Dainese, M., Drummond, F.A., Entling, M.H., et al. (2020). The effectiveness of flower strips and hedgerows on pest control, pollination services and crop yield: a quantitative synthesis. Ecol. Lett. *23*, 1488–1498. 10.1111/ele.13576.

34. Bartual, A.M., Sutter, L., Bocci, G., Moonen, A.-C., Cresswell, J., Entling, M., Giffard, B., Jacot, K., Jeanneret, P., Holland, J., et al. (2019). The potential of different semi-natural habitats to sustain pollinators and natural enemies in European agricultural landscapes. Agric. Ecosyst. Environ. *279*, 43–52. 10.1016/j.agee.2019.04.009.

35. Klaus, F., Tscharntke, T., Uhler, J., and Grass, I. (2021). Calcareous grassland fragments as sources of bee pollinators for the surrounding agricultural landscape. Glob. Ecol. Conserv. *26*. 10.1016/j.gecco.2021.e01474.

36. Diaz, S., Pascual, U., Stenseke, M., Martín-López, B., Watson, R., Molnár, Z., Hill, R., Chan, K., Baste, I., Brauman, K., et al. (2018). Assessing nature’s contributions to people. Science *359*, 270–272. 10.1126/science.aap8826.

37. Olafsdottir, G., Cloke, P., Schulz, A., van Dyck, Z., Eysteinsson, T., Thorleifsdottir, B., and Vogele, C. (2020). Health Benefits of Walking in Nature: A Randomized Controlled Study Under Conditions of Real-Life Stress. Environ. Behav. *52*, 248–274. 10.1177/0013916518800798.

38. Larson, L.R., Jennings, V., and Cloutier, S.A. (2016). Public Parks and Wellbeing in Urban Areas of the United States. PLOS ONE *11*. 10.1371/journal.pone.0153211.

39. Southon, G.E., Jorgensen, A., Dunnett, N., Hoyle, H., and Evans, K.L. (2018). Perceived species-richness in urban green spaces: Cues, accuracy and well-being impacts. Landsc. URBAN Plan. *172*, 1–10. 10.1016/j.andurbplan.2017.12.002.

40. Wood, S.L., Jones, S.K., Johnson, J.A., Brauman, K.A., Chaplin-Kramer, R., Fremier, A., Girvetz, E., Gordon, L.J., Kappel, C.V., and Mandle, L. (2018). Distilling the role of ecosystem services in the Sustainable Development Goals. Ecosyst. Serv. *29*, 70–82.

41. Wu, G.-L., Liu, Y.-F., Cui, Z., Liu, Y., Shi, Z.-H., Yin, R., and Kardol, P. (2020). Trade-off between vegetation type, soil erosion control and surface water in global semi-arid regions: A meta-analysis. J. Appl. Ecol. *57*, 875–885. 10.1111/1365-2664.13597.

42. Zhongming, W., Lees, B.G., Feng, J., Wanning, L., and Haijing, S. (2010). Stratified vegetation cover index: A new way to assess vegetation impact on soil erosion. CATENA *83*, 87–93. 10.1016/j.catena.2010.07.006.

43. Quinton, J.N., Edwards, G., and Morgan, R. (1997). The influence of vegetation species and plant properties on runoff and soil erosion: results from a rainfall simulation study in south east Spain. Soil Use Manag. *13*, 143–148.

44. Gyssels, G., Poesen, J., Bochet, E., and Li, Y. (2005). Impact of plant roots on the resistance of soils to erosion by water: a review. Prog. Phys. Geogr. *29*, 189–217. 10.1191/0309133305pp443ra.

45. Muchane, M.N., Sileshi, G.W., Gripenberg, S., Jonsson, M., Pumarino, L., and Barrios, E. (2020). Agroforestry boosts soil health in the humid and sub-humid tropics: A meta-analysis. Agric. Ecosyst. Environ. *295*, 106899.

46. Aguiar, T.R., Jr., Bortolozo, F.R., Hansel, F.A., Rasera, K., and Ferreira, M.T. (2015). Riparian buffer zones as pesticide filters of no-till crops. Environ. Sci. Pollut. Res. *22*, 10618–10626. 10.1007/s11356-015-4281-5.

47. Ramesh, R., Kalin, L., Hantush, M., and Chaudhary, A. (2021). A secondary assessment of sediment trapping effectiveness by vegetated buffers. Ecol. Eng. *159*. 10.1016/j.ecoleng.2020.106094.

48. Lyu, C., Li, X., Yuan, P., Song, Y., Gao, H., Liu, X., Liu, R., and Yu, H. (2021). Nitrogen retention effect of riparian zones in agricultural areas: A meta-analysis. J. Clean. Prod. *315*. 10.1016/j.jclepro.2021.128143.

49. Mayer, P.M., Reynolds, S.K., Jr., McCutchen, M.D., and Canfield, T.J. (2007). Meta-analysis of nitrogen removal in riparian buffers. J. Environ. Qual. *36*, 1172–1180. 10.2134/jeq2006.0462.

50. Genet, M., Stokes, A., Fourcaud, T., and Norris, J.E. (2010). The influence of plant diversity on slope stability in a moist evergreen deciduous forest. Ecol. Eng. *36*, 265–275. 10.1016/j.ecoleng.2009.05.018.

51. Kim, J.H., Fourcaud, T., Jourdan, C., Maeght, J.-L., Mao, Z., Metayer, J., Meylan, L., Pierret, A., Rapidel, B., Roupsard, O., et al. (2017). Vegetation as a driver of temporal variations in slope stability: The impact of hydrological processes. Geophys. Res. Lett. *44*, 4897–4907. 10.1002/2017GL073174.

52. Stokes, A., Norris, J.E., van Beek, L.P.H., Bogaard, T., Cammeraat, E., Mickovski, S.B., Jenner, A., Di Iorio, A., and Fourcaud, T. (2008). How Vegetation Reinforces Soil on Slopes. In Slope Stability and Erosion Control: Ecotechnological Solutions, J. E. Norris, A. Stokes, S. B. Mickovski, E. Cammeraat, R. van Beek, B. C. Nicoll, and A. Achim, eds. (Springer Netherlands), pp. 65–118. 10.1007/978-1-4020-6676-4_4.

53. Mao, Z., Saint-Andre, L., Genet, M., Mine, F.-X., Jourdan, C., Rey, H., Courbaud, B., and Stokes, A. (2012). Engineering ecological protection against landslides in diverse mountain forests: Choosing cohesion models. Ecol. Eng. *45*, 55–69. 10.1016/j.ecoleng.2011.03.026.

54. Genet, M., Kokutse, N., Stokes, A., Fourcaud, T., Cai, X., Ji, J., and Mickovski, S. (2008). Root reinforcement in plantations of Cryptomeria japonica D. Don: effect of tree age and stand structure on slope stability. For. Ecol. Manag. *256*, 1517–1526. 10.1016/j.foreco.2008.05.050.

55. Beegum, S., Jainet, P., Emil, D., Sudheer, K., and Das, S. (2022). Integrated Simulation Modeling Approach for Investigating Pore Water Pressure Induced Landslides.

56. Douglas, G., McIvor, I., Manderson, A., Koolaard, J., Todd, M., Braaksma, S., and Gray, R. (2013). Reducing shallow landslide occurrence in pastoral hill country using wide-spaced trees. Land Degrad. Dev. *24*, 103–114.

57. Emadi-Tafti, M., Ataie-Ashtiani, B., and Hosseini, S.M. (2021). Integrated impacts of vegetation and soil type on slope stability: A case study of Kheyrud Forest, Iran. Ecol. Model. *446*. 10.1016/j.ecolmodel.2021.109498.

58. Seutloali, K.E., and Beckedahl, H.R. (2015). Understanding the factors influencing rill erosion on roadcuts in the south eastern region of South Africa. Solid Earth *6*, 633–641.